Universidade de Aveiro Departamento de Electrónica, Telecomunicações e Informática
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Programa de Doutoramento em Informática das
Universidades do Minho, Aveiro e do Porto

Daniel Nunes Corujo

Middleware de Comunicações para a Internet Móvel Futura

Communication Middleware for the Future Mobile Internet

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Tese apresentada às Universidades de Minho, Aveiro e Porto para cumprimento dos requisitos necessários à obtenção do grau de Doutor no âmbito do doutoramento conjunto MAP-i, realizada sob a orientação científica do Professor Doutor Rui Luis Andrade Aguiar, Professor Associado com Agregação do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro.

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o júri / the jury

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palavras-chave Handovers Independentes do Meio, Mobilidade, Máquina-a-Máquina (M2M), Internet das Coisas (IoT), Redes Centradas na Informação (ICN)

resumo

A evolução constante em novas tecnologias que providenciam suporte à forma como os nossos dispositivos se ligam, bem como a forma como utilizamos diferentes capacidades e serviços *on-line*, criou um conjunto sem precedentes de novos desafios que motivam o desenvolvimento de uma recente área de investigação, denominada de Internet Futura. Nesta nova área de investigação, novos aspectos arquiteturais estão a ser desenvolvidos, os quais, através da re-estruturação de componentes nucleares subjacentes que compõem a Internet, progride-a de uma forma capaz de não só fazer face a estes novos desafios, mas também de a preparar para os desafios de amanhã. Aspectos chave pertencendo a este conjunto de desafios são os ambientes de rede heterogéneos compostos por diferentes tipos de redes de acesso, a cada vez maior mudança do tráfego *peer-to-peer* (P2P) como o tipo de tráfego mais utilizado na Internet, a orquestração de cenários da Internet das Coisas (IoT) que exploram mecanismos de interação Maquina-a-Maquina (M2M), e a utilização de mechanismos centrados na informação (ICN). Esta tese apresenta uma nova arquitetura capaz de simultaneamente fazer face a estes desafios, evoluindo os procedimentos de conectividade e entidades envolvidas, através da adição de uma camada de *middleware*, que age como um mecanismo de gestão de controlo avançado. Este mecanismo de gestão de controlo aproxima as entidades de alto nível (tais como serviços, aplicações, entidades de gestão de mobilidade, operações de encaminhamento, etc.) com as componentes das camadas de baixo nível (por exemplo, camadas de ligação, sensores e atuadores), permitindo uma otimização conjunta dos procedimentos de ligação subjacentes. Os resultados obtidos não só sublinham a flexibilidade dos mecanismos que compõem a arquitetura, mas também a sua capacidade de providenciar aumentos de performance quando comparados com outras soluções de funcionamento específico, enquanto permite um maior leque de cenários e aplicações.

keywords Media Independent Handovers, Mobility, Machine-to-Machine (M2M), Internet of Things (IoT), Cross-layer, Middleware, Future Internet, Information-Centric Networking (ICN)

abstract

The constant evolution in new technologies that support the way our devices are able to connect, as well the way we use available on-line services and capabilities, has created a set of unprecedented new challenges that motivated the development of a recent research trend known as the Future Internet. In this research trend, new architectural aspects are being developed which, through the restructure of underlying core aspects composing the Internet, reshapes it in a way capable of not only facing these new challenges, but also preparing it to tackle tomorrow's new set of complex issues. Key aspects belonging to this set of challenges are heterogeneous networking environments composed by different kinds of wireless access networks, the evergrowing change from peer-to-peer (P2P) to video as the most used kind of traffic in the Internet, the orchestration of Internet of Things (IoT) scenarios exploiting Machine-to-Machine (M2M) interactions, and the usage of Information-Centric Networking (ICN). This thesis presents a novel framework able to simultaneous tackle these challenges, empowering connectivity procedures and entities with a middleware acting as an advanced control management mechanism. This control management mechanism brings together both high-level entities (such as application services, mobility management entities, routing operations, etc.) with the lower layer components (e.g., link layers, sensor devices, actuators), allowing for a joint optimization of the underlying connectivity and operational procedures. Results highlight not only the flexibility of the mechanisms composing the framework, but also their ability in providing performance increases when compared with other specific purpose solutions, while allowing a wider range of scenarios and deployment possibilities.

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Acronyms

3GPP 3rd Generation Partnership Project

ADSL Asymmetric Digital Subscriber Line

ALTO Application-Layer Traffic Optimization

AP Access Point

API Application Programming Interface

AR Access Router

CAPEX Capital Expenditure

CCN Content-Centric Networking

CDN Content Delivery Network

CXTP Context Transfer Protocol

DPWS Devices Profile for Web Services

DSMIPv6 Dual-Stack Mobile IPv6

EPS Evolved Packet System

ETSI European Telecommunications Standards Institute

E-UTRAN Evolved UMTS Terrestrial Radio Access Network

EXI Efficient XML Interchange

GSM Global System for Mobile Communications

GPRS General Packet Radio Service

GTP GPRS Tunneling Protocol

IETF Internet Engineering Task Force

IMS IP Multimedia Subsystem

IoT Internet of Things

IP Internet Protocol

IPTV Internet Protocol Television

IPv6 Internet Protocol version 6

ISP Internet Service Provider

HTTP Hypertext Transfer Protocol

ICN Information-Centric Networking

LAN Local Area Network

LIPA Local IP Access

LMA Local Mobility Anchor

LTE Long Term Evolution

M2M Machine-to-Machine

MAG Mobile Access Gateway

MICS Media Independent Command Service

MIES Media Independent Event Service

MIIS Media Independent Information Service

MIHF Media Independent Handover Function

MIPv6 Mobile IPv6

MME Mobility Management Entity

MMS Multimedia Messaging Service

MT Mobile Terminal

MTC Machine Type Communications

NDN Named Data Networking

NFC Near Field Communications

OASIS Organization for the Advancement of Structured Information Standards

OPEX Operational Expenditure

P2P Peer to Peer

PAN Personal Area Network

PDN Packet Data Network

PMIPv6 Proxy Mobile IPv6

PoA Point of Attachment

PoS Point of Service

QoE Quality of Experience

QoS Quality of Service

REST REpresentational State Transfer

RTSP Real Time Streaming Protocol

SAP Service Access Point

SIPTO Selected IP Traffic Offload

SLA Service-Level Agreement

SMS Short Message Service

SNMP Simple Network Management Protocol

SOA Service Oriented Architecture

TCM2M Technical Committee M2M

TISPAN Telecommunications and Internet converged Services and Protocols for Advanced Networking

UMTS Universal Mobile Telecommunications System

URI Uniform Resource Identifiers

VOD Video On Demand

WAN Wide Area Network

WAP Wireless Application Protocol

WLAN Wireless Local Area Network

WSDL Web Service Definition Language

XML Extensible Markup Language

Chapter 1

Introduction

We, as human beings, have become accustomed to the fact that more and more our everyday interactions have both invaded and been invaded by technological influence. Fuelled by important platforms such as the Internet and mobile communications, today it is possible to virtually monitor and operate thousands of processes with a single key press, or interact with people in the other side of the globe. The technological advances which enable the continuous evolution of the Information and Communication Technologies, hereinafter referred to as ICT, have added an evergrowing digital aspect to our lives. Not only they facilitate the way we interact as human beings, they also allow us to optimize the way we work, do business or take decisions. These technological advances contribute as well to the enhancement of how and where new applications of ICT can reside. This allows us to witness the introduction of digital technologies into novel aspects everyday, which not only contribute to the optimization and simplification of existing processes, but also serve the imaginary as the base for even newer developments.

A concrete aspect resides in an evergrowing mobile access utilization for accessing on-line content, as shown in Fig. 1.1. With the increase of digital interaction while on the move, users want to be able to keep accessing the same content that they do while using their computer at home or while working, and not just having access to a subset of features (i.e., as was in the Wireless Application Protocol (WAP) case). This means that, besides access to phone calls and email, users want to use their social tools (e.g., Facebook, Twitter, Foursquare, LinkedIn) and access multimedia content (e.g., YouTube, Hulu, OnLive) while on the move, by the millions. In order to deliver this amount of content at faster speeds, more bandwidth is required from the new releases of cellular networks, which place higher demands on available spectrum.

Alongside this growing adoption of digital possibilities, so does our feedback, amount of usage and requirements over such technologies increase. As human beings, we are not fully ruled by structured behaviours (contrary to the digital entities which strictly adhere to a state machine, in a greater or lesser degree), and quite easily create deviations from pre-established

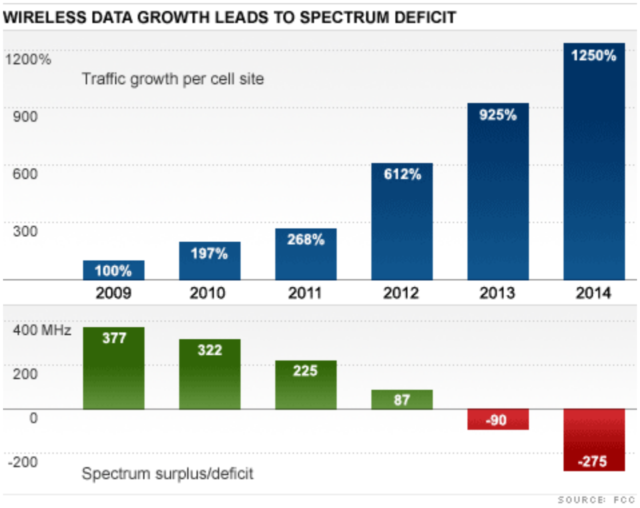

Figure 1.1: Wireless Data Growth and Spectrum Surplus/deficit (obtained from CNN.com)

paths. In this way, human ingenuity (which is also the source for new ideas) manages quite often to inadvertently find and generate new use-cases for existing technologies. As a result, sometimes the adoption of certain ICT applications not only exceeds expectations, but its usage is not always done according to plan.

This obviously means that the underlying technological infrastructure of, for example, the Internet, keeps being stressed to unprecedented new levels, stretching the capacity of the network dangerously close to healthy limits (e.g., affecting data rate, latency, call drop rate, quality and ultimately prices). To counter this, operators have started to search for solutions not only to fix the current situation, but also to contemplate the next coming years. Service level procedures, such as limiting the amount of data, throttling speeds or raising prices, always have a negative impact on the costumer. Increasing capacity through more equipment deployment and spectrum efficiency increase (or acquiring more) have an heavy toll on capital expenditure (CAPEX) and operational expenditure (OPEX). Also, as a final resort, merging operators with the aim of capacity increase has been thought of, but typically encounters resistance from regulative and competition ruling bodies.

In this context, research in a plethora of technological fields related with this problem (ranging from optimizing application and service design to make them aware of the conditions of the wireless access links, to mobility management protocols and spectrum efficient protocols) has become not only increasingly important but critically necessary. Not only the concepts associated with available ICT optimization and evolution need to be addressed, but also how the underlying technological fabric can be prepared and support tomorrow's utilization concepts, in a sustainable and feasible way.

In order to give some background to these research driving considerations, the upcoming section highlights a set of important, and innovative, Internet evolution trends, both in terms of core functionality, as well as in its usage.

1.1 Towards a Future Internet

The Internet is always evolving. The number of connected users just keeps growing, motivated by the desire to connect to an ever increasing number of novel and interesting services, providing the pervasiveness of being connected anytime, anywhere and in any way. This is in part supported by the simple architecture on which the Internet stands, but that same architecture is reaching a critical stage[1] where the problem is not only dealing with its current issues but also to consider the provision of a platform able to tackle the issues of tomorrow.

An important trait of the base Internet architecture has been its simplicity and its openness, which have been key factors that contributed to its success [1]. However, that same simplicity has stripped the underlying architecture of fundamental mechanisms that are required to support numerous features needed by the commercialization of today's Internet. Security, mobility, scalability both in terms of an increased number of users as well as in the demand for bandwidth, awareness of user preferences, management are all mechanisms that are not part of the base framework of today's Internet, and thus solutions to these issues are always decoupled solutions that were added on top of the existing mechanisms.

Although numerous protocols have been produced over the years, it has not been possible to introduce any major changes to the already-deployed base architecture of the Internet, due to backwards compatibility issues, updating costs on the infrastructure of carriers and operators, as well as clients and servers. As an example of this complexity, one can consider the amount of time it took for the first IPv6 services to finally become available, on the 6th of July of 2012[2] .

Since its conception, the Internet has been extended and enhanced with a plethora of new protocols and features that interact with it in multiple layers. This increased awareness to the shortcomings of the simple architecture, which had to be complemented with extensions and other mechanisms. This "patch-upon-patch" behaviour has added new facilities to the base design of the Internet, such as security, application-optimized protocols and multicast, evolving its infrastructure. However, the underlying architecture wasn't evolving, showing important limitations for working as a global infrastructure.

Discussions have been originated on whether the current architecture and existing protocols can keep their patching action, or if this course will lead to the collapse of the existing framework. From those discussions, a general consensus is emerging where a review of the current Internet architecture is required. Future Internet research thus considers this reviewing

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[1] Technology Review: The Internet Is Broken, `http://www.technologyreview.com/article/16356/`

[2] World IPv6 Launch, Internet Society, `http://www.worldipv6launch.org/press/world-ipv6-launch-unites-industry-leaders-to-redefine-the-global-internet/`

process and aims to propose a novel architecture that considers the desirable new attributes, while maintaining the simplicity and openness of today's Internet. For this matter, two major approaches are under consideration: a clean slate approach, and an incremental approach.

A clean slate approach aims to replace the current patching of the Internet by a whole new Internet architecture, not necessarily considering backwards-compatibility. It is mostly supported by the academia, because it can provide insightful and long-term research objectives. The current Internet should not impact the outcome of a clean slate approach. Instead, designers should be free to provide radical approaches to novel solutions. The clean slate approach aims to redesign the system from the start, without being restrained by already existing constraints in the current deployed system.

The incremental approach considers gradual improvements where individual challenges are addressed one at a time, aiming to provide a smooth transition to a system and architecture that support novel, or upgraded, features. It is more supported by the industry mostly because it is concerned with maintaining the existing infrastructure and not spending a vast amount of resources to implement drastic changes. Also, it is more interested in short to medium-term research objectives, aiming to ease the obtaining of financial revenues from newly launched designs and products. However, the introduction of small and incremental changes solving current issues and adding new functionality, can also introduce new issues themselves.

The scale of the current Internet prevents any major changes, and it is near impossible to convince stakeholders to believe and adopt a clean slate design, since it is just too risky, time and resource consuming. Even incremental evolution approaches need to reach a critical mass, in order to be widely adopted. To that end, a world-wide Future Internet research movement has sprung, aiming to present novel designs and solutions to overcome these shortcomings, and provide the way to develop a new iteration of global communications able to better support the challenges of tomorrow.

The European Commission has engaged in a commitment to provide valuable contribution to the Future Internet effort, aiming to become one of the major players. The 7th Framework Programme for Research and Technological Development (FP7) has seen the Future Internet as a key research activity. A number of consultation activities exist, undertaken by the European Commission, where both the academic and the industry communities help identify and approach the Future Internet Challenges. The Evolved Internet Future for European Leadership (EIFFEL[3]) initiative is a group of researchers with the aim of addressing the questions surrounding the definition of a Future Internet. They released a white paper[4] where they highlight the major drivers for this effort: pervasiveness of mobility-enabled wireless technologies, increased bandwidth and numbers of connected devices, more intelligent network elements fuelled by increased processing power and memory, location-enhanced context-aware services, frameworks for supporting user generated content, privacy supporting multiple identities and

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[3] EIFFEL Support Action, `http://www.eiffel-thinktank.eu/`

[4] EIFFEL White Paper, `http://www.future-internet.eu/uploads/media/Report_TT2008.pdf`

identifiers per user and, finally, service self-adaptation and configuration. In order to provide coordination on the increasing number of Future Internet research activities, the Future Internet Assembly (FIA[5]) was created to gather all major European research efforts. FIA became better known for its Bled Declaration[6] (named after the first kick-off meeting of the group, in Bled, Slovenia), which works as a call out for different sectors to develop a concrete Future Internet activity. The main objective is to consolidate efforts from the different projects by consideration of cross-domain issues, to promote a common understanding of the possible choices towards a Future Internet. FIA will also address standardization towards an openness and friendliness of Future Internet solutions, and also international co-operation, to help identify key partners that may aid the European effort.

The Future Internet Design (FIND)[7] is a long-term initiative sponsored by the National Science Foundation (NSF) of the U.S.A. research program on Networking Technology and Systems (NeTS). The NeTS, alongside with the Computer Systems Research (CSR), is the core research program on Computer and Network Systems for the NSF. The investments in NeTS provide funding up to 10 million dollars, for a duration of up to 5 years. The approach considers a wide scope of networking issues to help conceive the Internet of the future, emphasizing on a free and open society.

The AKARI program[8] is an Architecture Design Project from the National Institute of Information and Communications Technology (NICT) of Japan. AKARI, in Japanese, means a small light, which in turn provides the full meaning of "A small light in the dark pointing to the future". This is exactly the aim of the project, considering the development of a network architecture and design to support future technologies. As with the other initiatives, it addresses a broad number of research questions, considering novel approaches on optical and wireless networks, transport, identifier/locator split, security, routing with quality of service, virtualization, among others.

These research initiatives are active in a number of different research topics [2], composing areas such as security, content delivery, delay tolerant networking, management and control, services, routing and infrastructure design. This thesis explores four core interlinked research aspects with a large impact in the way ICT is operated in the coming years: i) the growing number of mobile devices with the ability to connect to different kinds of wireless access networks; ii) the different stringent requirements placed by the expected type of content traversing the Internet infrastructure, iii) the explosion of different kinds of devices being integrated into our environment with the aim of thrusting a digital fingerprint into our everyday life and, finally, iv) information-centric networking mechanisms for information inter-exchange optimization.

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[5] Future Internet Assembly, `http://www.future-internet.eu/home/future-internet-assembly.html`

[6] The BLED Declaration, Towards a European approach to the Future Internet, `http://www.future-internet.eu/fileadmin/documents/bled_documents/Bled_declaration.pdf`

[7] FIND, `http://www.nets-find.net/`

[8] AKARI Architecture Design Project, `http://akari-project.nict.go.jp/eng/index2.htm`

1.1.1 Mobility in Heterogeneous Networks

Over the recent years, the smartphone has seen a continuous growth in terms of consumer adoption. According to a recent International Data Corporation press release[9] smartphones represent 45.5 percent of all handsets shipped in the fourth quarter of 2012, to a total of 219.4 million devices in the same period (712.6 million for the total year), making a growth of 44.1 percent from the previous year. Smartphones not only provide a wide range of interactivity possibilities in terms of running applications and hardware capability, but they usually come coupled with multiple kinds of wireless access technology interfaces. Along with the traditional GSM/UMTS interface, it is common for smartphones to come equipped with other wireless interfaces such as WLAN, WiMAX, Bluetooth and Near Field Communications (NFC). This extended set of communication possibilities allows such devices to take advantage of more adequate connectivity opportunities available in their vicinity. As an example, a user with a packet data subscription from its mobile operator could reduce its cellular network byte download accounting if he or she activated its WLAN interface nearby an accessible hotspot, and did a download or accessed an on-line service using that link. The user could even save money from a call, if it was placed via a VoIP client (e.g., Skype) using the WLAN link.

However, this behaviour has a set or problems. First, it requires user intervention. In the example, the user had to activate the WLAN link deliberately and initiate the necessary applications under that new condition. A related, but more complex problem, is that typically the applications, services and operating systems have no dedicated mechanisms to take into consideration an IP address change: when a new connection is established in another link, a new IP address is negotiated. This means that, in order to take advantage of this new link, connectivity sessions belonging to applications need to be re-established. This is even more disruptive if the previous link is connected to a network that is fast fading, such as when the user is moving away from a WLAN access point. Lastly, services have no conception of the underlying access technologies specificities, in terms of link layer parameters and performance. They can provide dynamic mechanisms which allow services to adapt to changing network conditions (i.e., changing to a less bandwidth-demanding codec in a VoIP conversation). However, they have no means to do that in a predictive way or even to dynamically take advantage of other existing links.

Most of these problems have their root in the way the Internet was conceived. Its original architecture reflected a wired environment for accessing remotely located resources. As such, no special considerations were made considering terminals (and applications therein) changing their connectivity point with the network, while maintaining their on-going communication sessions. Even with the introduction of wireless technologies, and their subsequent access to the Internet, the architecture saw no changes related to those new technologies, requiring them to adapt themselves to the Internet, instead of the other way around.

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[9] IDC Press Release, 24 January 2013, `https://www.idc.com/getdoc.jsp?containerId=prUS23916413`

The Internet Engineering Task Force (IETF) initiated the research of IP mobility mechanisms, allowing applications to maintain their on-going sessions despite having their host devices changing to a new link. The Mobile IP protocol [3] was proposed in 2002 and marked the start of a growing set of IP session continuation mechanisms in a Wide area Network (WAN) (Section 2.1 references extensions done to the original IP mobility protocol). However, we haven't seen their generalized adoption as an Internet-wide mechanism. This is because *mobility* has to be more than just IP address maintenance: evolutions done to the base IP architecture typically follow a patch-upon-patch approach addressing a single issue, introducing complex interoperability issues with other existing mechanisms (e.g., security, authentication, accounting, QoS), often not solving wide scope problems.

For the scope of this thesis, the term *mobility* considers more than just allowing the operating system to maintain its IP reachability when the host device changes to a different link. Here, other aspects need to be considered such as the characteristics of the different access links. For example, prior to execute a IP mobility mechanism, the new link might need to be established (at Layer 2) which can be a costly process. Depending on the nature of the mobility protocol and of the application itself, unwanted service interruption can occur. Moreover, by disregarding the characteristics of the new link, the application can actually perform worse than it did on the previous link. As such, the mobility process requires the preparation of a *handover* in order to allow the mobile terminal and the network to specify and execute the necessary procedures for session maintenance.

The handover is one of the most critical aspects in seamless mobility. This is the process in which the point of attachment of a terminal changes to a new network. This is a complex process involving location identification, evaluation of performance of available networks at that location, decision to switch to a different network and actions to effect the switching. During the process of handover, the communication channel between the mobile host and a corresponding host may be broken, leading to loss of data. The communication channel is established after the handover is completed. Hence, there is no communication at least for the duration of handover, referred to as handover latency.

Handover latency has a significant impact on the performance of delay sensitive applications running on a mobile terminal. A large value of handover latency may increase the delay causing the drop of a VoIP or video session. The impact of handover latency is even higher if the user is mobile at high speeds, e.g. when travelling by car on a highway, or when the points of attachment change frequently.

Matters become further complex when considering that the handover process is not defined in an uniform way, but can occur with a wide variety of differences [4]:

- A handover can vary in terms of *scope*, producing **horizontal handovers** (e.g., involving different points of attachment of the same technology) or **vertical handovers** (e.g., when the mobile terminal is moving between points of attachment of different technologies).

- In terms of *control*, *initiation* and *assistance*, handovers can either be **network-controlled /initiated /assisted** or **mobile-controlled /initiated /assisted** depending on the degree of involvement of the terminal in those procedures.

- Regarding connectivity, a handover can be **make-before-break**, if the process establishes a new connection prior breaking the old one. It can also be a **break-before-make** when the old link is deactivated before the new one is made.

- Performance-wise, **fast** handovers deploy mechanisms for reducing handover latency, **smooth** handovers aim to minimize packet loss and **seamless handover** exercises no change in service capability, security or quality, albeit able to accommodate some service degradation.

- When considering the *area of effect* for the mobility process, it can either be **macro** (or **global**, when involving a large area (typically involving different domains), or **micro** (or **local**) when it occurs over a small area, and the protocol exploits the locality of the movement by confining movement related changes and signaling to the access network.

As such, different opportunities motivate the deployment of different handover strategies, whose architectures can be of radically different nature, including as examples: network controlled mobility approached [5], mobile-centric mobility [6], hierarchical mobility management [7] and host identity mobility management [8].

Moreover, the mobility process is also impacted by the different access technologies involved in the handover action. On one hand, the link association mechanisms, as well as the IP address configuration procedures, can be different depending on the access technology considered. On the other, the applications relying on the mobility process to maintain their connectivity sessions might behave differently after the handover, due to the characteristics of the new link.

To maintain simplicity, IP mobility protocols defined within the IETF operate only at layer 3 of the OSI stack. Optimizations for layer 2 transitions exist, such as IEEE 802.11r Fast BSS Transitions [9]. However, not only are these mechanisms typically aiming intra-technology handover procedures, but are as well standardized by different normalization bodies. As such, to accommodate a mobility management solution able to consider the different (and often complex) link layer handover procedures as well as the necessary layer 3 mobility execution, would create complex and hard to deploy solutions.

In order to facilitate and optimize handovers, the IEEE released in 2009 the 802.21 standard [10] for Media Independent Handover (MIH) services. This standard defines a cross-layer middleware which is able to abstract a series of operations (ranging from event notification to link control) belonging to different IEEE and 3GPP access technologies. Using these mechanisms, the same entity responsible for managing the handover procedure is thus able to integrate IP mobility procedures, and customize them over different access technologies [11] [12].

However, the standard itself does not define how the handover procedures should be managed or executed. As seen previously, handovers can be executed in a number of ways. For example, mobile initiated handovers and network initiated handovers originate quite different signaling sequences. As such, despite the availability of integration mechanisms between mobility and handover processes, an entity with the role of mobility manager is still required. Such an entity, akin to the Mobility Management Entity (MME) defined in the 3GPP, is able to collect information for the different handover opportunities surrounding the mobile node, and use them to create an optimized handover decision. This decision can be based not only in the preference of type of access network to be selected, but can also take into consideration policies from the network, requirements from the services being run in the mobile node, or even network conditions management (e.g., load balancing). However, the current developments of the MME for LTE in the 3GPP, consider mostly only bearer setup operations, or traffic offloading for domain-managed WLAN alternatives, and do not take yet full advantage of the wide array of existing Internet connectivity choices available to mobile terminals today.

1.1.2 Changes in Internet Traffic Utilization

With the technological evolutions felt in both capacity and possibilities of the devices we use today, the underlying communications infra-structures to which they connect to, and of the services and applications that they run, the habits and the way we use the Internet is changing.

In the beginning of the XXI century, with the proliferation of ADSL and cable broadband Internet Service Providers (ISP), file-sharing became the main source of Internet-generated traffic. The deployment of P2P file-sharing protocols (such as BitTorrent, ed2k, kaazaa and gnutella) contributed quite a lot for this, allowing large amounts of data inter-exchange in an easy to the users. This, of course, escalated bandwidth consumption world-wide. Traffic reports from 2008/2009 from Ipoque[10], shown that around 50 percent of all Internet traffic came from P2P usage (depending on geographical location).

However, the same study also shown that the growth of P2P traffic was gradually declining when compared to the previous years. According to a Sandivine Intelligent Broadband Networks report[11] this was due to an online video application: Netflix, as shown in Tab. 1.1. The study revealed that P2P was being surpassed by real-time entertainment, including

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[10] Ipoque Internet Studies, `http://www.ipoque.com/en/resources/internet-studies`

[11] Sandivine Global Internet Phenomena Report, Spring 2011

services like Netflixk, Huly, YouTube and Spotify. Such results were being also presented by other entities, with Cisco [13] identifying P2P as surpassed by video in 2010 achieving volumes close to 90% of consumer traffic by the end of 2015.

	Upstream		Downstream		Aggregate	
Rank	Application	Share	Application	Share	Application	Share
1	BitTorrent	47.5%	Netflix	32.69%	Netflix	29.03%
2	HTTP	11.45%	HTTP	17.48%	HTTP	16.59%
3	Netflix	7.69%	YouTube	11.32%	BitTorrent	13.47%
4	Skype	4.27%	BitTorrent	7.62%	YouTube	9.90%
5	SSL	3.57%	Flash Video	3.41%	Flash Video	3.04%
6	Facebook	2.19%	RTMP	3.12%	RTMP	2.81%
7	PPStream	1.73%	iTunes	3.05%	iTunes	2.69%
8	YouTube	1.64%	Facebook	1.78%	SSL	1.96%
9	Xbox Live	1.31%	MPEG	1.72%	Facebook	1.84%
10	Teredo	1.25%	SSL	1.69%	MPEG	1.49%
	Top 10	**82.63%**	**Top 10**	**83.88%**	**Top 10**	**82.83%**

Table 1.1: Peak hour traffic in North America (source: Sandivine)

An important trigger point for the raise of video are social networks, such as Facebook, Flickr, Twitter or even YouTube itself. These networks have a viral effect on the widespread of information, not only due to the their large user-base, but also due to the usage of simplified sharing mechanisms. Often, a simple mouse click allows a user to share a video link with thousands of friends: if these friends like the video as well, most probably they will share it with a thousand more, and so on. Each click on that video link, means a server download from the point of origin towards the user requesting it, meaning that not only more and more videos are watched, but every video is watched a large amount of times.

With this change, most of the protective mechanisms employed by ISPs to strengthen their networks against the widespread usage of P2P traffic (e.g., bandwidth throttling, traffic capping and others) were no longer useful. In fact, they could be potentially harmful to video traffic.

The nature of video traffic itself, behaves differently from P2P traffic. Whether it is composed by real-time video (e.g., video conference) or Video on Demand (VOD) (e.g., IPTV), video as a service is more sensitive to network performance issues than file-sharing: it places a strict set of minimum requirements that, if not met, are noticed by the user viewing the content. Although different architectures considering the deployment of multimedia facilities in specific operator-managed environments (i.e., IP Multimedia Subsystem (IMS), Content Delivery Networks (CDN) and caching) or IETF-defined protocols (i.e., Real Time Streaming Protocol (RTSP)), the fact is that, like mobility, this was not an initial requirement of the initial Internet architecture, and is thus consumed as a best-effort service.

As such, currently video can reach users by employing compensation mechanisms such as buffering [14], decreasing quality, or accepting low performance (e.g., video freeze). However, with the evergrowing introduction of video-related products (e.g., MEO Go, ZON Online), and the increase in requirements by the users (e.g., HDTV, using video while on the move in cellular networks) in a bottled-neck Internet, not only creates a time-bomb effect, but also hinders the development of novel services that go beyond video.

Moreover, performance and architectural design aren't the single problems. Taking into consideration the multiplicity of Internet access technologies (both wired and wireless) available, even more complex scenarios will be presented in the near future. For example, in order to provide an optimized Quality of Experience for the video being sent, the video service must behave considering that the end user can be connected to the Internet using very distinct technologies (e.g., fibre versus mobile). The scenario can be even more complex if the user is on the move, connected to a wireless technology, where the video service (in accordance with the network) must ensure that the video is delivered with high quality, despite fast-changing dynamic conditions. Lastly, the devices used to view the video can change themselves, considering scenarios where the user, when arriving home, would like that the video that he was watching on his mobile phone while commuting, was dynamically switched to his TV, in a seamless way.

1.1.3 An Internet of Things and Machine-to-Machine Communications

In the recent years, heterogeneity of new adopted technologies has not only been manifesting itself considering wireless access technologies, but on the devices that use them, themselves. Recent advances in miniaturization have allowed electronic devices to be coupled with networking capabilities, ranging from simple connectivity scenarios (i.e., low-cost sensors sending simple environment information bits using Personal Area Networks (PAN) technologies, such as Bluetooth[12], ZigBee[13], IrDA[14] and others) to full-fledged integrated environments composed by sensors, actuators, context servers and other enabling Ambient Intelligence technologies [15].

Here, the ultimate goal is to provide societal improvements through the provision of an environment filled with pervasive and supportive electronic devices and services. This vision is built on seamless interconnection of huge numbers of increasingly smaller and intelligent devices, acting as the building blocks for an Internet of Things (IoT) [16]. In the IoT, everyday objects are empowered with processing power and connectivity, allowing new kinds of services. This vision of bringing together the digital and physical worlds as spawned a rich area of novel and exciting research, as well as industrial deployment outcomes [1], but has become as well more a question of how to address the multitude of technical changes

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[12] IEEE 802.15 Working Group, `http://www.ieee802.org/15/`

[13] ZigBee Alliance, `http://www.zigbee.org/`

[14] Infrared Data Association, `http://www.irda.org/`

required (i.e., interoperability, radio spectrum, miniaturization, etc.), as well as user-related issues (i.e., privacy, data protection).

As an example of a specific deployment area of the IoT, Urban Computing [17] focuses on providing this vision to public environments such as cities and other urban areas. Here, the specific aim is to integrate computing, sensing and actuation technologies into the everyday life of urban inhabitants as well as their settings and places.

Furthermore, these concepts are being captured into intelligent network solutions featuring Machine-to-Machine (M2M) interactions, with the purpose of deploying enabling-technology products into the market. These products are able to enable, assist and enhance technological processes in an array of areas such as energy, vehicle telematics, e-health, retail, industrial automation, security, transport and logistics, consumer electronics and others. Specifically, when the dissemination of information from the different entities involves operated wireless access networks, this allows telecommunications stakeholders[15] to grow M2M into an important strategic business area[16].

The concept is, of course, not entirely new. In fact, M2M has been the base for the peer-to-peer approach of the information inter-exchange between remote Internet entities. However, with the proliferation of web-based service technologies, a plethora of M2M service delivery platforms have come to the market, pursuing a revenue opportunity. With the diversity of the specialization areas of the different developers of such products, the end result is a series of non inter-operable "vertical silo" solutions, leading to a disperse set of sensor and actuator network "islands" that are connected to the Internet [18].

With the possibility of integrating not only PAN, WAN but also cellular technologies into IoT devices (e.g., GPRS communication modules coupled into the device's hardware), mobile operators have started to roll-out M2M standards[17][18] with the aim of providing an uniform M2M Service Provider platform definition, and integrate it with open interfaces towards the underlying cellular access network providers.

However, in parallel, manufacturers are developing new kinds of devices everyday, with IoT possibilities. Even our own smartphones come equipped with a series of sensors (e.g., accelerometer, compass, light sensors) and access technologies (e.g., bluetooth, NFC, WLAN, cellular). This creates an immense array of interfacing possibilities that need to be considered, when conceiving integrated M2M platforms: different manufactures can provide different interfacing procedures and mechanisms (operating or not over different transport means) for their different devices. As such, in such a wide range of possibilities, a common ground must be found, that is flexible enough to take into consideration not only the specifics of each device, but also the accessing link technology.

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[15] Deutsche Telekom M2M Competence Center, `http://m2m.telekom.com/about/m2m-competence-center`

[16] Maximizing Mobile Operator Opportunities in M2M (Sponsored by Cisco), `http://www.cisco.com/en/US/solutions/collateral/ns341/ns523/ABI-CISCO_M2M_Operator_Opportunity.pdf`

[17] ETSI Machine to Machine Communications, `http://www.etsi.org/Website/Technologies/M2M.aspx`

[18] Global Initiative for M2M Standardization, `http://www.3gpp.org/Global-Initiative-for-M2M`

1.1.4 Information-Centric Networking

Nowadays, Internet users demand a more reliable and faster response when accessing services deployed over this massive worldwide network, due to the increasing societal reliance on the Internet and on-line services. The host-centric nature of its underlying design was initially exploited for simple resource-sharing applications and E-Mail communication which, through an evolutionary path, gave way to the Word Wide Web (WWW) where content was displayed in web pages. Now, as discussed in Section 1.1.2, Web2.0 has paved the way to the rise of applications such as YouTube and the social-networking paradigm, shifting the focus from the hosts into the content itself. However, that exact underlying framework supporting the access to content, was created to access machines and resources therein, tightly coupling host identifiers and the content name, to routing and name translation, requesting the support of naming protocols such as the Domain Name System (DNS) [19].

To address the limitations of the current Internet architecture, some authors are working on clean slate approaches. One of these approaches that is acquiring a significant relevance is the Information-Centric Networking (ICN) paradigm, which is based on information instead of the logical connections between machines as in the current Internet. Also, it solves other problems of the current Internet related with NAT Transversal, depletion of IP addresses, security, mobility and multicast communications [20].

The deployment of clean slate proposals naturally imposes a bigger investment by the network operators when compared with incremental proposals and, therefore, they have become hesitant to migrate to a new architecture. To increase network operator support in integrating new Internet architecture mechanisms, new solutions must be able to be incrementally deployed and, at the same time, develop some degree of coupling with the current IP network.

To support this work and contribute to its deployment in the future, different research projects have taken shape:

1. **PSIRP:** The Publish-Subscribe Internet Routing Paradigm (PSIRP[19]) project, extends the publishing/subscription paradigm to make content as the centre of networking operations, while removing the location-identity split commonly existing in current networks. It finished in October in 2010, leaving behind, in addition to a rich set of scientific contributions, an open-source implementation called Blackhawk[20] for the FreeBSD operating system;

2. **4WARD:** Amongst other aspects aiming to progress the Internet architecture under a clean slate approach, the 4WARD[21] had a specific work package dedicated to information-centric applications, from which resulted the Networking of Information

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[19] FP7 PSIRP,`http://www.psirp.org/`

[20] Blackhawk, A Publish\Subscribe System for FreeBSD, `https://wiki.hiit.fi/display/psirpcode/Home`

[21] FP7 4WARD, `http://www.4ward-project.eu/index.php?s=overview`

(NetInf[22]), an ICN framework instantiation focusing on the creation, location, exchange and storage of Named Data Objects. It features as well an open-source implementation[23], and finished in June 2010;

3. **PURSUIT:** The PURSUIT[24] project is the follow-up from PSIRP, focusing on routing and forwarding of information in a data-centric way. It features its Blackadder[25], an evolution from PSIRP's Blackhawk. The project has finished in February 2013;
4. **SAIL:** The Scalable and Adaptive Internet Solutions (SAIL[26]) progressed the work done in ICN by applying it to existing Future Internet lines of research, such as Cloud Computing, and enhancing the existing NetInf instantiation with such considerations. The project finished in January 2013;
5. **CONVERGENCE:** The CONVERGENCE[27] project addressed the ICN paradigm, under a publish/subscribe scope, but targeting more multimedia-related concepts, such as MPEG-21 based Versatile Digital Item (VDI) information naming. The project finished on February 2013, providing a downloadable CONVERGENCE Peer Kit[28], showcasing some aspects of the framework;
6. **CCN:** The Content-Centric Networking (CCN[29]) project, was an interest area for the Palo Alto Research Center (PARC). It targeted a human-readable hierarchical naming scheme, leveraging cache-assisted routing techniques, and intrinsically supporting mobility and security. This ICN instantiation framework provided a popular open-source implementation, in the form of the CCNx[30] software project, and was later on absorbed by the Named Data Networking project;
7. **DONA:** The Data-Oriented Networking Architecture (DONA) [21] is another ICN instantiation framework, targeting naming and name resolution aspects.

Despite the different approaches and research initiatives highlighted here, all of them aim at solving four main problems [22] (1) the naming structure of the content, (2) the mechanism to find the content, (3) how to deliver the content to the requester and (4) caching the content inside the network. This set of related problems motivated the Internet Research Task Force (IRTF) to assemble the Information-Centric Networking Research Group (ICNRG[31]),

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[22] NetInf, Network of Information,`http://www.netinf.org/`

[23] NetInf Open-Source Implementation, `http://sourceforge.net/projects/netinf/`

[24] FP7 PURSUIT, `http://www.fp7-pursuit.eu/PursuitWeb/`

[25] Blackadder: a Publish\Subscribe Prototype for Linux & FreeBSD, `https://github.com/fp7-pursuit/blackadder`

[26] FP7 SAIL, `http://www.sail-project.eu/`

[27] FP7 CONVERGENCE, `http://www.ict-convergence.eu/`

[28] CONVERGENCE Peer Kit, `http://www.ict-convergence.eu/demodownloads/`

[29] Content-Centric Networking (CCN), `http://www.parc.com/services/focus-area/content-centric-networking/`

[30] CCNx Software Project, `http://www.ccnx.org/`

[31] Information-Centric Networking Research Group (ICNRG),`http://irtf.org/icnrg`

addressing the research challenges and establishing baseline scenarios to serve as guidelines for experimental activities, interfaces/APIs, contributing to a common dissemination and integration effort.

Finally, the different research and standardization efforts also assist in ICN progression aspects, by exposing different system designs to evermore complex scenarios supported by large-scale experimentation from the Future Internet Research and Experimentation Initiative (FIRE[32]), enabling researchers to test new protocols and architectures in real conditions over production networks (e.g., through virtualization and software-defined networking mechanisms), simplifying the validation of future evolutions, reducing the gap between research and deployment solutions.

With the set of Internet evolution trends pertaining to this thesis research work defined, we now look at the motivation aspects that contributed to the shape of this dissertation.

1.2 Dissertation Motivation

Although each of the previously highlighted evolution trends has its own particular challenges when it comes to its integration, deployment and operation management in their respective actions, we can formulate a unifying motivational statement for this work: To optimize device and service usage through the provision of generic means for managing and controlling access interface link operations, while on the move.

This motivational statement can be further subdivided into a core set of motivating reasons for the research present in this dissertation:

- **Relevance and Timeliness:** The targeted areas reflect research venues by their own right, which are continuously being subject to novel evolutions and ideas. The explosion of dynamic multimedia content consumed by wireless devices on the move, with connectivity capabilities being deployed in many different kinds of smart devices, orchestrate an exciting heterogeneous environment which is in dire need of supportive control and management tools. Moreover, by crossing the different affected technological areas together, exciting new opportunities are further made available.

- **Technological challenges:** Controlling and optimizing link access in heterogeneous wireless environments, optimizing link connectivity based on service and traffic parameters, interfacing with a myriad of different smart devices and the usage of novel content-centric mechanisms, all pose complex challenges due to the nature of their associated processes and mechanisms. This is further exacerbated when the different areas are combined with one another, in the attempt to offer a combined control framework towards their generic optimization. It is not the same to develop a solution targeting

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[32] Future Internet Research & Experimentation, `http://cordis.europa.eu/fp7/ict/fire/`

devices with powerful characteristics, such as a recent laptop, and except that such a solution will operate without any performance hindering when applied to low-powered nodes, such as simple sensor devices. The sheer amount of specific and related problems between the different technologies thus needs careful addressing in order to avoid the elaboration of cumbersome, singleton solutions.

- **Understanding broader networking issues:** Information interexchange, under this heterogeneous combined setting scenario, assumes a prime importance due to the plethora of possible protocols, technologies and behaviours taking place in a communication process. Resulting deployment scenarios will provide an understanding of the impact that these differences have in the exchange of widely different kinds of information. Moreover, any attempt for optimization and simplification needs to be considered under a generally-adoptable approach, lest being only deployable over a small set of scenarios.
- **Laying the work for future frameworks:** By targeting Future Internet research as the base address point of this thesis, and by focusing on a set of core mechanisms that impact the foundation of its operations, one finds itself in the essence of creation for upcoming means of information dissemination. Particularly when addressing management and controlling aspects aiming to provide optimized behaviours in different aspects, it is natural to assume, and aspire, that resulting solutions will be present in core areas with the ability to impact many more operational aspects of their underlying structure. With this, the contribution possibilities, and impact, have the capability of reaching many other aspects and research efforts.

1.3 Problem Statement

The Internet has architectural problems, stimulated not only by the demands placed by the changes in how we use it, but hinders as well the possibility of future scenarios. Tab. 1.2 summarizes the research problems addressed in this PhD thesis, taking into consideration the the specific core research aspects identified in section 1.1.

The first issue comprises the impact of the evergrowing number of mobile Internet users. Not only this issue stresses the access networks managed by operators, where an increasing amount of devices use online services and download information generates an explosion of bandwidth consumption, but also compromises the quality of experience said users enjoy when using such services. As such, this issue requires the definition of a base flexible architecture, not only able to withstand the current increases in mobile Internet access, but also to be further extended in the future (not only to support new waves of increase, but also new services and architectural requirements).

The second issue considers the utilization of IP mobility support. It addresses the deployment requirements placed by such mobility protocols and the underlying infrastructure

Num.	Issue	Effect	Measures
1	Increased mobile access utilization	Decreases the capacity and quality of service. Prevents further deployment of new services	Flexible design allowing further extensions
2	Mobility protocols for session continuation	Requires deployment of an overlay mobility management framework. Signaling creates overhead and performance issues	Localized mobility enhancements. Integration into heterogeneous environments
3	Impact of mobility in services and access network integration	Services can suffer disruptions during the mobility process, or see their requirement unmet in the new network	The mobility process needs to be service aware, as well as access network aware. A MME is required for optimized mobility management procedures
4	Video traffic growth in the Internet	Video traffic is very sensitive to changing network conditions, with visible degradation noticed by the end-user	Adoption of video-aware optimization techniques when video traffic is involved. Integration into heterogeneous environments
5	Different kinds of usages made from a wide array of IoT devices	Different scenarios using different device characteristics in terms of both internal (i.e., provided API, included access technologies) as well as external (i.e., connectivity to the internet) possibilities	Definition of common access control procedures able to be understood by a wide range of devices.
6	Content as the main driver for Internet utilization	Content reachability will be done in an unoptimized way, since users and services have to transverse host-centric mechanisms to reach the information	Leverage of content-centric mechanisms for optimized information interexchange.

Table 1.2: Research Problems Addressed in this PhD Thesis

interfacing to make them work. The mobility process itself can be the origin of generated overhead, due to the required signaling for IP address updating. This not only can have a high impact in the services being used during the mobility process, but also requires a more seamless integration with the underlying access networking operations.

The third issue is a more specific problem related with the second, but whereas the second issue considers how mobility mechanisms impact the data services depending on it, the third considers the role that these services and high-level entities can have in optimizing the handover process itself. In this sense, having the services providing input to a mobility management decision entity can facilitate in selecting the handover target, and making sure that access network mechanisms are also considered in terms of the best approach.

The fourth item considers the current and near-future traffic utilization trends, and how they impact the service quality of experience. Since, for example, video is composed by visual and audible multimedia content, any disturbance caused by the network can be noticeable to the user. As such, different provisions and choices need to be done when deploying video services, particularly if different kinds of access networks are involved.

The fifth issue acknowledges that the technological evolutions surrounding the Internet are not only being done in terms of types of access networks and kinds of traffic traversing it, but also on the devices and services connecting to it. With the advances in electronics miniaturization, different kinds of devices are coupled with wireless connectivity capabilities, increasing not only the interesting opportunities and scenarios for new added-value services, but increases as well the amount of generated traffic. Moreover, when different manufacturers and kinds of devices are involved, this means that different interfacing solutions exist, which raise the complexity of having generic-purpose deployment scenarios.

Finally, the sixth issue considers the impact that the underlying architecture of the current Internet has, in supporting the upcoming content-centric paradigm. Specifically, even through ICN has become a research field by itself, one has to consider how it will be impacted with other areas beyond optimized content reachability, such as mobility and management aspects.

It is clear that this set of issues reflects the lack of a generic purpose **middleware** that can link the requirements placed by running services and applications to available link layers, allowing them to optimize the way the connection resources are used. Moreover, taking into consideration that a number of different network and user architectural entities can be involved in this optimization process, this middleware needs to be able to provide such cross-layer interactions in a remote way, composing a control mechanism that can be used to interlink both high-level procedures and lower-layer operations in a common supportive way. Furthermore, these concepts must as well be flexible enough to be deployed in a future-proof way, by exposing them to clean slate environments and evolutions of the current Internet architecture.

As such, the research problem of this thesis can be stated by evolving the unifying motivational statement from Section 1.2 into:

How to define a generic purpose ***middleware*** *enabling high-level entities and services to provide their requirements and allow them to serve as abstract inputs towards the execution of link layer mechanisms, with the mobility procedures being able to leverage that information and control towards the support of session continuation in a heterogeneous access network environment providing access to different kinds of mobile devices?*

1.3.1 Research Objectives

In this section, the research objectives addressing the outlined thesis research problems are presented.

- ***Research Objective 1:*** *How can a media independent* ***middleware*** *control plane be deployed over the current Internet architecture, that is flexible enough to operate in a multitude of devices with different specifications, connected using different access networks and running different services and applications?*

  The wide availability of web services making use of different kinds of devices (i.e., sensors and actuators) in IoT environments provide extremely heterogeneous scenarios in terms of defining, accessing and changing information and control of those devices. Different attributes, resource representations, interfaces and protocols are very complex to integrate, where customized solutions are made to link the devices to the services using them (a set of examples and their brief explanation is provided in Section 2.3). These high-level platforms often disregard the connectivity technologies that the devices use to disseminate their information and receive commands from controlling entities, as well as the differences in capacity (from processing power to available memory). Using these solutions, deployers have to pre-assess which devices and services will be involved, preventing the real-time integration of new entities into already-existing scenarios.

- ***Research Objective 2:*** *With the different requirements placed by services reaching mobile terminals connected to different access networks, how can a network mobility decision entity make use of a generic middleware to provide an optimized handover decision, making stringent use of the required signaling, and being able to procure and activate the necessary link resources?*

  IP mobility mechanisms have been being refined and enhanced taking into consideration the reduction of their signaling fingerprint, handover delay impact and complexity of deployment. However, even though that network operators are directly involved in the standardization of IP mobility protocols, the normalized solutions lack the support for executing related link layer procedures usually coupled to the mobility process (e.g., link scanning, attachment and even choice). For this, the mobility mechanism needs to be coupled with a management entity which is able to collect input from the mobile terminal, the network and (if necessary and/or possible) the services being affected by that mobility action. However, the access, control and interfacing with such link procedures are usually quite different depending of which is the technology involved. In these conditions, a management entity either becomes far too complex to be able to accommodate the full range of PAN, LAN and WAN accesses, or only provides mobility management for a limited subset. Both solutions are not feasible if operators want to both attract the most number of clients possible, as well as support the latest services and applications over any medium.

- ***Research Objective 3:*** *When video traffic places a set of minimum requirements for network conditions, how can a generic* ***middleware*** *support a mobility management process taking into consideration such requirements and the necessary link access procedures to execute handovers?*

  Contrary to downloading a file (or accessing some kind of delay-tolerant service, where packet reception latency or even the delay caused by losing and re-requesting packets), video traffic is highly affected by the network conditions. Not only real-time video (where performance is readily noticed by the used, which starts to experience video freezes or codec errors), but also other applications such as VOD become affected if network conditions deteriorate beyond the capabilities of the buffers towards the receiver. In this sense, it becomes necessary to develop a framework (already considering the evolutions towards mobility support and link layer abstraction from the two previous research problems), but that also takes into consideration the specificities and requirements of video traffic passing through.

- ***Research Objective 4:*** *When clean slate designs are being proposed as replacements of the network layer of the current Internet, aiming to optimize content interexchange, how can a control management* ***middleware*** *be generic enough to see its operational mechanisms be deployed in those environments as well?*

  With both academia and the industry recognizing the need for evolution in the underlying architectural aspects of the current Internet, its current base design is being questioned. This allows the berthing of radical new ideas, fomenting clean slate designs that overcome the increasingly growing barriers imposed by the ageing architecture of the Internet. As such, the innovations regarding the previous research objectives (achieved through incremental innovation) cannot be deemed future proof, if they are not subjected in this new kind of paradigm. As such, it is important to analyse the operational aspects of an ICN deployment, and verify how the management and control middleware mechanisms would contribute therein.

1.4 Achievements

The work presented here reflects the achievements and outcomes of the author towards a novel Future Internet framework, spawning into a number of different research areas and subjects, ranging from middleware cross-layer optimizations to mobility management mechanisms, the IoT, M2M communications and ICN.

This allowed the author to actively participate and engage in different international and national research projects, to establish internationally visible open-source software projects, to contribute to IEEE and IETF standardization and to generate a valuable collection of meaningful scientific contributions.

1.4.1 Research Projects

The different areas targeted by the research challenges identified in this dissertation, allowed the author to participate and contribute to different international and national research projects:

- The MEDIEVAL[33] project stands out as both a generator and recipient of novel ideas, targeting innovative cross-layer aspects in a novel Internet architecture addressing the optimization of video traffic in mobile networks. Here the author contributed many aspects of the project, both in architectural, design, and experimental deployment aspects. Highlighting the design aspects, mobility management contributions were applied into the project, providing enhancements in respect to protocols and system design, as well as the integration of media independent handover mechanisms and their extension to encompass video-service related requirements and optimizations.
- The national project APOLLO[34], in association with Portugal Telecom Inovação, addresses the exponential growth of M2M communications in IoT scenarios. Here, the concepts for establishing an operator-supported sensor and actuator management platform, are being researched and deployed in real-life scenarios, aiming to generate a new world of applications encompassing a wide array of activity sectors. Here the author contributed with the architectural and design aspects for the mediating layer between the different smart devices and the operator management framework.
- The OFELIA[35] project aims to create and offer a dynamically extendible Future Internet experimental facility, through the usage of Software-Defined Networking (SDN) mechanisms. Here, through an open-call process, the Instituto de Telecomunicações

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[33] MultimEDia transport for mobIlE Video AppLications, `http://www.ict-medieval.eu`

[34] The APOLLO project is partially funded by the Portuguese Innovation Agency and National Strategic Reference Framework (AdI/QREN) under grant agreement No. 2011/021580, `http://atnog.av.it.pt/projects/apollo`

[35] FP7 OFELIA, `http://www.fp7-ofelia.eu/`

composed a new work package with the aim of associating information-centric procedures to the SDN mechanisms, providing a new clean slate approach to reach for content with intrinsic mobility and multicast support. The author is currently contributing to the overall architecture specification and integration of ICN and SDN aspects, aided by IEEE 802.21 link layer information and control for optimization aspects.

- The ANDSFNet[36] is an Innovation Project in cooperation with Portugal Telecom Inovação, which targets the enhancement and deployment of an extended Access Network Discovery and Selection Function (ANDSF) [23], from the 3GPP Evolved Packet System [24], envisaging optimal wireless access network connectivity.

- The ONELAB2[37] project provided an experimentally-driven research support initiative, through the provision and operation of an open federated laboratory. Here, the the Instituto de Telecomunicações focused on benchmarking and generic performance metrics able to be used in different kinds of experimental scenarios.

- The 4WARD project (already introduced in Section 1.1.4), addressed innovations for a clean slate Internet. Amongst different research items, the Instituto de Telecomunicações focused on the Generic Path abstraction, aiming to re-utilize an object-oriented socket-like interface to enable connections to information elements rather than specific hosts.

1.4.2 Open-source Software Projects

Part of the concepts developed by the author has contributed to the creation of two open-source software projects:

- ODTONE[38] (Open Dot Twenty ONE) provides a flexible open-source multi-operating system supportive implementation of the IEEE802.21 Media Independent Handovers standard [10]. This implementation has had a decisive impact in the design and validation of many aspects proposed by the research outcomes achieved during this thesis, providing experimentally-driven proof-of-concepts and scientifically published results. This contributed as well to its external visibility, allowing ODTONE to become the official IEEE 802.21 implementation of the MEDIEVAL project, as well as allowing the verification of new extensions proposed in IEEE 802.21 standardization work, by the author of this thesis. Moreover, its system design and media independent abstraction mechanisms have also inspired the ICN management work.

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[36] ANDSFNet, `http://atnog.av.it.pt/projects/andsfnet`

[37] FP7 ONELAB2, `http://www.onelab.eu/`

[38] Open Dot Twenty ONE, `http://atnog.av.it.pt/odtone`

- OPMIP[39] (Open Proxy MIP) composes an open-source implementation of the Proxy MobileIPv6 mobility management protocol [25]. It provides the mobility management mechanisms enabling network localized mobility. Is was amply used as the mobility management protocol in scientific work published within scope of this thesis, and currently represents a flexible development base for PMIPv6 extensions being discussed by the IETF.

1.4.3 Standardization Contributions

The integration and evolution of the different technological components derived from the research challenges, exposed them to novel utilization aspects and procedures. As such, through the detailed analysis of their intrinsic operations, not only inadequacies and issues were found, but also new opportunities for enhancement were detected. This allowed us to approach the standardization bodies responsible for IEEE 802.21, and for analysing ICN deployment opportunities.

IEEE 802.21

The integration of media independent aspects into sensor-like environments, motivated the addition of multicast signalling support for standard IEEE 802.21 messages [26]. Later on, this consideration generated interest by the IEEE 802.21 working group, with a new Task Group (IEEE 802.21d) being created on March 2012 for Group Management Services. This amendment will establish the required changes to the original specification, in order to manage the mobility of groups of nodes, with the author invited to contribute to requirements and scenarios specification documents. Currently, the author is contributing to the proposal amendment document, which will be submitted to the ballot approval process this year.

Incrementally, the author is also participating as a reviewer of the IEEE802.21c amendment on Single Radio Handovers, which is currently in the final stages of the ballot approval process. Finally, frequent contributions regarding enhancement suggestions are corrections are also submitted and presented to the working group.

IRTF ICNRG

The management considerations developed over ICN frameworks [27], alerted the IRTF's ICNRG[40] to the possibilities of management requirements in ICN networking, but also the usage of the ICN mechanisms to execute the management procedures themselves. With this in mind, the author was invited to author a IRTF draft on ”ICN Management Considerations” [28], as well as to contribute to ICNRG work items on ”Research Challenges” [29] and

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[39] Open Proxy MIP, http://atnog.av.it.pt/projects/opmip

[40] Information-Centric Networking Research Group (ICNRG), `http://irtf.org/icnrg`

"Baseline Scenarios" [30], contributing on Mobility management aspects and the role of ICN on IoT, respectively.

The "ICN Management Considerations" draft was presented at the 86th IETF Meeting in Orlando, USA, receiving interest not only from ICNRG but also from IRTF's Network Management Research Group (NMRG[41]).

1.4.4 Scientific Publications

These research actions were supported, and also contributed, by an ample set of published scientific work. In total, 27 different publications were achieved during the lifetime of this thesis, summarized in Tab. 1.3:

Publication Type	Amount
International Conferences	13
National Conferences	4
JCR Referenced Journals	6
Other Journals	3

Table 1.3: Publications overview

One important aspect from this research work, was that each paper was able to simultaneously target several research challenges, from the ones identified in Section 1.3.1. Tab. 1.4 further breaks down the publication distributions per area as well as per project, providing specific key research outcomes and identifying associated item from the References section.

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[41] Network Management Research Group (NMRG), `http://irtf.org/nmrg`

Area/ Project	#	Outcomes	References
Video-enhanced Network Selection	4	Generic abstraction cross-layer mechanisms allowed the link layers to provide informational events about the status of the link, allowing network operations and video services to adapt and control connectivity aspects for content reception.	[31] [32] [33] [34]
IoT	12	The research outcomes affecting this project were addressed through the definition of IoT-aware Media Independent cross-layer middleware mechanisms that allow high-level entities to obtain information and control lower layers of devices in an abstract way.	[35] [36] [37] [38] [39] [40] [41] [42] [43] [44] [45] [46]
Mobility	13	Integration of mobility management with media independent cross-layer abstraction aspects, allowing them to interface with the different network nodes involved in the handover process, both supporting high-level and link-level optimizations for enhanced connectivity control	[47] [48] [49] [31] [26] [32] [33] [50] [51] [52] [34] [53] [27]
ICN	2	The research outcomes of this area, allowed its exposition to management aspects, thus evaluating its supporting capabilities as well as proposing improvements.	[27][54]
IEEE 802.21	13	Aspects of the IEEE 802.21 provided the core mechanisms, inspired similar or new ones, which were at the base of many of the research outcome solutions.	[47] [26] [50] [51] [52] [53] [35] [36] [39] [40] [41] [38] [44]
MEDIEVAL	6	Here, beyond the research outcomes targeting handover optimizations for video-enabled mobile services, the framework architecture, able to be deployed by operators, was presented.	[31] [48] [32] [33] [49] [34]
APOLLO	5	The project leveraged from the IoT abstraction and management mechanisms, providing the base for operator-driven control frameworks and empowering other supportive services such as information inference and ontologies.	[37] [42] [43] [45] [46]

Table 1.4: Publication areas contribution breakdown

1.5 Contributions

Following up from the research achievements, this section describes the main original scientific and advanced engineering contributions that were developed throughout this thesis.

- *Using an Open-Source IEEE 802.21 Implementation for Network Based Localized Mobility Management* [52]: Here a framework integrating the IEEE 802.21 and PMIPv6 standards was defined and developed. In one hand, IEEE 802.21 was exposed to a localized mobility management protocol acting as an optimizing mechanism and, in the other, the abstract link commands and events were used to solve the movement detection, which was unspecified in PMIPv6. Moreover, it served as well as a deployment test case for the designed IEEE 802.21 open-source implementation, ODTONE.

- *Hierarchical Neighbor Discovery Scheme for Handover Optimization* [50]: With the aim of empowering IEEE 802.21 mechanisms to further fuel new scenario deployments, the Media Independent Information Service was enhanced with a hierarchical distributed storage and provision of network information. This opened the way to provide more localized novel Information Elements, relative to the area where such queries might arise. When confronted with queries about other areas of the network, such requests would be sent towards higher hierarchical coordination nodes, and forwarded to the Information Server with the requested information.

- *Video-Enhancing Functional Architecture for the MEDIEVAL Project* [32]: The developments defined in this contribution deployed the Media Independent Handover mechanisms as a cross-layer middleware, enhancing handover control beyond its link and mobility capabilities, to encompass video service requirements and input. In this way, network mobility support mechanisms become able to operate transport optimizations based on the video services running therein.

- *Sensor Context Information for Energy-Efficient Optimization of Wireless Procedures* [40]: This work exploited the concept of Media Independent Handovers in new areas, going beyond the scope of handovers and mobility, providing frameworks developing the necessary enhancements and extensions for its support. This not only allowed the integration of new input for decision and optimization processes in mobility scenarios, but also to allow mobility to be coupled in otherwise non-mobile scenarios (e.g., sensors). Moreover, these enhancements were developed with extensions maintaining the underlying structures and interfaces of the base IEEE 802.21 standard.

- *MINDiT: A Framework for Media Independent Access to Things* [41]: Evolving from incremented Media Independent framework designs, enhanced in both capabilities and supported scenarios, a novel framework targeting generic access to information and control procedures was developed, maintaining the cross-layer design but detaching itself form pre-determined interfacing messages. In this approach, management support actions are used to discover and register in available information sources or controllable entities, providing as well for a flexible integration of interface discovery and inference mechanisms. In this way, the interaction opportunities are generalized into a single interface and protocol, but with the capability of being used in a wide range of scenarios.

- *Named Data Networking Flexible Framework for Management Communications* [27]: A novel flexible management framework for the Named Data Networking ICN instantiation was developing, not only enhancing the NDN's own mechanisms to operate and optimize both network and mobile terminal aspects, but also raising awareness to management capabilities of these new clean-slate approaches, in the research and standardization communities. As such, by exposing ICN to novel scenarios, a decisive contribution to the deployment considerations of novel Internet solutions was given.
- *ODTONE*[42]*, An Open Source IEEE 802.21 implementation:* Besides the previous set of selected scientific contributions, special attention is given to the ODTONE open-source software project, as a major contribution from this thesis. Both serving as the underlying base code for many of the different implemented frameworks throughout this thesis, as well as to disseminate the IEEE 802.21 standard, an open source implementation was designed, developed and is continuously being supported and updated. The overcome of the yet to come IEEE 802.21 support in IEEE and 3GPP device drivers, provided the definition of a novel mechanism towards link access control, by reusing the MIH Protocol internally, between the abstraction layer and the device modules. This not only allowed new mechanisms to be conceived (e.g., remote link Service Access Points), but also facilitated the integration of new technologies beyond the ones provided by the IEEE 802.21 standard, as well as their integration in a operating system independent way.

1.6 Dissertation Outline

The areas surrounding the scope of this thesis (composing mobility protocols, video traffic increase solutions, IoT device interfacing and ICN aspects) are quite broad on their own, pursuing their own research considerations whose full detail goes beyond the scope of this thesis. As such, herewith the scope of research conducted in this thesis is briefly introduced.

Fig. 1.2 shows the relationship between the four different research objective areas and the thesis scope. Each area possesses its own set of taxonomies, problem statements and state of the art (insights and state of the art on the subjects addressed in this thesis are presented in

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[42] Open Dot Twenty ONE, `http://atnog.av.it.pt/odtone`

Section 2). In the case of mobility research [55], there is a permanent search for new and better ways of reducing handover latency and providing more optimized mobility signaling schemes, as shown in Fig. 1.2. However, [55] also identifies that the different wireless access technologies provide a complex challenge in terms of seamless handover management. Video services are actively researching for means to ensure high quality video delivery in the Internet and wireless networks [56], through content adaptation, amongst other optimizations. Mobile operators are facing new challenges with the advent of new and innovative multimedia services, whose reliability is increasingly affected by the conditions of the underlying network. IoT represents a recent field of investigation, but has already berthed a plethora of architectural approaches [57], considering the utilization of different devices in different environments. And, lastly, different ICN instantiations are surfacing, providing different points of view for the content-centric paradigm [58].

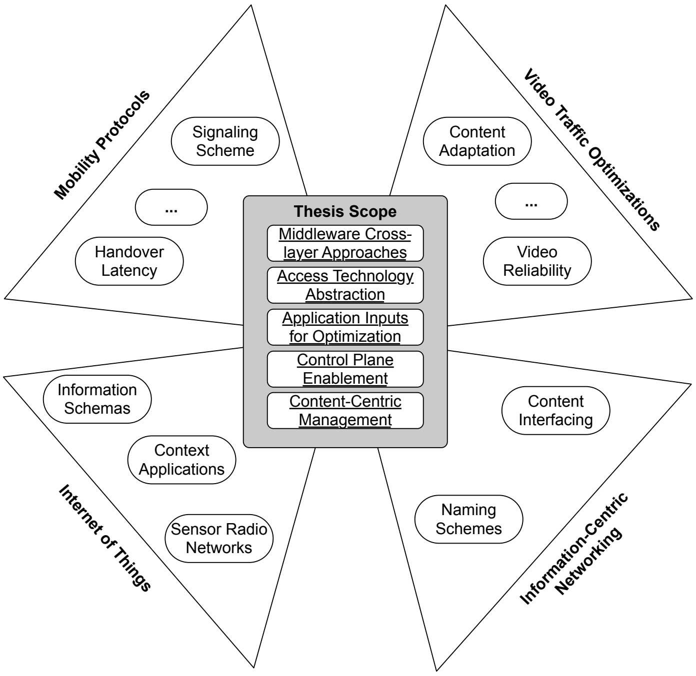

Figure 1.2: Identifying the Thesis Scope

This thesis does not aim to provide enhancements towards the solution of specific problems of the four addressed areas. Instead, it considers the common need for enabling *Middleware Cross-layer Approaches*, with which high-level entities and services (e.g., ranging from video traffic generation applications, to mobility modules) not only are able to receive input from the link layers, but are able to use that information to configure themselves according to dynamic conditions. In order to support this, *Access Technology Abstraction* mechanisms are needed to simplify the interfacing between the different available access link technologies and the different high-level entities. With a bi-directional abstraction approach, this means that these high-level entities themselves can also provide abstract information notifications, enabling other management entities to simultaneously be informed of not only the links conditions, but of the services executions as well. As such, by accessing to this information, and using the same abstraction mechanisms to control both the services and the link layers, manage entities can be part of a *Control Plane Enablement* with the aim of optimizing the network balance and end-user experience. Plus, in view of future clean slate Internet architecture deployments, these management concepts are also deployed in content-centric frameworks, providing feedback on the future-proof of the devised mechanisms.

The sections presented in this chapter provided an overview of the evolutions in how the Internet is being used, motivation, problem statements and research objectives.

The second chapter provides the state of the art on mobility protocols, video traffic considerations, devices in an Internet of Things (IoT), Information-Centric Networking and middleware cross-layer approaches. A detailed definition and explanation of the IEEE 802.21 standard is also presented therein, necessary to understand the media independent mechanisms that serve as a base for the solutions provided in this thesis.

The third chapter of the dissertation concerns short descriptions of the research contributions of selected publications and the individual contributions of this dissertation's author.

The fourth chapter finalizes with the thesis conclusions and plans for future work.

The appendix of the dissertation is composed by nine selected papers published by the author of the thesis. The structure of this dissertation is shown in Tab. 1.5.

No	Chapter Title	Aim	Description
1	Introduction	Presents the concepts motivating the research work presented under scope of this thesis, as well as associated challenges and contributions	• Internet evolution contextualization. • Problem statement and research objectives. • Contributions. • Outline.
2	Background	Evolution and current developments of mobility protocols, video traffic impact, cross-layer approaches, IoT and ICN	• Rationale and evolution of mobility protocols. • Solutions for video traffic increase. • Approaches on IoT device interfacing. • Named Data Networking • Cross-layer middleware analysis. • IEEE 802.21.
3	Paper Summaries and Contributions	Descriptions and research outcomes from selected papers published by the dissertation author	• Identification of the Research Objective targeted by each paper. • Relation establishment between the papers and the different research objectives.
4	Conclusions and Future Work	The end chapter of the thesis	• Research objective and general conclusions. • Directions for the future work.
Appendix	Included Articles	Showcase the full articles pertaining to the research outcomes achieved throughout the thesis life.	• List of papers in Tab. 3.1

Table 1.5: Outline of the Thesis

Chapter 2

Background

This section presents the state of the art on the key targeted areas addressed by this thesis, composing 1) Mobility Protocols, 2) Video Traffic Considerations, 3) Devices in an Internet of Things, 4) Named Data Networking as an instantiation of the Information-Centric Networking approach, 5) Middleware for Cross-layer Control and 6) the IEEE 802.21 standard. Each subsection also provides considerations on the aspects that have been contributing towards the need for specific new evolutions.

2.1 Mobility Protocols

The initial Internet design was not considered with mobility as a requirement: the objective was to access, via a stationary terminal, resources available in another stationary terminal (i.e., a printer, a data tape, etc.). As such, and as described in Section 1.1.1, whenever a user behind a terminal connected to the Internet switched the current point of attachment, it would be necessary to re-establish its connection resulting in a change of IP address, or having host-specific routes propagated throughout the Internet routing fabric. The IETF introduced the Mobile IP protocol [59] which solved this problem by allowing the mapping of its current address to a global permanent IP address through tunnelling between anchor points. The concept itself was not new, since it inherited several concepts from an earlier approach, called Cellular IP [60]. Unlike MIP, which considered macro-mobility aspects (i.e., mobility of user nodes in a WAN), Cellular IP employed mechanisms aiming micro-mobility domains (i.e, mobility of users inside a LAN), routing IP traffic just for a fixed range over wireless devices.

Celluar IP, although seeing its research initiated earlier, was never accepted as a formal standard, allowing MIP to become the de-facto IP mobility protocol. However, the MIP solution was achieved under strong constrains, since the Internet was conceived initially for fixed users. Therefore, in order for the solution to work, this had to be countered and, as a result, several issues were raised such as signaling overhead delay and load, which prevented seamless mobility and scalability [61]. This, of course, led to the continuous need for patching the Mobile IP protocol with extensions [62][63][25] which also created new issues in the form of other types of scalability, performance and security problems [64]. Even considering Mobility support for IPv6 [3] (or for dual IPv4 and IPv6 stack mobility support support with Dual-Stack MIPv6 (DSMIPv6) [65]), which takes advantage of IPv6's inherent mobility features, moving mobile devices on the Internet itself still presents a challenge in terms of scalability limitations associated with the anchor points for mobility. In particular, considering the novel case where multiple-technology enabled mobile nodes are able to connect to different radio types, increases furthermore the challenge of achieving mobility between points of attachment belonging to different media.

Parallel to this, Mobile IP-like solutions have continuously proved to be complex in their deployment and operation: to provide MTs with global reachability and session continuity, operators are required to install and configure an overlay network that has to rely on tunnels and anchor points. With the Evolved Packet System (EPS) representing the evolution of today's deployed 3G networks, some IP mobility adoption measures have started to be addressed, motivated by the introduction of a new IP-based Evolved Packet Core, alongside the evolved UMTS Terrestrial Radio Access Network (E-UTRAN, also referred as LTE). However, presently, mobility is still based on anchor points (Packet Data Network (PDN) Gateways (PGW)) and tunnels (based on the GPRS Tunnelling Protocol (GTP) [66]). This provides a limited solution, where mobility is offered as a default unspecific action for every user and service, unable to take into consideration specific characteristics of the terminal, or its current service conditions. In general, existing mobility schemes, along with supporting mobility management engines for taking handover decision, focus on radio usage optimization, considering mainly radio parameters as their input.

One important consideration to be drawn from mobility protocol research, are the drivers for the key stakeholders involved. In this case, we can identify the IETF as the Internet domain driver, making sure that mobility protocols stay within the boundaries of feasible Internet architecture extensions and ensuring that no disruptive mechanisms are favoured. On the other hand, the 3GPP is the main driver for the actual wireless device infrastructure deployment. The collaboration relationship between both bodies [67] establishes common principles and guidelines for the adoption of Internet specifications by the 3GPP, in order to avoid the duplication of work. However, it clearly specifies that each organization must operate according to their own rules and procedures, recognizing the need for additions and/or modifications to the use of IETF standards.

The downside of the previous consideration is that, although standards such as MIPv6 [3] follow a normalization path towards deployment, the 3GPP is always free to integrate modified versions of such standards into their own architectures, or even chose to follow completely new different approaches. However, on a positive note, this also means that 3GPP is an important requirements provider, not only in terms of having an architecture that addresses wireless node mobility, but also bringing into standardization discussion important aspects that are not directly related to the scope of the Internet, but their utilization highly impacts mobility in the Internet.

An example of such differentiation was with the creation of the PMIPv6 protocol [25]. In the height of the MIPv6 protocol, 3GPP and other members within the IETF placed a tremendous amount of pressure on the standard's design, regarding inherent problems of its deployment in the Internet such as bootstraping, [68], firewalls [69], localized mobility [70] and, more importantly, impact in mobile node design [71]: it was clear that involving the mobile node in the mobility signaling not only caused overhead, but also caused performance issues due to the latency of the link towards the network mobility anchor. As such, the IETF created the Network-based Localized Mobility Management (NETLMM) workgroup[1], aiming to define a mobile node intervention-free mobility protocol.

The most important achievement of this work group was the development of the PMIPv6 protocol. This approach, not only considered the removal of the mobile node from the active participation in the mobility signaling (thus simplifying mobile node design and reducing round-trip signaling delay) but also considered a localized mobility approach, where the mobility procedure was executed for smaller domains, aiming to reduce the impact of latency in the signaling.

PMIPv6 allows mobile nodes to change their PoA in different networks, without changing their IP address and without any modification to their IP stack. To realize this, two new network functional entities are introduced in selected routers, the Localized Mobility Anchor (LMA) and the Mobile Access Gateway (MAG), which are responsible for managing the IP addresses involved in MT mobility. Concretely, a LMA manages the reachability towards MTs through the creation of tunnels directed to one of several MAGs, constituting a PMIPv6 domain. For communications outside this domain, for example to nodes via Internet, the LMA works as a home agent, providing the home address prefix of the MT. As long as the MTs move around the same PMIPv6 domain, the MAGs always provide the same prefix to the MT, updating the tunnel to the LMA. In this way, entities outside the PMIPv6 domain who wish to communicate with the MT, are able to do so regardless of which MAG it is connected to. To update this tunnel, the protocol features a set of signaling messages, (shown in Fig. 2.1), the Proxy Binding Update (PBU) and Proxy Binding Acknowledgement (PBA), which are used between the MAGs and the LMA to update the MT's current location. This procedure is transparent to the MT which does not detect any change to its IP address after changing its PoA. More details can be found in the respective standard [25].

However, as can be seen from the message signaling chart, the defined entities are only involved in the signaling mobility process. Although they are important network operator

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[1] Network-based Localized Mobility Management, `http://datatracker.ietf.org/wg/netlmm/charter/`

nodes, they are completely unaware of the link characteristics of the original and handovered-to access networks. This means that the handover is made disregarding any resource availability query in the handover target network (i.e., to evaluate if the network conditions are satisfactory for the services being run in the mobile node). Moreover, considering today's heterogeneous availability of different kinds of wireless access technologies, it becomes complex to provide a single handover management mechanism that is able to obtain information and execute link procedures, aiming to optimize handovers. As such, performance evaluations of the PMIPv6 protocol typically do not consider these requirements, and only analyse IP behaviour performance [72] [73].

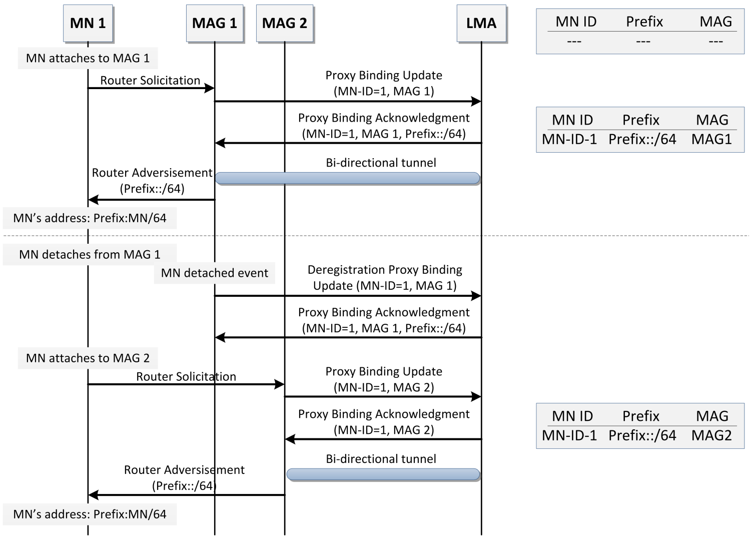

Figure 2.1: PMIPv6 Message Signaling Chart

To address the issues related to the growth of traffic in the core network, the 3GPP is currently investigating the possibility of introducing off-load techniques to optimally redirect Internet traffic out of the mobile core network, moving it to other alternatives such as femtocells [74] and Local IP Access and Selected IP Traffic Offload (LIPA-SIPTO) [75]. This has motivated the 3GPP to not only consider IP mobility approaches presented by the IETF (such as PMIPv6), but also to fuel the research on novel approaches such as distributed mobility management [76] and per-flow mobility [77].

In general, existing mobility schemes, along with their mobility management engines for handover decision, focus on optimizing radio usage and consider mostly radio parameters as their input. Further optimization approaches and mobility paradigms are necessary to face video-traffic requirements, especially looking at its expected growth and heavy impact on network resources. This is particularly affected by the kind of traffic that the mobile terminals access to while on the move, as well as the increasing amount of devices with networking abilities that access (or provide services through) the Internet.

2.2 Video Traffic Considerations

Mobile operators are facing new challenges with the advent of new and innovative multimedia services. They are giving the first steps to face the social network trend. The link between the mobile world and community based services is becoming a reality. As shown in Section 1.1.2, according to [13] P2P, as the current dominant source of traffic in the Internet, has been surpassed by video in 2010 achieving volumes close to 90% of consumer traffic by the end of 2015, with an increase of the total mobile traffic of more than 200% every year, as shown in Fig. 2.2. By the year of 2016, we will see video traffic quadruple in size, and the Internet traffic will be composed by two-thirds of video. If we account for video obtained through peer-to-peer file sharing, using services like BitTorrent, then video will reach to 90% of all Internet traffic in three years.

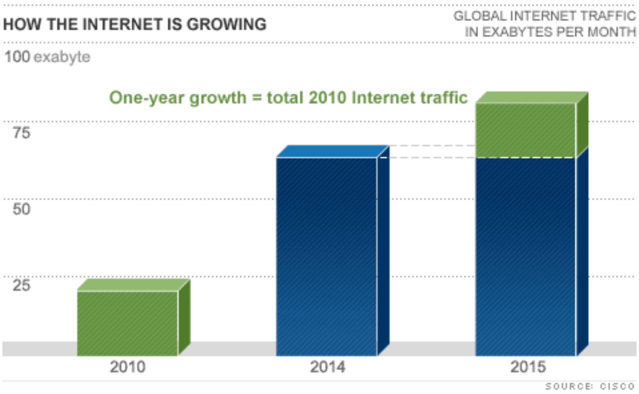

Figure 2.2: Cisco's annual Visual Networking Index Internet Growth (obtained from CNN.com)

This increase is accounted as the sum of all forms of video (including Internet TV, Video on Demand, interactive video and P2P video streaming) and is also motivated by a change in perception and usage of such a service, which instead of being regarded as simple streaming of content, will become a tool for personal multimedia communication, resembling today's explosive usage of personal messaging (i.e., SMS and Twitter). It is already possible to use MMS to publish photos or videos on Facebook. Additionally, Twitter messages may be sent and received over SMS. But the link between social networking services and mobile networks is still very incipient. There is a lack on normalized mechanisms to interconnect both worlds. Issues related with scale service announcement and discovery, mapping of service user groups into network-based groups, management of different content sources are still under discussion. Lastly, there is no common interface that allows different applications to deliver multimedia content to groups of users in an efficient way, taking into consideration the specificities of content adaptation and the requirements for a reliable delivery.

These increases in video traffic are also motivating manufacturers to provide solutions towards optimal network video support and monitoring. Video services, whether providing Telepresence, IP video conferencing or even surveillance, place stringent requirements over the network in terms of performance. Low latency, jitter and packet loss have an impact in the Quality of Experience that the user perceives from the obtained video. Factors such as available bandwidth, concurrent sessions, availability of multicast or dynamic scheduling, also have different levels of impact whether the video service is of interactive or streaming nature. As such, the plurality of video-based applications and usages require flexible video management mechanisms to be deployed by the network operators, offering tools that provide optimal user experience, as well as differentiate the different applications.

Cisco's Medianet[2] provides an end-to-end IP architecture that enables pervasive rich media experiences. Concretely, it provides:

- Automated device plug and play deployment;
- Media performance monitoring , troubleshooting and capacity planning;
- Media flow awareness for bandwidth management.

It uses a Media Services Interface API[3] that is embedded into end-points as a middleware, enabling such end-points to be automatically configured and monitored. With a SNMP-like management approach, Medianet control applications deployed on the operator or customer's premises enable to provide an end-to-end view including network, end-points, applications and management mechanisms. An example of an important feature is Media Monitoring, which allows performance metrics (i.e., fault isolation, SLA validation, baselining), dynamic monitoring and troubleshooting. However, the area of effect of this architecture considers primarily Cisco endpoints (although third-party support is provided, as long as video-related traffic flows are able to be detected) and provides only monitoring and configuration. As such, actual network control and optimization are not part of the solution, especially because it would mean access to operator equipment operating under standardized procedures (i.e., 3GPP, TISPAN, etc.).

In this way, research on video evolutions considered not only traffic control at network deployment, but also changes in the video traffic flows themselves in the form of content adaptation. The IETF developed the Real Time Streaming Protocol (RTSP) [78] (and its path towards version 2.0 [79]), which works as a client-server multimedia presentation protocol enabling a controlled delivery of streamed multimedia data over a IP network. It provides remote control functionality for audio and video streams, executing procedures such as pause, fast forward, reverse, and absolute positioning, both for live data feeds and stored clips. However, RTSP does not allow session negotiation, meaning that it does not encompass

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[2] Cisco Medianet, `http://www.cisco.com/en/US/netsol/ns1094/index.html`

[3] Cisco Media Services Interface, `http://www.cisco.com/en/US/solutions/ns340/ns857/ns156/ns1094/media_services_interface.html`

mechanisms allowing optimized content adaptation. This is particularly necessary since video can be watched from mobile terminals connected through varied means to the Internet (each with its own access specificities). Moreover, this protocol does not take into account real-time QoE parameters for multimedia session management, allowing dynamic changes to be applied to on-going sessions. In order to overcome this limitation, the 3GPP defined a protocol allowing the transmission of different QoE metrics over RTSP headers in [80]. Although this mechanism makes possible the video adaptation usage, it is still lacking on codec negotiation, which is an important characteristic that can wildly vary depending on the user terminal and video application.

Optimization of the video delivery can also be achieved though Content Delivery Networks (CDN) techniques. CDNs employ cached content networks that are typically replicated and deployed next to the users' access networks, improving access to the data by reducing latency. CDNs are well investigated and understood in the context of the Internet and when they are operated as a set of servers, even for different applications of video delivery [81] [82] [83]. However, there is a lack of knowledge about their operation in the context of mobile networks, where mobility support is an important requirement.

2.3 Devices in an Internet of Things

Evolutions in electronic components miniaturization have been contributing to the integration of wireless networking capabilities to everyday objects such as phones, cars, household appliances, clothes and even food. With these inter-networking capabilities such devices are able to connect to the Internet and can collect and share data. According to a recent European Commission press release[4], "*an average person has at least 2 objects connected to the Internet and this is expected to grow to 7 by 2015 with 25 billion wirelessly connected devices globally. By 2020 that number could double to 50 billion.*". This enables an ample amount of new connectivity scenarios, where everyday things are linked, with a large economic and societal potential.

The proliferation of new sensor technologies, able to work in a networked and cooperative way, will enable the interlink between the physical and the digital worlds as we have never seen, opening up new classes of applications and variety of business. Architectures supporting these services need to allow resource access and discovery, provided by middleware that constitutes the technological cross-point between both worlds. However, the cheer scale of sensors, and other technologies that empower these environments, is too great to be supported and transported by today's Internet. More scalable interactive methods should be employed to avoid overpowering networking nodes with information from millions of different items,

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[4] Digital Agenda: Commission consults on rules for wirelessly connected devices - the "Internet of Things" - `http://europa.eu/rapid/pressReleasesAction.do?reference=IP/12/360&format=HTML&aged=0&language=EN&guiLanguage=en`

each able to provide information regarding its surroundings.

M2M communications allow an automatic information exchange between devices and systems, absent of human intervention. Sensor devices, using wired or wireless technologies, send informational events towards applications which provide useful information to people or other systems, generating added value. Following an IoT tendency, the association of the different devices to the Internet facilitates the deployment of more and better services.

This area takes advantage from the strong cost reduction in sensor devices, as well as from the global dissemination of wireless communication infrastructures. As referred in [45] and [42], one can expect that M2M communications will involve a market of several thousand million euro, just in Europe. Thus, this area presents itself as a highly potential market and growth opportunity for the different involved stakeholders, particularly when considering its current fragmented, complex and heterogeneous chain of value (i.e., different manufacturers, telecommunications operators, service providers, system integrators and end-to-end M2M solution providers).

Currently recognized M2M usage scenarios are vast and cross the most varied activity sectors, ranging from telemetry, remote maintenance and control, security, health, as well transportation. These scenarios underline as well the interfacing and collaboration requirements between the different involved systems, not only allowing the definition of the interactive processes between the M2M-based entities, but to structure and uniformize the exchanged information structure as well.

As such, current advances in electronics miniaturization have allowed the coupling of electronic devices to objects and spaces, changing them into intelligent environments. In parallel with access technologies evolutions (particularly for wireless technologies), the possibility of remote access to these devices allows the exploitation of autonomous interaction procedures. In this way, processes aiming to facilitate and optimize M2M have been being developed, not only towards the devices, but also between the devices themselves and other systems.

In view of the possibilities allowed by such scenarios, and the different information exchanges resulting therein, standardization initiatives began to take form. Concretely, the Machine Type Communications (MTC) group of the 3GPP progressed on the specification of communication procedures under an operator perspective, taking as base a set of requirements [84], towards the consideration of functional architectures and protocols. On another hand, and more motivated towards service integration procedures and requirements [85] [86], ETSI embodied the Technical Committee M2M (TCM2M) providing a service-oriented framework [87].

Different IoT scenarios [17] [15] [16], motivate as well different kinds of smart devices, services and access technologies. Such disparity generates a heterogeneous environment, with associated challenges regards interfacing, at different levels and layers [57]. Studies, such as [88] and [89], highlight the beneficial deployment of middleware components acting as a interfacing mediator and simplifying access to the different sensors, despite their technological differences. Those studies also consider that the middleware can be further coupled with enhancements, allowing different dynamic programmable features, such as offering the capabilities and information of sensors as a service. However, although these solutions increase the capabilities of accessing more kinds of smart devices, they tend to adapt a vertical deployment architecture, which not only limits further increases in the scope of addressable devices, but target scenarios as well. As such, the resulting systems behave in an isolated and dedicated way, which complicate further extensions and impose complex access mechanisms for reaching different application frameworks, or devices with different constraints (e.g., low-powered).

In respect to this, increased standardization and efforts were made for the integration of service oriented architectures (SOA) with smart devices, through the usage of Web technologies [90]. The Organization for the Advancement of Structured Information Standards (OASIS) provided protocol stack supporting Web Services at the device level, in the form of the Devices Profile for Web Services (DPWS[5]). This protocol provides base mechanisms allowing discovery services, event processing and description, as well as entity addressing, and was at the base of the frameworks figured in research initiatives, such as Service Oriented Device and Delivery Architecture (SODA) [91], Service-Oriented Cross-layer infRAstructure for Distributed smart Embedded devices (SOCRADES) [92] and Integrating the Physical with the Digital World of the Network of the Future (SENSEI) [93].

However, even though the resulting frameworks also considered operations with resource-constrained and low-powered devices, research efforts resulting from those projects identified that the XML characteristics of the involved SOAP protocol produced large cumbersome messages, and required HTTP support. This motivated the normalization of XML enhancements in the form of the Efficient XML Interchange (EXI[6]) specification, which reduces overall overhead through XML encoding, albeit at the cost of computation resources expending in the devices. Moreover, DPWS needs to be coupled with other services, such as Web Service Definition Language (WSDL[7]), supporting the description of the services and information generated by the different devices.

In fact, defining and accessing information in smart devices is a complex issue that is further exacerbated in heterogeneous environments. A different, web-based information access approach was the REpresentational State Transfer (REST). Gaining leverage from the research initiatives associated with SENSEI [94] [95], REST used standard HTTP exchanges that identified information through the usage of Uniform Resource Identifiers (URIs), as a lightweight method for accessing smart devices resources as web services [96]. This allowed the direct access and integration into the Internet by smart devices that supported those mechanisms, while minimizing as well the overhead imposed by the transport layer, when

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[5] DPWS Specification, `http://docs.oasis-open.org/ws-dd/ns/dpws/2009/01`

[6] EXI Specification, `http://www.w3.org/XML/EXI/`

[7] WSDL Specification, `http://www.w3.org/TR/wsdl`

compared to normal XML and WSDL mechanisms. However, RESTful solutions still require HTTP client/server capabilities to exist in the devices, and are still impacted by the size of the XML describing the data. Moreover, as it happens with DPWS, XML enhancements for REST operations were developed [97], which, in the end, further increased computation resources consumption in the devices. Furthermore, it also required the adoption of service description protocols, such as the Wired Application Description Language (WADL[8]), further increasing the amount of operating resources to support simple device access.

Finally, if we further consider the exploitation of smart devices access in other Future Internet aspects, such as mobility scenarios [98], framework design will be severely impacted as well [99]. In order to provide mobility support in these environments, despite the link establishment and insurances that need to be contextualized between the old point of attachment to the network and the new one, both the smart devices and the gateways connecting them need changes. This has the downside of contributing to the resulting “silo” designs, creating different “islands” of device access frameworks. In addition, the management of the mobility aspect requires its own protocol and different supporting mechanisms, such as device discovery and handover candidate querying, which further increase the complexity of not only the framework, but also of the supported devices.

2.4 Named Data Networking

Named Data Networking (NDN[9]) is a project funded under the NSF’s Future Internet Architecture Program[10], which started in September 2010. Through the integration of CCN (discussed in Section 1.1.4), it provides an instantiation of a ICN framework, under the view of Palo Alto Research Center, and led by Van Jacobson, one of the primary contributors to the TCP/IP protocol stack.

In NDN the communication architecture is built on named data, where packets name content and the communication itself is driven by the consumers of data. In order to provide this named packet behaviour, a globally unique identifier is used to identify and recognize a content object. Moreover, NDN routing entities in the path between the content source and consumer are coupled with a content store that caches packets traversing that entity. This allows intermediate entities to serve data requests without having to forward them all the way to the source, when that content is already cached closer to the requester.

The procedure for retrieving content, as defined in [100], is briefly summarized in the next set of steps. Firstly, a consumer wishing to obtain a particular segment of content sends an Interest packet (depicted in Fig.2.3) towards the network, using existing interfaces. This packet carries an NDN name, identifying the content that the consumer wants to retrieve. NDN

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[8] WADL Specification, `http://www.w3.org/Submission/wadl/`

[9] Named Data Networking (NDN), `http://www.named-data.net/`

[10] NSF Future Internet Architecture Project, `http://www.nets-fia.net/`

uses hierarchical names that are structured into a set of components opaque to the NDN transport, allowing the applications to use any naming conventions that may be suitable for an adequate operation. For example, the NDN name `/itav/devices/airconditioner/office2/temperature` could be used by a consumer application to obtain the target temperature established in an air conditioner device located in office number 2 of the Instituto de Telecomunicações in the Universidade de Aveiro.

Secondly, the Interest packet issued by the consumer is propagated along a routing path towards the content source. This routing path takes into consideration that content names have been previously published into the network using an alternate mechanism.

Thirdly, whenever an NDN router receives an Interest packet, it starts by checking if the requested content is present at its local content store. When the content is cached, the Interest packet is consumed, and a Data packet (depicted in Fig. 2.3) is sent towards the original requester via the reverse path. When the content is not present in the cache, the Interest packet is forwarded by looking up its NDN name in a Forwarding Information Base (FIB), which is built by means of the execution of a routing protocol[11]. Interest packets forwarded upstream towards content sources are kept track of in another entity, the Pending Interest Table (PIT), indicating the reverse path for that content. Lastly, when the Data packet is being forwarded downstream towards the original requester, each NDN routing entity determines whether the content needs to be replicated in the cache, according to a pre-established caching strategy.

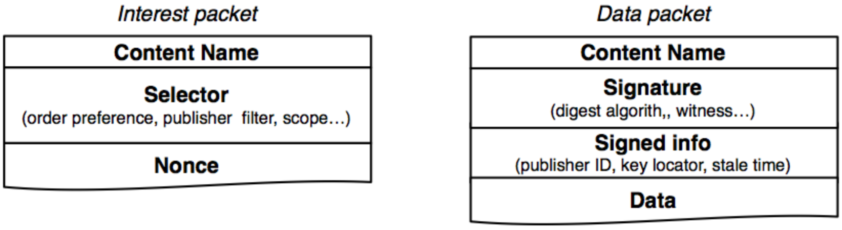

Figure 2.3: Interest and Data packets structure

NDN uses per-packet signatures, based on public key cryptography, to authenticate each piece of content. This way, the verification of a Data packet can be done by any entity receiving the Data. As it it illustrated in Fig. 2.3, each Data packet includes information about the public key that can be used to validate its signature. In particular, the packet carries a cryptographic digest of the public key (*publisher ID*), which is also used as a shorthand identifier of the content publisher, and a key locator, which allows the retrieval of that public key.

Although the NDN approach has been deployed in scenarios featuring voice media [101],

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[11] This protocol would operate in terms of names, allowing to propagate content name prefixes between NDN routers.

or even extensions enhancing caching mechanisms [102], there has never been an evaluation, or proposal for deployment, of NDN mechanisms in such demanding environments, as the ones provided by IoT scenarios.

2.5 Middleware for Cross-layer Control

The growth in usage of the Internet as a vehicle for information dissemination has lead to the widespread deployment of numerous kinds of applications and services, able to be used and accessed from mobile devices which connect to different types of wireless and wired access technologies. Moreover, this is also the case when IP-based solutions need to coexist with legacy and other kinds of technologies [103]. This heterogeneous environment provides a complex setting for network and service operators, when it comes in optimizing access and service delivery. Using a certain application or service over a mobile terminal using a UMTS link provides a different set of connectivity characteristics and parameters to the services being used, when compared to, for example WLAN. Moreover, when the deployment considerations of not only the terminals and wireless technologies can vary, but also of the services and applications involved, stringent management and control scenarios are necessary to be applied.

In this sense, one of the most important factors for the success of today's Internet (which is its simplicity), can actually prevent it from evolving into more managed and optimized means. More concretely, it's layered design, although simplifying application and services deployment, demands that different procedures have to be executed at the different layers, for the deployment of necessary procedures (i.e., resource requesting, connection establishment, etc.).

To allow application and services execution optimization, cross-communication between the higher-layers and the lower-layers of the network stack, becomes necessary and requires the definition of middleware cross-layer interfacing procedures [104]. Middleware is defined by [105] as a *"software layer or a set of sub-layers interposed between the technological and the application levels. Its feature of hiding the details of different technologies is fundamental to exempt the programmer from issues that are not directly pertinent to her/his focus (...). The middleware is gaining more and more importance in the last years due to its major role in simplifying the development of new services and the integration of legacy technologies into new ones. This excepts the programmer from the exact knowledge of the variegate set of technologies adopted by the lower layers."* In this way, through up-to-date information notification, applications and services can quickly react to lower-layer conditions changing and execute adequate optimizing measures.

Over the years, work on the topic of cross-layer approaches has motivated the creation of synergies between different research backgrounds and, thus, berthed different understandings of the concept. For the purpose of this thesis, a cross-layer approach stands as an architectural deployment that enables the control and information obtaining from different layers of the OSI model, through the usage of mechanisms provided by a middleware. This middleware provides as well the means to be interfaced by a management entity, which is able to understand the information provided by the different layers and use it to provide combined optimization procedures.

There is no specific location regarding which layers should be interfaced, in order to obtain a cross-layer behaviour. For example, [106] provides a survey on cross-layer design optimizations in wireless protocol stacks, where each layer of the stack is analysed in terms of interfacing possibilities (such as information inter-exchange) with both the layers below and above. In this way, high-level applications and services can access information from lower layers [107] (either through specialized middleware [108] or by interfacing directly with the layer parameters [109]). Moreover, the information and control provided by each layer can alternatively be sent towards a single centralized management entity [110], or used independently by each layer [111].

However, an important consideration from the previous set of mechanisms is that they value foremost the usage of lower-layer information by the applications, and not as much the usage of information from upper levels. On one hand, optimization operations involving wireless links mainly concern the lower layers. On the other hand, high-level layers can provide feedback and information that can be used towards service provisioning. An example of such an approach is the IETF's Context Transfer Protocol (CXTP) [112], which is used to re-establish service capabilities (for example, after a handover) without having to re-execute all bootstrap procedures again. Another example is the Application-Layer Traffic Optimization (ALTO) service [113], which conveys information about the network (e.g., preferences) to applications.

2.6 The IEEE 802.21 Media Independent Handover Services Standard

This is a standard from the IEEE whose purpose is to define extensible media access mechanisms that may facilitate handovers between 802 and cellular systems, as well as optimizing handovers between 802 systems, whether they are wireless or not. More specifically, it aims to provide link layer intelligence and other related network information to upper layers, or the mobility management entity responsible for handover decision making, to optimize handovers between heterogeneous media.

The standard supplies a framework allowing for transparent service continuity while a mobile node is switching between heterogeneous technologies. For session continuity it is important that the framework can properly identify the mobility-management protocol stack residing in the network elements supporting the handover.

Also, the network elements will feature a new entity, the Media Independent Handover Function (MIHF), within their protocol stack, with correspondent Service Access Points and associated primitives, to access the services therein.

A primitive is a unit of information which is sent from one layer to another. There are four classes of primitives: Request, Confirm, Indication and Response. The request is issued by the layer that wants to get the services or the information from another layer, and the confirm is the acknowledgment of the request. The indication is the notification of the information to the layer that requested the service, and the response is the acknowledgment of the indication. In this architecture, a layer can evenly communicate with each other.

The primitive consists of five fields: the protocol layer identifier to which this primitive should be sent, the protocol identifier to which protocol entity this primitive should be sent, the primitive class (i.e., request, confirm, indication, or response), the primitive name, and parameters.

There are three different usages of ”Primitives”:

- **To provide L2 information to upper layers immediately.** A ”Request” primitive is an acquisition request for L2 information. As a ”Confirm” primitive, L2 information returns immediately.
- **To notify upper layers of L2 events asynchronously.** ”Request” and ”Confirm” primitives are used just for registration. When an event occurs, an ”Indication” primitive is asynchronously delivered to an upper layer.
- **To control L2 actions from upper layers.** A ”Request” primitive is a request for operation. Ack or nack returns immediately as a ”Confirm” primitive.

The services are:

- **Media Independent Event Service (MIES)**, which analyzes/delivers local and remote events;
- **Media Independent Command Service (MICS)**, which provides a set of commands for MIH users to control handover states in the links;
- **Media Independent Information Service (MIIS)**, which provides an information repository, for query and response.

The primitives’ purposes are to collect link information and control link behavior during handovers. The MIHF is a logical entity which has no implication on the way its functionality is implemented either in the terminal or in the network. The MIHF is able to receive and transmit information either locally, from the link layers through the Service Access Points, or remotely, through messages exchanged through peer MIH functions existing in network elements. The specification defines mechanisms to support MN-initiated, MN-controlled, network-initiated and network-controlled handovers.

2.6.1 The Media Independent Handover Function

The Media Independent Handover Function is a logical layer in the mobility management protocol stack, both in the mobile node and the network elements. Its purpose is to aid and facilitate handover decision making though the supply of inputs and context to the upper layers, for handover decision and link selection. One of the key goals of the MIHF is to facilitate the recognition of handover occurrence, as well as the discovery of information on how to make effective handover decisions.

The MIHF provides abstracted services to higher layers, offering a single unified interface to them, through technology independent primitives. The MIHF itself relies on technology specific interfaces to communicate with the lower layers. The specification of these interfaces is not in the scope of this standard, since they are already defined as Service Access Points within their respective standards.

2.6.2 The Communication Model

The MIHF resides in different entities which can communicate with each other, for instance, to exchange information about the network with the terminal, in order to aid in the handover decision making process. The standard defines the communication relationships between the elements of the network that have a MIHF.

The PoA is an endpoint of the network side that includes a MN as an endpoint. This is associated to an interface instead of the ”whole” node.

The PoS entity is an element in the network side whose MIH Function exchanges messages with a MN’s MIHF. One has to note that a network entity can supply more than one Point of Service and provide different combinations of MIH services to a MN, based on subscription or roaming conditions. Also, a network entity composed of more than one interface has the PoS associated to the network entity itself and not with just one of its interfaces.

In case of a network model that includes a MIH proxy, the MIH network entity that communicates with that proxy does not have a direct communication with the MN and thus is not a PoS for the MN. Nevertheless, the same network entity may still act as a PoS for a different MN.

Between the different instances of MIH Functions, the communication can be made as following:

- MIH on MN and MIH PoS on the serving PoA, where L2 or L3 communication can occur;

- MIH on MN and MIH PoS on a candidate PoA where L2 and L3 communication can occur;
- MIH on MN and the MIH PoS on a non-PoA entity where L3 communication can occur, and also L2 is possible through Ethernet bridging, MPLS, etc.
- MIH on the PoS and a non-PoS in another network entity can encompass L3 communication;
- MIH on two PoS instances in distinct network entities can encompass L3 communication.

2.6.3 The MIH Services

The MIH Function provides synchronous and asynchronous services through well defined Service Access Points for link layers and MIH users. These services have the purpose to manage, determine and control the state of the underlying interfaces.

Media Independent Event Service

Mobile nodes using MIH services receive indications from link layers for asynchronous operations like Event service. Events can indicate changes in state and transmission behavior of the physical, data link and logical link layers, and also, with a pre-indicated confidence level, predict changes in these layers.

Events can be originated from the MIHF, called MIH Events, or from the lower layer, called Link Events. The typical flow of events has its origin at lower layers and are sent to the MIHF. Upon registration to the MIHF, a high layer entity can receive the events indicated in the registry message.

Events can also be local or remote. Local events are propagated across layers within the local stack of a single device, whereas remote events traverse across the network from one MIH function to a peer MIH function. These events can then traverse from the local MIH function to the local upper layer entity, supposing prior registration to receive that event.

Event registration is a mechanism that allows upper layers to indicate to the MIH which events they are interested in receiving. The event service typically is used to detect the need for handovers. For example, it can supply an indication to the higher layers that the link will go down in a near future (through analysis of the signal level and crossing a threshold) which can be used to prepare a new point of attachment ahead of the current one going down.

From the recipient's point of view, these events are mostly"advisory" in nature and not "mandatory". Also, higher layer entities might have to deal with freshness, reliability and robustness issues related to these events, specially in the case that they are remote.

The MIES supports several types of events:

- MAC and PHY State Change events: which correspond to changes in MAC and PHY state;
- Link Parameter events: triggered due to change in link layer parameters. Can be triggered synchronously (i.e. regularly) or asynchronously (i.e. when a threshold is crossed);
- Predictive events: express the likelihood of a future change in a certain property, with a certain degree of certainty, based on past and present events;
- Link Synchronous events: give indications of precise timing of L2 handover events that are useful to upper layer mobility management protocols;
- Link Transmission events: indicate the transmission status of higher layer PDU's by the link layer. This information can be used by upper layers to improve buffer management for achieving low-loss or loss-less handovers.

Media Independent Command Service

The MICS allows higher layers to configure, control and get information from the lower layers. The information provided by these commands is dynamic in nature comprising of link parameters such as signal strength, link speed, etc. These commands can be issued by higher layers, called MIH commands, as well by the MIH Function, called Link Commands. Typically, messages propagate from the upper layers to the MIH Function, and then from this to the lower layers.

MIH Commands may be local or remote. Local MIH Commands are sent by Upper Layers to the MIH Function in the local stack, whereas remote MIH Commands are sent by Upper layers to the MIH Function in the peer stack.

The commands generally carry the upper layer decisions to the lower layers on a local or remote device entity. An example is a policy engine entity to request a mobile node to switch link.

Media Independent Information Service

The MIIS provides a framework and corresponding mechanisms by which a MIHF entity can discover and obtain network information, with the purpose to facilitate handovers.

This service provides a set of Information Elements, the structure to store them and its representation, and a query/response mechanism for transferring the information. Different types of Information Elements may be necessary depending on the type of handover. For example, for horizontal handovers across different PoAs of the same access network, information from lower link layers can be sufficient. But, in the case of vertical handovers, the mobile node may move across different access networks. Then, it is necessary to select an appropriate PoA in the new network based in good lower link connectivity as well as in the availability of higher layer services.

This information can be made available via both lower and upper layers, and, if necessary, be obtained through a secure port. The Information service also provides access to static information such as neighbor reports, which help in network discovery. It also includes more dynamic information such as channel information, MAC addresses, security information, etc. This, in conjunction with high layer information (such as application requirements) may help in a more effective handover decision. The set of different Information Elements may evolve. Also, there is a need for flexibility and extensibility in the way this service provides the information, since, for example, the list of available access networks is always evolving. For this, the standard defines a representation schema, which allows a client of MIIS to discover the entire set of different access networks and Information Elements supported, in a flexible and efficient manner. This schema can be represented in multiple ways, such as Resource Description Framework (which is based on XML), ASN.1 (which is used in 802 MIBs), variants or a simple TLV representation of different information elements.

This service allows access to heterogeneous information about networks, to be accessible by both the mobile node and the network. A media-independent neighbor graph may be abstracted through the neighbor reports of specific technologies. This capability allows the terminal to use its current access network technology to query information about other technologies without activating that interface. One can also, for example, obtain knowledge of supported channels by different PoAs without resorting to scanning or beaconing. The MIIS and MICS information could be used in combination by the mobile node, or network, to facilitate the handover.

The information elements can be classified in three groups:

- **General Access Network Information:** provide a general overview of the different networks, such as list of available networks, operators, roaming agreements, cost of connections, security and quality of service;
- **Points of Attachment:** information such as addressing, location, data rates, etc;
- **Other information:** specific information and vendor specific.

2.6.4 Service Access Points

Service Access Points are used to exchange messages between the MIHF and other planes, using a set of primitives that specify the information to be exchanged and the format of those information exchanges.

The standard includes the definition of media independent SAPs, the MIH_SAP, that allow the MIH Function to provide services to the upper layers. These upper layers are called the MIH Users and use the services provided by the MIHF through the MIH_SAP. The MIH

Users have to register to the MIHF in order to obtain access the MIH generated events and the Link Events, which are generated by the layers below the MIH but are passed on upwards through the MIHF. MIH Users may also send commands to the MIHF. Also, MIHF entities may also send remote commands to other remote MIHF entities.

The standard also includes recommendations to define or extend existing media-dependent SAPs. These allow the MIHF to use services from the lower layers of the mobility-management protocol stack and their management plane. All the Link Events generated at lower layers and all the Link Commands sent through the MIHF are part of the media specific MAC/PHY SAPs and are already defined by their specific technologies.

These concepts can be combined in the following general MIH Reference Model, shown in Fig. 2.4.

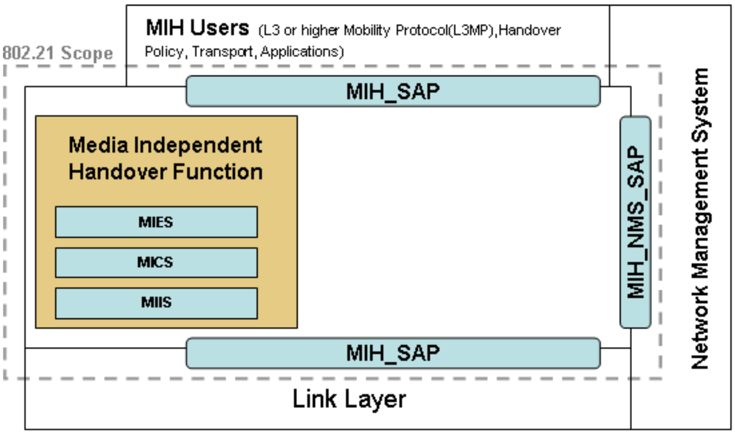

Figure 2.4: MIH Reference Model

2.6.5 The MIH Protocol

The MIH protocol defines the format of the messages (i.e., MIH packet with header and payload) that are exchanged between remote MIH entities and the transport mechanisms that support the delivery of the messages. The selection of the transport mechanism is dependent on the access technology that connects the MN to the network. These messages are based on the primitives which are part of MIES, MICS and MIIS.

MIH messages require reliability for remote communication on an end-to-end basis to ensure the receipt of data to the destination. Reliability may be provisioned with an optional acknowledgement service as part of the MIH protocol. The source endpoint may optionally request for an MIH ACK message to ensure successful reception of a certain event, command or an information service message. When this MIH ACK is received by the source, it may conclude that the message was reliably delivered to the destination. In case of a lost MIH ACK message, the source shall timeout and retransmit the same MIH message. This timer may be related to the RTT between the two nodes.

This mechanism is used through two bits in the MIH message header: the ACK-Req bit is set by the source and the ACK-Rsp is set by the destination. The underlying transport layer takes care of verifying the MIH message integrity, and thus not required at MIHF level.

The packet payload for these services may be carried over L2 management frames, L2 data frames or other higher layer protocols.

Services Provided by the Protocol

The MIH Protocol provides the following services:

- **MIH capability discovery:** so a MIHF can discover MIHFs on other entities. This allows for the negotiation and selection of an optimum transport for communication, as well as discovering the list of supported events and commands.
- **MIH remote registration:** so that a MIHF in an entity can receive remote events;
- **MIH message exchange:** using the messages supplied by the MIH services.

Protocol Identifiers

Successful communication between two MIHF peers requires addressing and identifying the session between them. Three identifiers exist to serve this purpose.

- MIHF ID, which is used to establish and initial connection between two MIHF peers after MIHF discovery and before the creation of a session;
- Session ID, used to identify an active session uniquely between two MIHF peers;
- Transaction ID, used to match uniquely the received responses with the requests previously sent.

Frame Format

The frame format is shown in Fig. 2.5. The MIH Protocol frame carries a source MIHF Identifier TLV and a Destination MIHF Identifier TLV, followed by MIH service specific TLVs. The last three items compose the MIH protocol payload. The MIH protocol header carries the essential information that is present in every frame, used to parse and analyse the MIH protocol frame. Its related fields are presented in Tab. 2.1.

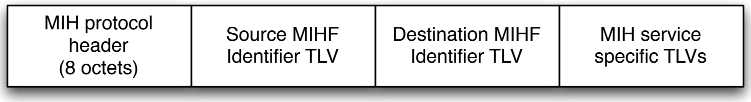

Figure 2.5: MIHF Frame Format

Field Name	**Size**	**Description**
Version	4	This field is used to specify the version of protocol used.
ACK-Req	1	This field is used for requesting an acknowledgement for the message.
ACK-Rsp	1	This field is used for responding to the request for an acknowledgement for the message.
Unauthenticated Information Request	1	This field is used by the MIH Information Service to indicate if the protocol message is sent in pre-authentication/pre-association state so that the length of the response message can be limited.
More Fragment	1	This field is used for indicating that the message is a fragment to be followed by another fragment.
Fragment number	7	This field is used for representing the sequence number of a fragment.
Reserved	1	This field is intentionally kept reserved.
MIH Message ID	16	Combination of the following 3 fields.
- Service Identifier (SID)	4	Identifies the different MIH services, possible values are: 1:System Management 2:Event Service 3:Command Service 4:Information Service
- Operation Code (Opcode)	2	Type of operation to be performed with respect to the SID, possible values are: 1:Request 2:Response 3:Indication
- Action Identifier (AID)	10	This indicates the action to be taken w.r.t. the SID
Number of additional header Identifiers	8	Indicates the no. of header identifiers (TLV for each) included in the variable MIHF header part
Reserved2	4	This field is intentionally kept reserved.
Transaction ID	16	This field is used for matching Request and Response as well as matching Request, Response and Indication to an ACK.
Variable Load Length	16	Indicates the total length of the variable load embedded into the MIHF frame and is the sum of MIH variable header length and MIHF payload length.

Table 2.1: MIHF Protocol HeaderFormat

The parameters in MIH Protocol Messages are expressed through TLV encodings. Messages are divided in messages for System Management Service, for Event Service, for Command Service and for Information Service Category, as shown in Tab. 2.2.

Primitive	**Service**
MIH_Capability_Discover	Service Management
MIH_Register	Service Management
MIH_DeRegister	Service Management
MIH_Event_Subscribe	Service Management
MIH_Event_Unsubscribe	Service Management
MIH_Link_Detected	Event Service
MIH_Link_Up	Event Service
MIH_Link_Down	Event Service
MIH_Link_Parameters_Report	Event Service
MIH_Link_Going_Down	Event Service
MIH_Link_Handover_Imminent	Event Service
MIH_Link_Handover_Complete	Event Service
MIH_Link_PDU_Transmit_Status	Event Service
MIH_Link_Get_Parameters	Command Service
MIH_Link_Configure_Thresholds	Command Service
MIH_Link_Actions	Command Service
MIH_Net_HO_Candidate_Query	Command Service
MIH_MN_HO_Candidate_Query	Command Service
MIH_N2N_HO_Query_Resources	Command Service
MIH_MN_HO_Commit	Command Service
MIH_Net_HO_Commit	Command Service
MIH_N2N_HO_Commit	Command Service
MIH_MN_HO_Complete	Command Service
MIH_N2N_HO_Complete	Command Service
MIH_Get_Information	Information Service
MIH_Push_Information	Information Service

Table 2.2: MIH Primitives per Service

Capability Discovery

The MIHF in the terminal, or in the network, may discover which entity in the network, or terminal, supports MIH capability by using the MIH capability discovery procedure. This procedure consists of a handshake and capability advertisement, and is achievable by exchanging MIH messages, as shown in Fig. 2.6.

In this case, the MIH service would simply requests the delivery of a message from the common protocol functionality, and leave the discovery and resolution procedures to other protocols such as DNS [114] and DHCP [115], or specific link layer broadcasting mechanisms (i.e., 802.11 beacons).

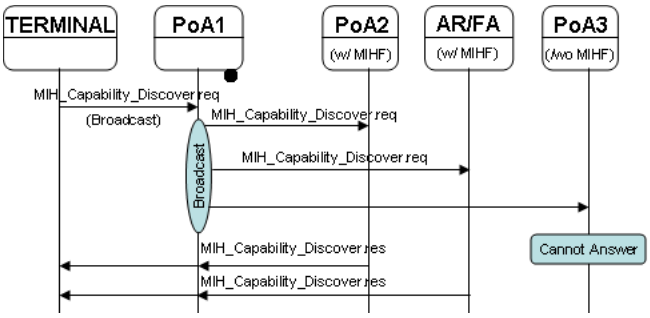

Figure 2.6: MIH capability Discovery Procedure

Encapsulation

Regarding encapsulation, the MIH message shall be inserted inside a UDP or TCP datagram which can fit in either an IPv4 or IPv6 packet, for L3 communication. Nevertheless, the standard, for IPv4, does not mention problems such as firewalls or NAT traversal. For L2, the MIH message can be inserted in the payload of management or data frames.

MNs will feature a MIH Application that sends and receives MIH messages through UDP on a unique port number that shall be registered and obtained from IANA. It is also assumed that the Mobility Management Entity, in case it exists and it is external to the MN, will have it's IP address discovered as per DHCP special option for discovering IEEE 802.21.

The process of a MIH message received in an MN (in this example, a UDP IPv4 message) has the following steps:

1. The Network layer receives an IP packet from its lower layers and strips off the IP header, processes it and then forwards it to the appropriate Transport protocol.

2. The Transport layer then receives a UDP datagram. Its headers are in turn removed and processed. The UDP protocol then forwards the contents of its data field to the appropriate Application layer. This is determined by the value of the destination port number. The MIH Application shall have a newly defined port number. Therefore the MIH message would be forwarded to the MIH Application.

3. The MIH Application would then decode the MIH message according to the IEEE 802.21 specifications and shall then react as required.

The steps taken by the MN to transmit a MIH message are symmetric to the steps explained above and the flow shall be in the reverse path as follows:

1. The MIH Application shall generate an MIH message and pass it to the Transport Layer through the newly defined port.

2. The UDP shall encapsulate the data in a UDP datagram and shall set the header fields accordingly.

3. The datagram is then sent to the Network Layer where it is in turn encapsulated in an IP packet and all the header fields of the packet are set accordingly. This packet is then sent to the appropriate lower layer for transmission to the network.

These processes are similar in network nodes also.

Reliability

The IEEE802.21 specification provides an optional ACK mechanism for MIH Protocol transport. It proposes timers as a solution for lost or delayed MIH messages. Because the contents of certain MIH messages are more sensitive to delay than others, the values of the timers should be different for the three MIH message types. For example, messages that contain information can be sent periodically to update the mobile node and can have the longest timer. On the other hand, in a network controlled handover scenario for example, the MM may issue a command to a mobile node to handover to a target access technology. Since this node manages the available network resources, such a message would be required to arrive as fast as possible. Thus, the timer associated with command messages should be shorter than those of messages with information. Thus, three timers should be used depending on the type of MIH message that is sent:

- Information timer that is set after the transmission of a message that is related to Information Elements.

- Event timer that is set after the transmission of a message that is related to Events.

- Command timer that is set after the transmission of a message that is related to Commands.

In addition, relying on the service layer to handle all reliability issues opens the question of whether timer values should be based on message transfer latency or application processing latency, and these two can differ significantly.

Reliable delivery for the mobility services may be essential, but it is difficult to trade this off against low latency requirements. It is also quite difficult to design a robust, high performance mechanism that can operate in heterogeneous environments, especially one where the link characteristics can vary quite dramatically. The option of an Acknowledgement mechanism, such as the one used in 802.21, has a number of disadvantages associated with it. The protocol designs ends-up re-inventing a lot of the functionality already available in lower layers at a higher layer where access to information about what is going on in the network is restricted. It also adds to the complexity of the higher layer protocol, and makes successful deployment less certain.

Nevertheless, allowing the option of a reliable transport service means that the additional recovery mechanisms within the service layer can be made very simple and robust because they do not need to be optimized for efficient recovery of message loss within the network.

Chapter 3

Paper Summaries and Contributions

This section introduces a set of selected papers, which illustrate the core aspects of the research outcome in respect to the challenges defined in Section 1.3.1. The list of selected papers is presented in Tab. 3.1, consisting of an expanded set from the contributions highlighted in Section 1.5, presenting the evolution of the research work as a whole. For each selected paper, the original contributions are justified and compared with the state of the art.

No	Title	Reference
A	Using an Open-Source IEEE 802.21 Implementation for Network Based Localized Mobility Management	[52]
B	Hierarchical Neighbor Discovery Scheme for Handover Optimization	[50]
C	Video-Enhancing Functional Architecture for the MEDIEVAL Project	[32]
D	Wireless Access Mechanisms and Architecture Definition in the MEDIEVAL Project	[33]
E	Media-Independent Multicast SIgnalling for Enhanced Video Performance in the MEDIEVAL Project	[26]
F	Sensor Context Information for Energy-Efficient Optimization of Wireless Procedures	[40]
G	A Framework for the Connectivity of an Internet of Things	[36]
H	MINDiT: A Framework for Media Independent Access to Things	[41]
I	A Named Data Networking Flexible Framework for Management Communications	[27]

Table 3.1: Selected Papers

The following subsections summarize each paper, presenting as well their main contributions.

Paper A

Daniel Corujo, Carlos Guimarães, Bruno Santos, Rui L. Aguiar, Using an Open-Source IEEE 802.21 Implementation for Network Based Localized Mobility Management, *in IEEE Communications Magazine, Special Issue on Communications Middleware for Mobile Devices and Applications*, September 2011

Paper **A** represented the initial step of the research, through an evaluation of the deployment synergies between IEEE 802.21 and PMIPv6, showcasing the flexibility of the former in respect to its adaptation in new scenarios, albeit still within its main scope of action (i.e., handover management). Here, a framework coupling media independent mechanisms to a network-based localized mobility protocol is defined, providing the necessary logical elements and signalling. An important contribution from this paper was the development of the ODTONE IEEE 802.21 and OPMIP PMIPv6 open-source implementations, with the former acquiring a featured place in the core mechanisms of the MEDIEVAL project architecture. The integration of both, in a physical testbed, allowed the evaluation of the signalling overhead and processing time, standing as a reference for handover control optimization in heterogeneous environments.

Concretely, the framework allowed the provision of a mobility detection mechanism, via the deployment of Media Independent Handover Events and Commands. This detection mechanism, although fundamental, is not specified by the PMIPv6 standard [25]. With the devised framework, this not only becomes possible, as it also allows the deployment independently of the access technology in use. Moreover, the ODTONE design allows it to be deployed in different kinds of operating systems, as long as they support the *Boost* libraries, unlike other open-source initiatives [116] [117], which are coupled to a specific system, or just encompass a specific set of implemented IEEE 802.21 features. Finally, the framework contributed with this paper aims to provide a flexible environment, where high-level modules (e.g., MIH-Users) can leverage on the link layer information and controls to deploy different kinds of decision algorithms, progressing from other works [118], which force the middleware to be tightly coupled with the decision algorithm mechanisms.

Following the results obtained through this work, two important considerations where observed from the obtained framework. Firstly, the hierarchical structure between the LMA and MAGs provided by the PMIPv6 protocol, allows the definition of different local action areas (for the MAGs), while supported by a higher level node (the LMA). This allows the protocol to simplify control node design, and place it in charge of a specific mobility area, increasing aspects such as scalability and proximity with the mobile node. Secondly, the handover decision procedures in this paper were only governed regarding link layer information. It can be considering that coupling the handover decision with higher layer information (e.g., supported services in the network) would further optimize network selections. However, enabling the dissemination of that information in a large scale and to potentially millions of users, requires information provision mechanisms that go beyond the current capabilities of the IEEE 802.21 MIIS. These two considerations were at the base of the research work pursued by paper **B** presented next.

Paper B

Fabio Buiati, Luis Garcia Villalba, Daniel Corujo, João Soares, Susana Sargento and Rui L. Aguiar , Hierarchical Neighbor Discovery Scheme for Handover Optimization, *IEEE Communications Letters* , vol.14, no.11, pp.1020,1022, November 2010

The handover management scope from paper **A** is maintained as well for paper **B**, but the evolutions therein target high-level mechanisms, in the form of the MIIS. Moreover, through the enhancement of the base MIH Protocol and MIIS operation mechanisms, a hierarchical model for network information dissemination was defined. This allowed for a distributed location-referenced way of storing the network information, simplifying Information Server design, and thus allowing the incorporation of more high-level details (e.g., services supported, their characteristics and requirements) for an increased optimal handover decision. This evolved the current design assumption [119] [120] of having just a single Information Server deployed in the network.

This framework then detached itself from the current state of the art by allowing Information Servers to forward requests between one another, through a hierarchical deployment. In this way, a zone Information Server could be configured with more detailed information about the network in their vicinity. Whenever a query from a mobile node was received, requesting information about other parts of the network, it would be forwarded through the Information Server chain towards the server with the requested information, which would provide the reply back to the user. The model was implemented in a NS-2 simulated environment, featuring a multi-operator environment composed by different access technology domains, where optimal connectivity control was supported by a more performing handover candidate discovery time. More importantly, this model also provided insight on the extension capabilities of cross-layer middleware for handover control, as is the case of IEEE 802.21, for integrating higher-layer information and assisting operator-wide network control.

With the hierarchical deployment of information allowing high-level information to reach the mobile terminal faster, and more location specific to its vicinity, an observation was raised regarding which kind of information could be used and in which scenarios. One important consideration was that the MIIS is used to convey information of a more static kind. Conversely, the usage of dynamic higher-layer information, such as video requirements or performance monitoring reports, could also be used to optimize handovers, akin to the dynamic inputs obtained from the link layers. As such, novel scenarios could be considered where applications could provide their own events to network decision entities, which would use that information to optimize the network beyond traditional aspects such as signal level. Those concepts were set as the base for the research of abstraction layer mechanisms, inspired both by IEEE 802.21 and these high-level considerations, that berthed the architecture explored in paper **C**, summarized next.

Paper C

Daniel Corujo, Albert Banchs, Telemaco Melia, Michelle Wetterwald, Leonardo Badia and Rui L. Aguiar, Video-Enhancing Functional Architecture for the MEDIEVAL Project, *Chapter in Mobile Networks and Management, Springer Berlin Heidelberg*, January 2011

Paper **C** was an early publication from the MEDIEVAL project, projecting what would become its key functional architecture. Therein, a cross-layer middleware abstraction component plays a vital role, with the provision of link layer information about the status of the network, and the ability to control such links based on both network control policy decisions as well as video services requirements. IEEE 802.21 provided an instantiation of such mechanisms, and was extended to convey video-specific information, (e.g., encoding parameters, real-time Quality of Experience parameters, amongst others), further increasing the detail of mobility management and network control decisions based on the current wireless conditions of the user receiver, as well as on the requirements established by the video service itself.

This allowed MEDIEVAL to evolve from previous designs, which targeted isolated improvements. Concretely, the OPTIMIX[1] project aimed to improve multimedia performance over wireless links, but to achieve that goal it derived a whole new wireless architecture from scratch, hindering deployment possibilities for operators. At video-service level, the PHOENIX[2] project proposed a cross-layer optimized video architecture, but not considering any mobility support, as was the case of the NAPA-WINE[3] project, which applied traffic and quality degradation for high quality TV delivery scenarios. By using enhanced IEEE 802.21 mechanisms at its core, the MEDIEVAL framework proposed in this contribution allowed for a cross-layer integration of different aspects of the network, towards video optimization, supporting both mobility as well as link-layer procedures towards link optimization.

By analysing this paper's outcome, it is clear that the IEEE 802.21 abstraction capabilities play a vital role in the MEDIEVAL project. It enhances the usage of its media independent interfacing mechanisms through its provision over different conceptual areas that go beyond mobility management, such as video services and transport optimization. However, in order to better operate at supporting those new usage scenarios, not only the middleware characteristics of this cross-layer approach need to be enhanced, but also its standard link layer and mobility management capabilities are able to be revisited regarding their own new en-

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[1] ICT-OPTIMIX, `http://www.ict-optimix.eu/`

[2] PHOENIX, `http://www.ist-phoenix.org/`

[3] NAPA-WINE, `http://www.napa-wine.eu/`

hancements. The next paper, addresses this specific Wireless Access functional area of the MEDIEVAL project, identifying the enhancements provided by new extensions over the base IEEE 802.21 standard.

Paper D

Daniel Corujo, Michelle Wetterwald, Antonio De La Oliva, Leonardo Badia and Marco Mezzavilla, Wireless Access Mechanisms and Architecture Definition in the MEDIEVAL Project, *in Proc. MediaWiN 2011 6th IEEE Workshop on multiMedia Applications over Wireless Networks, at the IEEE Symposium on Computers and Communications (ISCC)*, Corfu, Greece, June 2011

Paper **D** details the architectural aspects presented by paper **C**, by focusing on the specific aspects of its wireless access functional area. Targeting both coordinated-based (e.g., LTE) as well as contention-based (e.g., WLAN) wireless accesses, this functional area of the MEDIEVAL project provides a fitting place for the application of the media independent abstraction middleware capabilities of the IEEE 802.21 component. Besides the detail of specific enhancements to the wireless access parts targeted by the project, the paper also proposes extensions on the abstraction capabilities of the framework. Concretely, the support of LTE events and commands progresses the set of supported access technologies beyond the ones supported by the original standard [10], as is the set of extended Information Elements of the MIIS service, through its enhancement with information both regarding new link layer elements (e.g., support of jumboframes, MBMS, and flow-based mechanisms) as well as new higher layer elements (e.g., support of CDN). The flexible capabilities of the proposed middleware, concretely its interfacing capabilities, are further evidenced by the inclusion of intelligent logic through the inclusion of abstract QoS mapping mechanisms, simplifying the realization of resource requirements by both video services and network control procedures, in respect to mobility management, evolving from the improvements provided by cross-layer mechanisms shown in [121]. As such, with the support of these media independent mechanisms, the MEDIEVAL project is able to provide efficient video-aware mobility support for network operators.

One interesting consideration of the wireless concepts being explored in MEDIEVAL, was the inclusion of multicast mechanisms, such as MBMS. Although multicast concepts have been difficult to be deployed as an Internet-wide way, they make sense as an optimizing component in more localized networks. Concretely, when considering their use in control signalling, one can conceive scenarios where a single message is able to impact and control a set of nodes, with reduced signalling costs. This concept was leveraged in the research work that lead to the development of paper **E**.

Paper E

Daniel Corujo, Sergio Figueiredo and Rui L. Aguiar, Media-Independent Multicast Signalling for Enhanced Video Performance in the MEDIEVAL Project, *in Proc. 2011 Future Network & MobileSummit*, Warsaw, Poland, Jun 2011

This paper established the first concepts regarding multicast transmission of MIH Protocol messages. It firstly considers a scenario, motivated by the increase in number of mobile users connected to wireless access networks, where a network-controlled handover decision towards another network Point of Attachment would affect not just a single user, but blocks of users. Under the traditional MIH Protocol transmission mechanism, each handover command would be sent using a single unicast message. In this way, for the same handover decision, multiple messages would need to be forwarded through the network, wasting resources.

The application of broadcast and multicast mechanisms is no stranger to IEEE 802.21. However, they are only related in terms of supporting broadcast technologies by the standard [122], or by coupling handover procedures with multicast mobility mechanisms [123]. The paper thus evolves from these scenarios by proposing, and defining, the necessary MIH Protocol elements to support multicast signalling. Concretely, the support mechanisms of Discovery and Capabilities Discovery are incremented with parameters to identify node IEEE 802.21 multicast capability, new Information Elements are defined (allowing the identification of Points of Attachment with multicast capability), a new multicast MIHF identifier is provided (allowing the destination group identification of multicast messages), multicast information is added to the network protocol interfacing of the MIHF abstraction layer and, finally, considerations are presented for integrating these mechanisms with multicast group management protocols. In this way, handover management scenarios featuring multiple nodes are able to operate with just the transmission of a single message.

Another equally important consideration derived from the work achieved from this paper is the consideration of which other scenarios would benefit from this multicast handover optimization control capability (i.e., wireless sensors). In this kind of scenarios, with many sensors and smart devices being deployed in the same area, is common to see management and control actions being executed over groups of nodes, instead of single devices. Moreover, smart devices are now able to be equipped with different kinds of wireless link interfaces, becoming eligible for the handover optimization mechanisms provided by media independent middleware. With this, the concepts for extending the command and event capabilities to go beyond handover operations, and to actually control the base functions of smart devices as well, provided the guidelines for paper **F**.

Paper F

Daniel Corujo, Marcelo Lebre, Diogo Gomes and Rui L. Aguiar, Sensor Context Information for Energy-Efficient Optimization of Wireless Procedures, *in Proc. 22nd IEEE In-*

ternational Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Toronto, Canada, Sep 2011

This paper leverages from the sensor scenario possibilities triggered by the research outcome of paper **E**. Progressing those scenarios into mobile sensor environments, generated the concept of enhancing sensor connectivity procedures with the handover control capabilities of IEEE 802.21, as well as to increment its abstraction interfacing to allow the control, and sensor information gathering, to the sensor devices themselves. In this way, a framework was defined that provided the architectural concepts that lead to the extension of the standard MIH Protocol from the 802.21, by adding new generic-purpose sensor messages and parameters. These new messages enable the integration of sensor-related information into existing and novel enhanced handover scenarios, in an abstract way (i.e., independently of sensor model or make). In this case, this framework was deployed into real mobile node connected trough WLAN, and generating Media Independent Sensor information related with movement (e.g., an accelerometer sensor). That information was used to activate or deactivate the WLAN interface depending on the node mobility, thus conserving battery when no connection opportunities presented themselves. This was also integrated with a network-based contextual decision node, which was able to convey the abstract sensor information with abstract link layer information, thus generating a new unprecedented way of optimizing mobility and handover scenarios.

In this way, the presented framework evolves from other Energy Efficiency solutions that operated over specific wireless link technologies, [124], or focused on the wireless sensor network itself [125], thus tying themselves to specific sensor technologies. Moreover, when it comes to describe the information provided by the sensors themselves, the proposed solution deviated from XML-based designs (which required more information to be exchanged, as well as more processing) [126], or coupling high-level primitives that forced the deployment into a family of sensors [127].

With the sensor-enabled handover optimizing middleware concepts developed being progressed in a number of different scenarios, it became apparent that the sensor information containers and definition aspects were placing the base MIH Protocol under stringent requirements. With the base IEEE 802.21 information exchange structures originally conceived to target handover procedures, it was becoming complex to describe and parametrize different sensor information from a plethora of possible physical phenomena, as well as from other aspects, such as units used, different devices with different capabilities, amongst other heterogeneity issues. These considerations were explored by the research work from paper **G**, following next.

Paper G

Daniel Corujo, Marcelo Lebre, Diogo Gomes and Rui L. Aguiar, A Framework for the Connectivity of an Internet of Things, *in Proc. IEEE Sensors, Special Session: Ambient Intelligence Technologies & Applications Session*, Limerick, Ireland, Oct 2011

This paper contributed with an initial framework design featuring an extended Information Server where IoT device vendors could publish the interfacing characteristics of their devices (e.g., units, commands and information supported). With the assistance of a ontology-based interfacing description, the semantics of the different interfaces (here dubbed SAPs, from the IEEE 802.21 Service Access Points) could be interpreted and used to operate with the devices. These concepts were deployed into a simple proof-of-concept scenario featuring real life sensors, simulating a disaster situation where autonomous entities could become active, scan their surroundings and connect to a network in an opportunistic way to disseminate information and receive commands (e.g., reporting the detection of an injured person, or receiving a command to shut down a gas valve). The results further reflected the importance of maintaining the abstraction aspect of the different access networks, despite their specificities, because the information interexchange are impacted by the performance of both the links and the devices involved (i.e., in terms of performance).

The core contribution of this paper was to raise awareness that an Internet of Things can go beyond the access of devices, and actually encompass services as well, with both being accessible using the same generic procedures. As such, the presented framework evolves from other designs which only targeted a sensor-based Internet of Things, despite already leveraging a cross-layer approach [128] and providing semantic mappings of different behaviours, according to the device in use [129]. Solutions targeting service provision in Internet of Things [130] typically chose as well to aggregate services into functional groups and hierarchies, impacting the design flexibility when subject to different scenarios and interpretations.

The research outcome achieved with this paper, marked a first step in the generic controlling middleware framework based on extended media independent concepts. Although the base mechanisms were evaluated, it remained the evaluation of more finer grained details, such as its behaviour in different access technologies, as well as the capabilities for supportive procedures, such as node discovery, capability exchange and event registration. Moreover, these base concepts also provided insight on other generic-supportive mechanisms. An important problem to tackle in IoT management platforms aiming at generic reach, is that is needs to be sufficiently "light" light to be supported by low-powered devices, but still meaningful to be leveraged by more powerful devices and generate added value. These concepts led to the development of MINDiT, as described in paper **H**.

Paper H

Daniel Corujo, Marcelo Lebre, Diogo Gomes and Rui L. Aguiar, MINDiT: A Framework for Media Independent Access to Things, *in Elsevier Computer Communications, Special Issue on on Smart and Interactive Ubiquitous Multimedia Services*, Mar 2012

Paper **H** progressed and evolved the basic framework developed in paper **G**. Concretely, this paper contributed by defining refined concepts for a new abstraction middleware, that provided an ontology-defining mechanism, allowing different devices (i.e., going beyond the scope of just sensors) to provide their interface definitions, as well as to define the information they are able to generate, or the commands they are able to interpret. This information is then shared with other entities, using the same interface, allowing them to operate those devices, using a single common protocol. The framework considers a flexible and modular approach, allowing different dissemination modes depending on the device characteristics. For example, low-powered devices might not be able to encompass the full range of mechanisms considered so, through the exchange of capabilities and registration between nodes, more powerful devices can act as a middleware proxy, providing a communication flow for the devices control by management entities. Although the focus on ontologies and semantic learning are beyond the scope of both the paper and this dissertation, the framework was defined in a plug-in manner, allowing the coupling of different interface learning possibilities. In that way, armed with an example information representation mechanism, the paper contributes with the deployment of this framework in a rich heterogeneous scenario comprising different types of sensors, mobile nodes and laptops, using different kinds of access network technologies, generating different types of multimedia information and controlling actions. Different aspects were measured, such as wireless utilization, battery consumption, processing delay and even reliability, comparing against other more demanding high-level protocols. The paper thus provided valuable insight on the utilization of enhanced abstraction middleware mechanisms, with the ability to operate in truly heterogeneous scenarios, going well beyond the specific use case of handover management, and able to support and participate in different kinds of management and controlling procedures. This is especially important in current IoT efforts for operator-managed platforms, where both research and industry are struggling to generate a truly generic cross-layer control framework and move away from vertical concepts.

The framework evolved from available vertical deployment solutions, with their cross-layer mechanisms just contemplating a specific family of devices and protocols [57] [89] [131]. Moreover, with the target of increasing support possibilities, the framework leveraged simple transport and information definition mechanisms, avoiding large-sized messages and processing-hungry associated to web service-oriented procedures, present in other solutions [92] [93]. Lastly, this contribution also maintained the pursuit for one of the core research objectives of this thesis, regarding intrinsic mobility support. As such, it deviated itself from solutions where its support was existing only at a gateway-level [98] [99], and provide it at the device or service level.

This reflected the integration of novel generic control middleware aspects as an incremental approach over the existing Internet architecture. However, with research efforts on clean-slate designs growing, one but wonders which new possibilities are opened by this new paradigm, in terms of management. Also, it is important to verify if the devices incremental enhancements have any meaning or need at all, from these new scenarios. Particularly the case of ICN, where content becomes the core aspect of network operations, it challenging to consider how typically host-centric management and control concepts are viable in these content-centric environments. Paper **I**, summarized next, tackled that issue by selecting the NDN framework, and enhancing it with management and control capabilities.

Paper I

Daniel Corujo, Ivan Vidal, Jaime Garcia-Reinoso and Rui L. Aguiar, A Named Data Networking Flexible Framework for Management Communications, *in IEEE Communications Magazine*, Vol. 50, no. 12, pp. 36-43, Dec 2012

Paper **I** leveraged the previous media independent control middleware concepts over a clean-slate approach, in the form of the Named Data Networking framework, an instantiation of the Information Centric Networking paradigm. The paper contributed by re-utilizing the content-centric mechanisms of the NDN framework, for the realization of management procedures, not only on a single node itself, but between remote nodes (e.g., network controlled scenarios). It established a middleware component through the exploitation of the interfacing points between the NDN fabric, the link interfaces and applications. In this way, a Management Application was developed, which was able to collect information from the links and other applications, and convey it to a network controlling entity. In an optimal interface selection scenario, the framework allowed the network control entity to conjugate the received information with more elements (e.g., from other entities residing elsewhere on the network), and used to produce an enhanced connectivity solution for the mobile node.

In this way, the existing NDN [100] framework was enhanced with management capabilities. Moreover, the results obtained with this research effort, allowed the exposition of the ICN paradigm into management concepts, submitting it to new scenarios, which is a decisive action towards the improvement and deployment of ICN as a networking solution of the future.

Chapter 4

Conclusions and Future Work

In this thesis, several aspects related to the feasibility of deploying a media independent middleware providing control mechanisms in an evolutionary Internet architecture design, were addressed. Specifically, two complete frameworks addressing these mechanisms in mobility and M2M environments were proposed and evaluated, which together address how the flexibility of the middleware cross-layer approach can be adapted to support generic control procedures and optimizations. Following this approach, the media independent interfacing mechanisms were also extended to support video-aware parameters with the aim of supporting input from video applications, for optimizing mobility and link layer procedures, within the MEDIEVAL project. Finally, the same management and control concepts were deployed under an ICN paradigm framework, allowing the verification of their contribution in clean-slate networking architectures.

In this section, the thesis conclusions are presented, followed by directions for future work.

4.1 Conclusions of Research Objectives

The research problem addressed by this thesis was identified in Section 1 as being:

How to define a generic purpose ***middleware*** *enabling high-level entities and services to provide their requirements and allow them to serve as abstract inputs towards the execution of link layer mechanisms, with the mobility procedures being able to leverage that information and control towards the support of session continuation in a heterogeneous access network environment providing access to different kinds of mobile devices?*

This research problem was further split into four distinct research objectives. In this section, conclusions of those research objectives are presented.

4.1.1 Research Objective 1

This thesis has as the following first research objective: *How can a media independent* ***middleware*** *control plane be deployed over the current Internet architecture, that is flexible enough to operate in a multitude of devices with different specifications, connected using different access networks and running different services and applications?*

IoT scenarios featuring M2M interactions, present a complex setting in terms of device interaction. Not only each device can provide a different set of interfaces, but they can also operate over distinct link access technologies and be used for widely variant scenarios and purposes. Existing approaches are mainly composed of vertical "silos", where specific instantiations of sensor network technologies are integrated with custom-purpose middleware, providing only support for specific equipment and limited scenarios. More comprehensive solutions are provided in the form of Service-Oriented Architectures and different high-level protocol standardization initiatives, which, although providing the common means for IoT information inter-exchange, disregard the underlying characteristics of the devices themselves and of the access networks they are connected to.

In this thesis, the inherent media independent mechanisms of the IEEE 802.21 standard were enhanced with sensor-related parameters, enabling its deployment into IoT scenarios. The base MIH mechanisms were further enhanced by introducing a series of mechanisms that facilitate the collection of sensor information, using gateways. Furthermore, the information dissemination performance of this framework was implemented and measured, under scenarios different devices connected to a gateway sending information towards consumers. Results have provided insights on the usefulness of aggregation and compression mechanisms, as well as the support of different event dissemination schemes. Moreover, the framework was also compared in terms of frame structure and energy consumption with two protocols specialized in event sharing and sensor communication (CBE and DASIMA), showing that the addition of sensor information to the MIH protocol is both able to provide a simpler structure and low energy consumption. The signaling processing time and size between the newly created messages and the base MIH protocol messages were also compared, with results showing that the new sensor messages are on par with the base standard messages, allowing their utilization with no performance impact when compared to IEEE 802.21. This study shows that these new media independent sensor messages represent a resource efficient framework, whose dynamic structure supports both complex and simple data types, while creating an adequate deployment for a standard media independent transport protocol in heterogeneous environments.

Considering the media independent development made at this point, the thesis work progressed into the definition of a novel framework enabling the control of M2M mechanisms in IoT scenarios for ubiquitous smart environments. This Media Independent Access to Things (MINDiT) leverages on a set of profound evolutions from the standardized IEEE 802.21 MIH

(Media Independent Handovers) framework and its services, expanding them for the facilitation and optimization of media independent access to IoT devices and services. It enhances such concepts by introducing new generic-purpose ones, such as Dynamic Service Access Points (SAPs), which allow the definition of interfaces towards different devices and services using a unique communication procedure, based on an unified and enhanced MIH Protocol. It also defines an Information Domain Media Independent Information Service (IDMIIS) server, with the ability to store SAPs from different devices and services, allowing for the integration of different query mechanisms for accessing interfaces (ranging from simple XML query procedures to powerful high-level semantics and ontologies). To allow its deployment in a broad set of cases (ranging from interfacing with sophisticated services residing in powerful mainframes using optical wired connections, to low cost devices using simple wireless networking stacks), a proxy mechanism was also defined aiming to increase the interfacing opportunities with different kinds of devices and services.

This framework was validated through a prototype built over the open-source IEEE 802.21 implementation ODTONE. The message signaling mechanisms from MINDiT were compared to other SOA-based frameworks using Web Services (also implemented), showing that its lower message size required less resources utilization. To illustrate its flexibility, MINDiT was also deployed in a multimedia-enabled smart environment scenario featuring agents, mobile terminals in wireless environments and sensor technologies. The footprint imposed by its mechanisms was evaluated in terms of interfacing procedures, and information exchange requirements. Furthermore, to analyze the scalability, the framework response was studied when subjected to different rates of signaling generated.

Results demonstrated that the MINDiT middleware framework supports a broad range of features while requiring a significant low amount of information. This has the benefit of facilitating and optimizing its deployment in scenarios featuring low cost devices with stringent requirements (both in terms of processing power as well as wireless networking capabilities), which are currently increasing in availability (e.g., sensors in mobile phones and smart environments), without hindering flexible interactions with high-level services (e.g., through L3 transport protocols and broad support of information definition).

4.1.2 Research Objective 2

The second research objective was composed as: *With the different requirements placed by services reaching mobile terminals connected to different access networks, how can a network mobility decision entity make use of a generic* ***middleware*** *to provide an optimized handover decision, making stringent use of the required signaling, and being able to procure and activate the necessary link resources?*

The research work presented by this thesis provided a description of how media independent middleware mechanisms are able to be used to enhance mobility scenarios and provide optimized handover mechanisms. Its flexible cross-layer approach allows easy interfacing between the mobility decision modules and the link layers.

Moreover, an important issue of network-based localized mobility management procedures is that, with the mobile node absent from the mobility signaling exchange, it is limited in terms of providing information to the network regarding its perception of the link conditions. The integration with media independent mechanisms, such as IEEE 802.21, allows the network to receive event notifications from the mobile terminal, nor only regarding the signal strength conditions, but of the network attachment points available in the vicinity of the mobile terminal. With this information, the network can not only choose the best alternative, but also proactively prepare resources there.

To evaluate this integration, ODTONE was integrated with another in-house open-source software that was managed during the time of this thesis, OPMIP, a PMIPv6 implementation. ODTONE, alongside OPMIP, was able to provide a flexible fabric supporting a network controlled mobility scenario where MIH-enabled entities become able to provide events, information, and commands in a local or remote way.

With IEEE802.21 and ODTONE, the PMIPv6 protocol is complemented with the necessary features to fully operate in heterogeneous environments by having an abstract way of interacting with multiple technologies. ODTONE solves the out of scope mechanisms existing in the PMIPv6 standard, by having link-layer triggers regarding MT attachment supplied by IEEE 802.21. Results show that a network-controlled mobility scenario was able to support the signaling footprint that applying IEEE 802.21 to the support and enhancement of PMIPv6 procedures requires, while evidencing the software framework's flexibility to support other algorithms and mobility schemes.

4.1.3 Research Objective 3

The third research objective addressed in this thesis was defined as: *When video traffic places a set of minimum requirements for network conditions, how can a generic* ***middleware*** *support a mobility management process taking into consideration such requirements and the necessary link access procedures to execute handovers?*

With the increase of mobile users accessing video content online, mobile operators are turning to the development and deployment of video-aware optimization mechanisms. These mechanisms not only have to consider that high-level traffic solutions (such as CDNs and caching schemes) are required, but due to the different wireless connectivity means available to devices, the video traffic needs to be optimized taking into consideration the current conditions of the network. Moreover, the setting becomes even more complex when such users are on the move, changing their point of attachment to the network, but still wishing to maintain their service sessions active.

The research work presented in this thesis introduced a novel video transport architecture, being pursued under the FP7 MEDIEVAL project, and the important role that media independent middleware mechanisms have as the control plane facilitator between the different functional areas. Moreover, here were described the necessary changes that need to be produced over the base IEEE 802.21 standard, in order to support video-aware parameters, as well as support novel mechanisms such as flow mobility.

At this stage, the first design of the complete MEDIEVAL architecture has been performed, including the necessary subsystems and interfaces between them. The proposed architecture considers extensions at the functional areas of Video Services Control, Wireless Access, Mobility and Transport Optimization. The architecture also highlights a cross-layer approach to exploit the interactions between these subsystems, which are placed at different levels of the network stack.

In this architecture design, media independent mechanisms play an important role in the integral MEDIEVAL design, since it provides the common language used by the majority of MEDIEVAL's components belonging to the different functional areas, enabling them to communicate with one another. The main paradigm behind this framework is the use of the media independence concept to reduce the complexity of higher layer algorithms and management operations. In this way, the extensions provided by MEDIEVAL over the base 802.21 design, not only allow video parameters to be used as input for link layer actions, but they can also be used to give high-level entities access to novel link procedures, such as packet marking and selective packet drop.

These changes have been implemented over ODTONE, with the different international partners involved interacting with the software as MIH-Users or link modules. Currently, such software modules are integrating the interfacing towards ODTONE, towards a final demonstrator to be presented in September.

4.1.4 Research Objective 4

This final research objective was defined as: ***Research Objective 4:*** *When clean-slate designs are being proposed as replacements of the network layer of the current Internet, aiming to optimize content interexchange, how can a control management* ***middleware*** *be generic enough to see its operational mechanisms be deployed in those environments as well?*

It is said that adversities are also at the core of generating new opportunities. In fact, that is what it is assumed when one considers how the growth and evolution of the Internet utilization is stretching the capabilities allowed by its underlying architectural design. For many years its simple design was a blessing that allowed its exploitation as the de facto digital world information interexchange network. However, there are those that argue that it is also becoming a curse, with the simplistic nature of its design hindering new developments in light of an even greater growth in its utilization (both in terms of quantity of users and services, but also of new ideas and scenarios).

As such, clean-slate research has increasingly gained momentum, providing new architectural concepts and deployments with the ability to both solve the current Internet's issues, but better preparing it to even more far-ahead future innovations.

The research work presented in this thesis, evaluated the capability of NDN to encompass control management middleware aspects, not only managing to do it so, also proposing extensions and the exploitation of new possibilities and scenarios. This is very important in for research in this kind of frameworks, because research effort is often more guided towards routing performance aspects, or making sure that a certain set of popular protocols and services are able to run with a comparable performance with today's Internet.

The research outcome achieved through this thesis actually broke that trend, and concerned itself not with what ICN needs to mimic what is done with the current Internet, but placed its mindset more towards finding out what is possible to achieve with ICN beyond what the current Internet is capable of. In order to succeed in that, it is important to expose the framework into different new kinds of scenarios, aiming to identify and improve its shortcomings, as well as to further progress its own strengths.

This line of thought was vital in the possibility that was presented to the author, of channelling his views, ideas and results, into the IRTF's ICNRG, and assist to the effort there in providing guidelines for the deployment of ICN, and with a clear feeling of having contributed to the future in communications.

4.2 General Conclusions

As communication networks evolve, so do the services and applications that operate over them evolve, as well as the ways we utilize them. An unseen (but underlying) harmony between these three elements is necessary to maintain the balance of the procedures and mechanisms that support them. This is a reality in today's Internet usage: when a service (and its associated type of traffic) becomes popular, more and more users adhere to it. If the communications infrastructure does not predict or follow such increase of the other two elements, then their provisioning will fail. But the problem is not only about how the infrastructure is able to support or not the services and how they are used. If it evolves too much without applications able to take advantage of the "super-network", then it just becomes an unused and expensive tool, that is hard to be supported.

In this way, the Internet architectural design was able to mask this issue for quite some time, through the provision of a layered model (i.e., the OSI model). As such, the information inter-exchange process would involve different layers of that model, which would communicate with their"neighbor" layers in a structured and normalized fashion. Moreover, evolutions at the different levels could be pursued without affecting the other layers.

However, we have been witnessing a disjoint evolution process between the different layers.

The set of “service” layers has been boosting itself throughout the years, providing multimedia and Web 2.0 services and applications (that amply contribute to the growing usage of the Internet). The network layer, through the IP protocol, has been following an incremental “patch-upon-patch” approach, trying to evolve its simple architecture into incorporating mechanisms with evergrowing importance (i.e., security, mobility, identity, amongst others). At the “bottom”, link layers have been evolving on their own as well, with the proliferation of new wireless access technologies, providing truly heterogeneous connectivity environments.

Throughout the years, different initiatives have provided different solutions with the aim of bringing together different aspects of multiple layers, in a single controllable domain. Architectural approaches such as IMS or OMA provide insightful and attractive platforms for operators and service providers. However, they are built ”around” the Internet fabric, evolving from the inter-linking of the different layers with controlling mechanisms that appear appealing to either service provision or telecommunications operator management.

The challenge presented to the author of this thesis in its early stages was how to develop a sustainable and flexible underlying communication middleware, supporting Internet connectivity procedures under a mobility setting. Considering the challenges that the current Internet faces (which increasingly stress its architecture design, and severely hinder the deployment of novel future applications), the work evolved to the exploitation of cross-layer mechanisms for the purpose of optimizing network procedures (i.e., mobility) and high-level entity operation (i.e., video traffic generating applications) through interfacing with the underlying link control.

The generated work was driven by a deep and insightful analysis of media independent mechanisms, leading to a continuous extension and evolution of existing approaches (in the form of enhancements and re-designs of the base IEEE 802.21 Media Independent Handover services). This allowed to not only enhance the deployment of such mechanisms in the originally targeted area of mobility , but also allowed its incremental integration into the concept of video-aware optimization mechanisms and M2M communications control frameworks (with the former one providing results with better performance than existing area-specific solutions).

Moreover, the contributions from this work where able to impact not only the target areas addressed by the scope of the thesis, but other concepts as well (i.e., multicast), in different different groups such as the MEDIEVAL project, standardization work, collaboration work with international partners, open-source software, as well serving as a key driver for the genesis of new projects and further research work. Furthermore, the outcome of the work has also been published in a number of journals, book chapters and conference papers, which are referenced throughout the thesis.

4.3 Future Work

This section presents and discusses the topics for future work as follows: 1) Evaluation of MEDIEVAL enhancements, 2) Standardization of Media Independent Multicast Signaling, 3) Deployment of Media Independent Concepts into Telecommunication Operator-Driven Environments and 4) Toward Novel Information-Centric Networking.

4.3.1 Evaluation of MEDIEVAL Enhancements

The MEDIEVAL project is currently on its final year, out of a total of three. After a first year of architecture specification, identifying all the involved functional entities and required interfaces, the second year was dedicated to provide an initial prototype to validate the MEDIEVAL concepts. In this final year, refinement of the specifications has lead to the final integration and implementation efforts.

Currently, a set of scenarios showcasing MEDIEVAL's mechanisms have been specified, which compose the core part of a physical demonstrator installed in the premises of Eurecom[1], in Sophia-Antipolis, France.

The first scenario considers a multi-interface mobile node accessing a VoD service stream, while moving between three distinct wireless access networks: 3G, WLAN and LTE-A. The video flow will take advantage of MEDIEVAL's mobility mechanisms, which will move the video session into the new access network with no disruption to the service itself. Moreover, the network will take advantage of mobility triggers being sent to network caches existing at the access routers of each access network, improving the video reception quality. In this scenario, the MEDIEVAL-enhanced IEEE 802.21 mechanisms will provide support to the mobility management entity by providing heterogeneous link information and control.

The second scenario features a user terminal acting as a mobile real-time video source, with the capability of connecting to 3G and WLAN networks. This scenario is not only complex due to the source of the video feed is on the move (i.e., upload considerations in the network on behalf of the users are always complex to execute in operator domains), but also there are multiple listeners in a multicast session. In this scenario, the MEDIEVAL-enhanced MIH services will not only provide the necessary heterogeneous link support for the mobility process, it will also be responsible for identifying to the mobility management entity, the network points of attachment that support multicast.

Lastly, the third scenario will feature an inter-operator mobility process. In this case, the video content and services are provided by a third party. The scenario aims to compare the performance of an MEDIEVAL-enabled operator against a normal one. In this case, the LTE operator is coupled with the enhanced MEDIEVAL video traffic optimization mechanisms. However, the user terminal identifies a WLAN network belonging to another operator and

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[1] Eurecom, `http://www.eurecom.fr/en`

initiates an inter-operator handover to that location. However, despite being a WLAN network, the link is highly congested and it does not provide any kind of video optimizations. As such, the video in the WLAN network is presented in a lower quality. In this process, the MEDIEVAL-enhanced MIH mechanisms help in providing the detection of alternate points of attachment and support the mobility process.

Due to the importance of the IEEE 802.21 mechanisms, as well as from its MEDIEVAL-based extensions, all the entities involved will feature ODTONE's implementation of the MIHF and of the MIH protocol. Currently, the MEDIEVAL extensions to the MIH mechanisms are being refined into the code, leading to their deployment in the physical nodes of the testbed. The different partners providing the nodes acting as MIH-Users and Link modules are integrating the MIH Protocol from ODTONE into their developments as well. With the initial prototype evaluation done at the end of the second year, the third and last year of the project has been dedicated to a revision of the implementation aiming for full integration and final specifications.

As such, important outcomes are expected to be finalized in this work:

- Deployment of a real implementation of a MEDIEVAL-enhanced ODTONE IEEE 802.21 implementation in a complex environment, featuring different kinds of nodes, different wireless access technologies and different services.
- Collection of performance and usability metrics of the utilization of these mechanisms.
- Dissemination of experimental testbed results in different fora.
- Collection of feedback from users of the ODTONE open-source software project.

Moreover, the problems and results received by the end of the project (coupled with the parallel evolution of the state-of-the-art from the research areas targeted by MEDIEVAL) will undoubtedly fuel novel considerations and enhancement possibilities. As was pointed out in Section 1, video traffic is expected to keep on growth towards the year 2015. With the new services being deployed to the Internet everyday (placing high requirements in terms of bandwidth, mobility and different wireless access technology usage), there will never be a short demand for the development mechanisms optimizing the user experience in such heterogeneous scenarios.

4.3.2 Standardization of Media Independent Multicast Signaling

Media Independent Multicast Signaling is a concept that has been introduced in Paper **B**. Currently, ODTONE is being enhanced with the mechanisms that have been published in [26], allowing for group management of 802.21 multicast signaling.

Based on this on-going work, the author has teamed up with elements from the Universidad Carlos III de Madrid, in Spain, which are voting members within the IEEE 802.21 Working

Group. This working group has proposed the creation of a new Project Authorization Request (PAR) for an amendment on IEEE 802.21 regarding MIHF ID Group Management, thus becoming the IEEE 802.21d. Although the Advanced Telecommunications and Networks Group, from the Instituto de Telecomunicações in the University of Aveiro, is not a member, it has been recognized as an expert in the IEEE 802.21 matters, and a main participant in the architectural and implementation effort towards IEEE 802.21d. In a regular basis, the author of this thesis participates in audio conferences with several of the WG members, having contributed to key documents (e.g., requirements, scenarios and the current proposal).

With the increase in numbers of users accessing services online through wireless access networks, network management procedures can require the execution of link layer procedures in several users at once. With IEEE 802.21d, the media independent mechanisms of the original standard are able to evolve from the until-now necessary specific interaction per user, in to multicast signaling. In this way, not only handover control is further facilitated, but it also reduces overhead and consumed bandwidth.

Last year, the IEEE Plenary Session in Big Island Hawaii, USA, an enhanced version of ODTONE extended with multicast signaling was presented and demonstrated. Together with UC3M, ATNoG has been active in the definition of group management extensions to the IEEE 802.21 standard, enabling its deployment in a series of novel scenarios. The concepts provided in this demonstration contributed towards the acceptance of a motion to forward the IEEE 802.21d PAR to the IEEE-SA NesCom, which will lead to the full development of the new amendment to the IEEE 802.21 standard.

As such, important outcomes are expected from this future work:

- Contribution to standardization effort within the IEEE 802.21 WG.
- Exploitation of multicast mechanisms for the optimization of handover management in heterogeneous networks.
- Dissemination of results in different fora.

4.3.3 Deployment of Media Independent Concepts into Telecommunication Operator-Driven Environments for Machine-to-Machine Frameworks

When considering M2M, the market for this technological area is currently shifting from a niche situation, into an expected massification period occurring in the coming years. Contributing to this change are the growing numbers of network-enabled devices appearing in the market (beyond smartphones and computers), the diminishing cost of these devices as well as communication modules, the increase in standardization activities in different sectors involving M2M services, amongst others.

Paying close attention to this market, telecommunications operators are developing a plethora of different initiatives and strategies, aiming to position themselves in this value chain, with the objective of supporting new differentiated services. Currently, different approaches are being taken towards the M2M market. Some opt for the establishment of partnerships with hardware manufacturers and service platforms, while others chose to develop and operate their own.

In the past, most operators have been providing an approach to M2M via vertical service platforms, dedicated to a specific area of business, as a complement to the connectivity plane. However, with the paradigm shifting towards IoT, and with the operators' desire to integrate the value chain, new M2M service platforms are in demand, with the ability to support different business areas in a transverse way. Moreover, such frameworks should also expose, in a secure and controllable way, the relevant network capacities, allowing third parties to build new services and business.

This is an ample setting for the introduction of M2M-enabled media independent mechanisms discussed and presented in this thesis. Recently, with the APOLLO project, the target to develop the underlying technological framework for the support of new services in M2M environments becomes increasingly important. The framework developed in this project will support the management, control and monitoring of heterogeneous device networks (i.e., sensors and actuators), providing services for the building of a new generation of M2M applications, in different business sectors (i.e., agriculture and smart cities).

In this aspect, media independent mechanisms will provide a cross-layer resource that will simplify the access to the data information and control facilities of different devices, while taking into consideration their different wireless connectivity technologies.

As such, important outcomes are expected from this future work:

- Contribution of an important part of the results obtained from this thesis into a pre-product phase implementation.
- Awareness acquisition of telecommunications operators' requirements in terms of M2M.
- Dissemination of results in different fora.

4.3.4 Toward Novel Information-Centric Networking

The ICN research area has been increasing in the last few years in an exponential way. Nowadays is common to find dedicated workshops, special magazine issues or even whole international research projects devoted to progressing such mechanisms. It is clear that the Internet's request for new solutions provides a strong drive that fuels ICN research, and with this strong increase in contributions to the area, new scenarios and concepts are continuously being considered under its scope.

In order to progress the work, we have established a research partnership with elements from the Universidad Carlos III from Madrid, Spain, with whom we have already collaborated with [27], and extend our scenarios into novel areas.

Of course, considering actual large-scale deployments of clean-slate architectures is always met with a degree of resistance from operators and manufacturers, especially when there is so much to do and evolve. However, it appears that ICN does not need to walk alone in its pursuit for deployment. There are currently efforts being made to associate ICN with Software-Defined Networks concepts, not only allowing large-scale deployments of ICN, but also to complement it with virtualization concepts in new kinds of network virtualization scenarios. As such, not only more experimentation possibilities present themselves, they can actually contribute to the enhancement of ICN frameworks themselves.

Finally, the standardization work on ICN has just started, and is already generating appreciation in other areas (such as the request for interest from the NMRG over our ICN management considerations). As such, it is important to keep progressing and evaluating new outcomes, in order to properly define which are the guidelines for ICN utilization in the future.

In this way, future work on ICN will progress in the following ways:

- On-going international collaborations in new scenarios for progressing ICN and disseminate new results.
- Explore synergies between ICN and other existing networking mechanisms, such as SDN and virtualization.
- Progress the contributions to the standardization work.

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Appendix A

Included Articles

The articles included in annex have been reformatted into single-column, in order to increase their readability, while maintaining all the respective content unchanged.

Paper A

Daniel Corujo, Carlos Guimarães, Bruno Santos, Rui L. Aguiar, Using an Open-Source IEEE 802.21 Implementation for Network Based Localized Mobility Management, *in IEEE Communications Magazine, Special Issue on Communications Middleware for Mobile Devices and Applications*, September 2011

Using an Open-Source IEEE 802.21 Implementation for Network Based Localized Mobility Management

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Abstract

Taking advantage of the multi-mode ability of modern mobile terminals, cellular operators are investing in alternate access networks (such as IEEE802.11 and IEEE802.16) complementing the increasingly overloaded cellular accesses. Complementing this, IP mobility support is gradually being introduced into network architectures, providing session continuity. To facilitate and optimize handover procedures between different access technologies in a seamless way, the IEEE 802.21 Media Independent Handover Services standard provides technology agnostic mechanisms to obtain information and control link layers. Implementations of the standard are appearing, but since the support of IEEE 802.21 primitives directly at link driver level is not yet realized, they have to revert to proprietary wrapping mechanisms, or use specific operating system solutions, to circumvent this issue. In this paper we present ODTONE, an IEEE 802.21 implementation that is operating-system independent and open-source, and offers a novel approach towards interfacing with different link layers which facilitates the deployment of IEEE 802.21 mobility mechanisms in multiple scenarios. We present a scenario where we integrate our middleware with an IP mobility management protocol, Proxy MIP IPv6, highlighting ODTONE's supporting features and impact while providing an open handover control architecture for network based localized mobility management.

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1. Introduction

The proliferation of Mobile Terminals (MT) with multimode connectivity capabilities creates immense opportunities and appeal for the exploitation of heterogeneous networks. In the same geographical area, wireless networks of different technology may co-exist, managed by the same or different operators. Such conditions allow mobile users to discover and connect to different link technologies, offering different connectivity opportunities (both in terms of cost and capabilities) to running applications like VoIP, video and gaming. However, this adds to the complexity of managing different link connections on the terminal, as well as challenging the network operators ability to provide optimum connectivity. To overcome these challenges, the IEEE released in 2009 a specification for Media-Independent Handover (MIH) Services on Local and Metropolitan Area Networks, the IEEE 802.21 standard [1]. Its main purpose is to facilitate handover management in heterogeneous environments through the provision of a framework able to abstract the specificities of each link technology and exploit that abstraction to convey information from such links, allowing their control by higher-layer decision entities.

The realization of such handover management approaches requires the introduction of middleware entities within terminal and network nodes, interacting with the link-layers and the network stack within such devices. This interaction is largely dependent on their architecture, as well as operating system (OS). Although IEEE 802.21 defines the messages and parameters for supporting MIH mechanisms, its integration into specific network drivers and software is out-of-scope. As such, available implementations focus on a specific OS or are closed instantiations provided by operators or manufacturers. This specificity can particularly hinder the deployment of IEEE 802.21 in Network Based Localized Mobility Management scenarios featuring IP mobility mechanisms, where different network entities and MTs are required to interact remotely, each with their own specific set of architectural and OS requirements. Also, in multi-technology networks, the lack of participation from MTs in the mobility signaling can hinder optimized handovers, since the network is not able to consider the MTs perspective of different technologies. It is then necessary to couple IP mobility support mechanisms with the means to provide information regarding the MTs access, a task easily provided by IEEE 802.21.

With the increasing acceptance of IEEE 802.21, supported by efforts of standardization fora aiming towards its widespread adoption, an open implementation able to work independently of the underlying OS or hardware installed, is of great value. This is where ODTONE[1] (Open Dot Twenty ONE), an OS independent open-source IEEE 802.21 implementation, steps in. It provides a complete implementation of IEEE 802.21 mechanisms required to deploy and operate a MIH framework, providing an infrastructure able to easily interface with different link technologies operated in devices by distinct OSs, as well as to facilitate its extension with new mechanisms and integration opportunities.

In this article we describe the architecture of ODTONE, highlighting its approach towards interfacing with different link- layers which facilitates the flexible deployment of IEEE 802.21 mobility mechanisms in multiple scenarios. We first present a brief state-of-the-art and then introduce the general concepts of IEEE 802.21, followed by a detailed description of the software components belonging to the ODTONE architecture. We then proceed with the presentation of a use case where ODTONE is integrated with our own implementation of a localized mobility network initiated handover protocol, OPMIP[2], defining and analyzing the impact from the necessary information exchange between ODTONE and the mobility management components. Lastly, in the final section, we conclude the paper.

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[1] ODTONE Project, `http://atnog.av.it.pt/odtone`

[2] OPMIP Project, `http://atnog.av.it.pt/projects/opmip`

2. State of the Art

Throughout the development and debut of IEEE 802.21, the standard has been the subject of ample study [2]. For example, in [3] IEEE 802.21 is used to optimize the mobility management between 802.16 and 802.11 networks, exemplifying the architecture and necessary signaling. [4] presents the development of Media-Independent Pre-Authentication mechanisms leveraging IEEE 802.21 towards the support of optimized L2 handoffs. However, the IEEE 802.21 implementations used in these and most other works opt for a specific set of functions over a specific OS [5][6] or are tailored instantiations provided by operators or manufacturers.

While the availability of several different wireless access technologies can be offered by this IEEE 802.21 framework to multi- mode MTs, always-on access to services while on the move still requires the coupling of a mobility management mechanism. This enables connectivity and session maintenance while MTs are roaming from one access network to the other. For example, [7] introduces some guidelines for a context-aware middleware architecture enabling mobility management in Always Best Connected/Served wireless scenarios. It provides several components that evaluate network conditions and manage session continuity based in reference applications and provides a transparent access to interface capabilities through wrapper and feature modules available to different OSs, for different technologies. However, these components force this middleware to be tightly coupled with decision algorithms for context gathering, metric application and continuity management. This is in fact a key point for preferring the utilization of IEEE 802.21 as an enabling middleware for session mobility support: it provides abstract local and remote access to link-layer control and information, and can remain decoupled of the modules implementing mobility algorithms, allowing a flexible adoption of different schemes.

Another important factor for such Always Best Connected/Served scenarios is the enablement of a mobility solution at the IP level of the network stack. Many solutions have been thoroughly studied in the past [8], and have now been converging, at the cellular network level, to network-based and controlled approaches, which in one hand facilitate the management of mobility domains with hundreds of roaming MTs and, in the other, simplify MT design by conveying all necessary intelligence mechanisms to network nodes. These designs have culminated in the standardization of Proxy Mobile IPv6 (PMIPv6) [9]. However, several link-layer mechanisms which are important to PMIPv6 operations (e.g., handover candidate detection and selection, network resources querying and committing and network attachment detection) are out-of-scope of this standard. This provides a complex challenge for solutions enabling such behaviors that need to be able to be deployed in different network and mobile terminal entities, each with different requirements. Linking PMIPv6 and IEEE 802.21 signaling is thus a natural approach, where ODTONE aims to overcome this by providing a flexible and open approach towards high-level entities and link-layer interfacing in different OSs environments.

3. The ODTONE Architecture

This section describes the entities and mechanisms defined in the IEEE 802.21 framework, starting with the general concepts of the IEEE 802.21 standard and then moving on to our ODTONE implementation.

3.1. IEEE 802.21 MIH Services

The main objective of the IEEE 802.21 standard is to aid handover decision and execution entities, providing technology-agnostic means for information retrieval and control execution of different access links. To achieve this, a cross-layer function is added to all MIH-enabled entities, the Media Independent Handover Function (MIHF). This function, where the MIH services reside, provides Service Abstraction Points (SAPs) that act as an intermediary between higher-layer entities (or MIH-Users) and link-layers. The SAP provided to MIH-Users is named MIH_SAP, and enables the monitoring and control of link-layers in a technology-independent way. The MIHF interfaces with link-layers through the MIH_LINK_SAP, translating requests received at the MIH_SAP. This direct interfacing of the MIHF with each specific technology is achieved by mapping MIH primitives to their specific link counterparts. The SAPs allow access to the three core services provided by the MIHF:

- Media Independent Event Service (MIES) provides access to information regarding link status, such as indication that a link is going down, a new Point of Attachment (PoA) was detected, or the signal strength has crossed a pre- defined threshold.
- Media Independent Command Service (MICS) provides commands for link-layer control. These range from management primitives, such as event subscription and threshold configuration, to handover related primitives and link actions.
- Media Independent Information Service (MIIS) defines a set of Information Elements (IEs), and mechanisms to query them, which characterize network structure and parameters such as the Service Set Identifier (SSID) and channel. This information can be used to speed up handovers by pre-configuring at the terminal the required parameters of the target handover network prior to the handover execution. The information existing in the MIIS can also be used to provide information about nearby networks of different technologies without having to power up the remaining interfaces, conserving battery.

In addition, a network SAP enables MIH-Users to access services on other MIH-enabled entities by reaching remotely to other MIHFs through the usage of a MIH Protocol, defining the messages and parameters to access the MIH primitives in remote MIHFs. Figure 1 illustrates the local and remote interactions between MIH-Users and the link-layers, having as central point the MIHF. As an example, in an environment where handovers are controlled by a network entity, a MIH-enabled dual interface MT is able to provide IEEE 802.21 events indicating that the signal strength on its current link (e.g. Wi-Fi) is decreasing. Through this event, the network node is able to proactively prepare the network for handover procedures and transfer the on-going session from Wi-Fi to another available access technology (e.g. 3G). The MIH-enabled network handover decision entity is then able to issue an IEEE 802.21 handover command towards the MT, triggering a 3G link activation, and the required IP mobility procedures for session maintenance.

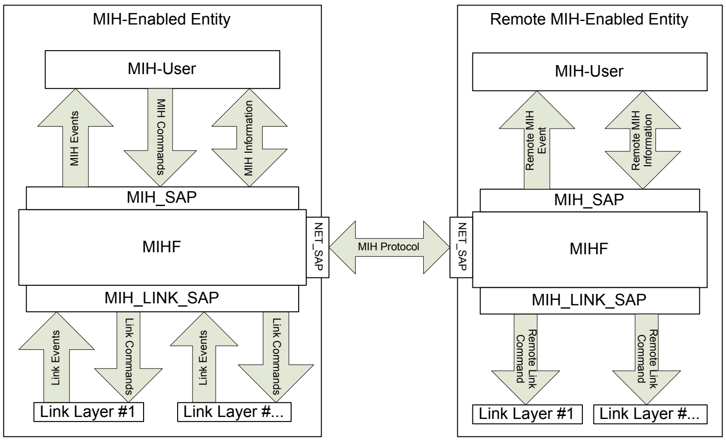

Figure 1: The IEEE 802.21 Framework

To provide MIH Services, the MIHF includes discovery and management mechanisms, such as discovery of MIH-enabled entities and registration for requesting access to specific MIH services at the local and remote MIHFs. More details on these mechanisms, as well as the frame format, messages and parameters of the MIH Protocol, can be found in the standard [1].

3.2. ODTONE Architecture

This section describes the architecture of ODTONE, that deploys IEEE 802.21 and overcomes several inherent standard limitations:

a) IEEE 802.21 does not standardize handover processes: for that, each specific technology already provides their own mechanisms. IEEE 802.21 aims simply to provide mechanisms which can be used by handover decision and execution entities, to facilitate and optimize handover procedures. In this way, a variety of handover and deployment scenarios (both mobile and network initiated or controlled) is possible. ODTONE had to be built in a flexible way, aiming to effortlessly support this diversity. For this matter, an OS and technology independent implementation were key development objectives.

b) The standard assumes that device drivers support IEEE 802.21 directly, which is not the case presently. Considering this, ODTONE was designed to allow easy plug-in of novel technology specific drivers to the MIHF, while maintaining standard functionality.

c) Some mechanisms required in the MIHF framework, such as storing event registration and neighbor MIH-enabled nodes information are implementation dependent and out-of-scope of the standard. As such, ODTONE had to consider a flexible and modularized approach regarding these mechanisms, enabling their simple modification if specific scenarios require it.

With these design considerations in mind, we developed the software components depicted in 2, featuring a MIHF providing interfaces to MIH-Users and link-layers, via the MIH_SAP and the MIH_LINK_SAP respectively. The components belonging to the MIHF and its SAPs have been implemented in C++ using Boost libraries, providing enhanced networking and development support over different platforms. This choice was taken considering the above mentioned assumptions regarding technology and OS independence, with ODTONE having been successfully deployed in Windows, Linux and Android.

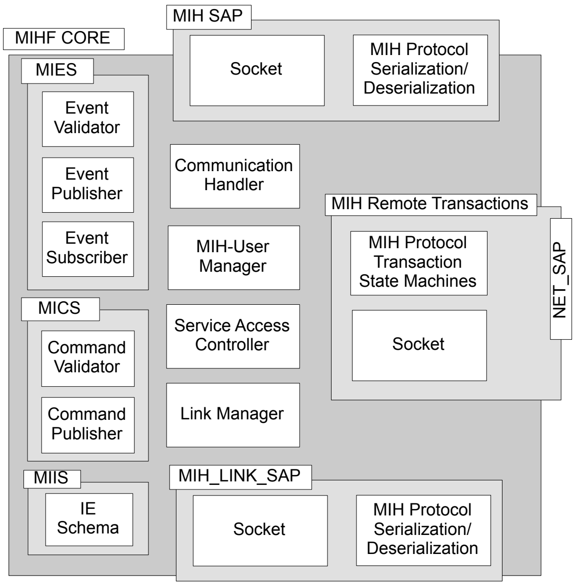

Figure 2: The ODTONE Software Architecture

ODTONE's MIHF, includes the following software components:

- **Communication Handler:** responsible for collecting messages received from the different SAPs or other MIHFs entities and forward them to the Service Access Controller.
- **Service Access Controller:** analyzes the header of MIH messages and identifies to which MIH service they should be forwarded to.
- **Link Manager:** provides the MIHF with information about available local links, as well as specific configurations.
- **MIH-User Manager:** acknowledges which MIH-Users interface with the MIHF.

- **Transaction State Machine Controller:** keeps state of each remote communication with peer MIHFs entities.

ODTONE's MIHF naturally also implements the three core MIH Services, each with a set of logical components:

- The **MIES** provides modules to manage the **Subscription**, **Validation** and **Publishing** of events. Respectively, these allow the MIHF to verify which MIH-Users (both local and remote) have subscribed to events originated from that node, if they are properly formatted according to the standard and determine if they need to be forwarded locally or remotely.
- The **MICS** also provides its own set of **Validation** and **Publishing** modules which allow the MIHF to validate received commands (also both local and remote) and handle their publishing.
- Regarding the **MIIS**, the definition of an Information Server (IS) is out-of-scope from the standard. However, most works on IEEE 802.21 realize that the inherent database features of the IS place it as a MIH-User. Following this approach, in ODTONE we provide the basic **IE schema** in both **binary** and **RDF**, facilitating the implementation of ISs.

3.3. Achieving OS independence by ODTONE

Although the MIHF stands as the core component of the MIH framework, the means by which this cross-layer function integrates with the remaining layers of the protocol stack is of utmost importance for its wide deployment. It is yet to be fulfilled one of the major requirements regarding the widespread of IEEE 802.21, that is, its direct support in device drivers. As such, to obtain support of all IEEE 802.21 primitives in the link-layer, solutions typically make use of wrappers which tightly couple MIHF implementations to specific OSs or technologies. Also, implementing the SAPs as software APIs mandates that MIH- Users and software modules managing links need to use the same programming language of the API, or complex translation techniques. Considering our previous assumptions regarding OS and technology independence, instead of implementing the SAPs as a software API, we cloned the MIH Protocol used in remote communications between MIHFs, and reused it in local communications between the MIH-Users and the MIHF, as well as the link management modules and the MIHF. In this way, as can be seen in Figure 3 both MIH-Users and link management modules have access to all the necessary primitives and datatypes, which can be coupled to their high-level and link-level software respectively, as long as they respect the MIH Protocol conventions defined in the standard. To facilitate this procedure, ODTONE provides a library featuring all the datatypes and primitives of the MIH Protocol, which can be used by MIH-Users and link management modules, to interface with the MIHF and thus turn them into MIH-enabled entities. These libraries are implemented in C++ Boost in the MIHF side, but can be implemented in other languages by the MIH-Users and link-layers, as long as they conform to the MIH Protocol. This enables not only a facilitated plug-in of entities interfacing with the MIHF, in different languages and OSs (Windows and Linux example implementations of LINK_SAPs are now available), but also allows the integration of new access technologies beyond those specified in the standard.

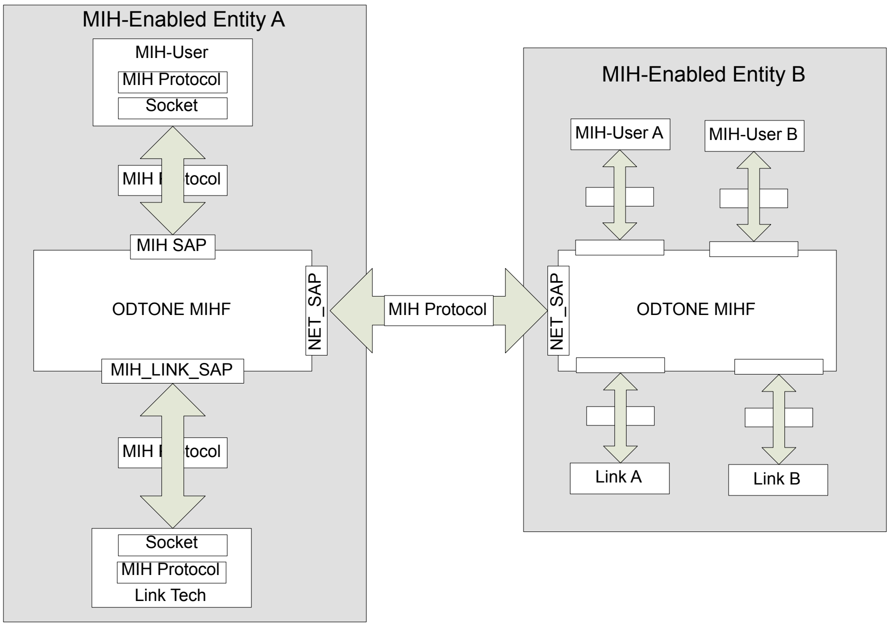

Figure 3: ODTONE Interfacing Design for Operating System Independence

Another major contribution to ODTONE's OS independence is the usage of Boost libraries. These allow the definition of datatypes and network-level operations that are system independent. Concretely, Boost.Asio was used for being a state-of-the-art cross-platform asynchronous network library based on the proactor pattern, while Boost.System, Boost.Thread, Boost.Build and Boost.QuickBook allowed the management of system error codes, threads, building and documentation to be done in a portable way. Finally, Boost.Variant and Boost.Optional facilitated the definition of MIH data types and handling of messages.

4. Integration with PMIPv6

In this section we present an integrated use case where ODTONE enhances the operation of a specific mobility management mechanism. Per itself, IEEE 802.21 does not realize mobility protocol actions, so it needs to be associated with management entities able to do so. We use the PMIPv6 protocol, and describe its integration with ODTONE, realizing make-before-break network-initiated handovers, achieving an optimized network-based localized mobility management.

4.1. PMIPv6

Seamless handover scenarios have to consider moving existing data sessions from the old links to the new ones, often without MT intervention. In a IP-governed network world, to achieve such session continuation, IP-aware mobility management techniques, such as PMIPv6, have to be employed. PMIPv6 allows MTs to change their PoA in different networks, without changing their IP address and without any modification to their IP stack. To realize this, two new network functional entities are introduced in selected routers, the Localized Mobility Anchor (LMA) and the Mobile Access Gateway (MAG), which are responsible for managing the IP addresses involved in MT mobility. Concretely, a LMA manages the reachability towards MTs through the creation of tunnels directed to one of several MAGs, constituting a PMIPv6 domain. For communications outside this domain, for example to nodes via Internet, the LMA works as a home agent, providing the home address prefix of the MT. As long as the MTs move around the same PMIPv6 domain, the MAGs always provide the same prefix to the MT, updating the tunnel to the LMA. In this way, entities outside the PMIPv6 domain who wish to communicate with the MT, are able to do so regardless of which MAG it is connected to. To update this tunnel, the protocol features a set of signaling messages, the Proxy Binding Update (PBU) and Proxy Binding Acknowledgement (PBA), which are used between the MAGs and the LMA to update the MTs current location. This procedure is transparent to the MT which does not detect any change to its IP address after changing its PoA. More details can be found in the standard [9].

4.2. ODTONE and OPMIP Integration

We have developed, alongside ODTONE, an open-source implementation of PMIPv6 called OPMIP. Although PMIPv6 is standardized on its own, we have integrated its mechanisms with those of IEEE 802.21, supporting the example handover flow provided by the IEEE 802.21 standard. In our integration, the OPMIP client residing at the MAGs acts as a MIH-User which connects to the MIHF implementation of our ODTONE framework. The integration of IEEE 802.21 and the PMIPv6 protocol enhances this procedure with media independent commands for resource availability check, preparation and release, as well as providing event indications regarding link status and commands to trigger PMIPv6-specific actions.

Figure 4 depicts the implemented mobility scenario where a MT is equipped with two wireless interfaces. Since IEEE 802.21 allows the support of different link-layers, this scenario could be deployed in different technologies (e.g., WiMAX and 3G) by implementing the necessary mappings between the different technologies and the generic IEEE 802.21 primitives, but still maintaining the signaling here presented. The network supports PMIPv6 through the deployment of two MAGs and a LMA. It also features a Mobility Decision Engine (MDE) acting as a IEEE 802.21 Point of Service (PoS) which receives indications from the MTs and network PoAs and controls the PMIPv6 handover process, supported by IEEE 802.21 signaling. Lastly, the network also features a IEEE 802.21 Information Server containing topological information about nearby networks. The MDE, MAGs and MIH-Enabled network entities are running ODTONE in a Ubuntu Linux 11.04 environment. All the involved nodes were composed by VIA Eden 1GHz processors with 1GB RAM. The node acting as MT had a 802.11b Atheros 5K and a 802.11abgn Atheros 9K radio interfaces. The nodes acting as PoAs had a 802.11abgn Atheros 9K interface as well as a Gigabit wired interface towards the remaining network nodes, which also were equipped with wired Gigabit links.

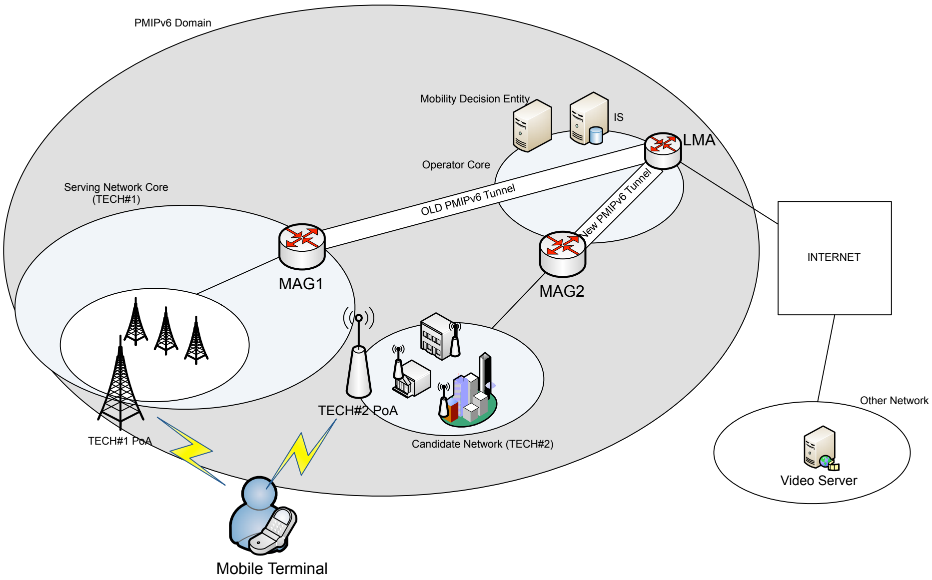

Figure 4: ODTONE and OPMIP Integration Scenario

Figure 4 provides a simplified example signaling on how IEEE 802.21 is used to both optimize the handover procedure, by providing information about nearby handover candidates, and facilitate the handover by providing technology-agnostic commands able to trigger the L2 attachment and the necessary PMIPv6 procedures. The white-triangle arrows indicate the IEEE 802.21 signaling directly affecting the mobility procedures of PMIPv6. The remaining messages empower the mobility procedures with candidate PoA selection, resource query and commitment, further optimizing the base behavior of the mobility protocol. Our MT starts connected to TECH#1 network (e.g., 3G) and within range of a TECH#2 network (e.g., WLAN), belonging to the same operator (in this case). The scenario starts with the MT receiving a video feed through its serving network, with the flow passing through a tunnel between the MAG1 and the LMA. Several triggers, such as detecting a non-optimal access technology preference of the MT user towards video, or even bad received signal strength at the current technology, prompt the MDE to query the IS for information about nearby networks (1). The MDE then issues a network-initiated handover by sending (3) to the MT conveying the information obtained from the IS, and acknowledges the MTs preferences about the preferred handover candidate (4). In this case, a handover to another network within the PMIPv6 domain is selected, which is served via MAG2 and thus requires a PMIPv6 address binding update. Prior to handover execution, the MDE queries resources availability in the selected candidate network (5). Based on the responses received (6) the MDE decides on the handover candidate target and informs it about an imminent handover and that resources should be prepared (7). Upon reception of this message, the MDE requests the MT to perform the handover to the selected candidate (9). When the MT receives this message, it executes the attachment to the WLAN link, and informs the MDE of its result (10). Parallel to this, the PoA at the Candidate Network is able to detect the MTs attachment and issues a Link Up event towards the PMIP Client (11) which is able to trigger a PBU message towards the LMA to register the location of the MT and update the tunnel towards the new MT location. Upon reception of the PBA message (13) the PMIPv6 Client at the MAG2 sends a Router Advertisement (14) towards the MT with necessary information to configure its IP address on the WLAN interface. Once this procedure is completed, the tunnel from the LMA is updated towards MAG2, from which the MT starts to receive the video feed. Upon the completion of this step, the MT signals the MDE that it has finished it handover procedures (15), triggering the MDE to signal the old serving network (16) to terminate its current binding with the MT, via a PBU message towards the LMA (17). Finally, the LMA responds to this message with the tunnel teardown result (18), enabling the MDE to acknowledge the handover completion (20).

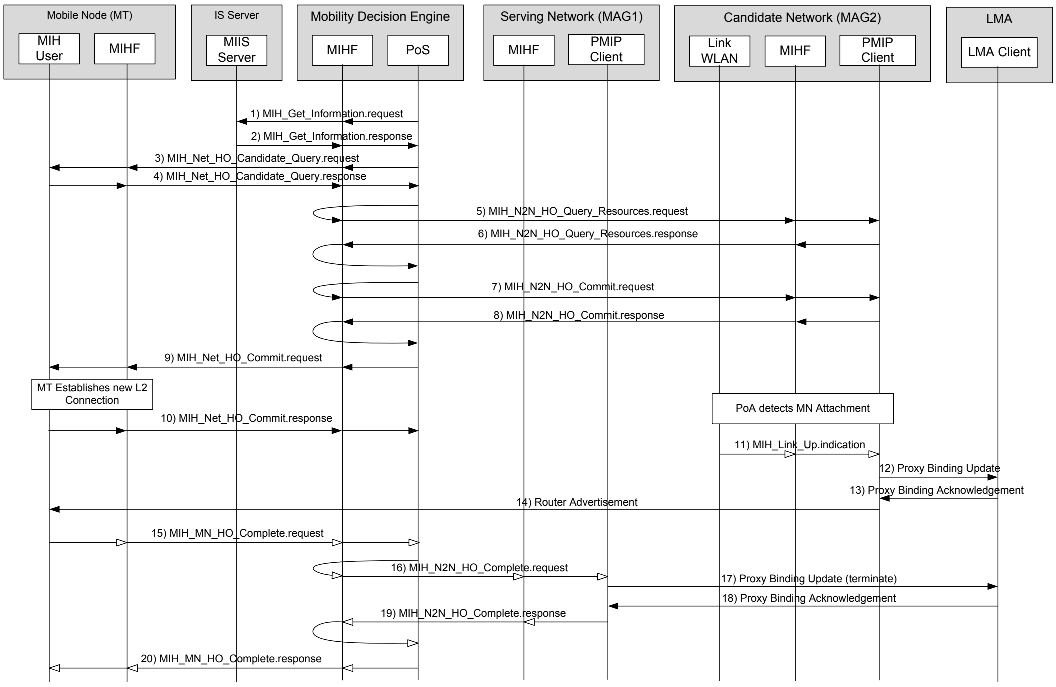

Figure 5: ODTONE and OPMIP Integration Signaling

4.3. Evaluation Results

In order to evaluate ODTONE's footprint in the proposed signaling framework, we here present our results. For brevity, we focus on the measurement of the amount of data exchanged and the processing time belonging to the interactions involving ODTONE's components (that is MIH-Users, MIHFs and links). Network transmission time is not accounted for, since it will depend on network deployment conditions, and the LMA is only involved in PMIPv6 signaling. Results in Table 1 show that almost 44% of the exchanged signaling data involves the MDE, compared to the MT which is only involved in 13% -an expected result since we demonstrated a network-based mobility control. Most of this exchanged information belongs to the IS query (about 42%), due to the RDF schema size in the query reply. In order to optimize this step, filtering mechanisms can be implemented at both the MDEs MIH-User and the MIIS, reducing the response size, or base only the handover candidate selection in scanning procedures of the MT both strategies can be easily incorporated in ODTONE. The MAG2 interaction reports to about 15% of the signaling data, highlighting its involvement in the resources querying and committing processes, as well as detecting the MT attachment for triggering the PMIP procedures. Regarding message transmission time, the active participation of the MDE causes it to be involved in almost 50% of the total signaling time. Even though the signaling that involves the MT is minimal, it accounted for 22% of the total transmission time, due to its assistance in the candidate query and handover completion processes. This side-result indicates the usefulness of network-controlled mobility schemes which reduce the participation of the MT in the mobility mechanisms (even though ODTONE is able to easily accommodate mobile terminal controlled scenarios as well). Lastly, we also measured the average transmission time between MIH-Users and the MIHF, which was approximately 0.5 milliseconds for all network entities and mobile terminal, evidencing ODTONE's deployment feasibility. We argue that these communication times represent an acceptable tradeoff for a system able to be deployed in different mobility scenarios and independent of the specific interfaces available in the MT.

5. Conclusion and Future Work

With the continuous growth of multi-technology operator solutions, the IEEE 802.21 standard will play a major role in near future communications, through the provision of MIH mechanisms for information retrieval and link-layer control. However, the path towards the adoption and execution of the procedures to support enhanced media independent handovers, still has challenges to tackle [10]. An important challenge lies in the adoption of IEEE 802.21 support in link drivers, enabling a unified media abstract interface over which the MIHF can provide support for its core services. Also, the addition of new features to the standard has already been identified, berthing several task groups within IEEE 802.21, dealing with security, pre-authentication, broadcast technologies and optimization of single radio handovers.

Scenario:ODTONE and PMIP			
			Total exchanged messages size (bytes)
	Total scenario size		4444
Per entity	Mobile terminal		556
	Mobility decision engine		1984
	Mobile access gateway 1		187
	Mobile access gateway 2		651
	Media-independent information service server		1066
Per message	IEEE 802.21 Commands	Information Service	1871
		Candidate query	415
		Resource query	497
		Resource commit	391
		Handover initiation	381
		Handover complete	687
	IEEE 802.21 events		202
			Processing Time (ms)
	Total ODTONE processing time in scenario		21.51
Per entity	Mobile terminal		4.64
	Mobility decision engine		10.50
	Mobile access gateway 1		0.77
	Mobile access gateway 2		4.12
	Media-independent information service server		1.48
Per message	IEEE 802.21 Commands	Information Service	2.77
		Candidate query	3.21
		Resource query	3.06
		Resource commit	2.84
		Handover initiation	3.07
		Handover complete	5.18
	IEEE 802.21 events		1.37

Table 1: Total signaling overhead and processing time in the ODTONE and PMIP scenario.

Even though this means that the standard is being complemented with mechanisms to fully support the core vision, it also means that current implementations will need continuous updates. Note that the availability of MIH signaling can cover a huge amount of scenarios, but there is no conformance regarding concrete signaling steps, hindering interoperation.

This work provided a description of how ODTONE, a software implementation of the IEEE 802.21 standard, is able to be used in an open, easily deployable and OS independent way, to provide optimized handover mechanisms. ODTONE tackles the three challenges above by i) providing an easily-deployable and unique way of interfacing the MIHF with MIH-Users and Link SAPs, ii) adopting a flexible design approach towards the addition of new features and the instantiation of implementation-specific items, and iii) being available as an open-source component. Its flexible design allows for easy extension to support other technologies, features and scenarios, making ODTONE a vehicle to push and disseminate new knowledge or even originating potential new standardization actions. In fact, ODTONE has been used in multiple projects, and is being adapted into new heterogeneity scenarios, such as sensor wireless networks and distributed information services. Also, the integration with OPMIP provides at this moment a tool to fully implement localized mobility management systems which can be trialed with multiple types of algorithms related with handover decisions, and in multiple scenarios.

ODTONE, alongside OPMIP, was able to provide a flexible fabric supporting a network-controlled mobility scenario where MIH-enabled entities become able to provide events, information and commands in a local or remote way. With the design of internal message exchange intrinsically using the MIH Protocol, high-level and link-layer management modules can complement their behavior easily by adding simple code to understand the MIH

Protocol, and interface with the MIHF, meaning that ODTONE can operate on top of any access link technology, independently of the underlying OS. With IEEE 802.21 and ODTONE, the PMIPv6 protocol is complemented with the necessary features to fully operate in heterogeneous environments by having an abstract way of interacting with multiple technologies. ODTONE solves the out-of-scope mechanisms existing in the PMIPv6 standard, by having link-layer triggers regarding MT attachment supplied by IEEE 802.21. Results show that a network- controlled mobility scenario was able to support the signaling footprint that applying 802.21 to the support and enhancement of PMIPv6 procedures requires, while evidencing our software frameworks flexibility to support other algorithms and mobility schemes.

We believe that the ODTONE project more than just providing a IEEE 802.21 implementation, furthers the standard and the communications field, by providing an accessible middleware framework that can be used to test, develop and evolve the borders of already-existing and future architectures, mechanisms, and protocols that aim to exploit distributed mobile management algorithms.

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Paper B

Fabio Buiati, Luis Garcia Villalba, Daniel Corujo, João Soares, Susana Sargento and Rui L. Aguiar , Hierarchical Neighbor Discovery Scheme for Handover Optimization, *IEEE Communications Letters* , vol.14, no.11, pp.1020,1022, November 2010

Hierarchical Neighbor Discovery Scheme for Handover Optimization

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Abstract

In the future mobile Internet, one of the most challenging aspects is to discover the available neighbor access networks and its characteristics as the user moves. Using the IEEE 802.21 Media Independent Handover (MIH) standard, this letter proposes a new neighbor network discovery mechanism, considering a hierarchical view of the network information. Through a NS-2 based simulation, it is shown that the proposed model can significantly improve the mobility user experience.

1. Introduction

The integration of different wireless technologies (UMTS, IEEE 802.11 Wi-Fi and IEEE 802.16 Wi-Max) allows mobile users to choose an optimum network interface in accordance with the desired requirements in terms of quality of service (QoS), price, transmission rate, security and other characteristics. The IEEE 802.21 standard [1] aims to facilitate handover procedures in heterogeneous access networks, by providing information, events and commands to the entities that assist in the handover decision. In this heterogeneity of technologies, discovering the available access networks is one of the main challenges.

The standard [1] specifies a Media Independent Information Service (MIIS) server supporting various information elements that provide network information within a geographical area. Based on information from several access networks and operators, a Mobile Node (MN) can take an optimized handover decision. The information available via the MIIS can be categorized as:

- General Information and Access Network Specific Information: presents a general overview about the networks covering a specific area such as network type, operator identifier, QoS, security, cost, roaming partners.
- Link connection point information: provides information about Points of Attachment (PoA) for each of available access network and categorizes aspects such as geographical location, data rate, channel configuration, and so on.

There have been proposals [2][3][4][5] that take in consideration the IEEE 802.21 MIIS service in the network discovery task. Current literature considers the existence of only one MIIS server in the network that responds with neighborhood information. However, the number of network entities and supported communication technologies directly impact the amount of MIIS information sent from the network to the MN, causing delay in the handover performance.

There are many shortcomings related to the specification of a single MIIS server: 1) too much information to store if hundreds of access networks and dozens of operators exist; 2) may be a single point of failure and 3) high discovery delay if the MIIS server is located many hops away from the MN. It's clear that the usage of a single MIIS server for a large city or a whole country with several operators is not desirable. Moreover, this centralized architecture is not scalable in the case that the information to be provided is constantly requested by the MN. Finally, inaccurate or unrelated network information results in sub-optimal handovers. Therefore, in this letter, we propose a hierarchical neighbor discovery scheme enhancing the performance of the MN in terms of throughput and discovery response time experienced.

2. Hierarchical Neighbor Discovery Scheme

This section describes our proposed scheme and its support for an optimized MN mobility performance. We argue that a solution considering multiple networks and operators has to contemplate a hierarchical splitting of the existing information. This is due to the fact that, the amount and detail of information pertaining to specific PoAs of a single access network, and the combination of all these details for a number of access networks and different operators, may be very large. The IEEE 802.21 allows the MN to restrict the response message size by setting the MaxResponseSize optional parameter in the query message. In case that the response message exceeds the maximum size, some information must be removed from the MIIS response. Clearly, this is not suitable for the user. Removing important information may cause a sub-optimal handover decision. Considering this, and in order to improve the MIIS response in quality, we propose a hierarchical neighbor discovery scheme in which the network coverage area is divided into mobility zones, managed by different MIIS servers as illustrated in Fig. 1.

From bottom to up, the first level of the hierarchy is composed by mobility zones defined by the amount of existing networks, users, even considering areas where networks are overlapped. In the second level, there are Zone MIIS servers (ZMIIS) which are in charge of supplying highly detailed information about specific PoAs in a particular mobility region. The third level refers to the Local MIIS servers (LMIIS) managing information of different mobility zones, belonging to the same operator. Finally, a Global MIIS server (GMIIS) is specified to be used in multi-operators environments. Fig. 2 shows the operations of the hierarchical neighbor discovery scheme.

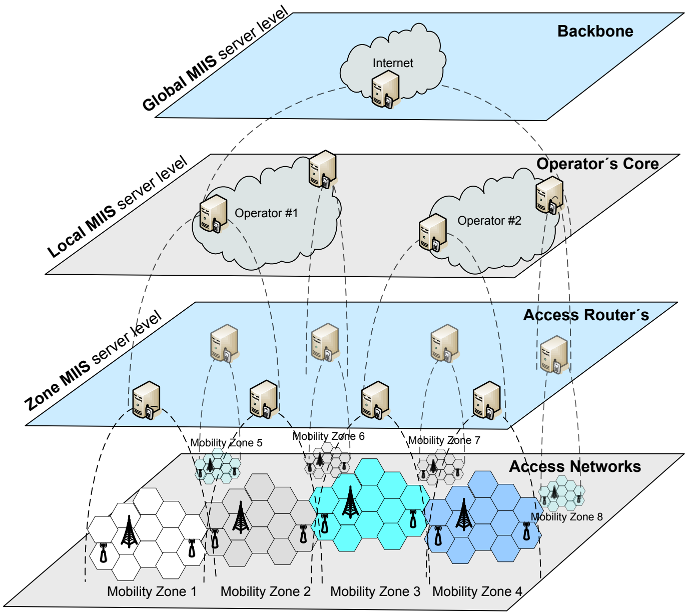

Figure 1: Hierarchical Neighbor Information Scheme

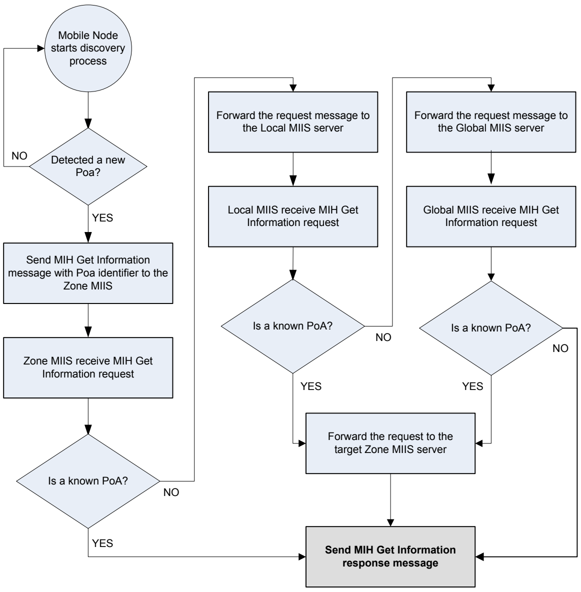

Figure 2: Hierarchical Neighbor Discovery Algorithm

Whenever a MN wishes to obtain information regarding the surrounding networks, it sends a MIH Get Information request message to its ZMIIS server. The available options to the MN are to send the message when it detects a new network or when the signal level is dropping below pre-defined thresholds. In this work we have opted for the first method of triggering the MIIS query message. The MN sends a request message to the ZMIIS server through the current PoA link. If the query is related to an entity outside that zone, it is forwarded to the LMIIS server which is able to contact the target zone s ZMIIS and obtain the required information. In the case that the request zone belongs to another operator, the LMIIS forwards the message to the GMIIS server, acting as an interface pointer between relevant mobility regions of different operators. In this way, it knows which ZMIIS server holds the desired information, to which it replies using the MIH Get Information response message. In case none of the MIIS servers store information about the detected PoA, the GMIIS server replies with a null MIH Get Information response message.

Accessing critical information from other operator through non-secure links, and 3rd party servers, raises important security issues as well. Other than service agreements, the LMIIS servers must be able to access Authentication, Authorization and Accounting (AA) frameworks where users can be authenticated prior to do the information query. One solution in secure inter- domain handover is presented in [2]. The authors propose a Media Independent Pre-Authentication (MPA) framework that enhances the inter-domain and inter-technology handover. The MPA specifies that a MN can establish a security association with the candidate network before it attaches to it and, subsequently, performs a security communication. Using such a technique, two or more different MIIS can establish a secure communication and interchange information. We also consider that a node can obtain direct network information without authentication, but in that case the information the MN receives is minimal.

3. Performance Evaluation

To evaluate our hierarchical MIIS system performance, we have implemented the MIIS functionality, enhancing the existing MIH implementation software package NS-2 [6]. The scenario (Fig. 3) is composed by two operators. The first one holds one UMTS network, two Wi-Fi PoAs and two Wi-Max PoAs. The second operator consists of one Wi-Max PoA. For each single operator, the ZMIIS is installed on the Access Router (AR) of an access network, and the LMIIS server is installed on the core network side. The GMIIS is a server located in the Internet or some common operator s backbone. Finally, a multi-modal MIH- capable node is moving through the scenario, performing several handovers. The network parameters for the simulation are described in Table 1. Two performance metrics are evaluated (representing the average of fifteen independent runs): the average throughput and the neighbor discovery time.

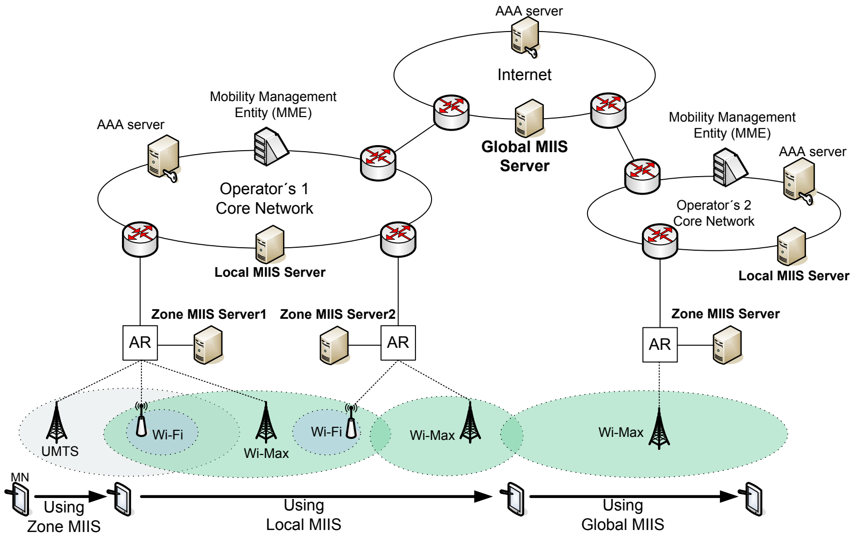

Figure 3: Simulated Heterogeneous Scenario

Access Network	Description	Data Rate (Uplink / Downlink)
	Operator 1	
UMTS	PoA without load	384 Kb/s
Wi-Fi	PoA with background traffic	1 Mb/s
Wi-Max	PoA without load	11 Mb/s
	Operator 2	
Wi-Max	Poa without load	11 Mb/s

Table 1: Access Networks Characteristics

3.1. Throughput

We first measure the average throughput experienced by the MN when moving through the scenario illustrated in Fig. 3.

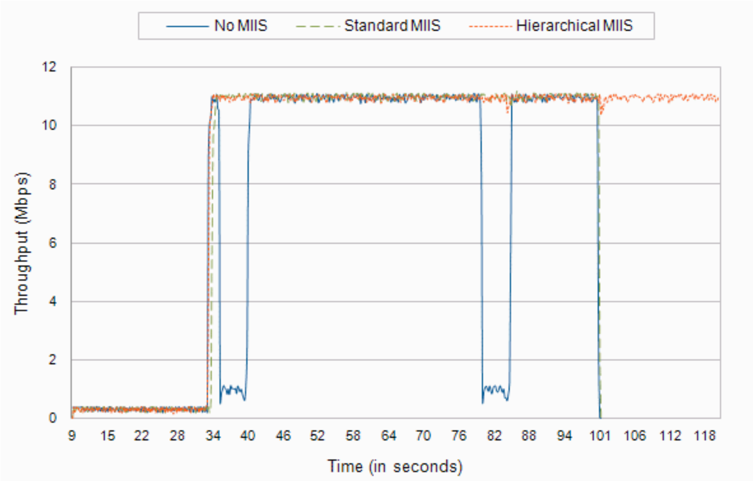

Figure 4: Average MN Throughput

Without using the MIIS functionality, the MN performs handovers to non-optimal PoAs, due to the fact that it has no information about their status, as illustrated in the Fig. 4. Using the standard IEEE 802.21 MIIS, the MN performs optimized handovers, enjoying the PoAs without load obtaining a good throughput. However, the standard MIIS does not perform handover between different operators, thus not taking advantage of the Wi-Max network from Operator 2, after the 100s mark in the figure. Finally, using the hierarchical MIIS deployment, the MN has knowledge of which networks are good handover candidates. Through the GMIIS, the MN performs an inter-operator handover in the 100s mark, achieving much better throughput in the movement.

3.2. Neighbor Discovery Time

We also evaluated the neighbor discovery time, which is the total time from the instant the node requests network information by sending a MIH Get Information request message, up to the time where the node receives a MIH Get Information response from any MIIS server. The discovery time mainly depends on two values: the wired backbone delay; and the number of hops between the MN and the MIIS server. For this scenario, the one-way delay of the wired part of the network is set to 5ms and the number of hops is summarized in Table 2, close to the values used in [4].

The results (Table 2) show that the user experiences a discovery time from 34 ms up to 207 ms using the hierarchical MIIS deployment. Considering these times, the ZMIIS has a very fast response time, allowing the MN to make optimized handover decisions. The Standard and the LMIIS provide similar discovery times since they have the same physical location

MIIS	Hops from the MN	Discovery Time
Zone	2-3	34-45 ms
Local	3-6	64-103 ms
Global	4-10	108-206 ms
Standard	3-8	54-104 ms
No MIIS	-	80-5829 ms

Table 2: Neighbor Discovery Time

inside the network. The GMIIS presents a clear tradeoff between response time and handover quality, allowing inter-operator handovers. As values for comparison with other schemes: [5] presents a query delay of 2.2s for a MIIS centralized implementation and [3][4] show that the MN may experience a discovery delay ranging from 80 ms to 5.8s, depending on the technology and the scanning method.

4. Conclusion

The deployment of this hierarchical view of information storage regarding multiple-operator scenarios with different access and types of networks provides a major benefit where a terminal, is provided with a complete and consistent view of detailed handover possibilities, without having that information stored in a single central entity. Also, this information availability can also be pushed to the terminal at bootstrap providing it with a view of nearby existing networks, to determine which interfaces to power up or to achieve an optimized connection right from the start.

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Paper C

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Video-Enhancing Functional Architecture for the MEDIEVAL Project

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Abstract

The MEDIEVAL project aims to leverage today's Internet with the necessary fabric to provide optimized video services in a mobile wireless world. It is expected that video traffic will surpass Peer-to-Peer (P2P) in volume in the coming years, and thus novel mechanisms and techniques need to be provided to better suit its unique requirements. This article describes the key functional elements of the MEDIEVAL architecture, which provides a video-aware networking core coupled with abstracting interfaces which cater to service and access technology specific requirements, aiming to enable efficient video transport and novel video service development.

1. Introduction

The EU project MultimEDia transport for mobIlE Video AppLications (MEDIEVAL) [1] is a collaborative project with a three-year duration starting on 1st July 2010, having as partners Alcatel-Lucent Bell Labs France, Telecom Italia, Portugal Telecom Inovacao, Docomo Communications Labs, LiveU Ltd., Instituto de Telecomunicacoes, Universidad Carlos III de Madrid, Consorzio Ferrara Richerche and Eurecom. It aims to evolve todays mobile Internet architecture to more efficiently support the upcoming growth of video services. According to [2] P2P, as the current dominant source of traffic in the Internet, will be surpassed by video in 2010 achieving volumes close to 90% of consumer traffic by 2012. This increase is motivated by a change in perception and usage of video services such as Internet TV, interactive video, Video on Demand (VoD), among others, which instead of being regarded as simple streaming of content, will become a tool for personal multimedia communication, resembling todays explosive usage of personal messaging (i.e., Short Message Service (SMS) and Twitter. However, the Internet, and the mobile technologies therein, have not been designed to properly sustain such an increase of video, in an optimized way. This is where MEDIEVAL intervenes by providing a more suitable video transport architecture, commercially deployable by network operators. This article is organized as follows. In the next section, we will present the vision of the MEDIEVAL project, focusing on its concept and main objectives. This is followed by section 3 where we discuss the general MEDIEVAL architecture, which provides video-specific enhancements at different layers of the protocol stack, by exploiting cross-layer approaches that aid in better video support. In the subsequent three sections we will describe the major points over which the architecture is impacted and aims to provide solutions, detailing some of the approaches: network requirements for video (Section 4), packetization (Section 5), and multicast mechanisms for video optimization (Section 6). Finally, we conclude in Section 7.

2. Vision

The vision of MEDIEVAL considers the evolution of video as a primary source of content, accessed as well as generated, over the Internet. This is exactly where MEDIEVAL aims to contribute: evolving the mobile Internet architecture for efficient video traffic support.

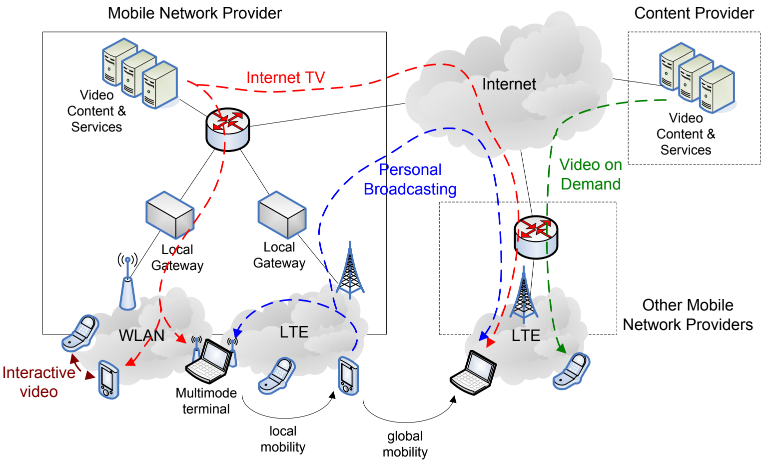

Figure 1: The MEDIEVAL vision

Fig. 1 presents a visualization of this vision, highlighting what we foresee as the required evolutionary path for a true video-for-all philosophy, providing selected application examples. Four primary video services are considered, comprising VoD, Internet TV, Interactive Video and Personal Broadcasting, offered by the providers in the figure. These services are accessed by terminals supporting different access technologies (Long Term Evolution (LTE) and IEEE802.11 in the figure), while on the move, through both local as well as global mobility procedures, in intra and inter-domain scenarios. The video services are accessible from content and services providers available at a home operator domain (visible inside the Mobile Operator Provider part of the figure), as well as from content providers or other mobile network providers (visible in the separate Content Provider part of the figure). However, MEDIEVAL also envisages scenarios where users, and thereby their mobile terminals, are the source of generated video content, enabling scenarios of direct interactive video.

The necessary technical solution and problem solving that enable such vision span to all areas of mobile communications, starting from the need to enhance wireless access technologies, requiring efficient mobility management as well as optimized transport, to video distribution mechanisms and network-aware applications and services. We believe that a cross-layer approach will not only provide clear innovations in all the mentioned fields, but will also lead to a realistic evolutionary path for mobile networks, truly providing an environment where users can benefit from the MEDIEVAL vision.

This vision, and the subsequent architecture, will address the following five key issues:

- Design and specification of a set of interfaces between video services and the underlying network mechanisms, allowing the video services to customize the network behavior in an optimal way.
- Enhance the wireless access to provide an optimized video performance experience through the coordination of the features of the wireless technologies and the video services.
- Design and specification of a novel mobility architecture for the next generation of mobile networks, truly adapted to video service requirements.
- Optimize video delivery systems with Quality of Experience (QoE) driven network mechanisms through the combination of Content Delivery Networks (CDN) and P2P techniques for optimized video streaming focusing on the location of caches and peer selection.
- And lastly, support for broadcast and multicast video services, including Internet TV and Personal Broadcasting, through the introduction of multicast-aware mechanisms at the different layers of the protocol stack.

Through the addressing of these key issues, MEDIEVAL intends to perform technological developments based on an operator-driven architecture aiming to have an innovative impact in terms of video services performance improvement over existing solutions, while providing an integrated video solution that can be implemented by an operator. This integrated solution will observe better QoE of video to users by providing a joint view of user and video services requirements, wireless network conditions (such as performance and load) and transport optimization, all of which impact mobility decision taking.

The support of this vision requires not only the development of a video transport architecture, but also a high emphasis on its commercial deployment suitability. To further this, the design of a set of specific mechanisms and enhancements with application on video services will have to be developed and presented to the relevant standardization bodies.

Even though the architecture focuses on video, this kind of traffic is the most demanding in terms of bandwidth thus enabling other applications to work since the network is dimensioned for video, and with the same protocols (albeit using different algorithms) we can treat other kinds of traffic.

3. Architecture

The MEDIEVAL architecture relies on four functional cornerstones, which are depicted in Fig. 2, considering Wireless Access, Transport Optimization, Mobility and Video Services and described in the following subsections.

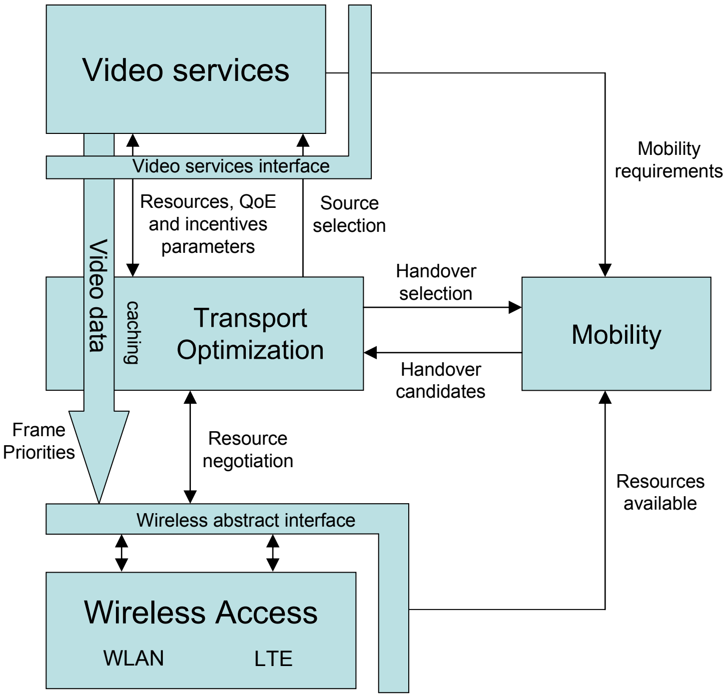

Figure 2: The MEDIEVAL architecture

3.1. Wireless Access

Wireless access considers coordination mechanisms between video services and the different wireless access technologies in order to optimize overall performance. MEDIEVAL will focus on the LTE of the Universal Mobile Telecommunications System (UMTS) for coordination-based access, and the IEEE802.11 standards for contention-based wireless access, enabling a video over wireless concept. On the IEEE802.11 side, the high rates placed by video services when this kind of traffic is prioritized against non-real time traffic allow for good QoE, but only in limited scenarios[3][4]. To counter this, numerous approaches have been presented but are either based on heuristics and do not guarantee optimal performance [5][6] or introduce significant complexity while requiring the interaction between codecs and the MAC layer, increasing their deployment difficulty [7][8][9][10]. On the LTE side, cross-layer optimizations are key improvements over existing cellular technologies regarding the support of video services, along with data rate increase obtained through intelligent exploitation of radio resources, which enable interesting scenarios complemented with the introduction of point-to-multipoint capability such as Multicast/Broadcast Multimedia Service (MBMS) [11] and evolved MBMS (eMBMS). An interesting project concerning cross-layer mechanisms to improve multimedia performance over wireless links is OPTIMIX [12], but it derives a new wireless architecture from scratch which can seriously hinder deployability with operators and does not consider entirely mobile scenarios.

In MEDIEVAL, interaction with different technologies will be achieved through heterogeneous cross-layer mechanisms for interface abstraction (i.e., IEEE802.21 [13]), facilitating interfacing with the upper layers and their exploitation of specific features for video optimization. Another key innovation will be the introduction of enhanced dynamic configuration procedures based on the current network conditions, while also exploiting advanced terminal features such as multiple-input multiple-output (MIMO) capabilities, cognitive networks and multi-hop transmission in centralized technologies.

3.2. Video Services

Video services control will provide these services with the tools for reliable video delivery over an evolved mobile network. Some approaches already consider content adaptation and the use of RTSP (Real Time Streaming Protocol) but they do not consider, in the first case, the dynamicity of the network, the various network policies, QoS requirements and, in the second case, do not allow session negotiation. Other measures, such as packet prioritization, are not yet investigated in relatively new codecs (i.e., H.264, AAC audio and SVC), and Forward Error Correction (FEC) mechanisms negotiation at application level does not exist. All of these are imperative requirements in mobile environments. PHOENIX [14] proposes a cross-layer optimization of wireless access where video is an application of the proposed optimization framework. However it does not consider entirely mobile scenarios and video is just regarded as another application.

MEDIEVAL will provide video services with an interface enabling them to interact with core network mechanisms, considering requirements and features from both, and properly adapt the service execution. Through this interface, video services are able to provide indications regarding the type of video data in order to request frame prioritization to the wireless layers, as well as providing resources, QoE and incentive parameters to better optimize transport procedures. Other measures such as algorithms to better adjust video streaming to the network conditions will be tackled considering cross-layer dynamic adaptation management techniques, prioritization methodologies and appropriate FEC mechanisms.

3.3. Transport Optimization

To capitalize from the video-aware features of both the wireless access and video services functional components, the architecture also provides video-aware transport optimization mechanisms for efficient video delivery, offering resilient and mobility- aware QoE to video services. Several techniques already exist such as analysis of interactions of video transport with other layers [15] and CDN. However, they miss a global system view and there is a lack of knowledge about the operation of CDN in the context of mobile networks. The NAPA-WINE [16] project considers P2P systems for high quality TV delivery, managing traffic and quality degradation, albeit not considering mobile networks nor broadcast/multicast solutions as well as operator-controlled mechanisms.

MEDIEVAL aims to develop transport optimization cross-layer mechanisms able to execute resource negotiation with the wireless layers, considering an optimized source selection, while adapting the video service to current network conditions. The usage of CDN architectures in mobile environments will also be pursued as well as providing solutions for dynamic rate-control and caching schemes. Resource reservation procedures are considered to be in place and MEDIEVAL will use them as implemented by each technology (LTE and WIFI). However, here we go one step further addressing QoE in a different manner by enabling the network to understand what traffic is traversing the routers and will be able to take decisions before routing the packets (e.g., dropping specific video frames, using a different path, etc.).

3.4. Mobility

The reference network architecture for MEDIEVAL is the EPS specified by 3GPP (Release 8), and Proxy Mobile IPv6 (PMIPv6) [17] and Dual Stack Hosts and Routers (DSMIPv6) [18] are the two major IP mobility protocols proposed. However, these efforts are still based on anchor points and tunnels, and mobility is offered as a general service which can employ unnecessary overhead when not needed. CARMEN [19] addresses a mesh architecture with mobility support, while considering video at carrier grade. MEDIEVAL also aims at the design of a novel mobility architecture but focuses more on video efficiency rather than just support it.

Considering the mobile environments over which video services will be used, the architecture will provide mobility mechanisms which are also video-aware, and will interact with the core network to ensure optimized connectivity for the terminals. This is achieved through the collection of handover requirements from video services, the identification of available resources and their impact in handover candidate selection taking into consideration an optimized transport execution. These four architectural components will feed handover selection algorithms through the provision of parameter values that consider an overall view of the best choice possible.

These mobility mechanisms will address both local mobility and global mobility, considering, in the first case, the provision of service continuity customized to the different requirements of video services and, in the second case, addressing inter- operator roaming issues without requiring the deployment of global anchor points in the operator's network. Here the focus is also on session continuity. An important innovative point from MEDIEVAL is to consider mobility in terms of specific flows.

Thus, the mobility architectural part will consider three main areas of intervention: i) mobility mechanisms for multi-mode terminals and moving networks supporting mobile and network initiated handovers; ii) video-aware interface for heterogeneous wireless access conveying video relevant information for optimal decision taking by the mobility function and iii) IP multicast mobility by both sources and receivers, (i.e. considering their issues with tree-based approaches).

4. Cross-layer Mechanisms for Addressing Network Requirements

For an optimized video experience, the full set of MEDIEVAL's functional architecture needs to work cooperatively, providing the bridge that allows video services, and their traffic, to be adapted to current network conditions based on the user terminals selected technology while on the move. An open problem to be tackled is how to interrelate network dynamics and QoE requirements for video services in wireless environments. Proposals addressing these issues don't consider session negotiation or only allow it before the connection is established [20], which prove unfeasible in dynamic environments. Under these environments, mobility has been thoroughly studied, leading to extensive optimization efforts for handover execution, but never considering video specifically. The transport video traffic under these conditions gains a key importance where increasing requirements for more bandwidth are coupled with stringent delay constraints, while operating in heavily congested networks. Network requirements have to be considered under the general- purpose behavior of the Internet, where other different kinds of traffic coexist, raising the interest of the IEEE802.11 in previous extensions [21].

To address network requirements in such environments, we explore cross-layer interactions, focusing on all layers of the network stack, applying improved management towards reliable and smooth transmission. An important tool to be used for this cross-layer interaction is the IEEE802.21 Media Independent Handovers (MIH) standard. MIH considers the optimization of handovers in multi-technology environments, by providing mechanisms that rely on the abstraction of the different connectivity technologies and provide media independent information and control to deciding entities, regarding the medium status. The introduction of MIH mechanisms work as a layer 2.5 abstraction concept, enabling MEDIEVAL to encompass future communication systems while tackling their inherent heterogeneous characteristics and challenges. Also, the media-independent signaling provided by the IEEE802.21 MIH protocol will provide the interaction between the different cross-layer components on which MEDIEVAL intends to impact.

However, the IEEE802.21 standard was not conceived for any specific kind of traffic and does not attempt to take the optimization perspective of the network for video delivery. Its introduction in the MEDIEVAL framework will leverage and enhance it to support video specific extensions (e.g., link capacity versus packet prioritization), by taking advantage of its intrinsic signaling primitives. Concretely, MEDIEVAL will extend the interfaces with higher layer services considering the interaction between mobility and transport optimization components, enabling IEEE802.21 to provide fine granular IP flow mobility management, while the interaction between the video service and the mobility components will also leverage already existing protocols, such as DIAMETER [22], through the creation of the required extensions. Thus, IEEE802.21 will be extended to convey video-specific information (such as encoding parameters, real-time QoE parameters, among others) enabling the provision of indications to handover decision entities which assist in applying the best procedure possible, depending as well on user credentials.

Although the extension of the MIH protocol to execute new personalized behavior has already been proposed in other contributions (such as European projects), to our knowledge, this is the first time that a similar rationale is applied to video and its inherent services. An important distinguishing point is that the objective is not to use media independent mechanisms to provide the same abstraction for different technologies, since in this case they are based on different principles that operate very differently when it comes to video traffic. As such, our aim is to provide a set of abstract interfaces allowing each medium to report its capabilities to decision video- aware entities which can then exploit them through the same interfaces.

MEDIEVAL will benefit from the inclusion of ODTONE [23], standing for Open Dot Twenty ONE, which is an open-source implementation of the IEEE802.21 standard from the Instituto de Telecomunicacoes (Aveiro, Portugal). ODTONE is implemented in C++ using Boost and provides an operating system independent Media Independent Handover Function (MIHF), the core entity of the IEEE802.21. To enable its integration with the different link layer technologies, being managed by different operating systems, ODTONE provides a library based on the MIH protocol, which can be used to implement the different link Service Access Points (SAP). This provides an ample platform able to be executed in different environments, featuring different terminals and access technologies and thus not being dependant of a single operating system, which is the case of other initiatives such as [24]. The open-source nature of the project, and the expertise gained by its development, will provide to the MEDIEVAL project with the necessary tools with which to extend the base IEEE802.21 behavior, enabling it to provide optimized execution for video services aware mobility and data transport.

5. Packetization

MEDIEVAL will exploit packet-level mechanisms and techniques available to its functional elements and core network in the various types of technologies. The control plane of the LTE Radio Access Network (RAN) will intervene at user plane entities with the aim of selecting and prioritizing video frames. With respect to the lower layers of the wireless technologies, the project will evaluate mechanisms, such as the ones under standardization in 802.11aa, where dynamic prioritization for frame marking and discarding are supported, and techniques such as graceful performance degradation are employed.

The usage of jumbo frames to aggregate packets while enhancing video delivery mechanisms to achieve higher video throughputs will be evaluated, taking into consideration the necessary extensions for the cross-layer interaction of video services with LTE and IEEE802.11 networks. Jumbo frames allow the usage of larger frames extending them to 9KB which take advantage of reduced MAC overhead, increased throughput and less CPU usage. However, they also introduce new problems such as larger hardware requirements on routers, and more video data is lost when a packet is lost or delayed. This is crucial in wireless environments running interactive video services, requiring the adoption of important measures such as zero-loss mechanisms, needing a feasibility study considering their effect in mobile environments and their impact on real-time services and video buffers. In this feasibility study, the suitability of current IEEE802.11 mechanisms (i.e., such as the TXOP (Transmission Opportunity) parameter of the MAC protocol) will be analyzed for the case of jumbo frames aiming towards video services optimization. The TXOP parameter has been extensively used as the means for modification of the standard transmission procedure to achieve optimized results [25][26]. However, the MEDIEVAL framework intends to provide a comprehensive cross-layer approach towards the optimization of video services and thus application of jumbo frames at the MAC layer is not enough (or even only at the IP level itself [27]): the other layers, involving the video services, the transport and mobility procedures, must be aware of this factor and to know if the conditions are favorable towards its usage. As such, the interface between layers needs to be extended to convey this cross-layer information, towards the optimization of the usage of larger frame sizes to increase video performance. The studies executed at these two fronts will determine whether jumbo frames will be used in WLAN technologies or not, and, in parallel, the feasibility for the usage of this kind of frames will also be analyzed within LTE, towards the enhancement of video delivery mechanisms. Here the objective is to extend the cross-layer interaction of video services evidenced in the WLAN case, with the LTE architecture [28], enabling the usage of jumbo frames to achieve higher throughputs for video under this wireless technology as well.

6. Multicast Mechanisms

A key development for the proliferation of video traffic is its widespread diffusion within social network, as witnessed today on Facebook or MMS. However, the deployment of such features in todays Internet while considering video traffic being generated by millions of mobile wireless users, emphasizes the lack of interconnection mechanisms supporting this trend. It is just not feasible to send independently video feeds towards users viewing the same content. Although solutions for multicast exist, these approaches do not consider scale service announcement and discovery as well as mapping video service groups into network-based groups while managing different content sources. MEDIEVAL will focus on providing a common interface that allows different applications to efficiently deliver video content to user groups, leveraging multicast and broadcast context solutions (MBMS and eMBMS). The inclusion of these mechanisms at IP level, with special nodes acting as the heads of the multicast distribution trees, will also be enhanced with bearer service preparation to optimize scenarios where terminals change into a new cell not yet in the session topology.

Another key intervention point for MEDIEVAL is the crossing of multicast and mobility mechanisms, particularly network-based localized mobility management solutions. For this, a thorough analysis on optimal multicast support in PMIPv6 [17] will be done. Here, the project will benefit and contribute to standardization via a recently formed IETF working group in the Internet Area: Mobility Multicast (MULTIMOB) [29], aiming to provide guidance and multicast support in a mobile environment. An important consideration to tackle, considering that a mobility management protocol that is network-based such as PMIPv6 does not consider the user terminal as an entity that is involved in the mobility signaling, and thus its integration into mobility-aware group subscription is problematic. In the context of MEDIEVAL we plan to study not only receiver mobility but also the impact of sender mobility in a network-based localized mobility management architecture. Concretely, this area of the project intends to address:

- Mechanisms for mobility support of listener nodes in a non-relying way to bi-directional tunneling
- Topological correctness and transparency of source addressing
- Mechanisms for optimized multicast distribution tree updating

Additionally, another study item will be the coupling between the handover process, the change between layer-2 point of attachment and the actual group subscription. The strategy for the multicast distribution update depends on the envisioned service in MEDIEVAL, with two possible paths: specific to the source, or related to any source. Regarding this point, and in the context of localized mobility management, the multicast tree creation may interact with route optimization in a mobility point of view.

The use of cross layer information to better synchronize subscription information and actual point of attachment especially in case of predictive handover will be a key study point, particularly in the cases where the change between L2 point of attachment is not synchronized with the L3 change (i.e., homogeneous and heterogeneous handovers). Cross layer information can be used to better synchronize subscription information and actual point of attachment especially in case of predictive handover. Here, the application of IEEE802.21 mechanisms is a possible tool to ensure the feasibility of these processes. Also, IP multicast optimizations will be proposed both from the network mobility perspective (i.e., due to handovers) as well as from the service perspective (i.e., fast change of multicast groups, required by IPTV). MEDIEVAL will also benefit from the on-going efforts for the development of a PMIPv6-compliant protocol stack, performed by several partners of the MEDIEVAL project.

7. Conclusion

In this article we have presented the key points and challenges that the MEDIEVAL project will address aiming to deliver video services in an optimized way over wireless mobile access. The major architectural areas have been highlighted as being wireless access technologies, mobility, transport optimization and video services, which reflect the general work items of the project. We also have detailed key innovation points and research objectives for the areas of jumbo frames, MIH signaling extension and network localized mobility management with multicast support, which are important tools and mechanisms in the overall MEDIEVAL design. The work will start with the exploitation of the individual work items into the development of a cross-layer design that leverages the joint effort of each item, into an evolution of the Internet architecture for efficient video traffic support. The results achieved with the project will fall in a number of research subjects and will provide a set of extensive and measurable outputs, where possible solutions for this architecture will be evaluated and quantitatively assessed, particularly its impact to standardization and the development of new video services. Lastly, the resulting architecture will be implemented in a demonstrator showcasing the developed functionalities. These results will be further disseminated in scientific fora, including leading conferences and journals in the field, as well as active pursuit of opportunities for standardization bodies influencing.

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Paper D

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Wireless Access Mechanisms and Architecture Definition in the MEDIEVAL Project

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Abstract

Wireless network access and the exchange of multimedia flows over the Internet are becoming more and more pervasive in the everyday life. However, simple technological advances in terms of improved network capacity cannot satisfy the increasing demand of such services, since a paradigm shift from the current Internet architecture is required. The EU FP7 MEDIEVAL project tackles this issue by addressing novel architectural frameworks and viable strategies to efficiently deliver video services in a wireless Internet context. This paper reviews the currently ongoing activities of the project for what concerns wireless access, in particular the identification of useful techniques for the considered access technologies (WLAN and LTE-A) and the general definition of architectural schemes to efficiently support video flows.

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1. Introduction

During these last years, a joint evolution of demand and offer for multimedia content over wireless has taken place. On the one hand, the diffusion of new mobile devices which combine multimedia features and Internet connectivity, yet realized with different access techniques, has reached high penetration rates worldwide. Nowadays, wireless networks include smart phones, netbooks, or other small and portable devices all equipped with multimedia encoding and decoding capabilities. On the other hand, multimedia content exchange is starting to dominate the Internet traffic, with applications for watching on-line videos, exchanging user-generated video content, or video-chatting that impose constraints in terms of latency and data transmission reliability. However, the current Internet and its wireless extensions do not glue these two sides of the evolution well together. Since they were designed having in mind a different paradigm for content exchange, demand and offer of multimedia content are still mismatched in terms of provided Quality of Service (QoS) and Quality of Experience (QoE) for the end users.

More in general, the explosion of multimedia content demand actually poses several challenges in terms of efficient *delivery* of this content throughout the network to the end user.

In this spirit, the main goal of the EU project MultimEDia transport for mobIlE Video AppLications (MEDIEVAL) [1] is to tailor future architecture for the wireless Internet in order to support enhanced multimedia support, as described in [2]. In particular, this paper deals with the issues more specifically related to wireless access. The main reference scenario of the project consists of an operator supporting connectivity through heterogeneous access technologies, and whose network architecture needs to be optimized for video transport. Thus, the focus of this paper is to describe the architectural solutions envisioned to provide enhanced video delivery in the last (wireless) hop, mainly focusing on existing access techniques.

According to how they make use of the wireless medium, we can classify access techniques into *contention-based*, such as the IEEE 802.11 standards for Wireless Local Area Networks (WLANs) [3], and *coordination-based*, e.g., the Long Term Evolution Advanced (LTE-A) of the Universal Mobile Telecommunications System (UMTS) [4].

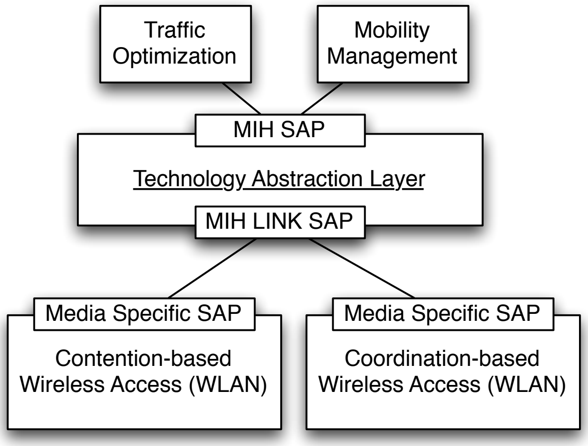

Figure 1: MEDIEVAL Wireless Access Architecture and Cross-layer Design

For each access category, the project aims at developing novel mechanisms to enhance video transmission over wireless access, allowing adequate QoS support and enabling cross-layer optimization in the interaction with upper layers. The analyzed methodologies include algorithms for packet prioritization and selection, and strategies to improve the actual bandwidth that can be extracted from the wireless medium such as *jumbo frames*.

In the literature, several works focus on cross-layer optimization techniques adopted to improve multimedia transmission over wireless channel: in [5] is presented an approach that combines the flexibility and programmability of application layer adaptations with low delay and bandwidth efficiency of link layer techniques, while in [6] are shown the significant improvements that can be obtained by deploying a joint application-layer adaptive packetization and prioritized scheduling along with MAC-layer retransmission strategy.

The MEDIEVAL architecture encompasses the cross-layer optimization through enabling mechanisms for the different layers to talk between them. In this sense, a cross-layer signalling is implemented between the lower layers and the video application and services, as well as with mobility services. An example of this cross-layering can be seen as follows: information gathered into Media Specific SAP (Service Access Point) such as video services characterization (that is, bit rate guarantees, priority, tolerated delay/jitter/packet dropping), together with link quality indications perceived by all the LTE subscribers, are used to generate a utility function that is associated to each user, and will be used to optimally allocate the LTE wireless resources. Another example of cross-layer interaction as listed previously is packet marking. The video services or transport optimization components insert some specific marking in the Internet Protocol (IP) header of each video packet, based on video coding and avoiding deep packet inspection at the wireless access level. According to some pre-defined signalled agreement and on the wireless access type, each packet is processed individually, which results in forwarding the packet on the wireless link, prioritizing it or even dropping it if the available bandwidth on the wireless link is not sufficient.

The rest of this paper is organized as follows. In Section 2 we discuss optimization techniques for contention based wireless access which are currently proposed and under evaluation in the MEDIEVAL project, whereas in Section 3 we describe such techniques for coordination based wireless access. Then, in Section 4 a description of the abstraction layer is provided along with a novel transmission technique represented by the usage of jumbo frames to increase system throughput. In Section 5 we discuss the implementation of IEEE 802.21 [7] within the project. Finally, we conclude in Section 6.

2. Enhanced Contention-based Wireless Access

MEDIEVAL focuses on extending two aspects of current IEEE 802.11 technologies. On the one hand, to leverage the maximum bandwidth achievable by the technology, optimal configuration of the Medium Access Control (MAC) parameters of the stations and access points is required. In order to configure appropriately the MAC layer parameters, a similar approach to the one presented in [8] will be followed. On the other hand, MEDIEVAL focuses on cross layer interactions and multicast, hence the second point of optimization is the cross-layer packet marking to be able to better queue flows with different QoS and perform group-cast.

The increasing trend on video distribution over the Internet and the use of wireless distribution systems to connect different multimedia commodities within the home environment have triggered the IEEE 802.11 Working group to extend current functionality of Wireless LAN specifications to tackle the distribution of video streams. One of the key points of video distribution on wireless environments is the use of multicast; however, current multicast realizations over WLANs are extremely unreliable, due to the lack of ACK mechanisms. To increase their reliability, it is necessary to deploy a new set of MAC mechanisms while still remaining compatible with legacy IEEE 802.11 stations [3]. This is the aim of the upcoming

IEEE 802.11aa specification [9], which basically defines two main functionalities with reference to video transmission: improved multicast transmission modes, namely Direct multicast Service (DMS) and Group-cast with Retries (GCR) Service, and Improved video service differentiation by extending the Enhanced Distributed Channel Access (EDCA) mechanisms to provide a Stream Classification Service (SCS).

The former corresponds to the new functionality to increase the reliability of multicast transmissions in Wireless LAN environments. The DMS, introduced in the IEEE 802.11v draft standard [10], transforms multicast flows in a set of unicast flows. In this way, an access point (AP) will retransmit a given frame until an ACK is received or the retransmission limit is exceeded, in which case the frame is discarded. This mechanism exchanges throughput for reliability because of the need for individually transmitting multicast frames which could be critical, e.g., I frames in a Moving Pictures Expert Group (MPEG) stream. The GCR Services extends the (ACK) policy of DMS with two new mechanisms for multicast:

Unsolicited Retry: The AP will retransmit a frame several times to increase the probability of correct reception at the stations. Again in this case, some resources are wasted to improve the successful delivery rate which may be required for real-time flows.

Block ACK: This is an extension of the Block ACK defined in IEEE 802.11e for group addressed frames [11]. There, the sender transmitted a burst of data frames and explicitly requested an ACK to the receiving station. In 802.11aa, the request, represented by a modified Block ACK Request (BAR) control frame, is sent by the AP and contains a sorted list of the multicast group members. Then, each station can recognize the multicast group it belongs to and replies with individual Block ACKs in the proper order. Thus, throughput is decreased due to the control frame exchange to reduce unnecessary retransmissions, but reliability is increased.

With respect to the multicast extensions defined in IEEE 802.11aa, one of the objectives of the MEDIEVAL project is to implement the mechanism which allows an AP to switch dynamically between the GCR-DMS, GCR-Unsolicited-Retry or GCR-Block-ACK delivery modes, taking into account that only one delivery mode may be active at any given time for each GCR group address. Based on preliminary simulation results, the choice of groupcast mechanism requires a careful assessment of the usage scenario since in terms of performance achievable or reliability of the transmission, there is no clear winner. Hence, based on the number of receivers, the bitrate of the transmission and the number of background stations, one mechanism is more suitable than others. This assessment is one of the objectives of the MEDIEVAL project.

Finally, the IEEE 802.11aa specification also defines a new differentiation service which extends standard EDCA queues. The SCS increases the granularity of the service differentiation already provided by 802.11e for audio and video. IEEE 802.11aa introduces two additional queues within the EDCA Access Categories (ACs): one for audio and one for video, in order to support prioritizing mechanisms between queues and to differentiate video streams. In addition to the intra AC prioritization, packets are tagged with their drop eligibility which defines a different maximum number of (short and long) retries. The availability of additional access categories and the drop eligibility bit can also be used to enforce the graceful degradation of the video quality in case of bandwidth shortage. This approach requires the definition of an internal interface configuring the MAC parameters of IEEE 802.11, i.e., EDCA queue, minimum and maximum congestion window, Transmission Opportunity limit, Arbitration Inter-Frame Space (AIFS), as well as the multicast mechanisms defined by 802.11aa with their parameters (number of retries or the requested stations in a BAR). These parameters affect both the APs and the stations according to the upper layers requests. It is also necessary to provide an information service to indicate the upper layers with the available multicast capabilities so that they can monitor the mechanism being used and decide the optimal configuration.

It is worth mentioning that none of the novel mechanisms proposed in 802.11aa is supported by available implementations of the IEEE 802.11 standard. Moreover, management mechanisms at the hardware/MAC level do not permit to handle either ACKs or Block ACKs for multicast and broadcast frames. Therefore, with the current 802.11 standard, multicast traffic cannot be converted into unicast at MAC layer nor (Block) ACKs, as well as there are no means to force unsolicited retransmissions. The previous considerations result in difficulties to implement such mechanisms in order to evaluate their performance in real-life conditions and understanding the resulting tradeoffs and design criteria. However, the project is expected to shed light on these issues through quantitative evaluations, e.g., by means of simulation.

3. Enhanced coordination-based wireless access

Among coordination-based access, the main focus of the project is on LTE-A. In this context, a first task to be performed by LTE-A wireless access is to gather channel measurements performed at lower layers and inform the related decision entities about them. E.g., knowing the load of the cell at network level or the quality of the links perceived by the mobile terminal improves the decision-making algorithms in the upper layers entities. Then, a novel medium access strategy will be applied, taking into account the characteristics of video flows and identifying techniques to interact with upper layers, to design access techniques, which are aware of the video content delivery in a network-wide perspective. In particular, allocation strategies, proposed at MAC level, exploit the cross-layer techniques to allocate as many users as the LTE-A wireless channel can admit, trying not to affect the perceived QoE by the end users. Moreover, equipment capabilities announced at network attachment, must be exploited to improve the bandwidth occupation of the video signal flowing in the last wireless hop of the network. Then, based on the information received through the abstract interface, the control plane instructs the user plane entities to select and transmit towards the air interface only those video frames which are adapted to the receiving device capabilities. This operation is accomplished before video frames enter in the wireless access technology protocols, then such information is received when the User Equipment (UE) connects to the network, and can be correlated with some pre-defined coding levels of the video signal to determine the optimal quality level corresponding to the equipment. The frame level of each video packet is marked by the application or service layer in the IP header and it is provided to the transmitting entities, which then prioritize or even drop the video packets, thus reducing the bandwidth occupation in the downstream nodes, especially in the last wireless hop. The statistics related to this filtering are reported at the wireless network entry node, e.g., the base station. In the case of multicast sessions, further correlation is maintained to handle the knowledge of the users who joined the service.

In LTE-Advanced, multicast mainly means to support and extend the evolved Multimedia Broadcast and multicast Services (eMBMS) Bearer service specified in the LTE standards [12]. The objective of the MBMS is to enable point-to-multipoint communications over the radio interface (or Access Stratum), allowing resources to be shared in the network. In the LTE-A model, this means supporting some specific logical channels. The first channel is the Multicast Control Channel (MCCH), which is dedicated to the broadcast of MBMS control and scheduling information in the cell. The second channel, the Multicast Traffic Channel (MTCH) is used for transferring the data packets. There is one MTCH per session, received by all the Mobile Terminals interested in the session. MEDIEVAL plans to support some level of QoS for this channel, in order to improve the efficiency of the video frames transfer. In the physical (PHY) layer, the MCCH and MTCH are mapped on a specific physical channel, the MCH. In the MTCH, multicast data are transported in an unacknowledged mode radio bearer, as usually defined for streaming flows in the 3GPP QoS (Quality of Service) architecture. The handling of multicast flow has disappeared in the transition between MBMS and eMBMS, mostly due to business causes and deployment costs. In the LTE and LTE-A systems, only broadcast sessions are proposed. In MEDIEVAL, the plan is to re-introduce the multicast sessions, which are essential to some of the user services providing video delivery identified in the project, while improving their overall management. This has a strong impact since it implies supporting some specific MBMS procedures in the control part of the Access Stratum (AS). In particular, MEDIEVAL plans to simplify the multicast session start and stop procedures at the eNodeB and the associated mobile notification. Another important feature is the counting of listening mobiles in each cell by the eNodeB. This information is interesting to trigger the multicast session if needed, or move the flow back to a point-to-point bearer if only one user in the cell is listening. To avoid disturbing other types of traffic (e.g., voice) that could take place simultaneously, it is important to establish a coordinated control of unicast and multicast communications in a cell providing the MBMS service. Supporting multicast and video traffic in eMBMS influences also the way the data traffic is handled in the LTE-A interfaces. In the eNodeB, they must be able to forward the IP multicast packets towards the multicast bearers in the air interface and enable the reception of the packets in the mobile. The impact is expected also on the configuration of the radio access, to take into account the spectrum usage and the resource allocation. Multicast flows require bandwidth reservation based on the dedicated eMBMS Bearer parameters received from upper layers and the worst CQI (Channel Quality Indicator) of multicast clients measured in the lower layers. This results in a bad spectrum usage because users with a robust link underutilize the bandwidth resources. The proposed solution combines H.264/SVC (Scalable Video Coding) together with cross-layer optimization to dynamically tune the QoE for each user according to the channel feedback.

Ns-3 network simulator [13] is the simulation tool used for validating the proposed optimization approaches for LTE networks. A basic description of the protocol stack entities can be found in [14], while the whole framework can be downloaded and executed in [15].

4. Abstracted mechanisms

To achieve efficient video transport in heterogeneous networks, high transparency and seamless intercommunication within the system components is needed, able to operate in both types of wireless technologies. This is accomplished by a set of functions defined in the abstraction layer, together with some ad-hoc features designed to further enhance the video flows transfer over the air. In the following, we present a key concept of the MEDIEVAL design, the abstraction layer and its mutual interactions with the transport and mobility layers.

Abstraction Layer: The abstraction layer is the heart of video delivery optimization process, as it provides the means for the interaction between the radio access network and upper layers in order to accomplish cross layer functionalities and underlying technologies transparency. This twofold goal is realized by using abstract interfaces defined to establish a functional connection with both upper and lower layers: video transport and mobility management on the one hand, wireless access on the other hand. This interfaces are designed in such a way that they provide a common functionality regardless of the specific underlying technology. In the following we present the different interfaces and functionalities provided by the abstraction layer.

Transport Optimization: This abstract interface provides the upper layers with information and configuration mechanisms regarding the video characteristics available at the lower wireless technologies in an abstract way, translating generic video parameters into video specific extensions defined by the underlying heterogeneous technologies.

The objective of this cross-layer interface is to enable an efficient and optimized video transport by providing information about the availability of the wireless accesses and the dynamic variations of the radio channel, and informing about specific jumbo frame functionalities such as aggregating non-related traffic (or traffic from different flows), as well as providing indications necessary for the transport of jumbo frames, such as frame size and queue delay. Then, it enables transport alternatives (other than User Datagram Protocol (UDP) and Transmission Control Protocol (TCP)) such as multicast and, upon request, it reports information about the Mobile Nodes (MNs) capabilities such as the size of the screen, the list of available network interfaces, active links and flows, or the counting of session receivers in the case of multicast. Moreover, it receives information to enhance the configuration of the wireless access: flow requirements (for QoS and multicast mechanism), flow identification, marking criteria, configuration parameters for multicast and jumbo frames procedures.

The use of this information at the transport layer allows the operator or video service provider to implement smart optimizations such as: *i)* design evolved cross-layer algorithms and mechanisms between the video services and the network layer and to dynamical optimization of video services with suitable network support, *ii)* develop new procedures and algorithms to better adjust the video streaming taking into account the network dependencies or *iii)* improve cross-layer communication in order to have Forward Error Correction (FEC) mechanisms in a joint coordination between the wireless access module and the service layer controller.

Then, we achieve an end-to-end interface through the transport optimization layer and, at the same time, a dynamic cross-layer interface targeting video improvements and content delivery. This will provide support to video coding: FEC/Automatic Repeat reQuest (ARQ) [16], Available Bit Rate (ABR), scheduling, transcoding according to device capability and QoS availability. Other important features to be addressed are the Process Priority settings (marked packet for prioritization and selection), the indication of jumbo frames availability, the quality of the link information provisioning, and the support of signal split across multiple channels.

Mobility Management: This functionality interacts with the mobility management mechanisms by reporting abstracted parameters from the wireless accesses and forwarding downwards the received commands relative to interface or flow mobility. The objective of this cross-layer interface is to extend the media-independent signalling functionalities provided by IEEE 802.21 and support extra mobility functionalities and video aware services to optimize the user experience while performing handover. Hence, in order to provide a better mobile user experience within a network, the Media Independent Handover Function (MIHF) will support flow mobility (identification of flows, flow granularity at the primitive level) and new mobility protocols which work as MIH Users and that are not currently contemplated in the standard, such as Distributed Mobility Management (DMM) approaches.

One of the most interesting functionalities offered by IEEE 802.21 is its ability to provide dynamic and static information, through the Media Independent Event and Information Services. In order to enable mobility decisions, information about link quality and QoS levels must be provided to the mobility management entities, along with static or semi-static information regarding the video specific features implemented in the network, such as signalling the availability of surrounding access networks, Point of Access (PoA) link layer parameters, PoA capabilities (IP multicast, mobility scheme support, jumbo frames support), upper layers capabilities (video services supported, transport optimization mechanisms available), and availability of multicast support in the network.

The above interfaces represent the exchange of information between the higher layers and the media abstraction provided by the abstraction layer. In order to be able to actually work with the real technology, the abstraction layer talks with the underlying technologies through media dependent abstract interfaces, which are in charge of gathering the technology measurements to inform the upper layers transparently and dynamically about the current radio conditions.

Although the role of the abstraction layer may appear as a simple translator of media independent events/commands/information, this layer is designed as an intelligent module able to provide also extra-functionality apart of translating between abstracted and media specific languages. The novel functionality included in the abstraction layer is called the Abstract QoS Mapper. The objective of this module with the abstraction layer is to provide a comprehensive mechanism for the higher layers to be able to map their requirements in terms of QoS or even QoE to a set of abstract parameters that the lower layers can understand. In this way, the higher layers will provide through the video transport interface, the flow requirements in terms of QoS and multicast. By using this information, the flow requirements are mapped to a certain traffic class or general protocol parameters that will be translated so that the specific technology can be configured accordingly.

Finally, in the following sub-section we present the concept of jumbo frames, which is another generic technology that is being investigated for video delivery optimization.

Jumbo frames: Jumbo frames, or jumbograms, are packets with a size larger than 1500 bytes, where 1500 bytes is the normal Ethernet size being used since its creation (around the 80s). The major benefit of using a larger frame size is that, when compared with a lower one, the same amount of information can be sent in fewer packets (i.e., less fragmentation occurs). Each frame, both when sending or receiving, requires CPU processing and has header overhead associated, thus fewer frames will require less CPU processing and generate less overhead, as well as increased throughput.

The mechanisms designed within the MEDIEVAL project will consider a flexible approach and therefore will aim to have a negligible impact in the current or upcoming network developments. Also, the deployment of jumbo frames in this manner requires that some important issues are tackled. One of these issues is the mobility experienced by terminals which can seriously impact and alter conditions such as packet loss, which highly impact the usage of larger frames. Also, considering the number of users associated to the same AP, the usage of greater Maximum Transmission Unit (MTU) sizes can cause fairness issues in multi-user environments. As such, the development of new resource allocation through, for example, channel hopping, is required. Otherwise, jumbo ability can be emulated at higher layers of the protocol stack, impacting only queues at the lower layers.

The usage of jumbo frames considers not only the last hop towards mobile users (which is wireless), but also the full path from mobile users to the content provider. This means that different media will be crossed at different points of the network, which need to be aware of jumbo frames. However, the wireless part, due to its inherent operation constraints and changing conditions of the wireless medium, provides the most challenging part for the development of performance-increase mechanisms. As such, the usage of jumbo frames is being addressed in the wireless environment, so this means the last hop, between MN and the Point of Attachment (PoA). In order to simplify things, evaluation will contemplate the PoA acting as a Point of Service (PoS), in order not to mix wireless jumbo frames, with wired jumbo frames.

5. IEEE 802.21 in MEDIEVAL

The IEEE 802.21 Media Independent Handover (MIH) [17] is a standard that aims to facilitate and optimize handover procedures between different access technologies. It adds an abstraction layer (in the form of the Media Independent Handover Function (MIHF)) that abstracts the different link technologies to high-level entities, here deemed MIH-Users. This abstraction is achieved through the provision of a set of services: the Media Independent Handover Event (MIES) service, which allows MIH-Users to receive events about link conditions, the Media Independent Command Service (MICS) which enables MIH-Users to exercise control over the links and the Media Independent Information Service (MIIS) which provides network information that can be used for optimal handover candidate selection. These services can be accessed remotely between MIH-enabled entities via the MIH Protocol, enabling the network and Mobile Terminals to exchange media independent information with which network management and handover control can be optimized.

The role of IEEE 802.21 in MEDIEVAL is to provide media independent interfaces to the decision entities in the architecture, towards control of the network access links, while facilitating handover procedures. The events, command and information defined in the protocol provides the common interaction fabric with which the different aspects (video services, wireless technologies, mobility and traffic optimization) can interact, in order to provide an enhanced mobile video experience in wireless environments.

The MEDIEVAL project plans to implement IEEE 802.21 through Open Dot Twenty ONE (ODTONE) [18], which is an open-source operating system independent implementation of IEEE802.21. It is written in C++ using Boost libraries, allowing the support of several mechanisms such as portable datatypes, networking and low-level I/O in different platforms (i.e., Microsoft Windows, Linux and Android). ODTONE implements the standardized MIH services (MIES, MICS and MIIS), which are managed in the MIHF. ODTONE is able to work both in a local or remote way, through the usage of the MIH Protocol, which is able to be carried over UDP or TCP. To support its design, ODTONE provides a MIH Protocol library which can be included in any MIH-User code, or link layer management code. In this way, the existing link layer software or driver mechanisms implemented need only to include the MIH Protocol library, besides adding MIH processing behaviour. Similarly, high level entities just require the inclusion of the same library and the ability to process the received messages. ODTONE also provides an implementation of the Information Elements Basic Schema (IEBS) in binary and Resource Description Framework (RDF), which can be used for creating MIIS Servers.

IEEE 802.21 standard defines reference models for IEEE (i.e., 802.3, 802.11 and 802.16), 3GPP and 3GPP2 technologies. For these technologies it provides a direct mapping for the link events, commands and parameters that are available for MIH-Users to interact with links. However, later developments of cellular technologies, such as 3GPP LTE-A, provide meaningful differences which were not considered by 802.21. As such, in the project, we are developing a mapping between 802.21 parameters and LTE-A parameters [19] with the objective to replace the existing mapping between 802.21 and UMTS parameters. For a detailed explanation, see [17]. As an example, in Tables 1 and 2 a list of measurement and configuration parameters is provided in order to define the services to be handled in the LTE-A Media Specific SAP to perform an efficient protocol extension; in fact, dynamic channel information such as Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ) are reported to higher layers, whereas UE physical capabilities and system resource usage attributes are exchanged in the lower layers for radio access purposes. Then, such information might be integrated into standardized MIES to extend the protocol capabilities, in the same way as parameters listed in Table 2 can be used to to configure the air interface, or Access Stratum, based on information received from the upper layers (MICS).

Reported to RRC and upper layers	**Executed but not reported**	**To be reported**
RSRP	UE, eNodeB: PHY	(*)
RSRQ	eNode: MAC/RLC (*)	UE capabilities

Table 1: LTE-A Measurement Parameters

Information Elements (IEs) provide a scheme of information residing within an Informa-

RRM	**MAC/PHY**	**RRM→MAC/PHY**
RLC Mode	Spectrum Info	e2e Bearer Specs
HARQ	Transmission Mode	(**)
Buffer Size (**)	Transceiver Specs	

Table 2: LTE-A Configuration Parameters

tion Server, which can be used to find information regarding specific PoAs. This optimizes the process of handover candidate selection by providing information on supported capabilities, which can be used by mobility management to retrieve information about specific PoAs. As video becomes a core aspect of the MEDIEVAL project, we have provided different degrees of video-awareness into 802.21. For wireless access mechanisms, we are adding a set of new IEs that provide video-related capabilities within networks such as MBMS support, jumbo frames support, and Content Delivery Network (CDN) support.

To better support the integration of video-awareness into the mobility and wireless decision processes within the MEDIEVAL project, we are revising the set of standard events and commands defined in the IEEE 802.21 standard, empowering them with parameters that are able to provide information about video related features. For example, we are providing commands and parameters that enable network decision entities to control video applications to alter video streaming parameters in order to better adjust to radio conditions. Currently, these commands and parameters are still under definition according to the cross-layer mechanisms defined between network control processes and video application services.

6. Conclusions

This paper presented the concepts for the wireless access component in the network architecture designed for the EU project MEDIEVAL. The wireless access part of the architecture aims at optimizing the last hop for video flows, with target access technologies classified in contention-based techniques, such as WLAN, and coordination-based techniques, such as LTE-A. Several cross-layer functions and enhancements have been proposed within this architecture. In the WLAN side, the upcoming IEEE 802.11aa amendment will improve the multimedia transmissions by increasing their reliability, enhancing the multicast support or introducing frame prioritization and graceful degradation of the video quality. In LTE-A, the objective is to introduce multicast sessions in the eMBMS framework, frame selection and prioritization in the radio interface, optimized medium access strategies or innovative relaying techniques. In both types of technologies, the reporting of measurements such as link quality or cell load plans to enable the operation of cross-layer algorithms in the video transport or mobility management modules of the network architecture. To achieve an efficient cross-layer communication with heterogeneous access, an abstraction layer has been introduced which hides the specifics of each technology to the upper layers, by the usage of generic parameters and primitives. This layer is based on an extension of the MIH services offered in the IEEE 802.21 standard. Another generic technology under study introduces the concept of jumbo frames in the wireless access, where packets have sizes larger than the usual MTU values. Future work on all these functionalities will consist in developing the generic cross-layer signaling flows and scenarios, and deriving an extended set of primitives between the wireless access technologies, the abstraction layer and the video transport and mobility modules. These techniques and optimization algorithms will be evaluated more precisely using our enhanced simulators. Most of them will be ported and tested against a real-time testbed equipped with WLAN cards and drivers, an experimental LTE software radio platform and the upper layers components acting as MIH Users.

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Paper E

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Media-Independent Multicast Signalling for Enhanced Video Performance in the MEDIEVAL Project

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Abstract

With the foreseen major increase in video traffic over the coming years, the current Internets design is being perceived as inefficient for handling the demanding flow of video over wireless access networks, populated by an ever increasing number of mobile terminals. The MEDIEVAL project aims to evolve the current Internet architecture to provide an optimized video support in all layers of the protocol stack. With its cross-layer approach, abstraction mechanisms such as IEEE802.21 will work as enablers between the different architecture modules. With the widespread diffusion of video being realized over multicast and broadcast channels for resource optimization, using 802.21 signalling to optimize handovers affecting groups of users will generate multiple messages to each individual terminal. In this article, we extend 802.21 to support multicast transport of its signalling, enabling more efficient group handover scenarios.

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1. Introduction

The proliferation of mobile terminals provided with different kinds of mobile wireless accesses, such as WiFi and 3G, are placing an increasing demand on network operators which now have to provide multimedia services and applications to users on the move. According to recent studies [1], it is foreseen that P2P will be surpassed by video traffic in 2011, reaching volumes close to 90% of consumer traffic by 2012. Considering this, the provision of real-time video services over wireless access to mobile users places stringent requirements over the Internet, whose architecture was not conceived considering such demanding operations. Under this setting, the EU project MultimEDia transport for mobile Video AppLications (MEDIEVAL) is researching the architecture and inherent mechanisms for evolving today's Internet towards the efficient support of video services over wireless access networks with mobility support, commercially deployable by operators. Providing a cross-layer approach, it relies on the IEEE 802.21 Media Independent Handover standard [2] as an enabler of interactions between the different access technologies and high-level decision modules, under a common and abstract set of services. With multicast and broadcast transport mechanisms being used in MEDIEVAL to optimize the widespread diffusion of video services, when network conditions change and handovers are required, the effects typically affect not only a single terminal but blocks of terminals, and thus multiple handover commands need to be sent. Considering this, in MEDIEVAL we evolve the 802.21s design to have its signalling transported over multicast protocols, enabling the issue of a single command to handover users affected by the same phenomena. This article is organized as follows. In the next section we present an overview of the MEDIEVAL architecture, focusing on its main areas. This is followed by Section 2 where we present our 802.21 design extensions to support multicast signalling. In Section 3 we provide use case scenarios and then conclude the paper in Section 4.

2. The MEDIEVAL Architecture

MEDIEVAL's architecture is focused in 4 main components: Video Services, Mobility, Transport Optimization and Wireless Technologies. Besides these main blocks, multicast and IEEE 802.21 MIH are also central components that will be explored. The notion of cross-layer is the crucial concept in the project: by providing video-awareness to the whole stack, MEDIEVAL aims to optimize video in mobile environments, avoiding current problems resulting from the lack of layer interaction. This is depicted in Figure 1.

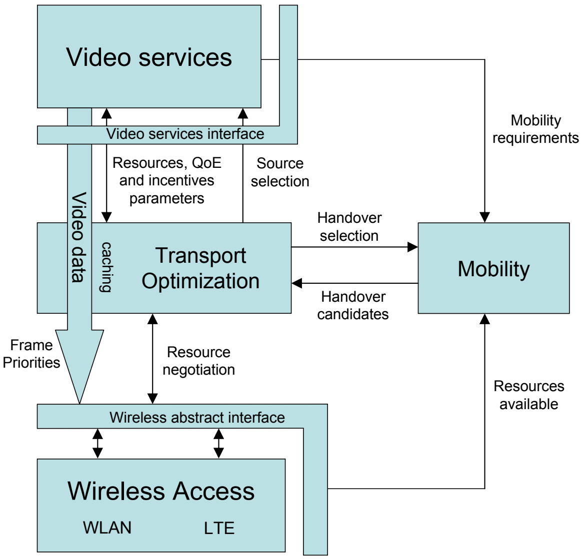

Figure 1: MEDIEVAL main blocks

2.1. Video Services

In MEDIEVAL, the considered range of video services will be enhanced with interfaces for proper content adaptation and triggering mobility or transport related optimization. It will tackle issues such as: network dynamicity in terms of QoS requirements and network policies; session negotiation (i.e. RTSP); packet prioritization in relevant codecs (i.e. H.264) and specific link layer mechanisms for video optimization [7][8]. MEDIEVAL furthers this by specifically providing an interface for video services, enabling them to interact with network core mechanisms, providing video-specific information and requirements to the other intervening architectural blocks.

2.2. Mobility

MEDIEVAL project uses as reference architecture 3GPPs EPC (Release 8) [18], and as reference mobility protocols PMIPv6 and DSMIPv6. Mobility mechanisms span over three areas: i) multi interfaced terminals and network mobility, ii) video-aware mobility management considering video services properties and iii) IP multicast mobility.

2.3. Transport Optimizations

Transport optimizations include optimal source selection or video content adaptation based on wireless access conditions, dynamic rate-control and caching schemes. Attention is paid to Content Delivery Network (CDN) architectures, which can benefit from the previously referred mechanisms, particularly the dynamic caching adaptation to users' mobility. MEDIEVAL will evolve concepts for jitter and delay handover triggers [1], giving them a global view, and P2P systems [4] but providing mobility support.

2.4. Wireless Technologies

MEDIEVAL improves service performance and reliability through the coordination of specific wireless technology properties and video services. Both contention-based (i.e. IEEE 802.11) and coordination-based (i.e. 3GPP) access methods are considered. In coordination-based ones, video traffic prioritization allows for significant QoE improvement, though constrained to specific conditions [5]. Other solutions either are based on heuristics and do not assure optimal performance [6] or are too complex, making deployment uninteresting for operators [7][8]. The introduction of cross-layer optimizations in LTE was an important step beyond previous cellular networks for data service delivery, particularly video. MEDIEVAL will support multiple wireless access technologies by taking advantage of standard IEEE 802.21, a cross-layer solution for interface abstraction for handover preparation.

2.5. Multicast

MEDIEVAL provides a common interface for allowing applications to efficiently deliver video content to user groups, leveraging multicast and broadcast context solutions, namely MBMS and eMBMS. Special focus is given to the network-based mobility multicast, as is the scope of MULTIMOB [9], tackling the non-involvement of the terminal in mobility signalling, which prevents it from participating in mobility-aware group subscription. IP multicast optimizations will consider mobility under the network perspective (i.e., due to handovers) as well as the service perspective (i.e., fast change of multicast groups, required by IPTV).

The aim of 802.21 is to facilitate and optimize handovers between different access technologies, through the introduction of a cross-layer entity, the Media Independent Handover Function (MIHF).

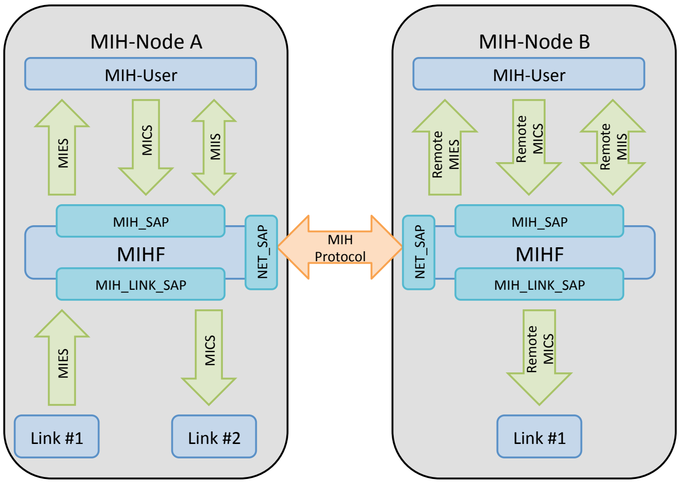

Figure 2: The IEEE 802.21 Framework

As can be seen in Figure 2, it provides an abstract interface, the MIH Service Access Point (MIH_SAP), to high-level entities, here dubbed MIH-Users. It enables MIH-Users to collect information and issue commands towards link layers of different technologies, using standardized common primitives, without having to tackle the specificities of each independent technology. To map the generic abstract commands into specific technology commands, the MIHF interfaces with each specific link SAP. Three services are available to MIH-Users: i) the Media Independent Event Service (MIES), providing real-time events about link status, such as indication that a link is going down, or that the signal strength as crossed a pre-configured threshold, ii) the Media Independent Command Service (MICS) enabling link control for configuration, querying information and initiating handover steps and iii) the Media Independent Information Service (MIIS), which provides a set of Information Elements (IEs) stored in a database schema, supplying network information to aid in optimal network selection. These services can be accessed either locally or in a remote way, through the MIH Protocol. Remote MIH-enabled entities use specific 802.21 discovery mechanisms to gain awareness of surrounding MIH-enabled nodes. The NET_SAP is responsible for the transport services over the data plane. In the MEDIEVAL framework, these mechanisms will be employed and extended [13], in terms of new events, commands and mechanisms, to support optimized video-service access.

With the mechanisms provided by the 802.21 framework, scenarios can be conceived where a Network Decision Point (NDP) acts as a MIH-User and is able to receive remote events from the links of multiple mobile nodes. The information supplied by such events enables it to have a view of the network conditions experienced by the terminal, and use the command service to initiate handovers when required. Several scenarios involving different kinds of access technologies have been being defined for quite some time [11][12]. However, all of these scenarios use unicast signalling to transport MIH Protocol frames, and do not consider the overhead impact of sending multiple 802.21 commands in order to have groups of users handover due to the same phenomena. Particularly, in [12] the MIH signalling impact was analyzed and it was verified that it was loading the network very lightly. In this article, we evolve from this study, by providing a different perspective where increasing numbers of mobile terminals motivate stringent network management to preserve radio conditions, which are made difficult by the expected increase in bandwidth- hungry Future Internet video services. Also, the application of multicast has been applied to 802.21 in the past, but only related in supporting broadcast [14] technologies, such as DVB, or by coupling handover procedures with multicast mobility [15]. However, none of them considers the application of multicast to the MIH signalling itself. MEDIEVAL will also benefit from the inclusion of ODTONE [17], an open-source operating-system independent implementation of the 802.21 standard.

3. Multicast Transport for MIH Services

The usage of MIH signalling generates overhead due to the required information in the MIH frame. Message fields such as source and destination MIHF ID, service ID and others need to be present in every message. Also, the message exchange mechanism assumes a request/response method, further increasing the amount of data flowing in the network.

Our study considers groups of users, connected to the same or nearby access networks, accessing broadcast or multicast video services. We argue that, when network conditions change due to the same phenomena (i.e., network congestion, servicing, or environmental causes) and affect a video feed received by several users nearby, it affects not just a single user, but blocks of users. In traditional MIH signalling, each single user would be the subject of an independent MIH signalling transaction. In the MEDIEVAL framework, we aim not only to extend the core 802.21 mechanisms to support video-enhancing events and commands, but also to take advantage of the underlying multicast and broadcast framework, enabling the provision of 802.21 signalling via multicast.

The concept is shown in Figure 3.When the NDP needs to send 802.21 messages affecting all nodes at the PoA, if it supports multicast 802.21, a single message is required. However, if there is no multicast 802.21 support, one message per terminal is required. To achieve the intended new feature over 802.21, four key interventions to the 802.21 mechanisms must be done:

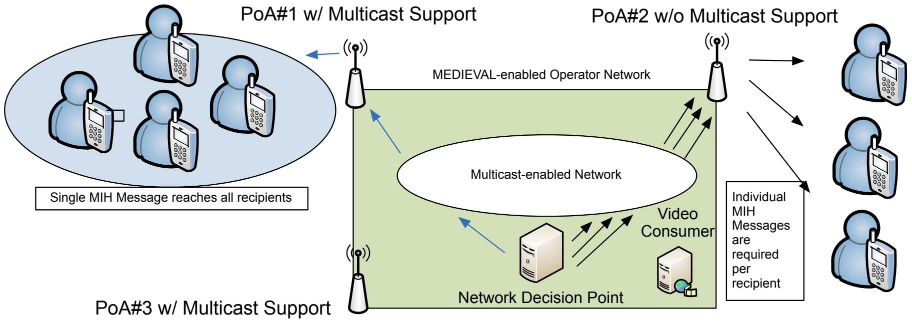

Figure 3: IEEE 802.21 Multicast Signaling

3.1. Discovery and Capabilities Discovery

MIH-nodes are able to discover each other and exchange information regarding supported services, using a MIH_Capability_Discover.request/response exchange, in a solicited or unsolicited way. In the first case, when the address of a node is already known, the message is issued with that address as a target. In the second, the node broadcasts the message and collects responses from nodes which have received it. The message contains the parameters presented in Table 1.

Name	**Description**
SourceIdentifier	The invoker MIHF ID
LinkAddressList	An optional list of link addresses and types supported by the node
SupportedMIHEventList	Optional list of supported events
SupportedMIHCommandList	Optional list of supported commands
SupportedISQueryTypeList	Optional list of supported MIIS query types
SupportedTransportList	Optional list of supported transport types
MBBHandoverSupport	Optional list to indicate if a make before break handover is supported

Table 1: MIH_Capability_Discover.request parameters

The SupportedTransportList parameter is a 16bit map, with two defined values (i.e., ’0’ for UDP and ’1’ for TCP) and the rest reserved. We added value ’3’ indicating “Multicast support”. We have also proposed a new optional parameter, “MulticastAddress” indicating the multicast address of that operator, over which multicast signalling is sent. This address can either be in IPv4 or IPv6, and is used by terminals to subscribe to the multicast group, and to indicate to 802.21-enabled network management entities their multicast support.

3.2. New Information Elements for MIIS

The MIIS provides standard IEs, which can be queried by terminal or network nodes, in order to obtain information about PoAs. IEs related to PoAs are presented in Table 2.

Information Element	**Description**
IE_POA_LINK_ADDR	Link address of this PoA
IE_POA_LOCATION	Geo-location of the PoA
IE_POA_CHANNEL_RANGE	Supported channel range
IE_POA_SYSTEM_INFO	System information supported by the PoA
IE_POA_SUBNET_INFO	Information about supported subnets
IE_POA_IP_ADDR	IP Address of PoA
Vendor Specific PoA IE	Vendor specific IEs

Table 2: PoA Information Elements

In the MEDIEVAL project, we will add two new items: IE_MULTICAST_SUPPORT, which indicates if this PoA supports multicast, and IE_MULTICAST_ADDRESS, which indicates the multicast address pertaining to the group of this PoA. These two new IEs assist in identifying PoAs with multicast support, which can have impact in handover candidate decision.

3.3. Multicast MIHF Identifier

Issued 802.21 remote commands and events must contain the source and destination MIHF identifiers. While using multicast 802.21 signalling, a new destination identifier has to be defined, which represents not one but all the nodes involved in the multicast group. In this case, the DESTINATION MIHF ID will be replaced with the IP multicast address, identifying the destination multicast group. Upon the creation of such message, this parameter will be evaluated by the MIHF and be sent as a multicast message towards the designated multicast group.

3.4. NET_SAP

The NET_SAP interfaces with remote transport services on which the MIHF is running. It uses a primitive, MIH_TP_DATA.request, to designate that a MIH frame should be transported, which has the parameters presented in Table 3.

Name	**Description**
TransportType	The transport protocol to be used
SourceAddress	The source transport protocol address
DestinationAddress	The destination transport protocol address
ReliableDeliveryFlag	Usage of message reliability
MIHProtocolPDU	The MIH PDU to be sent

Table 3: MIH_TP_DATA.request parameters

For this matter the TransportType parameter was extended to support a 8 bit map, where the option Multicast could be added to the other two (i.e., L2 and L3). Upon the reception of this primitive with the Multicast parameter, the transport services of the node interface with a multicast protocol to send the frame.

3.5. Integration with multicast group management protocol

In order to update the multicast tree, a core extension needs to be done to the MIHF. An MIH-User was created which was able to interface with a multicast group management protocol (i.e., IGMPv3 for IPv4 or MLDv2 for IPv6). Whenever a multicast 802.21-enabled node starts the discovery and capability procedures, and exchanges MIH_Capability_Discovery.request / response messages, the MIH-User interfacing with the group management protocol is fed with the multicast address provided by the capability message exchange (i.e., the new MulticastAddress parameter). With this multicast address, the MIH-User is able to initiate IGMP or MLD procedures, and thus the node is announced to the multicast router, which is now able to update the multicast tree.

4. 802.21 Multicast Signaling Scenario Use Case

To showcase the usefulness of using multicast 802.21 signalling, the following scenario is considered, based in Figure 3. In this scenario, a group of users is attending a press conference and connected to a WiFi hotspot. Using MEDIEVALs Personal Broadcasting Service, they start broadcasting the live interview using video, which quickly stresses available resources at that hotspot. Considering this, the NDP needs to move a block of users to another hotspot, for load balancing. Using MEDIEVALs multicast 802.21 signalling, a single signalling action is required per block of users, instead of per specific user. The signalling flow is depicted in Figure 4, showing only remote 802.21 signalling.

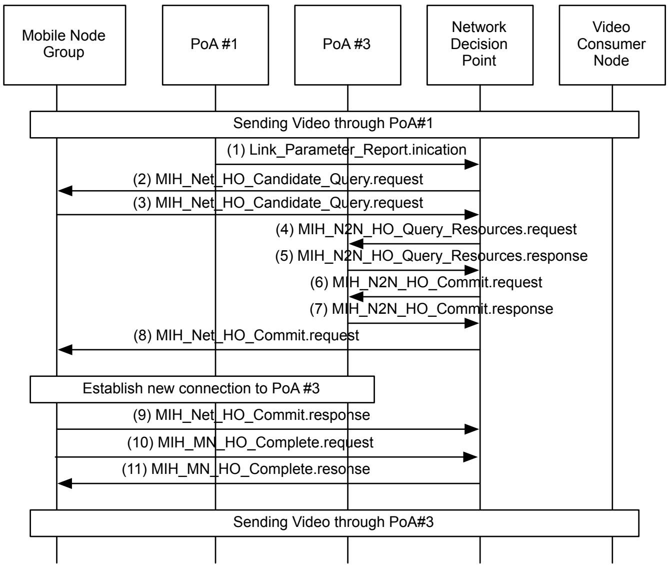

Figure 4: MEDIEVAL multicast 802.21 handover scenario

When the PoA that is serving the Mobile Node Group (MNG) detects that network conditions are decreasing, it generates a report event (1) towards the NDP, which then sends (2) towards the MNG in order to evaluate which other PoAs are within range. Notice that the message sent by the NDP is transported in multicast, but the answers are received independently, and thus it is able to evaluate for a common PoA within range of all nodes belonging to that block. The NDP selects PoA#3 as the handover candidate and sends (4) to query resources. Upon receiving the answer and verifying that PoA#3 is able to accommodate the user block, is commits those resources via (6), and commands the MNG to start handover procedures with (8). When this message is received, nodes are able to execute the L2 attachment at PoA#3 and report its result via (9). At this point, the MNG can initiate L3 mobility procedures if required after which (10) is sent to the NDP, which can trigger other procedures such as clearing resources at the old PoA. Finishing the signalling, the terminals at the MNG are now able to send video through PoA#3.

5. Conclusion and Future Work

In this work we provide an overview of the MEDIEVAL project, which aims to enhance the current Internets architecture to efficiently handle the increase of video traffic over wireless access networks, used by an ever increasing number of mobile terminals. We have highlighted a key innovation factor involving the abstraction layer to be used in the MEDIEVAL framework, the IEEE 802.21, and detailed the required extensions that enable it to support multicast signalling. A use case scenario was presented and described, featuring the feasibility of this new concept, showing that the number of signalling messages from the network to mobile terminals can be reduced to one per group, instead of one per terminal. On future work focusing on multicast signalling for 802.21, the project is further analysing how to tackle the dynamic creation of multicast groups, considering not only their PoA location, but also service and user profiles. The project is also analysing how to place reliable delivery mechanisms over multicast signalling, and how to further improve performance by designing the necessary mechanisms to support bi-directional multicast ability for IEEE 802.21 signalling.

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Paper F

Daniel Corujo, Marcelo Lebre, Diogo Gomes and Rui L. Aguiar, Sensor Context Information for Energy-Efficient Optimization of Wireless Procedures, *in Proc. 22nd IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Toronto, Canada, Sep 2011

Sensor Context Information for Energy- Efficient Optimization of Wireless Procedures

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Abstract

The wide deployment of Wireless Local Area Networks (WLAN) we are witnessing today increases connectivity opportunities for mobile terminal devices, such as smartphones. However, continuous scanning for WLAN points of attachment can be a power exhausting mechanism for such battery-powered devices. These mobile devices, besides being equipped with different wireless access interfaces, are also coupled with sensors such as accelerometer, GPS, luminance and magnetic compass. In fact, sensors are increasingly being coupled into different devices and environments and are able to convey sensing information through networks into decision entities able to optimize different processes. In this paper we propose a framework where media independent sensing information is used to enhance wireless link management towards energy-efficiency. This framework enables the dissemination of sensing information towards local and remote decision entities, enhancing other processes (e.g. mobility) with sensing information in order to provide true Ambient Intelligence scenarios. We introduce this framework into a wireless management scenario able to provide energy-efficient optimal network connectivity.

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1. Introduction

In recent years, the increase of publicly available WLAN infrastructures has provided wireless-capable mobile devices with an alternative to other access technologies (e.g., 3G and HSDPA). To take advantage of these connectivity opportunities, mobile devices need to activate their wireless interfaces for scanning and attachment procedures, which highly impact energy consumption. However, these devices are also coming equipped with different kinds of sensors, which can aid in determining the best opportunity for activating specific wireless procedures. In fact, sensor devices are increasingly being coupled into different devices and scenarios. The evolution made over their capabilities and transmission technologies (e.g., 802.15.4 and Zigbee) has motivated the increase of off-the-shelf devices, encompassing a considerable range of different and diverse applications [1]. Sensors have became accessible to developers outside the sensor networks community and present a platform ready for software development, enabling the conception of Ambient Intelligent scenarios, encompassing sensing input into different processes, such as industrial, entertainment and personal applications.

Accessing and disseminating such information is a prime objective when considering an Internet of Things, contributing to shortening the gap between our surrounding environments and the digital world and enabling sensors to provide context information towards entities that are able to consume it and use it to enhance other processes. However, this approach also introduces new problems. With the proliferation of sensor devices, manufacturers have supplied the market with different technologies, which operate distinctively and provide sensor information through very different formats. As such, sensing information frameworks have to resort to complex solutions in order to understand the different kinds of information and control the sensor devices.

With sensors deployed everywhere, constantly sending information through sensor and infrastructure networks in a multitude of scenarios, overall energy consumption will inevitably increase. This is currently a major concern for Information and Communication Technologies (ICTs), which have been mobilized by efforts such as the ICT for Energy Efficiency (ICT4EE[1]), aiming to facilitate the transition to an Energy-Efficient (EE) and low-carbon economy. We argue that sensors can provide context information, which can be used by ICTs (as well as other sectors) to improve EE processes, by using that information to optimize the operation of other processes, enabling them to be more efficiently controlled.

In this sense, we propose in this paper a framework that is able to integrate the information collected by different sensors, disseminates it towards consumers independently of the underlying transport technology, and which can act upon that information to optimize the EE of different processes. This framework is able to operate seamlessly in a bidirectional way, providing the means to control the sensors and configure how the information can be collected. We introduce this framework into a wireless management scenario, where the sensing information is used to improve EE of wireless processes as well as to provide triggers for optimal network connectivity.

This paper is organized as follows. In Section I2 we present related work, followed by Section 3 where we introduce the architecture of our framework. In Section 4 we submit our framework into an example scenario, first describing its integration with a EE wireless activation algorithm, following with results presentation. Finally, we conclude in Section 5.

2. Related Work

EE procedures have been a constant research topic in the evolution of wireless communications for decades now, providing different solutions at different levels of the stack over the years, comprising of physical, system and application level optimizations. However, single solutions are always reduced in scope, and when applied to cross-layer concerns, they present tradeoffs and inefficiencies. This has motivated methodologies combining not only link-layer EE improvements, but also other layer mechanisms such as [4] and [5]. The first considers adding a server with knowledge of the network workload to control the terminals network

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[1] `http://www.ict4ee.eu/`

card power configuration. In the second, a policy for network card selection based on power consumption is employed. Even though both present interesting energy savings, they are deployed in specific technologies (WLAN and Bluetooth) and make use of pre-designed policies working in specific scenarios, not considering sensors at all. We argue that a framework aimed at improving EE should be technology-agnostic, able to support different policies and support a large scope in terms of scenario deployment.

The deployment of sensors in ambient intelligence scenarios is typically associated to the wireless communication involved in reaching their sensing data. With the low-power characteristics of sensors, the power consumption used for wireless communication is a prime concern. When considering EE processes in wireless sensor networks, the typical approach is to focus on optimized wireless link protocols or energy conservation measures such as in [6]. Here, an optimized multi-hop sensor network is established showing that increasing the sensor node density in a wireless sensor network increases EE. However, solutions like these focus on the lower layers of the sensors, and the sensor network itself. This requires complex solutions when incorporating different technologies of sensors or integrating with high-level entities for sensor control and information usage in different scenarios.

The sensor information itself can play only a small role when it comes to providing it to complex higher-layer or application procedures, enabling their adaptation to dynamic environments. Several architectures exist with the purpose of collecting and distributing context information such as [7], featuring an agent-based architecture supporting context-aware systems, through a Context Broker. Other solutions, such as [8] rely on OSGi-based middleware. Both resort to XML information description which place higher processing and networking requirements, and require specific agents when sensors belong to different manufacturers. Also, [10] considers the provisioning of context as a service in heterogeneous environments, but the solution involves coupling to a specific set of high-level mechanisms and information representation, limiting deployment scenarios. This is where in fact our contribution aims to evolve, by providing a cross-layer approach for media-independent access to the control and information gathering from not only link interfaces but also sensorial devices, able to support different high-level mechanisms (e.g., mobility management) as well as allowing their integration in new scenarios, such as EE optimization.

3. Sensor Context Information Framework

In order to achieve EE wireless management procedures assisted by sensor information, our framework considers a set of goals. These are: media independent access to sensor information and control in heterogeneous sensor devices environments, the ability to affect wireless interface parameters and mechanisms for EE, and dissemination of the sensing information towards decision modules through a generic protocol able to work independently of the underlying transport technology.

To fulfill the first two goals, we have built our framework over the base concepts of 802.21 [2]. Here, a cross-layer entity (the Media Independent Handover Function MIHF) abstracts link layers (accessed through link Service Access Points (SAP)) to high-level entities (here dubbed MIH-Users), via an abstract SAP called MIH_SAP. The MIHF has the ability to convey events, commands and information locally as well as remotely towards other MIHF-enabled entities, via the MIH Protocol, which can be transported over L2 or L3. In this way, both local and remote MIH-Users are able to receive information regarding the link interfaces of MIH-enabled nodes (in the form of events) and issue commands over them based on their own specific algorithms.

For the third objective, we have enhanced the base 802.21 behavior by adding new events, commands and information allowing control and information-gathering able to be used independent of the different sensor technology. These extensions are assembled in the GENERIC_SENSOR_SAP, via simple adaptations that implement the MIH Protocol and interface with the MIHF, detailed in [3]. Figure 1 presents a high-level view of our framework, highlighting the base 802.21 components along our generic sensor extensions.

Equally important is that incorporating 802.21 services into our framework, allows us to control link interfaces for EE operations. More concretely, we take advantage of existing link commands to execute actions over the link behavior such as powering on or off the link, activate or deactivate wireless link activation, or even switching between passive and active scanning. Also, 802.21 allows the reutilization of the same signaling and decision mechanisms independently of the media used (e.g., WLAN, WiMAX or 3GPP), since the MIHF is able to abstract the commands and events from the MIH-Users towards the different link technologies, via their specific SAP. We retained that media independence by equally providing our sensor interactions in the form of a SAP.

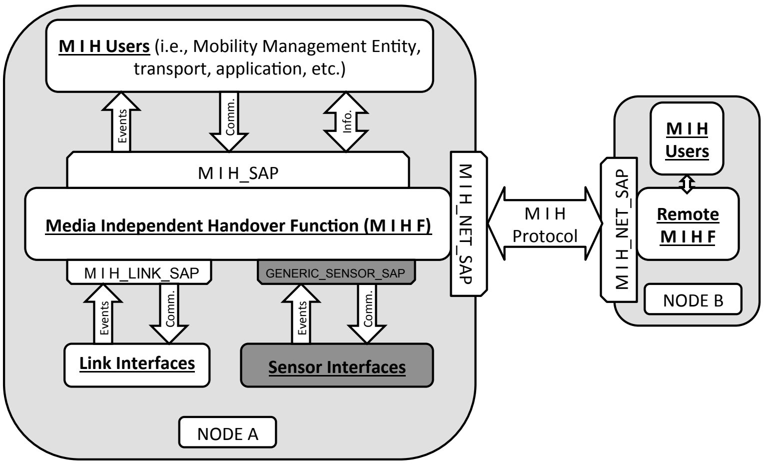

Figure 1: Generic Sensor SAP Extension to 802.21

We present two deployment examples of our framework operation, depicted in Figure 2. In the first case, sensor devices within the mobile terminal are abstracted by the MIHF towards a local MIH-User, residing in the terminal. This MIH-User is able to use the sensor information as input towards EE decisions, using the MIH services to impact the wireless links for energy conservation. In the second case, the sensing information is conveyed to a MIH-User installed in a remote server, able to consider other network-related processes (e.g., mobility, Quality of Service, policies, etc.) or even the information provided by the sensors of multiple mobile terminals, and act on their wireless link interfaces for a global EE optimization procedure.

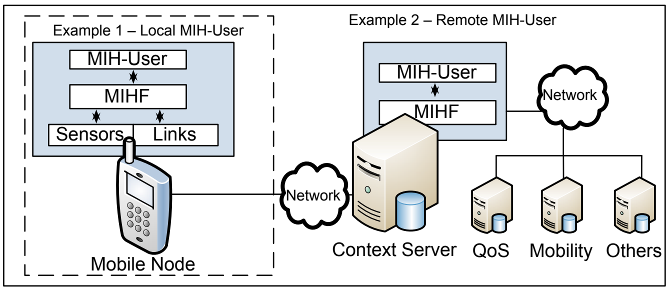

Figure 2: Sensor Information Usage Scenarios

With the features provided by 802.21, along with our generic sensor extensions towards collection and control of sensor devices in heterogeneous environments, we are able to provide the basis for, on one hand, integrate sensing information into existing processes such as mobility and, on the other, to provide a set of services that enable the abstraction of control and information gathering from different families and kinds of sensors, while enhancing them with media-independent service management mechanisms for node discovery, capability identification and service registration. We combine these possibilities towards sensor-aided EE wireless management procedures.

4. Performance Evaluation

Frameworks leveraging on sensors have to consider the limited processing, memory and network performance of such devices. With the abstraction capabilities provided by our framework, as well as the ability of conveying that information towards remote network decision entities, one might fear that sensor-related operations become burdened with the introduced mechanisms. Thus, it becomes necessary to assess the performance of our framework, even in very simple cases, but without withholding the amplitude of applications over which it can optimize procedures, particularly EE ones. As such, we developed and deployed a testbed scenario showing how a context-aware server can analyze media independent sensor information conveyed by a mobile terminal, and use such information to optimize EE capabilities on a multi-technology mobile terminal. Specific results on network performance using our developed signaling can be consulted in [3], whereas a study on the effect of our signaling in both node number and battery consumption can be found in [9].

4.1. Energy-Efficient Sensor-Based Wireless Operation

We setup a bi-partite testbed featuring two scenarios, depicted in Figure 3. The first scenario (the Base Run) was built for base comparison. Here, a mobile terminal with two Wi-Fi cards has one of them (wlan0) connected to AP1. The mobile user will approach AP2 and perform a handover using wlan1, returning to AP1 when it leaves the vicinity of AP2. In this scenario, although a handover is performed, both Wi-Fi cards are active and continuously consuming energy. For scenario deployment simplicity, we feature two Wi-Fi cards, but the media independent mechanisms provided by our framework allow us to conceive multi-technology scenarios with little or no effort, simply by replacing these with interfaces belonging to different technologies, and enabling them with 802.21 support.

The second scenario (the Sensor Run) features a context server able to analyze media independent sensor events provided by the mobile terminal, issue remote commands accordingly and is also aware of the ESSID (Extended Service Set ID) for wireless networks in its vicinity for handover control. In this scenario, the mobile terminal is connected to AP1 using wlan0, and wlan1 is powered down, conserving energy. When the mobile terminal moves (Movement 1), the accelerometer sensor sends a sensor event towards the context server, which processes it and remotely enables the wlan1 providing it with an ESSID for a closer AP (AP2), thus performing a quick attachment mechanism, saving on scanning time/energy. After attaching to AP2, the wlan0 is powered down, further conserving energy. On Movement 2), the opposite occurs: as the mobile terminal departs from AP2, a sensor event sent to the context server triggers a command to power up wlan0, also providing the ESSID so it can directly attach to AP1, powering down wlan1 as well.

4.1.1. Testbed

In our testbed we separated the two APs by a distance of four meters, enabling the mobile terminal to move and experience signal strength changes from both APs. Our framework enables the setting of a threshold value that, when crossed, generates an event towards the context server with the information about the users movement.

Each scenario experiment has a duration of 10 minutes. In the first two minutes, the mobile terminal is close to AP1, then it moves to the AP2 and stays there for approximately 6 minutes, then returning to AP1 for another 2 minutes.

4.1.2. Energy-Efficient Wireless Activation Algorithm

Figure 4 represents the algorithm used in scenario 2, initiating its procedures after one interface becomes attached. The mobile terminal informs the context server when motion is detected, through a sensor event, which then sends a MIH command (MIH Link Action request), for powering up the inactive interface, along with the ESSID of a more suitable AP. Upon reception of this command, the mobile terminal powers up the inactive interface and attaches to the recommended AP. If this is unsuccessful, the terminal maintains its attachment to the current AP. In case of success, the previous interface will power down (thus conserving energy) and the mobile terminal will become attached to another interface. Although this is a simple handover algorithm, our scenario can be easily extended to encompass more complex features, such as full mobility protocols, using link events reporting radio conditions for optimizing handover opportunities or even able to interface with Authentication, Authorization and Accounting frameworks (AAA).

4.1.3. Energy-Efficient Wireless Activation Architecture

Figure 5 shows the message sequence diagram, depicting the message exchange by all entities present in the network. The used messages are sensor extensions implemented in ODTONE[2], an 802.21 open-source implementation, taking into consideration the messages defined in [3]. Initially, in step 0 we assume that the mobile terminal is already connected to an AP1. Step 1 represents the sensor event triggered by our Sensor SAP in the mobile terminal, which is sent to the MIH-User in the Context Server. Step 2 shows the triggered command flowing from the Context Server to the mobile terminal due to the movement generated by the mobile terminal while approaching AP2. This message promotes a handover from AP1 to AP2 (Step 3), powering up the inactive interface, while attaching it to AP2 and powering down the previously used interface connected to the AP1. Steps 4 to 6 highlight the opposite operation of steps 0 and 3 where the mobile terminal moves away from AP2 and approaches AP1 again.

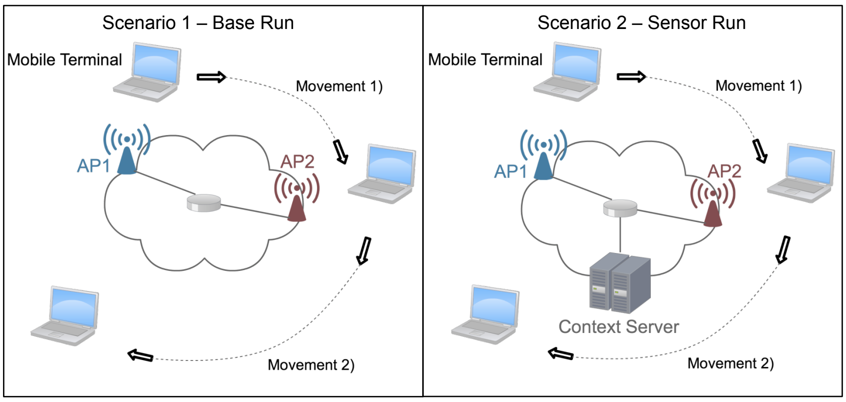

Figure 3: Scenarios: Base Run (1) and Sensor Run (2)

4.2. Evaluation of Energy-Efficient Sensor-Based Wireless Operation

To evaluate our framework we analyzed the energy consumption to assess the efficiency of optimizing wireless activation and how it would reflect on the mobile terminals battery. The mobile terminal consists of a laptop with an Intel Centrino Duo processor, 2GB of RAM and

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[2] ODTONE, `http://atnog.av.it.pt/odtone`

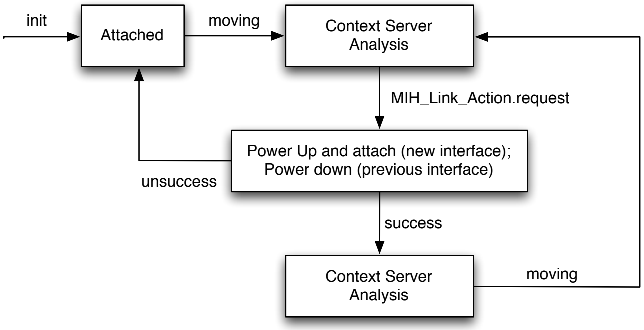

Figure 4: Sensor Wireless Activtion Algorithm

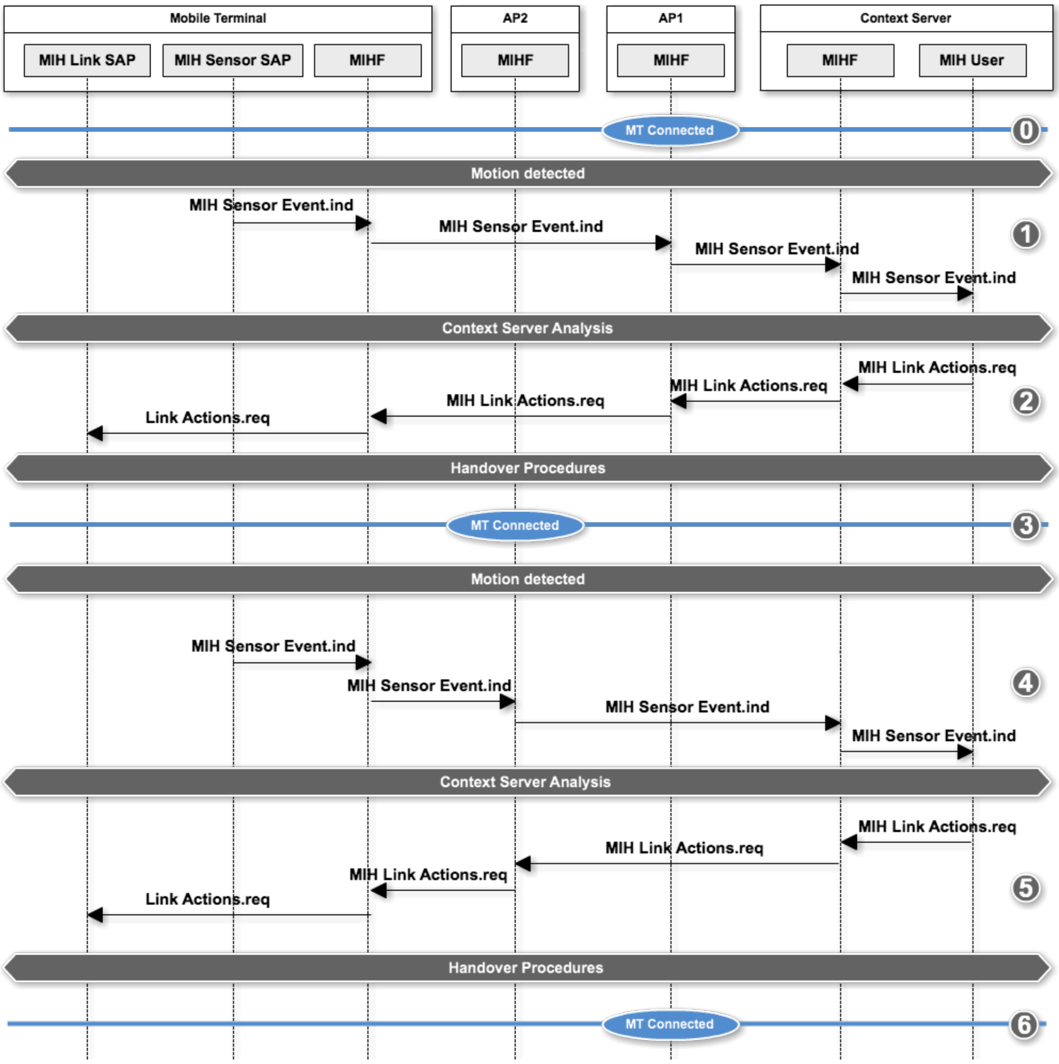

Figure 5: Sequence Diagram for Wireless Activation

two wireless cards. In this experiment we monitored the battery consumption continuously taking 2 second samples.

To analyze the energy consumption of each scenario we measured battery consumption for each scenario using the referred laptop. As the obtained measures were consistent, Figure 6 shows the comparison between two randomly chosen measures, one for each scenario, repeated for ten times.

Energy consumption was averaged in time intervals of 60 seconds during the 10 minutes duration of the scenario. This study shows that an average of 12.8 mWh and 11.73 mWh were consumed per sample for scenario 1 and 2 respectively.

The overall analysis provided by the ten repetitions on the battery consumption shows that scenario 1 has consumed an average total of 3784 mWh of the batterys capacity and scenario 2 consumed 3579 mWh, representing an average saving of 200mWh.

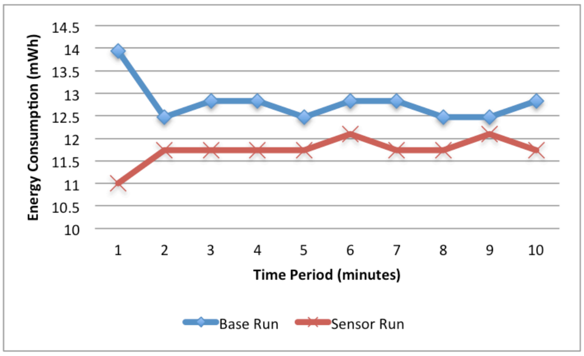

Figure 6: Scenario Energy Consumption

5. Conclusion

In this paper we presented a framework where sensor information was added to the media independent mechanisms of the 802.21 standard, using that information to enable EE scenarios. Through a simple live experiment, we were able to convey sensor information obtained from a mobile terminal (enhanced with our media independent sensor-enabled mechanisms) towards a Context Server. This sensor information allowed decision mechanisms at the Context Server to control the activation/deactivation procedures of wireless interfaces of the mobile node for energy conservation, while providing pre- configured link information for optimal handover candidate selection and unnecessary wireless scanning avoidance. Even considering this simple deployment of our framework, we were able to evaluate the usefulness of sensor context information and achieve reduced power consumption at the terminal, even when such sensor information is conveyed remotely towards an external entity, such as the Context Server, for decision taking.

We argue that conveying sensor information obtained at mobile terminals towards network decision entities, enables them to take into consideration other contexts which are only obtainable from the mobile terminals point of view, such as the energy requirements (and statuses) of mobile devices. These considerations can be furthered integrated with other procedures, such as optimal handover selection and decision, enabling network operators to fully optimize network management procedures (considering mobility, AAA, service optimization and other procedures), while also enabling the optimization of mobile terminal operations. By maintaining the structure and integrity of the MIH Protocol when extending it to contemplate sensor context information, we are not only enhancing the 802.21 mechanisms, but we are also allowing the integration of sensor information into any 802.21-enabled scenario, empowering handover decisions with more specialized elements, aiding in a more optimized process. This paper demonstrated a basic scenario, employing our framework over simple remote wireless activation/deactivation procedures while assisting in access point attachment, but these were already enough to obtain positive results on EE improvement.

Regarding future work, we are currently extending our scenarios and deploying our framework to more complex handover scenarios, considering different IP mobility protocols and decision algorithms. We are also implementing extended EE mechanisms over different wireless interfaces, beyond Wi-Fi, for a truly heterogeneous networks energy-efficient sensor-aided environment. Lastly, we are also experimenting with sensors (and actuators) from different manufacturers, not only to further refine our sensor-enhanced 802.21 design, but also to integrate them into complex energy-efficient ambient intelligence environment scenarios.

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Paper G

Daniel Corujo, Marcelo Lebre, Diogo Gomes and Rui L. Aguiar, A Framework for the Connectivity of an Internet of Things, *in Proc. IEEE Sensors Conference*, Limerick, Ireland, Oct 2011

A Framework for the Connectivity of an Internet of Things

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Abstract

The evolution of telecommunications has allowed the coupling of networking features to an ever-increasing plethora of devices, enabling their connectivity and berthing of an Internet of Things (IoT). However, the assorted nature of such things implies disparate specifications, requirements and interfacing, for interaction with high-level decision modules, services and agents involved in the most distinct kind of scenarios. The joint operation of all networkable things in a truly integrated IoT vision requires a flexible framework able to facilitate interfacing with different elements and concepts. In this paper we present a framework that builds over the concept of Media Independence, further enhancing it to encompass the abstraction of different things, by providing the means for accessing their different interfacing procedures. We highlight the feasibility and flexibility of this framework by introducing it into an IoT scenario, enabling a flexible way for interface retrieval and control of different entities, paving the way for a truly universal and dynamic connectivity vision.

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1. Introduction

Internet of Things environments aim to allow services and decision entities to interact with devices, controlling them or accessing their information to empower a number of mechanisms and scenarios. However, these scenarios require these entities to be coupled with pre-conceived interfaces for accessing said devices. Although most interaction interfaces are standardized, proprietary solutions also exist, and the huge variety of interfaces available to different devices and technologies difficult dynamic and generalized access in fully integrated IoT scenarios.

Abstraction technologies, such as IEEE802.21 [1], have been created to facilitate the interaction with different link layer technologies in a media independent way for mobility purposes. In this work we go beyond what is defined in the standard by creating the necessary extensions and mechanisms, through the development of a comprehensive framework that allows decision entities to dynamically request schemas describing the interaction procedures with different devices, along with the necessary communication protocol to forward those procedures to such devices. The objective is to allow entities and services to view devices as in a true Internet of Things, empowering them with a dynamic and automated way of learning how to interact with such devices based in a tri-partite semantic definition of technologies, items and procedures. To enable this, an ontology defining interfaces is made available in globally deployable information servers that can be queried by services and decision entities in order to obtain the interaction procedures for different kinds of technology devices. These schemas allow the automated learning of the necessary primitives that can be produced and sent towards the devices, using different transport schemes over small networks or the Internet.

This paper is organized as follows. In Section 2 we present related work, followed by Section 3 where we introduce the architecture of our framework. In Section 4 we submit our framework into an example scenario and provide results. Finally, we conclude in Section 5.

2. Related Work

With the aim of integrating the physical and the digital worlds, researchers and the industry have been developing extensive work in the vision of IoT for some time. Here, the concept of Ambient Intelligence [2] allows the development of pervasive environments where devices (e.g., sensors and actuators) and their interconnectivity come together to improve processes and the overall quality of life of its users.

However, the pursuit of this vision comes coupled with a major challenge: interfacing and interoperating with devices of different nature. [3] introduces a set of requirements regarding the cooperation of devices for creating value-added services in a IoT. The authors highlight the need for a seamless cooperation between involved entities, referring not only standalone but also infrastructure assisted connectivity. To achieve this cooperation, works such as [4] focus on the development of sensor-based networks and IP connectivity, introducing mobility and security aspects, bringing sensors closer to an all-IP world. Complementary to this view, solutions providing sensor-networking optimizations considering cross-layer approaches [5] are starting to appear. Also, IoT-related works have been actively pursuing automated behavior where the resources made available by devices can be dynamically accessed and learnt. [6] introduces a semantic middleware for the IoT, providing a framework which maps different automated discovery standards (e.g. UPnP [7]) to an abstraction in the service layer using Semantic Markup for Web Services [8] (OWL-S). Although this method is able to suit devices and existing interoperation standards, it does not consider the plethora of Internet services and how to add them in a global connectivity scheme. In this sense, [9] provides a framework for service provision in a IoT, but the solution already dictates how key mechanisms should be tacked in terms of functional groups and hierarchies, which can impact the design flexibility when considering different scenarios and policies.

We argue that a truly global IoT vision goes beyond the interconnection of sensors and actuators, expanding into an open platform where also services and high-level entities will share the connectivity fabric. This is where our work contributes, through the development of a framework that provides a bridging between an IoT and an Internet of Services [10], allowing devices, services and decision modules to be universally interfaced, supporting a multitude of ubiquitous scenarios.

3. Media Independent Service Framework

3.1. General Architecture

The objective of our architecture is to provide the means allowing entities to dynamically retrieve and understand the interfaces for interacting with devices and services in a true IoT environment. In that sense, we provide an abstraction interaction layer existing in all entities, enabling their discovery and providing capabilities information. This information can be used to query special Media Independent Information Servers (MIIS), which we have enhanced to retrieve the entities specific API, becoming Information Domain MIIS (IDMIIS). Through a tri-partite semantic definition of technologies, primitives and phenomena, these APIs are translated into Media Independent Commands, which can be sent remotely to the abstraction interaction layer of devices, empowering fully global IoT scenarios.

The abstraction interaction layer is an evolution of the Media Independent Handover Function (MIHF) defined in the IEEE802.21 standard [1]. There, its purpose is to facilitate and optimize handovers through the provision of a single abstract interface between high-level entities (e.g., MIH-Users) and the link layers. With this behavior, these MIH-Users are able to obtain information and control link-layers by using a previously known and common abstract interface, instead of using each technology specific API. The MIHF achieves this by providing a MIH Service Access Point (MIH_SAP) which provides a set of primitives towards the MIH-Users. In turn, the MIHF then translates these commands into technology-specific commands, mapping them into link specific SAPs (e.g., LINK_SAP). IEEE802.21 also provides the MIH Protocol, enabling remote interaction between MIH-Users and links in different nodes, either via L2 or L3.

The IEEE802.21 standard considers LINK_SAPs for IEEE technologies (e.g., 802.11, 802.16) and 3GPP wireless access technologies. In previous work [11], we enhanced this list with a Sensor SAP, allowing abstract control and information collection from different sensor families, as well as providing different dissemination models to facilitate context dissemination in sensor-enabled environments [12].

In our framework, we extend this abstraction behavior by decoupling the MIHF from a static set of pre-defined SAPs, providing instead the means for MIH-Users to dynamically identify and request whatever SAPs they require from a special server, the IDMIIS. These SAPs empower the MIH-User with the necessary information to create the necessary commands for interacting with the desired devices and services (which also share the SAPs), using an adapted version of the MIH Protocol. Fig.1 presents a MIHF-enabled node featuring a MIH-User and coupled with a set of pre-defined SAPs. The MIH-User is able to use our extended MIH Protocol to query an IDMIIS and request additional SAPs. This server has the ability to forward the query to other servers if it cannot fulfill the request using an hierarchical approach [13]. The requested new SAP is sent back towards the MIH-User, which is able to use it to create MIH Protocol commands and forward them to the respective IoT device. The device is also coupled with the same SAP, enabling it to understand and execute the received commands. In this way, the MIH- User is able to obtain the interfaces to interact with virtually any kind of device and service, allowing a generalized global IoT connectivity environment.

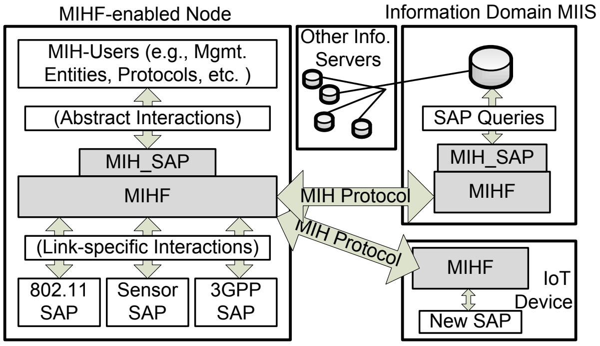

Figure 1: General Architecture Example

3.2. Information Organization Structure

To allow a dynamic adaptation of the MIH-Users pre-defined behavior to the received primitives in the obtained SAPs, our Information Structure allows the usage of tags related to the tri-partite model. As an example, a MIH-User could query the server indicating its interest in sensor (the technology), temperature (the phenomena) and set_threshold (the primitive). With this query, the server would reply with a SAP containing the necessary information for the MIH-User to create a generic MIH Protocol command (e.g., MIH_Action.request) with its parameters configured according to the information obtained from the SAP, able to be sent to any kind of sensor which supported setting thresholds on a temperature event. Our current deployment stores the information and executes the queries using XML, as can be seen in Fig.2. However, our framework is flexible enough to support other more advanced approaches such as RDF and OWL schemas. The structure also enables queries to be done in a tiered mode, allowing query customization. In this way, a MIH-User could only provide a phenomena tag to the server, and receive all the primitives available from devices and services able to interact with said phenomena, and execute queries in a step- by-step approach to better refine results.

3.3. IoT-Enhanced Information Servers

The MIIS provided by the standard IEEE802.21 can be queried by MIH-Users for obtaining network information, with the aim of optimizing network selection. Therein an information schema is defined, able to be used in either RDF or binary objects, query able via SPARQL with MIH Protocol commands. In our framework, we have extended this schema to accommodate the definition of SAPs from a multitude of different technologies, phenomena and

```xml
<?xml version="1.0" encoding="UTF-8"?>
<thing>
    <primitives>
        <commands>
            <primitive message="MIHS_Action.request" name="avoidDistrict" AID="12" OPCODE="1" SID="3">
                <parameter label="actionID" datatype="UINT(1)">2</parameter>
                <parameter label="value" datatype="UINT(1"></parameter>
            </primitive>
            <primitive message="MIHS_Action.request" name="valveOpenClose" AID="12" OPCODE="1" SID="3">
                <parameter label="actionID" datatype="UINT(1)">4</parameter>
                <parameter label="value" datatype="UINT(1)"></parameter>
            </primitive>
            <primitive message="MIHS_Subscribe.request" name="subscribe" AID="13" OPCODE="1" SID="3">
                <parameter label="actionID" datatype="UINT(1)">6</parameter>
            </primitive>
        </commands>
        <events>
            <primitive message="MIHS_Sensor_Event.indication" AID="9" OPCODE="3" SID="2"¢¢>
                <parameter label="value" datatype="UINT(2)"></parameter>
            </primitive>
        </events>
    </primitives>
    <technology>
         <gateways>
            <entity type="disaster">
                <address>192.168.1.1</address>
                <mihID>disasterGateway</mihID>
            </entity>
            <entity type="traffic">
                <address>192.168.1.2</address>
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            </entity>
        </gateways>
    </technology>
</thing>
```

Figure 2: Schema Query for SAP example

primitives. Using tags, other nodes can query the servers to obtain the necessary primitives for interfacing with other devices and services.

Our architecture allows a flexible way for deploying the IDMIIS. The server can be deployed in a centralized way, where manufacturers and service developers can publish (in a certified way) their product SAPs, which can be accessed in a global way by nodes when needed. Also, by taking advantage of the MIH Protocol service management capabilities, our framework also allows a more local and distributed deployment of the IDMIIS, allowing operators or network managers to provide SAPs interfacing with the devices and services located in their local domains.

3.4. Agent and Device Deployment

As defined in [12], we have extended the MIH Protocol to enable the interaction with devices deployed in a flexible way, according to the characteristics and deployment of devices. In this way, agents can interface directly with devices, through a gateway coupling different devices or through translation nodes when devices are not able to accommodate a MIHF. These agents can operate in an autonomous way, through the pre-provision of behavior routines inserted into their code. These routines, instead of using a static API for interfacing with devices and services, uses tags which can be replaced by specific parameters and information, when receiving the interfaces description from a queried IDMIIS. The parameters and information obtained therein are placed into generic MIH Protocol service management primitives, which are then sent towards the devices for controlling them. These devices are able to understand the service management primitives formatted according to their specific SAP. Due to paper length restrictions, we do not provide a code example of this process here, focusing instead on the evaluation of the overall approach, which is presented in the next section.

4. Evaluation

In order to evaluate the feasibility of our approach, we have implemented our IoT connectivity concepts over the open- source IEEE802.21 implementation ODTONE [14]. We have submitted our mechanisms to a live testbed equipped with SunSPOT [15] sensors connected to their respective base-stations via IEEE802.15.4, and featuring an IDMIIS, MIH-User node and gateways consisting of wireless laptops with an Intel Centrino Duo processor, 2GB of RAM, connected to a wireless Linksys WRT54GL router.

4.1. Scenario

A prime deployment case, where agents need to interface with different devices and services in an autonomous way, is disaster situations. In our scenario, an earthquake has occurred damaging a city centre area, where a number of gas pipes pass underground. This city recently deployed an overseer agent, which is an automatic monitoring and reaction process, coupled with disaster procedure routines. In our scenario, the overseer will close gas valves and redirect traffic away from the city centre. For that, it is able to use our framework to interface with sensors, actuators and the traffic lights service, as per Fig.3. As visible in Fig.4, it starts its Grounding Phase where it requests for available interfaces related to gas valve shutdown, and traffic light rerouting using different technology, phenomena and primitive tags sent to the IDMIIS, which replies with the according SAPs (Steps 1 to 3). With them, the overseer is able to produce and send the necessary MIH_Action.request messages to the devices controlling the gas valve (Step 4), reroute traffic using the lighting service (Step 5) and subscribe events related to temperature and pressure in the gas pipes, for monitoring activities (Step 6).

4.2. Results

We have measured both the time taken to execute these procedures as well as the amount of data generated by them, presented in Tab.1. Ten experiments were conducted, presenting here the averaged results with a 95% confidence interval. We separated the measured time into the amount of time taken for the IDMIIS to process the queries (Steps 1 to 3) and the time taken by the devices to process the requests sent by the overseer (Steps 4 to 6). It is visible that the first takes between 5 and 8 ms to process, which is related to the size of the query. The second processing took longer for Steps 4 and 5 (around 130ms), highlighting the impact caused by the sensor interfacing procedures when interfacing with the SunSPOT OS. As a contrast, Step 6 features a command that only involves interfacing with the MIHF component, accounting only for 20ms. Regarding the communication times, Steps 1 to 3 were quite fast (between 26 and 28ms), whereas Steps 4 to 6 took between 500 and 620ms. In this case, the IEEE802.15.4 wireless interface used between the SunSPOT gateway and sensors motivated the delay. The total procedure took approximately 2 seconds to be executed, and totaled an amount of 1608 bytes of data. Overall, IDMIIS was involved in 1% of the total processing and 3% communication times, whereas direct device interaction was involved in 15,6% of processing and 79% of the communication times.

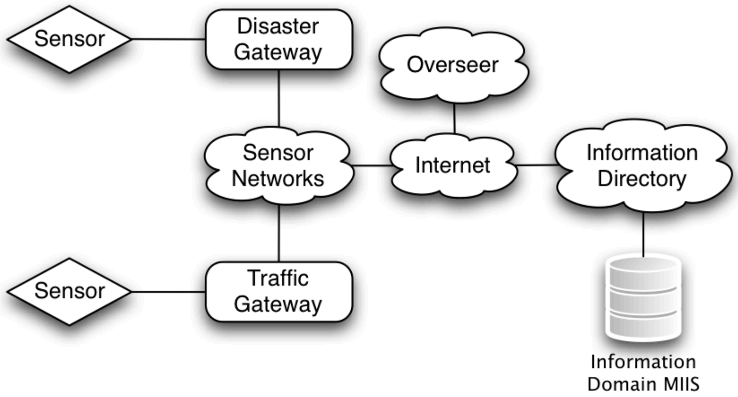

Figure 3: Scenario Deployment

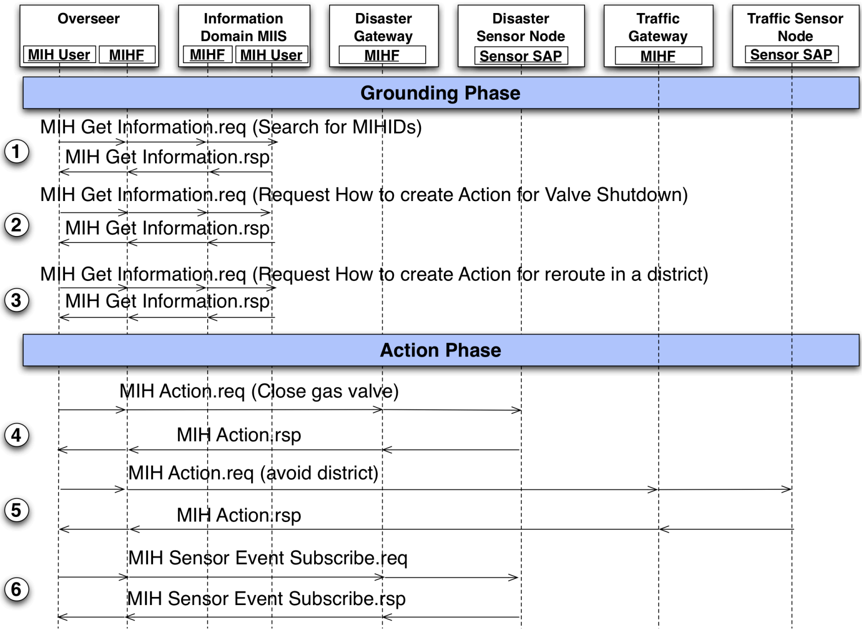

Figure 4: Message Sequence Chart for the Disaster Scenario

5. Conclusion

This paper presented a framework enhancing current Media Independence approaches, enabling a flexible and dynamic way of obtaining the necessary interfaces allowing high-level entities to interact with different devices and services. The aim of this work is to conceive a first approach towards a truly dynamic and generic approach towards IoT. The

Step	**Proc. Time (ms)**	**Comm. Time (ms)**	**Total Step Time (ms)**	**Req. Size (bytes)**	**Rsp. Size (bytes)**
1	5.8±0.5	20.4±2.9	26.2±3.0	57	349
2	7.3±0.7	21.6±2.8	28.9±3.1	75	372
3	8.1±1.9	18.1±3.6	26.2±3.8	74	370
4	130.5±1.6	491.3±34.7	621.8±34.3	39	71
5	150.5±1.6	451±36	581.5±35.2	38	71
6	20.7±0.3	491.5±17.7	512.2±17.7	49	43
Tot.	302.9	1493.9	1796.8	332	176

Table 1: Scenario Results

enhancements were done over an IEEE802.21 implementation and deployed on a testbed featuring a user node, an IDMIIS, sensors and devices connected to a gateway. Results show that the mechanisms defined within our framework have a negligible impact when considering the time taken with the direct device technology interfacing. Concretely, the SunSPOT devices procedures related to sensors, and the IEEE802.15.4 communication between the SunSPOT base station and sensors, were the biggest impact factors. We argue that the specific device technology APIs and wireless capabilities impact the framework performance, but are not a direct consequence of its usage. As future work, we are currently integrating our framework over more devices, to analyze its impact in different technologies over a broader range of scenarios. Part of the research leading to these results has received funding from the FP7 MEDIEVAL project.

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Paper H

Daniel Corujo, Marcelo Lebre, Diogo Gomes and Rui L. Aguiar, MINDiT: A Framework for Media Independent Access to Things, *in Elsevier Computer Communications, Special Issue on on Smart and Interactive Ubiquitous Multimedia Services*, Mar 2012

MINDiT: A Framework for Media Independent Access to Things

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Abstract

Deploying Smart Environments often implies a plethora of co-existing devices and services, each with their own set of features, requirements and interfacing characteristics. These intricate scenarios are further exacerbated when such devices are coupled with networking capabilities, globalizing their interaction opportunities to create the so-called Internet of Things. In such interconnected heterogeneous environments, the joint operation of entities requires a flexible framework that enables and simplifies interfacing between elements. In this paper, we propose MINDiT, a framework that provides a common abstract interface towards the communication support with different entities. It incorporates cross-layer mechanisms inspired on the existing IEEE 802.21 technology, suitably modified to facilitate and optimize deployment in scenarios featuring both high-level, and low-powered network-restricted entities. MINDiT was validated through a prototype built over an open-source IEEE 802.21 implementation. We further compared its signaling impact against other solutions, and evaluated its performance over a smart environment featuring a multimedia scenario with multiple devices and services.

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1. Introduction

Evolutions on networking access technologies and protocols have created a plethora of new connectivity scenarios featuring an ever-increasing amount of devices and networking entities. In the Internet of Things (IoT) vision, the traditional view of the Internet as a network for remote resource sharing has evolved into an heterogeneous environment, where a multiplicity of devices and services co-exist and use the Internet fabric to share their functionalities. This vision creates immense possibilities, where real-world devices (both sensors and actuators) and services deployed anywhere in the Internet can be accessed and manipulated to interact with one another, jointly conceiving and realizing Smart Environments able to impact and improve every aspect of our everyday life.

This heterogeneity (considering the diversity of connectivity technologies at pico, micro and macro level, as well as different services and interfacing possibilities that are reachable on-line) raises complex interoperation issues: different devices from different vendors, providing distinct features accessed by diverse services using disparate protocols, standards and interfaces for exercising various kinds of behaviors, all pose a difficult canvas for the definition and deployment of common-based scenarios.

Realizing this IoT vision requires a common interface that enables and facilitates networking and control procedures. However, such interface must be able to operate over specific technological functionalities and requirements from high-level services (e.g., mechanisms supporting decision modules, management entities, service provisioning), as well as low cost constraints (e.g., low-powered sensors, fast versus slow links, mobile wireless environments). It also has to take into consideration the way the Internet is evolving, with users accessing services while on the move, and reports [1] heralding the dominance of ubiquitous multimedia services and content.

To address these challenges, in this paper we propose and define MINDiT, a framework able to provide a common abstract interface towards the connectivity of agents wishing to interface with different entities in an IoT. It provides a comprehensive and flexible approach towards the definition and retrieval of interfaces for interacting with both services and devices. To efficiently cope with the different specific requirements posed by both higher and lower layers of the network stack, we couple MINDiT with existing management concepts assisting the network: we evolved MINDiT over the Media Independent Handover (MIH) services concept introduced by the IEEE 802.21 [2] standard. Taking advantage of the MIH versatility, MINDiT enables common interface mechanisms to operate in demanding mobile-aware scenarios, as well as providing the flexibility for interface dissemination and representation. The performance of our framework is evaluated through a prototype built over an open-source implementation of the IEEE 802.21 standard, interfacing different devices and services.

The remainder of the paper is organized as follows. Section 2 identifies related work on technologies for smart and ubiquitous services, followed by Section 3 which describes our framework architecture. Section 4 presents a functional and resource utilization comparison between MINDiT and major Web Service-based frameworks. Next, Section 5 presents a multimedia smart environment scenario which serves as a deployment example for our framework, whose implementation performance results are presented in Section 6. Finally, section 7 concludes the paper.

2. Related Work

The plethora of different smart devices and services that compose IoT scenarios [3] [4] [5], have since long raised the associated challenge of heterogeneous interfacing [6]. A proposed solution is the deployment of middleware that provides an intermediate software architecture and simplifies the access to different kinds of sensor technologies [7]. Other approaches consider enhancing this middleware with dynamic programmable features [8] and sensor clustering into virtual machines viewed as applications [9]. These solutions, although enlarging the scope of interfaced sensor information sources, adopt a vertical deployment approach that limit not only the adoption of new kinds of devices, but also its extension to multiple target applications (e.g., Urban Computing).

On the other hand, the differences in accessing low-powered devices and application frameworks often results in isolated and dedicated systems, hindering the design of new services or the support for new devices. To close this gap, increased research and standardization efforts were made towards the integration of small devices through service oriented architectures (SOA) using Web technologies [10].

Works developed under the umbrella of projects such as Service Oriented Device and Delivery Architecture (SODA) [11], Service-Oriented Cross-layer infRAstructure for Distributed smart Embedded devices (SOCRADES) [12] and Integrating the Physical with the Digital World of the Network of the Future (SENSEI) [13], have explored frameworks deploying Web Services at the device level, through the usage of the Devices Profile for Web Services (DPWS[1]) protocol stack. This OASIS (Organization for the Advancement of Structured Information Standards) standard provides services for discovery, event processing, description and addressing. However, despite targeting resource-constrained devices, the XML nature of the used SOAP messages makes them large in size and requires devices to support HTTP. To counter the former issue, solutions such as the Efficient XML Interchange (EXI[2]) specifies XML encoding procedures that reduce this overhead. Nevertheless, such operations require computation resources that might not be easily available in low-powered devices. Lastly, DPWS still requires its integration with other services, such as Web Service Definition Language (WSDL[3]), to describe the services running in devices.

A different web service device information access (and incrementally supported in several works related to SENSEI), the REpresentational State Transfer (REST) approach provides lightweight means for accessing resources as web services, using standard HTTP methods with Uniform Resource Identifiers (URIs). Frameworks employing REST [14] [15] allow direct access from the Internet to the sensor network and minimize the overhead introduced by the transport layer, when compared to XML and WSDL. Particularly, [16] considers that the lightweight nature of this approach is feasible for low-powered nodes in terms of sensor data acquisition time and power consumption. However, RESTful solutions also require a HTTP client and server embedded in the device, and is also constrained by the size of the XML-based data. Like in the DPWS case, the latter issue has motivated the adoption of EXI-like solutions [17], demanding more processing from involved devices, and requiring the usage of other protocols (such as Wired Application Description Language, WADL[4]) for describing services.

Lastly, integrated frameworks tightening the connection between sensors and IP mechanisms such as mobility, have also surfaced [18] [19]. However, the availability of such features

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[1] DPWS Specification, `http://docs.oasis-open.org/ws-dd/ns/dpws/2009/01`

[2] EXI Specification, `http://www.w3.org/XML/EXI/`

[3] WSDL Specification, `http://www.w3.org/TR/wsdl`

[4] WADL Specification, `http://www.w3.org/Submission/wadl/`

has to be made at a gateway or sink node level (due to the demands they exert for their operation) creating different "islands" of device access frameworks. In addition, many of the solutions require the deployment of different protocols for different mechanisms (i.e., device discovery and information querying), increasing the complexity of not only the supported devices but also of its users.

3. The MINDiT Framework

When addressing an IoT that encompasses entities of very distinct nature, operation requirements have to be considered in diverse scenarios and meet stringent demands. IoT goes beyond interfacing with sensors and actuators, but also includes communication with other kinds of devices as well as interfacing with high-level services. This is where MINDiT aims to contribute: providing a flexible common abstract interface for controlling and accessing the information flow coming from both high-level services, as well as low cost devices.

MINDiT is built exploring MIH concepts defined in the 802.21 standard [2] as its base. Developed to facilitate and optimize handover procedures in different wireless technologies, 802.21 provides an abstraction cross-layer called the Media Independent Handover Function (MIHF). It provides a set of core services (Events, Commands and Information) for media independent control and information obtaining from different access technologies (i.e., Ethernet, WLAN, WiMAX and 3GPP), through a common abstract interface, which can be used locally or remotely via the MIH Protocol. Entities using this interface (dubbed MIH-Users) have their abstract requests turned into technology specific primitives by the MIHF, which maps them to existing Service Access Points (SAPs). MINDiT furthers this principle, not only extending the interfacing with different devices and services in a media independent way (e.g., beyond the wireless handover use case of the standard), but also introducing a series of enhancements to the base standard, enabling it to become a valuable asset in operating IoT scenarios. MINDiT goes beyond the static interfacing nature of 802.21, and provides mechanisms that allow dynamic interface definition and retrieval based on the needs of requesting consumers. MINDiT also introduces MIH Protocol enhancements, allowing our framework to efficiently operate with both demanding high-level services, and low cost devices.

3.1. General Architecture

The objective of MINDiT is to facilitate and generalize access by agents aiming to control or obtain information from services and devices in IoT environments. To allow that, entities containing services or devices available for interfacing are coupled with the MINDiT Media Independent Function (MMIF) as well as a specific SAP. The MMIF provides a set of enhancements over the 802.21 MIHF, but maintaining its behavior as an abstraction and interaction layer, enabling such entities to exchange both L2 and/or L3 enhanced MIH Protocol messages. The SAP provides the necessary definition in MIH format, of the primitives and parameters made available by services and devices. In addition, the MMIF and enhanced MIH Protocol allow MINDiT entities to reuse the service management mechanisms of the 802.21 standard, for entity discovery, registration and event configuration, as defined in [2].

802.21 MIH-Users become MINDiT Media Independent-Users (MMI-Users) which are high-level entities wishing to interface with such devices, according to supported SAPs. Contrary to the base 802.21 framework and the MIHF, MINDiT does not consider that the MMIF comes deployed with a pre-defined set of SAPs. As shown in Fig. 1, MINDiT allows MMI-Users to identify the necessary SAPs for interfacing with discovered devices (Step 1), and request their specification from a SAP repository. This repository is an enhanced version of the Media Independent Information Server (MIIS) (which we call the Information Domain MIIS, or IDMIIS), which can be queried using the MIH Protocol (Step 2). The requested SAP is sent back towards the MMI-User (Step 3), providing it with the information required to assess and create the necessary MIH Protocol commands for interfacing with the respective IoT device (Step 4). In this way, the MMI-User is able to obtain the necessary interfaces for interacting with virtually any kind of device and service, allowing a generic IoT interfacing environment.

To further support this vision, MINDiT provides a set of important evolutions over the base 802.21 mechanisms, comprising the support of dynamic SAPs (other than just specific link access technologies as in 802.21), the definition of a single purpose action primitive to interact with entities based on retrieved SAPs, an enhanced MIIS server allowing for the query of SAPs, and the support of integrated communications using different communication models, including a proxy mechanism.

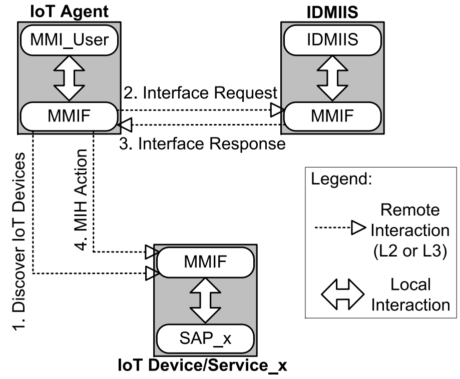

Figure 1: The MINDiT Framework Generic Architecture

3.2. Dynamic Plug-in of Device/Service Interfaces

To support the usage of different SAPs, the MMIF required the enhancement of the MIHF to couple, in a *plug-in* manner, with different SAPs in a dynamic way. We call this new ability ”Dynamic SAPs”, where we decoupled the SAPs from the MMIF, as shown in Fig. 2. Instead of implementing SAPs as a software API towards the link layers using specific driver calls, we cloned the MIH Protocol used in remote communications between peer MMIFs, and reused it in local communications between MMI-Users and the MMIF, as well as between the link layer modules and the MMIF. In this way, developers of different services and devices can create their own SAP, and couple it to the MMIF via usual MIH Protocol definitions.

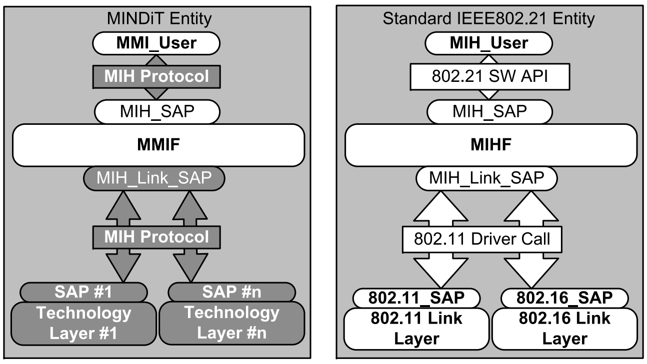

Figure 2: Decoupled SAP architecture for the MINDiT framework

3.3. Interfacing with Devices and Services

Interfacing between MMI-Users and a large number of different devices and services raises the need for an adaptive mechanism allowing access to different primitives from different SAPs, using the same generic MIH protocol. The standard MIH Protocol defines header and payload formats, using Type-Length-Value (TLV) encoding. The payload includes the Source MMIF identifier TLV, the Destination MMIF identifier TLV and MIH service specific TLVs. The header contains, amongst others, a Service identifier (e.g., events, commands or information), an Operation code (e.g., *request*, *response* or *indication*) and an Action identifier (e.g., specific command identifier), which are filled according to the primitives supported by the MIH Protocol. The base 802.21 framework features a fixed set of MIH primitives, used for service management, handover and link control.

However, with MINDiT allowing the flexible coupling of new and different SAPs, a more generic MIH Protocol is required, supporting a different number of primitives from distinct entities. To support this, we defined a new generic *MIH Action* message that, through the inclusion of a SAP Identifier, is able to specify which actions to execute on an entity, as shown in Fig. 3. Each SAP has its own identifier, and each of its supported primitives is accessed by indicating a specific Action identifier.

The Action Value parameter (which specifies how the action should operate) can be simple or complex. For simple situations, such as turning on/off an actuator, the parameter is composed by one single element/datatype, whereas in more complex situations, sequences of parameters can be provided. This generic approach allows MMI-Users to use a common message to operate the different *actions* supported by receiving devices and services. The

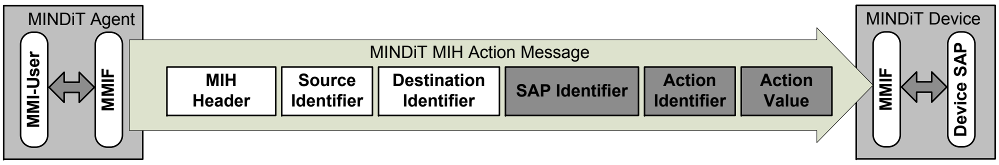

Figure 3: New Generic MIH Action Message

definition of what each action procedure does in each device is provided by its specific SAP, which is obtainable from the IDMIIS, defined next.

3.4. Information Domain MIIS

By retaining the base mechanisms of the original MIH Information Server, the IDMIIS provides a queryable MMI-User that is composed by Information Elements (IEs) organized in containers reflecting a network's topology. IEs provide details about the operator, network and Points of Attachment (PoAs) which can be used for optimizing network selection and network interface pre-configuration. IEs can be represented in either binary form, allowing TLV queries, or using a Resource Description Framework (RDF) that is queryable through the SPARQL Protocol and RDF Query Language (SPARQL). The base MIIS also provides filtering mechanisms, allowing the definition of a maximum query response size and prioritizing some IEs over others.

Our proposed IDMIIS evolves the standard MIIS, fulfilling the added role of SAP repository. The process of obtaining access interfaces towards the different elements present in the network is performed by querying the IDMIIS (as shown in Fig. 1).

3.4.1. Representation of Things - Technology, Phenomena and Primitives

In order to facilitate the definition of SAPs and primitives, we developed a simple tripartite model that defines the relationship between devices, phenomena and primitives. Tags are used as identifiers for combinations of such relationships, aiding in querying and identifying intended behavior. In this way, it becomes possible and simpler to define the *things*, their *actions* and over which *phenomena* they operate (Fig. 4). For example, an agent can query an IDMIIS indicating that it is interested in interacting with *sensors* for obtaining *temperature* (respectively using these names as the tags for identifying the *technology* and the *phenomena*). The IDMIIS would then reply with a list of possible primitives related to temperature sensors, or even provide a whole SAP as response.

We have created our IDMIIS extensions in a way that enables deployers to define the specific mechanism used to implement this model. In our tests (and the mechanisms presented in the next subsections), we used a simple XML schema, but relational databases or more advanced semantic and ontology schemes based on Semantic Markup for Web Services (OWL-

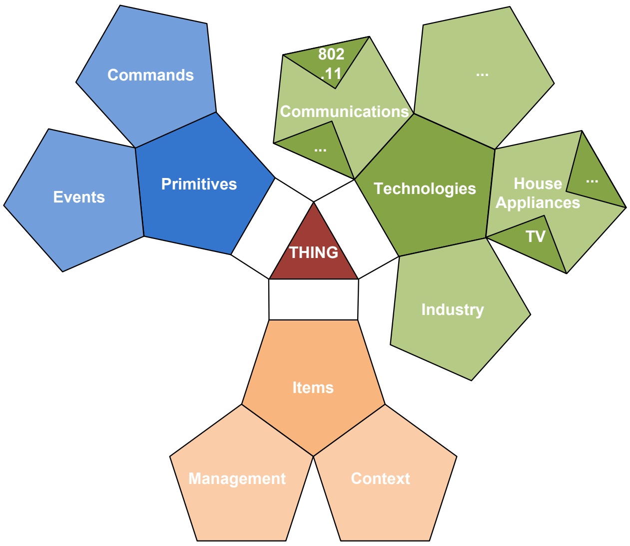

Figure 4: Tri-Partite representation

S[5]) or Web Service Modeling Ontology (WSMO[6]), using descriptions in WSDL and XML, can be devised. The important factor here is to retain the SAP definition according to our extensions defined over the MIH Protocol format.

In this way, MMI-Users can query the interfacing information to interact with different devices and services based on simple behavior representation. Moreover, since this process only involves the interfacing agent at the services invocation and the IDMIIS, no processing or memory restrictions are imposed from the devices represented by the SAPs.

3.4.2. Accessing Interfaces

The process of linking the semantic and syntactic description for interfacing with an entity is typically called *grounding*. Fig. 5 illustrates the full MINDiT grounding procedure, showing the involved entities and exchanged messages, composed by three phases. In phase 1, a MultiMedia Agent (MMAgent) acting as a MMI-User, after discovering a MINDiT-enabled device, queries a IDMIIS for obtaining the necessary interfacing information. In phase 2, the IDMIIS replies with the necessary interfacing information. Lastly, in phase 3, the MMAgent builds a action command based on the interfacing information received from the IDMIIS, allowing it to interact with the device. For simplicity, the figure only shows part of the messages payload.

During the query phase, through a *MIH Get Information request* message, the querying MMI-User provides tags and attributes in the form of a list, as shown in phase 1 of Fig. 5. Each tag can be accompanied by various attributes that facilitate the identification of the

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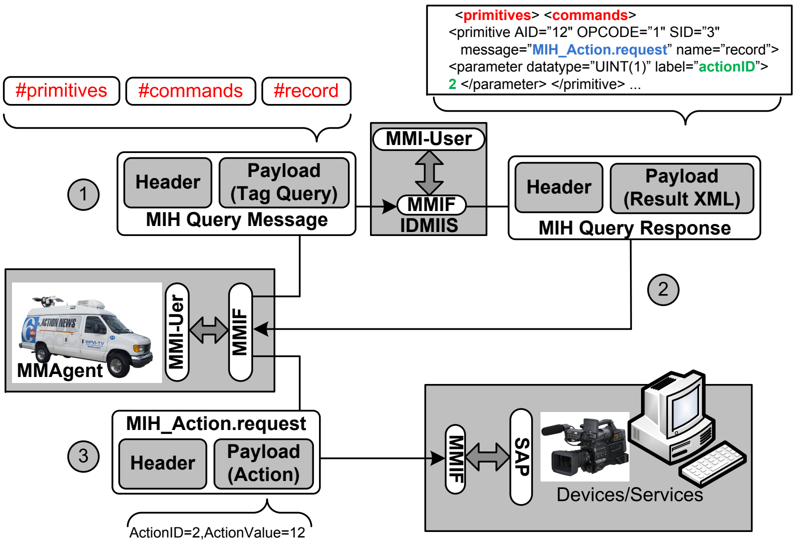
[5] OWL-S Specification, `http://www.w3.org/Submission/OWL-S/`

[6] Web Service Modeling Ontology, `http://www.wsmo.org/`



```
<primitives> <commands>
<primitive AID=”12" OPCODE=”1" SID=”3"
  message=”MIH_Action.request” name=”record”>
<parameter datatype=”UINT(1)” label=”actionID”>
2 </parameter> </primitive> ...
```

Figure 5: Grounding procedure for obtaining a SAP using a IDMIIS

intended interface. When the IDMIIS receives a query in this format, it transforms this list into an XML Path Language (XPATH[7]), and applies it to the main XML Database, retrieving and sending the result, as shown in phase 2 of Fig. 5.

When the requesting agent entity receives the query results obtained from the IDMIIS, the first step is to retrieve the data regarding intended primitives from the XML (e.g., the OPCODE, SID, and AID values) to construct the MIH Header of the MIH Action message (as shown part 3 of Fig. 5). All entities of the resulting XML can provide tags that may be used as guidelines for the grounding or to simply provide extra information on the parameter.

3.4.3. Querying Support Mechanisms

As implied before, our framework also extends the filtering mechanism supporting queries, allowing the requesters to send queries with different degrees of detail. It enables querying agents to execute phased queries, using the information obtained from responses to refine sequential queries, with the aim of better pinpointing the intended interfacing primitives. Considering the example depicted in Fig. 5, instead of asking directly for elements present in the network that comply with the three tags at once, we could divide the query into three separated messages. In this case, first the MMA would search for all available primitives and, depending on the ones discovered from the corresponding response, it could create another query message to retrieve all available commands for a specific technology. Again, through the received results, it could create one last query specifying the required SAP.

An often overlooked procedure is how interfaces are added to servers providing them. The IDMIIS is able to have definitions of new SAPs pushed into its information structure, using

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[7] XML Path Language Specification, `http://http://www.w3.org/TR/xpath/`

a modified *MIH Push Information request* message. In its original 802.21 form, this message is only available for the operator to push network information towards a user terminal. We have enhanced it to allow service providers, manufacturers and other parties, to push SAPs into the IDMIIS.

3.5. Dissemination Models

In 802.21, MIH Protocol messages are exchanged between peer MIHF, enabling a MIH-User in one entity to interface with the SAP existing at another. However, low cost devices might have hardware limitations, and might not be able to include a full MIHF and/or SAP module in their stack.

By decoupling the SAPs from the MMIF (as identified in section 3.2), MINDiT explores the exchange of remote information between these two modules, allowing the deployment of Gateway nodes which contain a MMIF, and interface remotely with devices which are only capable of incorporating a simple SAP. Through the realization of discovery and registration procedures, the Gateway node can discover SAP-enabled devices, and act as a serving MMIF on their behalf and simplifying their design.

Considering even more stringent device deployments (e.g., devices with closed APIs, or legacy devices), MINDiT is able to employ a SAP module in the Gateway node, enabling it to translate the MIH Protocol into whatever API or protocol necessary to interface with the target device. In this way, the MINDiT framework is able to encompass different scenarios, according to the capacities of the involved devices and services. [20] provides details on the deployment of such dissemination models.

3.6. Proxied Actions

IoT environments provide different connectivity deployments and opportunities for the devices and agents operating therein. It is possible that some types of devices are connected to a specific infrastructure, while others are made available in ad-hoc manner. Considering these matters, we extended our dissemination models to provide the means for MINDiT to support proxying. Our design allows MMI-Users to send commands to third-party entities (after gaining knowledge of them through the proxy entity), using the proxy node as an intermediary. For this procedure we introduce a Proxied Destination Identifier header, which allows the receiver of the message to forward it towards other entity, and then retrieve its response back to the original source (exemplified in Fig. 6).

The proxying mechanism design presented here focuses on the connectivity provisioning mechanism (in deployments of this framework, security and authentication considerations are important). For simpler deployments, the execution of the proxying mechanism can be dependent of configuration parameters of the MMIF and Proxy MMI-User: MMIFs can be configured to support access from all proxy requests, or ignore them. Also, the execution of

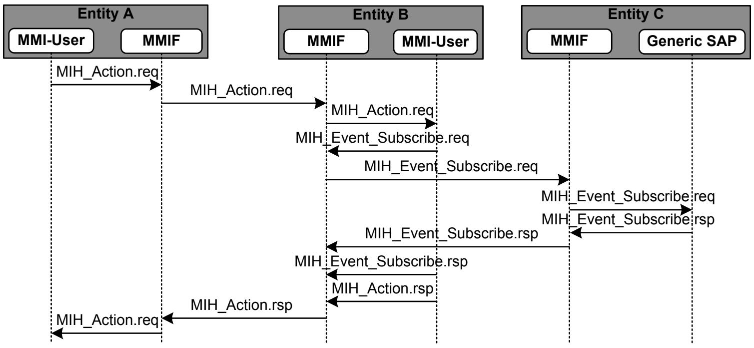

Figure 6: Sequence Diagram of Action Message for Proxy

MIH Protocol procedures can be integrated and occur only after specific link access technology security and authentication procedures (e.g., 802.1X) have been executed. The 802.21 standard itself does not provide any considerations regarding secured and authenticated interactions between peer MIHFs (such efforts are currently being pursued in a new amendment, 802.21b). Although we do not address the deployment of such procedures for our framework in this paper, we argue that its flexible design is able to encompass the definition of secure and authenticated communications at the MMIF level, incorporating them into discovery and capability exchange procedures.

4. Comparison with Other Frameworks

The deployment of solutions providing access to different kinds of devices and services in IoT environments have almost naturally resulted in SOA-based architectures using Web Services for the realization of necessary procedures. In this section, we highlight the features provided by MINDiT, identifying them as the evolutions made over base 802.21 mechanisms for the enablement of such functions, and compare them with traditional Web Services based technologies.

4.1. Functional Comparison

Table 1 presents a functional comparison on the features provided by the base 802.21, our MINDiT framework and generic Web Services based frameworks.

Related with feature (1), MINDiT facilitates information inter-exchange by generalizing it into events, commands and information elements. It inherits the base structure from 802.21, but enhances it with the ability to go beyond handover-related operations, and a static set of SAPs. Our extensions on 802.21 bring it closer to the interface dissemination mechanisms such as WSDL in web services-based deployments. It actually goes one step further by providing a common protocol for both accessing the interfaces and using them, unlike web services which can require different protocols and XML structures, potentially hindering deployment.

Num.	Feature Description	IEEE802.21	MINDiT	Web Services
1	Defines a uniform description for information dissemination as well as entity interfacing	−	++	+
2	Provides the means for discovering, determining capabilities and registering at other framework-enabled entities	+	+	+
3	Allows the subscription of events, directly at the services and devices providing them, allowing threshold and period for event reporting	+	++	++
4	Remote interaction is able to be sent either via L2 or L3 protocols	++	++	−
5	Provides abstracted services to higher layers, interfacing them with both other higher-layer services (e.g., context and content servers) as well as lower layer technologies (e.g., sensors and actuators)	−	++	+
6	Different dissemination models	−	+	++
7	Integrates proxying mechanisms to extend access to other framework-enabled entities beyond the discovery range	−	++	+
8	Provides a uniform protocol, able to be used for both service management/control, as well as operating entities according to the obtained interfaces	−	++	+
9	Flexible enough to support different interface definition schemes	−	++	++
10	Supports Energy-Efficient operation	+	++	−

Table 1: Functional comparison between base IEEE802.21, MINDiT and Web Services based frameworks ("plus" is better)

About (2), MINDiT reutilizes L2 and L3 discovery mechanisms from 802.21, providing for capability interexchange using the same protocol. Web-service based frameworks supports discovery using specific protocols (such as the Universal Description Discovery and Integration (UDDI[8]), thus requiring the additional support of yet another protocol by the framework.

Feature (3) is also supported by all three frameworks, with MINDiT enhancing the 802.21 event service beyond-handover features. This allows it to have an uniform way of reaching for events in IoT devices and services, as well as defining thresholds and period for event reporting. Web Services handle this information inter-exchange in a P2P fashion: each device (or other services) needs to implement the means for its integration with the event registration and dissemination mechanism of the framework, whereas MINDiT is able to use the same event service over all SAPs.

Feature (4) refers to the transport capabilities for remote interaction. The MIH Protocol used in MINDiT can be transported over different L2 (e.g.,Data and Management frames) and L3 (e.g., UDP, TCP and others) transport mechanisms. By supporting L2, MINDiT is able to reach non-IP devices, whereas Web Services provide application level protocols only.

(5) highlights a major feature, where the base 802.21 abstractions are extended in MINDiT to access not only different link layers, but also different high-level services. This is in fact an evolution over the web services approach as well, since their realization requires device support of application protocols and mechanisms required by web services (which can hinder deployment in low cost devices).

Feature (6) highlights the enhancements done over 802.21 by MINDiT allowing not only

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[8] UDDI Specification, `http://www.uddi.org/pubs/uddi_v3.htm`

the interaction between peer-MMIF entities, but between entities acting as gateways for low-powered devices. Web Services do not impose any dissemination model.

In (7) MMI-Users in MINDiT can obtain the interfaces and operate other services or devices through entities working as proxies, unlike 802.21 and Web Services architectures. The last ones, however, can achieve this behavior by introducing special mechanisms in combination with HTTP proxies. However, there are no specific definitions of proxy mechanisms at web service level, that enable reaching the procedures of third-party nodes.

(8) highlights the extension of the MIH Protocol to support IoT interaction, in an uniform way: the MIH Protocol in MINDiT is an adaptative mechanism, working as a transport mechanism between the framework-enabled entities, allowing their management and operation. Web Service frameworks can use different SOAP-based protocols, but these produce varied flavors for interacting with entities (e.g., the XML structure of the different protocols involved).

In terms of supporting the grounding for the interfaces of different entities, feature (9) shows that although MINDiT has been tested with a simple XML definition of a tag-based tri-partite definition of technologies, phenomena and devices existing in a IoT, more refined methods can also be employed (e.g., OWL, relational databases). This represents an important evolution made over 802.21 for the support of IoT scenarios. This feature is also a core concept of web-based solutions.

Lastly, (10) concerns with operating in environments where low-power consumption is important. In multi-interface battery-powered devices, both 802.21 and our framework allows obtaining information about different technologies, without having to power up the respective interface, by querying the MIIS. MINDiT also supports optimized energy-aware L2 transport. Web Services based frameworks do not possess any intrinsic support for this, thus being less energy-efficient than MINDiT.

4.2. Impact on Device Procedures Comparison

To further analyze the effectiveness of the generic interfacing capabilities provided by the MINDiT framework, we developed a comprehensive study focusing on the signaling size impact on a sensor device, against a set of Web Services based frameworks: DPWS, REST and DPWS featuring EXI encoded messages. A simple testbed was assembled, featuring a Sun SPOT[9] mote connected via USB to a Linux Laptop, acting as Gateway. Sun SPOT devices contain a JAVA programmable embedded microprocessor and have simple networking capabilities using 802.15.4, with limited processing capabilities (512KB SRAM, 4MB Flash and a 400MHz ARM 926ej-S processor). It contains various kinds of sensors, providing information on luminance, accelerometer and temperature. We simulated a scenario where the Sun SPOT mote randomly accesses one of the sensors, encapsulates that information according to the

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[9] Sun SPOT World, Oracle Labs, `http://http://www.sunspotworld.com/`

format of the underlying framework, and sends it over the wireless interface with different event number generation rates. For each framework, we implemented the necessary event messaging format directly in the sensor, according to that framework specification. In the case of MINDiT, this evaluation was done using a prototype implementation built over ODTONE[10] [21], an open-source IEEE 802.21 implementation. For all frameworks, we analyzed in the sensor the amount of time for sending the messages, the battery consumption and memory usage. As a guideline, we also compare these values when sending this information using raw sensor data, to verify the impact caused by the Java Event Device Drivers in operating the devices. Each execution set of multiple events was run 100 times, a trade-off between execution time and confidence intervals. Tab. 2 presents the size of the messages used by each framework. Take into consideration that string-based frameworks vary the message size depending on the the value being measured (i.e., more bytes allocated for extra characters).

Framework	Message Size (bytes)	Total Allocated Memory (Kbytes)
Sun SPOT Raw	3	206.013
MINDiT	60	213
DPWS	551-553	209
DPWS w/ EXI	377	226
REST	219-221	214

Table 2: Message Size and Memory Utilization per Framework

4.2.1. Average Time for Sensor Event Dissemination

These results account for the average wireless utilization time taken by the sensor to send an event message through its wireless interface. As shown in part a) of Fig. 7, results are impacted by the different framework message sizes, when the event generation rate is increased. The most impacted framework was DPWS with an average time of 576ms, followed by DPWS using EXI (431ms), REST (292ms), MINDiT (105ms) and raw (98ms) (in this order and for the case of 10 events being sent). Compared to the other frameworks, MINDiT has a very low wireless utilization time to send the same event. In average for the different rates of event generation, MINDiT requires less 83% wireless utilization time than DPWS, as well as 77% and 66% for DPWS using EXI and REST. In fact, it only requires a marginal increase of 6.6% more time than the raw SUN SPOT information to be sent.

Due to its relatively small message size requirement, MINDiT is able to send its events and free its wireless resources faster. This not only allows for the next message to be sent sooner, but also requires the wireless interface to be active for a lower amount of time, saving energy.

Tab. 2 also presents the impact that the different signaling formats place over the Sun

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[10] ODTONE - Open Dot Twenty ONE, `http://atnog.av.it.pt/odtone`

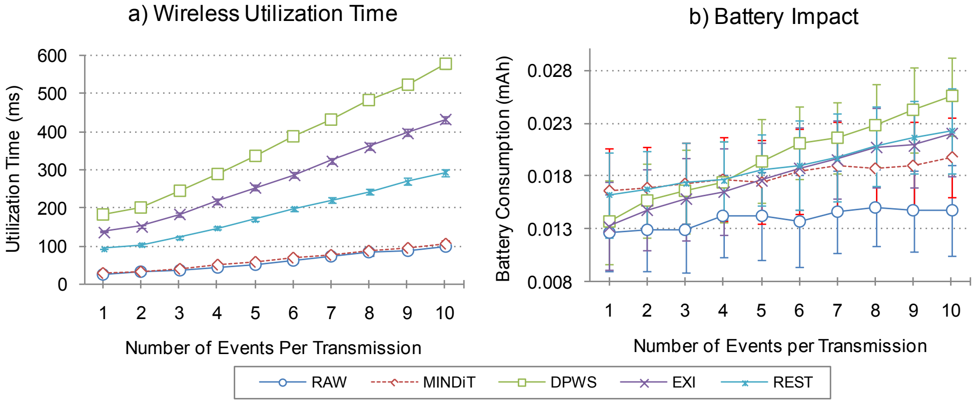

Figure 7: Average Wireless Interface Utilization Time and Battery Consumption

SPOT motes. The amount of allocated memory was measured in the device after each message transmission. It was verified that the message generated rate did not impact the results. Values include the Sun SPOT SQUAWK Java Virtual Machine footprint. These show that the most memory-demanding signaling scheme is DPWS with EXI, which requires more 10.2% allocated memory and 15.5% freed memory, when compared to Sun SPOT raw. This is followed by MINDiT (3.4% and 5.7%), REST (4% and 6.3%) and DPWS (2% and 3%), in this order respectively. In this way, MINDiT is able to reduce its signaling size, making its memory utilization on-par with other XML-used SOA approaches, while requiring less memory resources than binary-format SOA mechanisms.

4.2.2. Battery Consumption

Regarding battery consumption, results show very small variations considering the battery total capacity of 720mAh. Focusing on the consumption differences between frameworks, as can be seen in part b) of Fig. 7 (confidence intervals varied between 0.003 and 0.004 mAh and were removed from the figure to improve readability), greater event generation rates show an increase in battery consumption for all frameworks. The SUN SPOT raw provides the lowest consumption of all and, with a low variation of 0.002 mAh between its maximum and minimum consumption values, and provides an indication bound for the different rates. It is interesting to notice that up to 5 events generated, the different formats are able to exercise a similar or lower battery consumption, when compared to MINDiT (in average, DPWS, DPWS with EXI and REST consume less 7.5%, 11.7% and 0.9% respectively, between 1 and 4 events sent). Past this point, DPWS consumption reaches to 0.026 mAh, in the case of 10 events generated, (more 22.5% and 42.1% consumption than MINDiT and raw, respectively), whereas MINDiT becomes the least consuming of the four frameworks with 0.019 mAh (more 25.4% than raw). Thus, for greater event rates, the lower message size from MINDiT not only allows for a lower wireless utilization time, but lower battery usage as well.

5. Scenario Test Case

This section presents a deployment scenario for MINDiT, considering a multimedia musical concert for the grand opening of a major shopping mall. The location has the latest technology in ambient intelligence and assisted living, integrating sensors (e.g., light, temperature), actuators (e.g., mechanical window shades), devices (e.g., surveillance cameras) and services (e.g., shop advertising), all interconnected by our connectivity framework. The mall owners have decided to cover the concert by their own news report team, allowing them access to all the devices and services of that area. The crew has got a camera, but also have a MultiMedia Agent (MMA) able to connect to our framework, for controlling the video production with the aim of generating a high-quality news coverage of the event.

5.1. Phase 1 - Discovery

In the first part of Fig. 8, the MMA accesses MINDiT to discover and dynamically learn how to use the devices and services in its surrounding, finding input for the news cover. The unit is deployed in the concert hall and the discovery mechanisms of our framework alert it to the existence of several smartphones from the mall personnel (coupled with multimedia abilities), as well as the cameras from closed-circuit television (CCTV). The MMA is programmed to discover the capabilities of the devices by broadcasting a *MIH Capabilities Discover request* message, to which entities within range respond providing their capabilities.

5.2. Phase 2 - Grounding

After learning the capabilities, the MMA obtains the necessary SAPs to interface with the cameras of the smartphones and the CCTV, with the objective of activating them and obtaining different perspectives and video-effects for covering the concert. As shown in the second part of Fig. 8, this is achieved via a query to the IDMIIS, providing tags existing in the MMA routines, related to *VideoCamera* (e.g., the technology), *Picture* (e.g., the phenomena) and *Record* (e.g., the primitive), included in a *MIH Get Information request* message. Upon receiving this, the IDMIIS is able to process the received query message (as defined in 3.4.3) identify the proper interfacing SAP, providing it to the MMA in a query response.

5.3. Phase 3 - Smartphone and CCTV Interface Access and Usage

With the received SAP, the MMA agent is able to create the necessary *MIH Action request* primitive to interface with the CCTV, and request it to start recording and send the feed back to the MMA agent, as shown in Fig. 9.

5.4. Phase 4 - Proxy Device Discovery

While experimenting with the video feed, the news crew verifies that the lighting multimedia system used for special effects during the concert is very dynamic, and can potentially hinder the quality of the video shooting. Since the CCTV cameras are spread in different

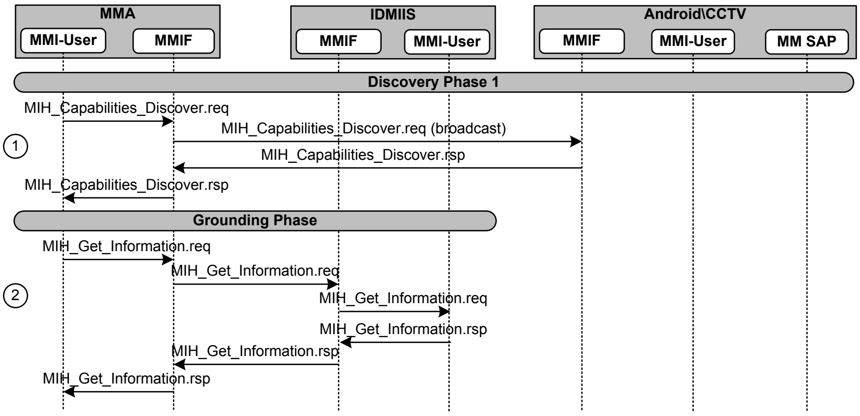

Figure 8: Discovery and Grounding Phases (Phase 1 and 2)

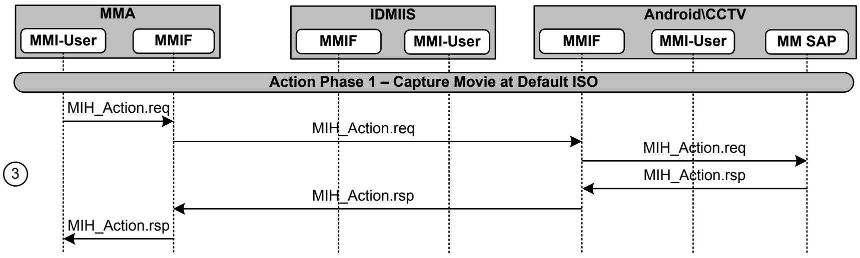

Figure 9: Action for Capturing Movie at Default Quality (Phase 3)

spots of the concert hall, the lighting parameters can be different for the distinct devices. The MMA determined, in the discovery phase, that certain smartphones also possessed a proxy-dedicated MMI-User. With this, the MMA agent is able to interface with services and devices beyond its connectivity range, and instructs the proxy to do a device discover in their surroundings, learning that some of the smartphones are within range of the shopping complex luminance sensors. To achieve this, the MMA sends a *MIH Action request* message to issue a proxy broadcasted *MIH Capability Discover request* to have the smartphones execute a discovery in their surrounding, as shown in Fig. 10. The respective response provides the MMA with a list of found devices with the ability to be controlled as luminance sensors.

5.5. Phase 5 - Proxy Sensor Event Subscription

By using the smartphones as a proxy, the MMA uses the generic MIH protocol service management primitives to subscribe to luminance events on the detected sensors, as shown in the first part of Fig. 11. There, a *MIH Event Subscribe request* message allows for the definition of a threshold, indicating the luminance value that is configured in the Sensor SAP for triggering the event. In this way, our framework is able to optimize network usage, by allowing the event information to be sent at a specific time, instead of periodically or requiring a constant query/response approach.

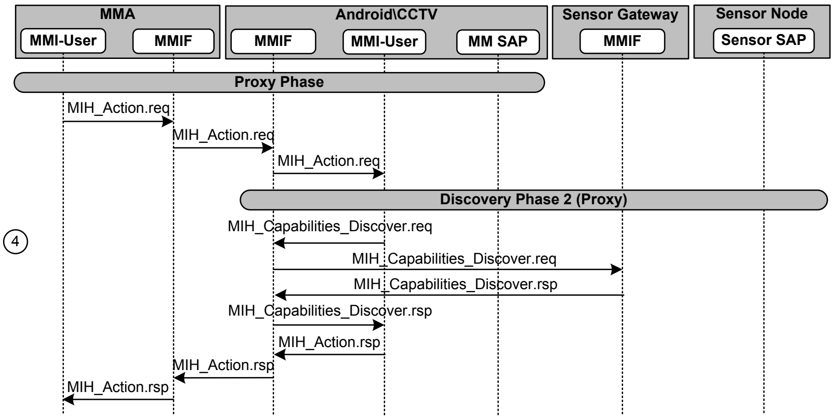

Figure 10: Proxy Discovery (Phase 4)

5.6. Phase 6 - Proxy Sensor Event Triggering and Dissemination

When the sensors obtain a luminance value that crosses the pre-defined threshold, an MIH event is sent towards the smartphones. The event is then proxied towards the MMA, as seen in the second part of Fig. 11.

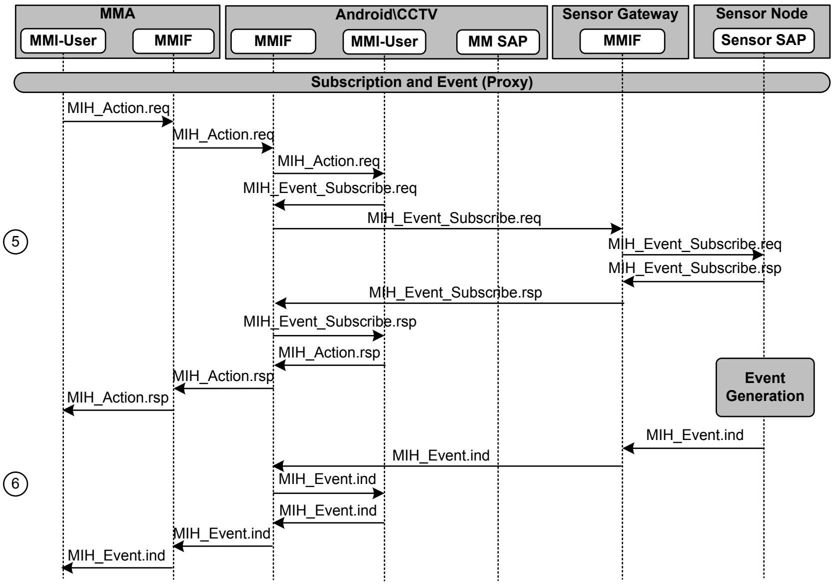

Figure 11: Proxy Subscription and Event (Phases 5 and 6)

5.7. Phase 7 - Optimal Multimedia Configuration using Sensor Information

Using the event information related to the luminance perceived by the sensors, the MMA is able to instruct the camera recording configuration to dynamically adjust video parameters (e.g., type of environmental lighting, ISO, etc.), and optimize the recorded video quality. For this purpose a new *MIH Action request* message is sent towards the CCTV cameras (as shown in Fig. 12) with new video recording parameters.

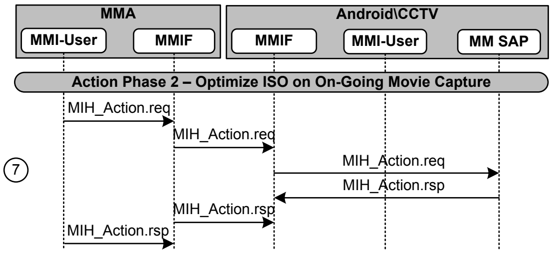

Figure 12: Proxy Action Optimizing Movie Capture (Phase 7)

6. MINDiT Framework Results

This section evaluates the performance of our framework when subjected to the operations defined in the scenario presented in section 5. Even though MINDiT supports multiple scenarios, we present the footprint placed by our approach in this example, focusing on its flexibility aspects by deploying its mechanisms in different kinds of devices. As such, we measure time duration and size of the signaling, considering the different phases on the scenario, and their impact in the complete scenario. We further explore the scalability of our framework, by evaluating its behavior and signaling impact in the different devices, when subjected to different message generation rates.

6.1. Testbed Implementation

Beyond the implementation of the MIH extensions defined in section 3 and compared in section 4.2, we have also implemented different MMI-Users and SAPs to operate with different devices, as well as a IDMIIS to provide SAP querying.

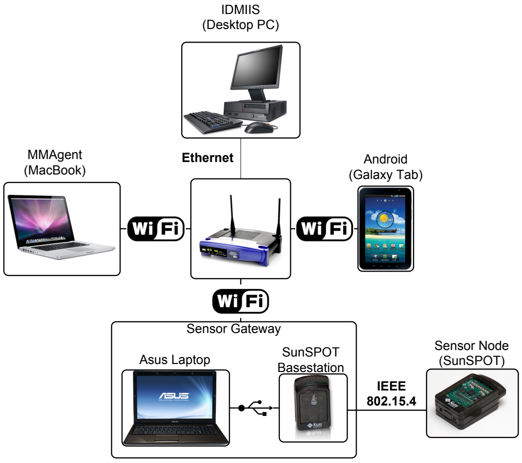

Figure 13: Testbed deployment

Fig. 13 shows our scenario testbed composed by two laptops connected via a Wi-Fi infrastructure to a Linksys WRT54G wireless router, and a desktop PC connected via Ethernet.

All entities are coupled with our MMIF, except the wireless router which only provides connectivity between the nodes. The first wireless laptop is a Apple Macbook (2.4GHz CPU and 2GB RAM) coupled with a MMI-User acting as a MMA. The desktop PC connected via Ethernet (Pentium 4 3.2GHz CPU and 1GB RAM) is coupled with a MMI-User acting as a IDMIIS. A Samsung Galaxy Tab (1GHz ARM Cortex A8 CPU, 512MB RAM, 2.2 Android Froyo firmware, 2.6.32.9 kernel version) coupled with a Proxy MMI-User and a Multimedia SAP allows media independent access to its video camera controls. This device fulfills the role performed by the smartphones identified in the scenario. Finally, our second laptop connected to the Wi-Fi infrastructure (T5450 Intel Centrino Duo CPU and 2GB RAM) is coupled with an USB Sun SPOT Basestation, connected to a Sun SPOT sensor via IEEE802.15.4. All the MINDiT entities defined in this testbed operate under the signaling defined in section 5. To simplify the scenario deployment, the Android device doubles as the proxying entity as well as the CCTV, due to its camera and processing capabilities.

6.2. Signaling Footprint

For each scenario phase, we measured the time taken by the internal procedures of each entity involved in the information exchange. In Tab. 3, we present these local results per entity, as well as the total amount taken by the local and remote procedures. We also present the total time taken by the procedures of each entity for the duration of the phases, and the whole scenario, as well as total local and remote times. Results presented reflect average values taken from executing the scenario ten times, presenting confidence intervals calculated at 95%.

Phase	Entity				Total Local	Remote	Total Time
	MMA	IDMIIS	Android	Sensors			
1	29.4±3.26	0.0±0.0	21.5±4.53	0.0±0.0	50.9±5.95	145.2±37.97	196.1±40.24
2	4.1±0.35	17.73±2.88	0.0±0.0	0.0±0.0	21.9±3.10	3.3±0.51	25.20±3.19
3	61.5±16.46	0.0±0.0	2411.7±118.75	0.0±0.0	2473.2±120.75	147.1±91.1	2620.3±118.94
4	3.0±0.29	0.0±0.0	21.8±8.15	2.50±0.33	27.3±8.25	26.20±10.6	53.5±8.79
5	3.0±0.41	0.0±0.0	25.0±6.98	283.7±10.41	311.7±11.95	286.8±58.86	598.50±62.81
6	1.1±0.20	0.0±0.0	49.4±3.33	263.0±57.75	2313.5±116.43	139.7±57.86	2453.2±121.72
7	61.5±16.46	0.0±0.0	2411.7±118.75	0.0±0.0	2473.2±120.75	147.1±91.1	2620.3±118.94
Total	163.6	17.73	4941.1	549.2	5671.63	2894.8	8567.1

Table 3: Scenario Delay in milliseconds with totals calculated using the average values

We can verify that the total amount of time taken by phases 4 to 7 is twice as much that from phases 1 to 3, composing almost two thirds of the total scenario duration of 8.5 seconds (in average). Further analysis also reveals that, in average, each phase sees 66.2% of its duration dedicated for local processing, with the remaining time for remote message sending over the air (the smallest and largest values are respectively 26% for phase 1, and 94% for phases 3 and 7). Three main points have to be considered: i) phases 3 and 7 involve accessing the video camera functionalities of the Android device, ii) phases 4 to 7 contain proxy behavior whose communications have to pass through the proxy entity, (whereas phases 1 to 3 are done in an end-to-end manner) and iii) interfacing with the Sun SPOT sensors is done over 802.15.4 which are operations that take a considerable amount of time.

In fact, when analyzing the impact in time duration per entity, the Android device is the most solicited entity, being involved in 58% of the duration of all the phases in the scenario, when considering local processing times (85.6% of its time in phases from 1 to 3, which are end-to-end). This is quite a large amount of time when compared with the local processing in other entities (e.g., 2% for the MMA, 0.2% for the IDMIIS and 6.4% for the sensors in total scenario duration). We investigated further the amount of time involving the Android device, and discovered that the main impact factor was the activation of the video procedures (e.g., these interactions take about 92% of the time duration of phases 3 and 7). We did separate experimenting with the primitives available by the Android Software Development Kit on the Samsung Galaxy Tab, and, from the local processing values obtained by that device in phases 3 and 7 (which took over 2 seconds), around 95% of the time was dedicated to Android-specific processes involved in activating and starting the recording in the video camera of the device. As such, in those phases, the time taken for actual MIH processing was around 131ms, and 147.1ms for remote message sending and receiving.

We have also analyzed another source of delay in the scenario, which was the time taken to produce the event sent by the sensors, with the luminance information. In fact, the local procedures belonging to phase 6 took around 94% of the total phase duration. Due to erratic values being obtained by the luminance sensors, we analyzed the internal hardware procedures provided by the sensor available on the Sun SPOT board and verified that accessing the sensor values took (in average) 39ms. However, in order to allow an accurate value to be sent to the MMA, the pre-defined threshold configured at the sensor SAP required an assessment of the average luminance value of the past two seconds. When this average value crossed the defined threshold, the event would be triggered and sent. This was, however, a design decision implemented to deal with the specificities of the values produced by the Sun SPOT sensors and is independent of our framework. In fact, MINDiT is flexible enough to allow such case-by-case implementations to be included in the SAP, to better integrate with the diversity of devices and technologies, allowing for different results if other kind of sensors were used.

Considering the impact produced by remote MIH message signaling, phase 5 takes the longest time. This is due to the fact that it consists of a proxy command being sent by the MMA, proxied by the Android device and acted upon the sensors, which send a response indicating the command execution result all the back to the origin (also, through proxying). This means that, in total, six remote message exchanges were executed (including the 802.15.4 path between the Sun SPOT basestation and sensors), for a total of 286.6ms.

An important factor to note is that the SAP querying (e.g., Phase 2) requirements in terms of time are quite low (around 4.1ms for the MMA and 17.73ms for the IDMIIS, for a total time of 25.20ms). This highlights the feasibility of MINDiT to adopt more powerful (and of course more demanding) methods and mechanisms for the definition and querying of device and services interfacing, as pointed out in section 3.4.

6.3. Data Footprint

According to the results presented in Table 3, the largest verified performance impact was the local processing of device-specific controlling aspects (e.g., camera activation in the Android Tab and erratic sensor values). Remote signaling times have been minimal, despite the different wireless and wired technologies involved. Considering this, we analyzed the amount of signaling information exchanged by each node and in each phase, presenting the results in Table 4.

Phase	Entity				Total
	MMA	IDMIIS	Android	Sensors	
1	72	0	37	0	109
2	347	80	0	0	427
3	70	0	34	0	104
4	49	0	93	37	179
5	70	0	80	46	196
6	51	0	51	0	102
7	70	0	34	0	104
Total	729	80	329	83	1221

Table 4: Amount of information remotely received in bytes during the scenario

The total amount of information received over the air using the MIH protocol in this scenario was 1221 bytes, considering only MIH Protocol sizes. The entity most involved in this message exchange was the MMA, which was responsible for 60% of the information received. Of that information, 67% was related to phases from 1 to 3. In fact, phase 2 was the most data consuming procedure, involving 347 bytes from the MMA and 80 bytes from the IDMIIS, highlighting the importance of the query for obtaining the SAP.

In contrast, the sensor device was the second least entity involved in the message signaling exchange (6.8% against 6.6% of the IDMIIS). This emphasizes the feasibility and flexibility of MINDiT in interfacing in different ways with low cost devices. In this particular case, the usage of MIH mechanisms allowed the definition of a threshold value to trigger the sending of an event with luminance information towards the MMA, only when such threshold value was crossed.

The second most involved entity in the signaling exchange was the Android device, participating in 27% of the overall remote information. Of these, 78% belonged to the set of phases from 4 to 7, indicating that this message amount is due to the proxy mechanism. But even so, the Android device was only involved in sending 258 bytes of information in that group of phases, which is a small value for a device with its capabilities.

Not considering the query phase with the IDMIIS, the average amount of information exchanged per phase is 132 bytes. This is more predominant in the set of phases from 4 to 7, due to the proxy behavior between the MMA and the sensors, using the Android as a proxy.

6.4. Performance Evaluation

We submitted the different nodes involved in the previous scenario to a command message being generated at different rates. The objective is to analyze the framework impact over the different kinds of nodes, in increasingly stringent conditions. For these tests, the MMA transmits 100 *MIH Action request* messages towards the sensor node, which sends a respective *response* message (both using the Android as proxy).

6.4.1. Average time per packet

Fig. 14 presents the average packet reception rate of the packets received by the nodes. Results highlight that both the *request* (Fig. 14-a) and the *response* (Fig. 14-b) reception rate are slightly affected by the different message intervals. Part a) of the figure distinguishes the performance of the WLAN network involving the MMA, the Android and the GW (39.13 ms in average), and the 802.15.4 network (679.12 ms in average). This clearly identifies the sensor communication as the most limiting factor in terms of message reception rate. This is further emphasized by part b) of the figure, where the delay caused by the sensor reception rate of the *request* message, is propagated all the way back towards the MMA for the reception of the *response* message (average reception rates of 672.02 ms for the gateway, 684.36 ms for the Android and 701.70 ms for the MMA).

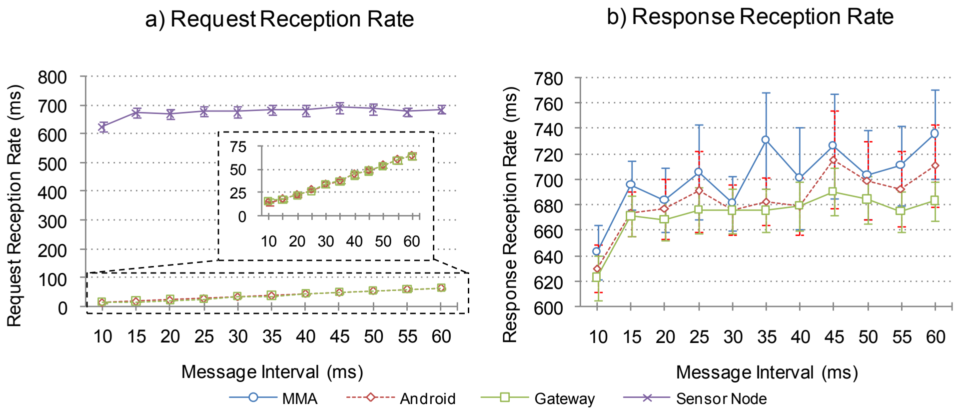

Figure 14: Average Packet Reception Rate

6.4.2. Incomplete Transactions

We measured the percentage of incomplete transactions (due to packet loss), in terms of unsuccessful exchanges of *request* and *response* messages between each pair of nodes involved. Fig. 15 shows that incomplete transactions are only verified between two entities that share the WLAN medium: the MMA and the Android. We can see that the values start high (46% for the MMA and 24.3% for the Android) for low message intervals. These decrease considerably for larger message intervals, stabilizing at 25 ms interval time (11.75% for the MMA and 4.16% for the Android). It is interesting to note that there are no incomplete transactions with the sensor node or the gateway. With some of the messages between the MMA and the Android being lost, the rate at which they arrive to the gateway decreases. Considering the slow sensor network response verified in section 6.4.1, the rate at which the *response* messages reach the gateway is even lower. This means that there are not only fewer messages on the way back, but they are also slower. We performed evaluations on the scenario regarding the amount of lost packets on the return path, confirming that these never raised above 4 packets per test.

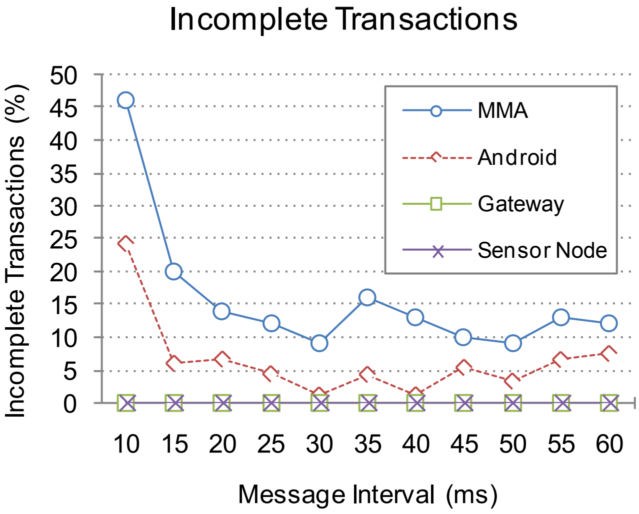

Figure 15: Percentage of Incomplete Transactions

6.4.3. Amount of Packets Exchanged

Fig. 16 shows the direct consequence of the incomplete transactions affecting this metric: with fewer requests reaching the gateway, fewer responses also are returned. This provides an approximate difference of 86 bytes between the amount of data received by the MMA/Android and the gateway/Sensor pairs. Like in the previous case, it is noticeable that the values start to stabilize past the 25 ms message rate. Results also indicate that, with shorter message intervals, the amount of packet loss reduces the amount of data received by the MMA, which can impact its utilization of the devices interfaced.

6.5. Handling Incomplete Transactions

Motivated by the number of incomplete transmissions, we devised a simple reliability mechanism similar to the one defined by 802.21: when the *response* fails to be received by the source of the original *request* message within a timer-defined window, the later is re-sent.

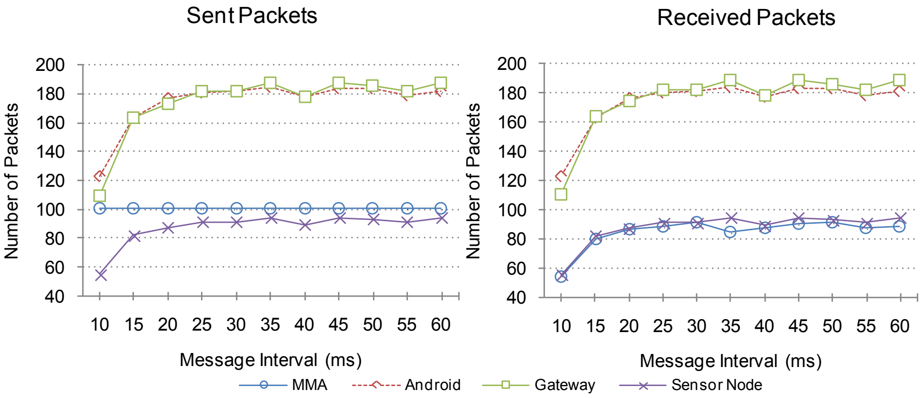

Figure 16: Amount of Sent and Received Packets

For simplicity, we evaluated this mechanism only at the MMA, which is the original sender of the command. Fig. 17 shows the total number of necessary retransmissions for obtaining 100 successful transactions, as well as the number of received, sent and lost messages. Results show that all metrics gradually decrease their value as the timer duration increases, stabilizing at 800 ms. Past this timer configuration, the number of retransmissions drops to nearly zero, which also reduces the other metrics.

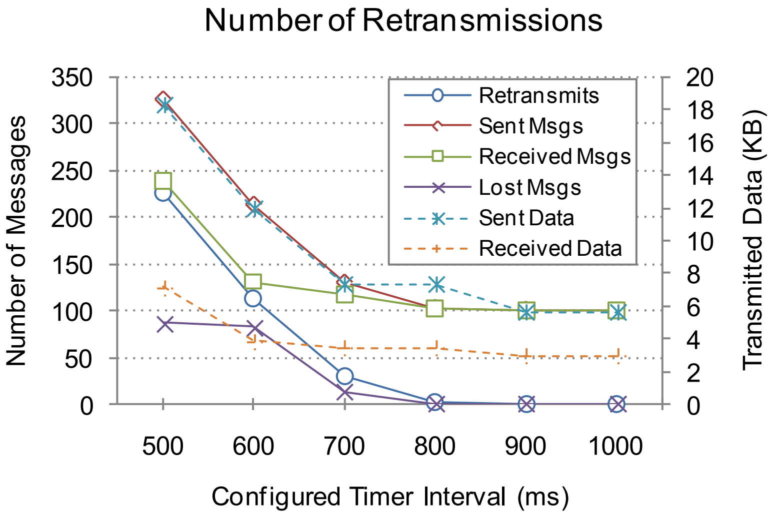

Figure 17: Number of Retransmissions

Fig. 18 follows the trend of the previous metric, indicating that the average time for receiving a *response* with reliability active stabilizes at a 800 ms configured timer. Moreover, these last two metrics indicate that retransmission timers below that value tend not only to generate more transmissions but also larger average time. Timer configuration is thus an important factor to be considered in these heterogeneous environments: its incorrect configuration can lead to over-zealous side-effects, where a small timer can trigger a *request* re-send while the *response* is still in transit, originating superfluous retransmissions and overhead.

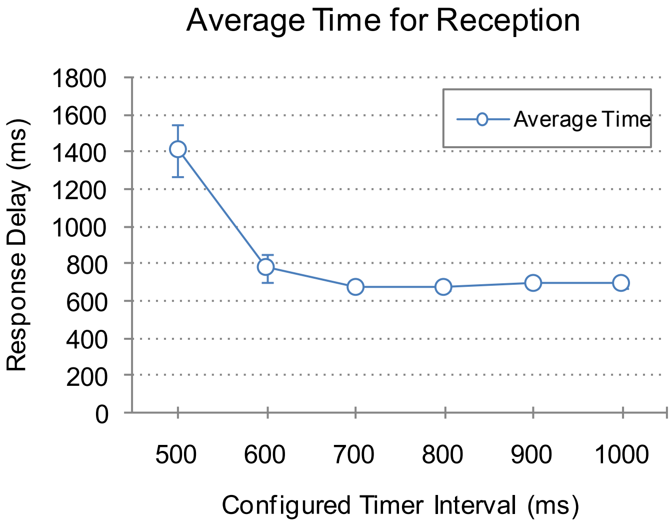

Figure 18: Average Time for Successful Response

7. Conclusions

In this paper, we presented MINDiT a novel framework whose features enable the operation of IoT scenarios for ubiquitous smart environments.

Our framework relies on a set of profound evolutions from the standardized IEEE 802.21 MIH (Media Independent Handovers) framework and its services, expanding them for the facilitation and optimization of media independent access to IoT devices and services.

We proposed the concept of Dynamic Service Access Points (SAPs) that allow the definition of interfaces towards different devices and services using a unique communication procedure, based on an unified and enhanced MIH Protocol from the IEEE 802.21 standard. We have defined an Information Domain Media Independent Information Service (IDMIIS) server, with the ability to store SAPs from different devices and services, allowing for the integration of different query mechanisms for accessing interfaces (ranging from simple XML query procedures to powerful high-level semantics and ontologies). To allow its deployment in a broad set of cases (ranging from interfacing with sophisticated services residing in powerful mainframes using optical wired connections, to low cost devices using simple wireless networking stacks) we have defined a proxy mechanism aiming to increase the interfacing opportunities with different kinds of devices and services.

To validate the benefits of our proposal, we implemented a prototype based on an existing open-source IEEE 802.21 implementation (ODTONE). The message signaling mechanisms from MINDiT were compared to other SOA-based frameworks using Web Services (also implemented), showing that its lower message size required less resources utilization. To illustrate its flexibility, MINDiT was also deployed in a multimedia-enabled smart environment scenario featuring agents, mobile terminals in wireless environments and sensor technologies. The footprint imposed by our mechanisms was evaluated in terms of interfacing procedures, and information exchange requirements. Furthermore, to analyze the scalability, we studied the framework response when subjected to different rates of signaling generated.

Results demonstrated that our framework does support a broad range of features while requiring a significant low amount of information. This has the benefit of facilitating and optimizing its deployment in scenarios featuring low cost devices with stringent requirements (both in terms of processing power as well as wireless networking capabilities), which are currently increasing in availability (e.g., sensors in mobile phones and smart environments), without hindering flexible interactions with high-level services (e.g., through L3 transport protocols and broad support of information definition).

Acknowledgements

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Paper I

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A Named Data Networking Flexible Framework for Management Communications

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Abstract

The ongoing changes in the way we use the Internet are motivating the definition of new information-distributing designs for an interworking layer. Recently, information-centric networking (ICN) concepts have defined mechanisms focusing on what information to get rather than where it is located. However, the still unfledged architectures instantiating such concepts have disregarded vital operations, such as management aspects aiming to optimize content retrieval by the User Equipment (UE). In this paper, a flexible management framework is proposed, which enhances existing Named Data Networking (NDN) architectures in allowing both the network and the UE to employ management mechanisms over the NDN fabric. We illustrate our management framework with an implementation over an open-source NDN software, considering the specific case study of interface management. We quantitatively access the performance gains achieved through the usage of this framework in such scenarios, when compared to un-managed NDN mechanisms.

1. Introduction

In recent years, rapid developments in how we access an ever-increasing amount of new online content have changed current communication patterns. Traditional communication between a pair of networked machines has evolved into a scenario where new services generate unprecedented amounts of content (e.g., video traffic and cloud access), and at the same time allow multi-link mobile devices to access that information via different connectivity opportunities. The existing host-centric architecture has been patched to encompass content-oriented mechanisms such as Content Delivery Networks (CDN), peer-to-peer overlays and HTTP proxies, deployed over the existing infrastructure. Supporting these enhancements to access content, network operators employ a series of management procedures governing a complex heterogeneous environment, through the cumulative usage of mechanisms such as Quality of Service (QoS), network policies, load balancing, failback actions, over-the- air updates, amongst others. However, the sheer amount of content being accessed has highlighted functional limitations in terms of flexibility, performance and cost, motivating the development of more adequate network paradigms for an Internet of the Future.

The focus on content distribution has led to the concept of Information-Centric Networking (ICN) allowing content to be addressed by name and not by location or end-point addresses. This principle has motivated different approaches, such as Data-Oriented Network Architecture (DONA) [1], Publish/Subscribe Internet Routing Paradigm (PSIRP) [2], Network of Information (NetInf) [3] and Named Data Networking (NDN) [4]. A survey on ICN approaches can be found in [5].

These proposals leverage the evolution required by todays Internet to support this content-centric vision, focusing on aspects such as hierarchical content naming, information-centric communication and content-based security, which are core features of NDN [4]. However, there has been very little consideration on management aspects for ICN architectures, which are fundamental for supporting network operations, such as, e.g., those aiming to increase user experience when accessing content with different requirements. We argue that the provision of intrinsic management functionalities is important for the successful future deployment of ICNs, incrementing existing and new Future Internet scenarios, with support for QoS, network policies management, amongst other operations.

In this paper, we focus on the NDN architecture to discuss management enhancements potentially addressable as well by other ICN architectures. To achieve that, we define an integrated and flexible framework that:

1. Considers a generic approach allowing management procedures to collect input or triggers from various sources, and use that information to optimize network operations. These aim to assist or control network attachment procedures of terminals, towards network resource optimization and user experience satisfaction;
2. Defines interfacing points with the NDN fabric while proposing improved mechanisms allowing the integration of management procedures.

The remainder of this document is organized as follows. Section 2 introduces the base mechanisms of NDN and provides insight into current evolution. Section 3 presents our NDN flexible management framework, followed by Section 4 where we focus on a specific use case (i.e. management of the terminal's connection point for content retrieval) and we evaluate the performance that can be achieved with our framework, in this specific use case, from an experimental perspective. Lastly, Section 6 presents conclusions and future work.

2. Background and Related Work

2.1. NDN Basic Operation

NDN relies on two packet types defined in [4]: Interest and Data. Interests are used by a consumer to ask for content. They contain a Content Name based on a hierarchical structure: its components are separated by /, (similar to a URL, such as `/domain/content/Videos/videoA.mpg/version/segment`), with the prefix providing global and organizational routing information, and a suffix showing versioning and segmentation details. When an Interest packet reaches any node with data matching the Content Name, it consumes the Interest and responds with a matching Data packet, carrying back the content.

When an NDN-node receives an Interest packet, a set of functional structures is consulted: the Content Store (CS), the Pending Interest Table (PIT) and the Forwarding Information Base (FIB).

The CS is checked to see if the requested data is already available. If the name requested no entry there, the PIT is checked. This structure keeps track of Interests forwarded to content sources that were not yet consumed. If an Interest has no match in either the CS or PIT, a new PIT entry is created and the packet is forwarded towards one or more interfaces that might lead to the respective content sources. For this, the FIB associates Content Name prefixes towards potential holders of the content, with some routing protocol defining the forwarding state in the FIB, (e.g., routes to applications or physical interfaces), or through a registration in a local NDN store.

An interesting detail from [4] and [6], is the ability for FIB entries to address multiple interfaces[1]. Each NDN-node contains a Strategy Layer that can use several options to forward an Interest packet. The forwarding strategy can vary from sending an Interest sequentially on each face until a Data is received, to more elaborated designs that evaluate which interfaces provide better performance in retrieving specific content. A specific mechanism for best face determination is described in [4], where the Strategy Layer runs experiments in which an Interest is sent (e.g., every second or when a packet is lost) through all available faces, towards a given prefix. If a face provides lower end- to-end delay than the previous best face, it becomes the new one until the next test. Hereinafter, we refer to this process as probing. Another possibility suggested in [4] and [6], is to define a program within each FIB entry that defines forwarding choices and behaviour. This program could be configured with a set of instructions, such as sendToAll and sendToBest, determining the forwarding of Interests under a predefined and static strategy. However, this behaviour is not thoroughly explored in [4] and [6], which provides a default strategy of sending Interests to all broadcast capable faces and, if no answer is received, all other faces are tried out in sequence.

2.1.1. NDN Evolution

There have been several proposals enhancing the base architecture of NDN not only to better tackle the problems it proposes to address, but also to improve its behaviour when handling current or future traffic patterns.

The work in [7] evaluates the performance of NDN when mapped to a Voice over IP (VoIP) application, transporting SIP and RTP data in a real-time conversation.

Extensions supporting NDN-node mobility, without having to undergo a full Interest re-

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[1] In fact, under NDN, the term *interface* is replaced by face (which we will use from now on) because packets are not only forwarded over hardware interfaces but also directly between application processes.

routing toward the content source, have been proposed [8]. This work considers a proxy acting as an anchor point for Interest and Data packets. When nodes connect to an NDN-domain, they associate with that proxy (using it to reach content on their behalf) and when they move, they report movement changes to it, updating the Data packets being forwarded to the new location. However, this update does not provide any preferences, policies or any other information which could be used for assisting and managing this mobility procedure, thus allowing only un-optimized handovers.

The authors of [9] analyse how Interest route selection is affected by policies, exploring content name granularity. However, it focuses on the economic incentives for routing only, not considering aspects such as different content requirements, content/application-driven policies or dynamic route selection based on different interface technologies.

2.1.2. Management Requirements in NDN

A thorough analysis of deployment motivations for NDN as a future internetworking architecture is presented in [10], highlighting the need for network- grade solutions, such as manageability aspects that allow the network to control the content reception by the user (i.e., optimal link selection, Quality of Service, policing, etc.). In fact, considering the outline of the NDN project [6], management procedures are only considered for Storage and Usable Trust. These, along with the previously mentioned Strategy Layer, do not consider network input or intervention in their management processes. As such, they are limited to operation based on static rules, or relying on information collected locally by the node. Its management, as it is, is completely local. As a result, there is no coordinated effort between NDN-nodes and the network as a whole, with which to provision or optimize not only NDN operating aspects, but also the performance of Data packet reception in terms of policies. The usage of policies, analogous to the IP world, allows the network to control and suggest to NDN-nodes the most preferable access network, by providing discovery information (e.g., which WLAN networks are available within a 3G cell) or by indicating a set of rules considering preferred access points at different times of the day, or routing traffic flows depending on the content[2].

3. The NDN Flexible Management Framework

3.1. General Architecture

This section describes the management framework proposed in this paper for NDN. We argue that the interaction between information existing in the network and information within the point-of-view of the terminal could be used to impact NDN operations, optimizing both network procedures and user experience. This framework was designed as a comprehensive

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[2] The example policy characteristics highlighted here are based on the Discovery and Inter-Routing policies as defined by the 3GPP in the 3GPP TS 24.312 technical specification (Release 10).

and flexible solution, capable of supporting the functionalities that may be required by different management procedures in a future content-oriented network, such as QoS provision and face management.

Figure 1 shows a general overview of the different functional entities comprising our framework. It considers the deployment of a Manager Entity (ME) in the network, able to interact with a set of Management Agents (MA) located in different devices, such as network and user equipment. For simplicity, in the remaining of this paper we focus on MAs deployed in User Equipment (UE). As a result of the interaction between MEs and MAs, the network and any UE can exchange information to appropriately coordinate procedures, taking advantage of the different information available in the network and locally at the UE. By deploying the different management entities as application processes, the framework can be easily decoupled from the underlying network architecture, enabling easy interoperation with any Information-Centric network approach.

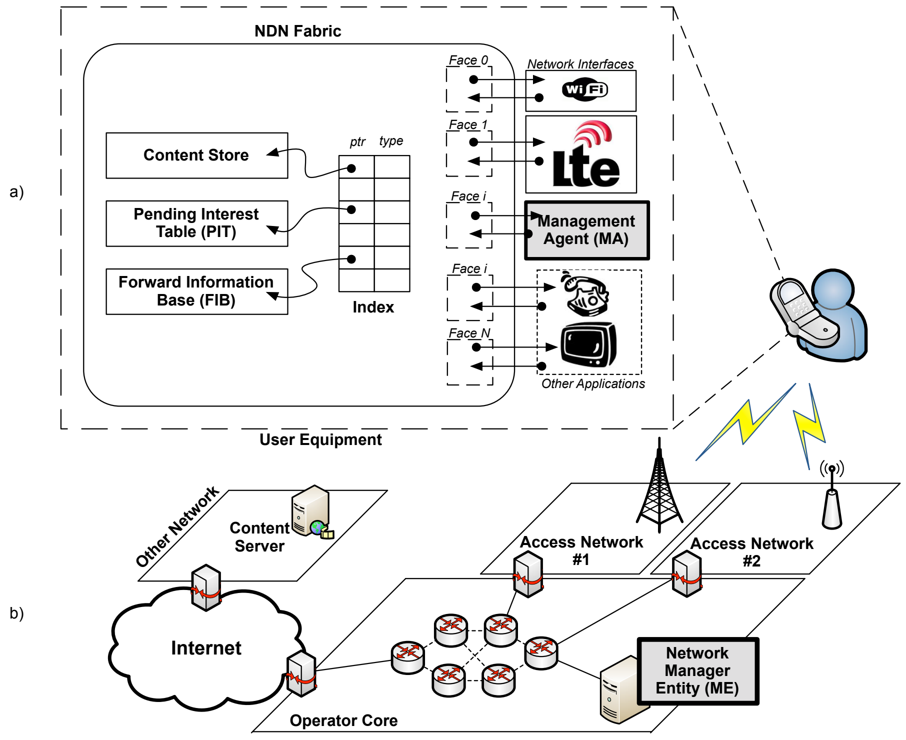

Figure 1: The NDN Flexible Management Framework: a) Manager Agent interfacing with the NDN fabric; b) Deployment of the management framework in an operator network featuring a Manager Entity

Considering this traditional network management approach, the challenge is centred on how the MA and ME entities interface with the NDN fabric. Figure 1a presents the core components of the NDN architecture at the UE, also coupling an MA. This functional entity can be deployed as a single application process that interfaces with internal NDN structures, such as the PIT and the FIB. Thus, the MA is able to access and update these structures as a result of any management procedures. The UE can run end-user applications, such as web browsing, telephony or Internet TV, which are able to exchange Interest and Data packets. Our framework also regards management (e.g., event generation and sending/receiving commands to optimize a NDN-related process) as content exchanged through Interest and Data packets. MAs residing inside NDN- enabled UEs behave as producers and consumers of content related to management operations, and any management information provided by the ME is viewed as an NDN name (e.g., under the name prefix /domain/management/ME/). Moreover, the MA can also interface with local applications to obtain information about the content to be retrieved. This provides relevant information that may be used to guide the decisions of the management processes. As an example, a local application can provide the MA with information about QoS requirements for a specific video content. This information can be provided to the ME, which can coordinate an appropriate resource delivery in the network. Finally, the MA is capable of interfacing with the lower layers of the UE, obtaining link information that can also be relevant to the management procedures (e.g., identifying available wireless access networks in the vicinity of the UE).

Shown in Figure 1b, the ME is a functional entity located in the operator network that interacts with MAs to handle management procedures. The ME is triggered by different mechanisms, existing elsewhere in the network, to report information that can be relevant to aid management. The ME processes this information, which can then be used to coordinate any necessary management operations. For example, the ME can be notified when the traffic load of a given access network exceeds predefined thresholds. Information about traffic load can then be used by the ME to coordinate an appropriate selection of faces in the UE for content retrieval. This logical entity can be implemented in a single centralized network node, or distributed over nodes residing in different parts of the network, for the sake of scalability and redundancy. The flexibility of the proposed NDN management mechanism can be reutilized in different ways to support distributed coordination, allowing the exchange of state amongst different MEs belonging to different domains, or by using other distributed network mechanisms to act as triggers for NDN management operations. Such interfacing can go beyond triggering and can take many forms (e.g., SNMP), but is out of scope of this paper.

The flexibility of this model allows its application to a wide range of management scenarios. As an example, in QoS provisioning, the MA could be used to dynamically provide user and application requirements to the ME in the network. This information can be used to initiate the necessary admission control and resource reservation procedures in the network, using NDN interfaces located in the required entities. On the other hand, in the case of face management, a change in access network traffic conditions can trigger a management procedure in the ME. Here, the ME can provide new traffic policies to the MA of the UE, describing other usable access networks. As a result, internal NDN structures such as the FIB can be updated at the UE to enforce network management decisions. All management traffic will look like regular NDN traffic to the NDN-nodes, identified by specific names.

3.2. Support Procedures

The framework presented in Section 3.1 requires the exchange of management data between the MA and an ME. This exchange must fulfil the following properties:

- **Security.** MA and ME must be able to authenticate and determine the trust that can be established on management data. Also, a UE can use a broadcast interface towards a Point of Attachment (PoA), and it is necessary to protect the confidentiality, integrity and authenticity of the content exchanged, as it may contain sensible information that must not be vulnerable to unauthorized eavesdropping, modification or creation.
- **Asynchronous exchange.** Other than just pulling content via an Interest/Data packet exchange, both the MA and the ME must be able to push unsolicited management content to one another.
- **Reliability** (optional). NDN transport can operate on top of unreliable data delivery services. Nevertheless, in some use cases, content exchanges between the MA and the ME must proceed reliably (e.g., to send the ME a set of QoS requirements that should be satisfied to retrieve a specific video content).

3.2.1. Bootstrapping for Reliable and Secure Management Content Exchange

Inspired by the procedures used to setup a secure Voice-over-NDN conversation [7], we have defined a bootstrapping procedure between the MA and the ME, illustrated in Figure 2.

The first step involves the MA discovering an appropriate ME, by broadcasting an Interest with the name `/domain/management/mgmt-case/ME` to its local network. The name component `mgmt-case` refers to the management capacities that the MA requires from the ME (e.g. an ME to handle QoS provisioning can be discovered by issuing an Interest to `/domain/management/qos/ME`). As a result, the UE obtains a short hand identifier for the ME (i.e. the `ME-publisher-id`) and a key locator, which indicates the name that can be used to retrieve the public key of the ME. Assuming that the public key of the ME is authorized by another key trusted by the MA, (e.g. a public key corresponding to `/domain`), the MA can identify the ME as an acceptable signer for management data. The MA selects an encryption algorithm, out of those indicated by the ME in the Data packet, and generates a session key, `Ks`. Then, it registers its desire to serve Interests matching a given NDN name (e.g. `/domain/management/mgmt-case/MA-publisher-id`), where `MA-publisher-id` is a global and unique identifier for the MA, such as the cryptographic digest of its public

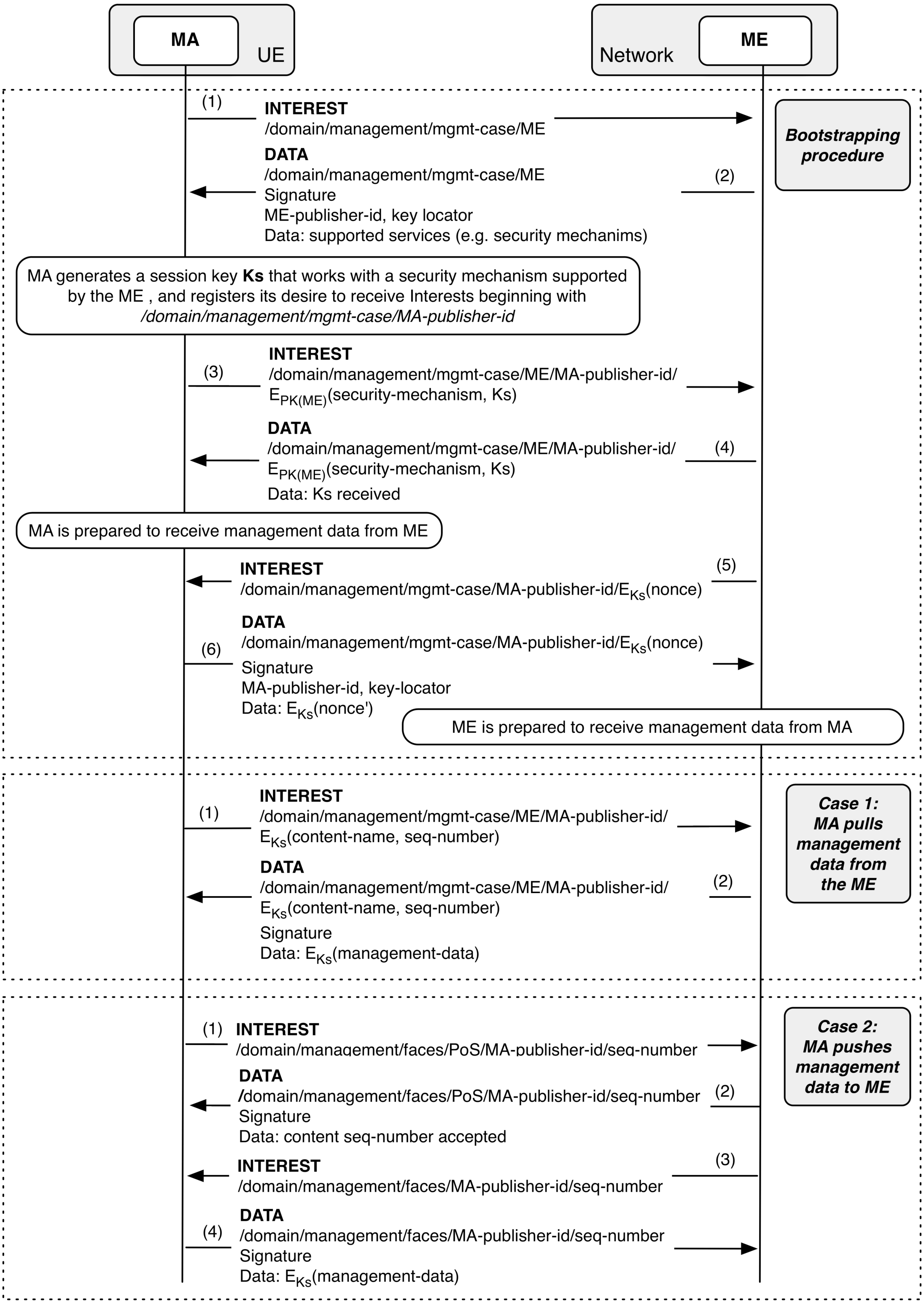

Figure 2: Bootstrapping and management data exchange

key). Finally, the MA sends a new Interest to retrieve management Data from the ME that includes, as NDN name components, the shorthand identifier of the MA (`MA-publisher-id`) and some additional information encrypted with the public key of the ME, such as the encryption algorithm (security-mechanism) and `Ks` chosen to guarantee confidentially of the content exchanged between the MA and the ME. Note that different security infrastructures could be used in this approach, suitably adapted. With this, the MA is prepared to securely receive content from the ME.

Nevertheless, before the ME starts exchanging management content with the MA, it generates a challenge (i.e. a nonce) and expresses the Interest in obtaining the response to this challenge from the MA. The MA responds to the Interest with a Data packet containing the answer to the challenge. Consequently, the ME can retrieve the public key of the MA and identify it as an acceptable signer for management content. In addition, the ME verifies the signature of the Data packet and checks the validity of the answer to the challenge. Therefore, this exchange allows the ME to verify that the encryption algorithm and the session key are valid for the MA. At this point, the ME is prepared to receive management data from the MA.

Once these initialization procedures conclude, MA and ME can exchange information to coordinate the execution of any management activities.

3.2.2. Asynchronous Exchange of Management Data

After bootstrapping, the framework allows the MA to securely pull management content from the ME and vice versa. Case 1 in Figure 2 shows the scenario where the MA retrieves a specific management information item content-name from the ME (the procedure of having the ME pulling content from the MA would proceed in a similar way).

In addition, pushing unsolicited content (e.g., commands to nodes, or informational events to the network) between the MA and the ME is also supported. As suggested in [6], we support pushing content between applications by implementing a double Interest/Data exchange. Case 2 of Figure 2 shows the necessary procedures allowing the MA at the UE to push management data towards the ME. The procedure to push content from the ME to the MA follows a similar approach.

This procedure starts with the MA sending an Interest to the ME soliciting it to receive management content with a local sequence number. Sequencing is necessary to enable the recovery of new content instead of cached content. If the ME is interested in retrieving content from the MA, it answers back with a Data packet, indicating its willingness to accept management content. Then, the ME sends an Interest to retrieve the management data with the sequence number given by the MA. The MA responds with a Data packet containing the information it wanted to push to the ME. The information contained in the Data packet is encrypted with the session key established during bootstrapping.

Finally, if reliability is desired, MAs and MEs must retransmit Interest packets not satisfied in a reasonable period of time (either to pull or push management content). This mechanism is suggested in [4] and [6], and improves the reliability of the asynchronous data exchange.

4. Evaluation

In this section we evaluate the feasibility of our framework, addressing the particular use case of face management (i.e., configuring and selecting an appropriate face to retrieve a given content). In this context, we argue that our approach can provide a better-performing alternative to the mechanisms presented in [4] and [6], such as probing at the NDN strategy layer.

To evaluate the benefits of our framework in this use case, we considered the simple validation scenario depicted in Figure 3. The main objective is to show that an ME residing in the network, with the ability to know the topology and the network conditions surrounding PoAs or a UE[3], is able to assist the latter in network discovery and selection procedures, according to the operator policies. This would enable the network operator to perform a global and more appropriate management of the available access resources, achieving an adequate distribution of the load among different access networks, which is globally beneficial for the users, while incurring a negligible overhead.

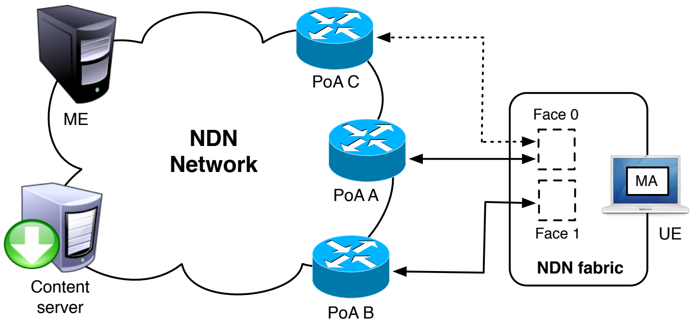

Figure 3: Validation scenario

The figure features a UE with two network interfaces, providing it with physical connectivity to PoA_A and PoA_B respectively. Additionally, PoA_C is available to the UE at its current location from one of its network interfaces, but is not initially attached to it. The scenario includes a Content Server that receives Interests matching a given prefix requested by the UE. An ME is also deployed, allowing the network to assist the UE in face management procedures. The different entities are interconnected by means of an NDN network. Under this validation scenario, we can vary the traffic load at the different PoAs and evaluate the

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[3] For example, schemes using IEEE 802.21 provide a Media Independent Information Server indicating the topology for a network, and allow the usage of events indicating changes in wireless link conditions.

feasibility of our framework, and the performance that can be achieved compared to probing mechanisms locally executed by the UE strategy layer.

The test-bed was deployed in different virtual machines connected to the same virtual network. We introduced bandwidth constraints, by limiting the capacity of every link to the UE to 1 Mbps (bidirectional) using the tc (Traffic Control) tool. The test-bed uses the CCNx software[4] and our framework software. Three Java applications were implemented, using the CCNx Java API: an NDN UE (featuring an MA), a Content Server and an ME.

The NDN UE generates periodic Interests matching a given prefix and computes the RTT of each Interest/Data exchange. This application can be launched in a basic NDN mode or in a framework-managed mode. The NDN Content Server receives Interests from the UE and replies back with random content. The basic NDN mode represents an extension of the procedure defined in [4], where the UE occasionally sends a regular Interest through all the available faces associated with a prefix and measures the RTT for each Interest/Data exchange. The face that obtains the lowest value of RTT becomes the current face and is used for subsequent Interests associated with the prefix, until the next probing takes place or an Interest times out. In addition, our implementation supports sending multiple Interests through each face in order to compute the best Interface for Data retrieval. In the framework-managed mode, the MA changes the UEs current face when it receives management information from the ME reporting a better face for content retrieval, or an alternative PoA that could be used to improve the performance. The mechanism is independent of the format of the management information, depending solely on the MA and ME implementation, and how they interface with the UE access interfaces and network information, respectively. For testing purposes, we assume that the ME has an up-to-date access control indication of the UE location, its supported access interfaces and current network conditions on the PoAs at its vicinity.

Each experiment comprises a 160 seconds time interval, divided in four periods of 40 seconds. We vary the background traffic traversing each PoA in each period, according to the configuration presented in Table 1. Background traffic is generated using iperf[5] according to a Poisson distribution. The average rate for low, medium and high traffic loads was calculated to obtain significant differences in the RTTs measured at NDN UE, taking into account the Poisson distribution of the background traffic and the capacity of the links connecting to the UE.

Three different trials were defined to compare the performance that can be achieved governing face selection by means of probing mechanisms and our management framework: (1) basic NDN with 1 probe per face, (2) basic NDN with 5 probes per face, and (3) NDN under a framework-managed mode. In trials (1) and (2) the probing period was set to be one every 200 packets, as suggested in [4].

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[4] `http://www.ccnx.org/`

[5] `http://iperf.sourceforge.net`

Period	Load in the Point of Access		
	PoA_A	PoA_B	PoA_C
First (1-40)	Low	Low	Low
Second (41-80)	Low	Medium	Low
Third (81-120)	Medium	Low	Low
Fourth (121-160)	High	Medium	Low

Table 1: Load of the PoAs for the different time periods of the tests

4.1. Results Discussion

Figure 4a shows the results for the UE running in basic NDN mode and sending a single probe Interest per available face. It shows the instantaneous RTT obtained for each Interest sent from the UE, the average RTT computed from the instantaneous values in the last 5 seconds and the current face used by the UE to send Interests. As can be observed, under similar traffic load conditions (e.g. time period 0-40 seconds), probing with a single Interest per face may lead to the selection of any of the available faces, (as any PoA can provide a better RTT in an isolated probe), which may imply instability due to oscillations in the face selection. On the other hand, even under different average traffic conditions the decision is subject to error, (e.g., choosing a PoA with medium or high load), as can be observed from the wrong face selections made during the experiment (e.g. choosing face 0 in periods 80-120 and 120-160 seconds). Increasing the number of Interests used in a single probing process may improve the performance, but with the cost of increasing the overhead and thus decreasing efficiency. To illustrate this, we executed a set of experiments increasing the number of Interests per probing process to 5. Due to space constraints, instead of including new figures related with probing, we just present a brief summary of all the experimental results that we obtained under this specific test-bed in Table 2.

	Basic NDN with 1 probe per face	**Basic NDN with 5 probes per face**	**Framework-managed NDN**
Average RTT (ms)	86.6140	84.685	78.9840
CI (ms)	(84.6350, 88. 5930)	(83.8573, 85.5127)	(78.5232, 79.4448)
Overhead (%)	1.2908	5.7677	0.1121
Losses (%)	1.8102	1.5478	0.3728
Handovers/s	0.0594	0.06	0.0125

Table 2: Summary of experimental results.

Figure 4b shows the results for face management using our framework. As can be observed, face selection remains stable in the UE until performance significantly decreases at the beginning of the period 80-120 seconds. This is a consequence of the increment in the traffic load traversing PoA_A (face 0). When this happens, the ME sends an informational message to the UEs MA, which starts retrieving Data from PoA_B (face 1). In the period

120-160 seconds, traffic load traversing this PoA increases to medium. In this case, the ME can instruct the MA to detach the UEs face 0 from PoA_A and to attach to PoA_C, (otherwise invisible to the UE), improving performance.

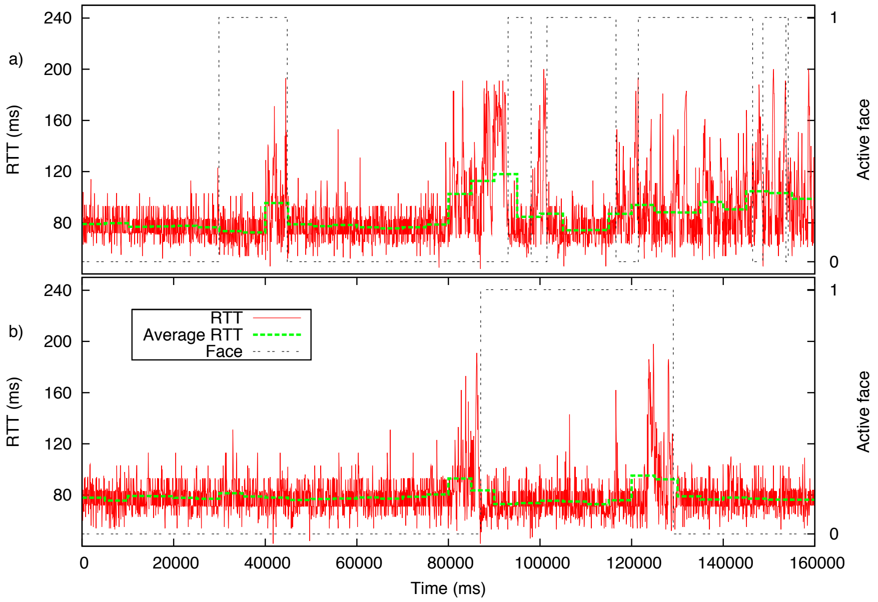

Figure 4: Results of the evaluation: a) RTT in basic NDN with probing, 1 probe per face; b) RTT in NDN under a framework-managed mode

As shown, the face management service implemented using our proposed framework improves the performance when compared to probing, also achieving a reduced overhead. This is due to a more stable face selection, assisted by operator policies, not subject to transitory variations of traffic load traversing the PoAs, and to the fact that the UE can take advantage of information provided by the network about new candidate PoAs for attachment. As a particular example of this, by using a new PoA in the interval 120-160 seconds, which is available in the vicinity of the UE, the management framework can achieve a reduction of 14.78% in the average RTT with respect to basic NDN with 1 probe per face. In addition, with the management framework, face oscillations are avoided.

Unlike probing, our framework does not require all interfaces to be always active. As shown in Figure 4b, since only face 0 is used for data retrieval in the time interval 0-80 seconds, face 1 could be deactivated and re-activated when strictly necessary, (i.e. after 80 seconds), when performance achieved through face 0 significantly decreases. Activating and deactivating network interfaces can be especially useful for resource saving (e.g. battery-operated handheld devices). Note that this cannot be done with probing, where all the faces must be active to decide which one is the best for content retrieval. Furthermore, the ME can decide which of the UEs attached to a saturated PoA should be moved to a different PoA, in order to improve the network usage.

5. Conclusion

In this paper, we presented a flexible and comprehensive management framework for NDN. This framework introduces a Manager Entity (ME) in the network, which can interact with a set of Management Agents (MAs) located in the User Equipment (UE) to coordinate management procedures. The proposed solution does not require significant changes to the NDN architecture, as the mechanisms defined to securely pull/push management content between MEs and MAs use the regular NDN transport through specific management naming. Our approach provides a reliable, secure and asynchronous management structure. Furthermore, the framework can be easily decoupled from the underlying network architecture, enabling an easy interoperation with any Information-Centric network approach.

To evaluate the feasibility of our framework, we have covered the particular use case of face management in the UE, and we have evaluated its benefits with respect to probing at the NDN strategy layer, by means of a validation scenario based on the CCNx software.

Our future work will focus on enhancing the control interfacing capabilities of the management content exchanged between the ME and the MA, as well as studying the applicability of our framework to other areas where management plays an essential role, such as QoS provisioning, policy management, remote administration of NDN-nodes and inter-domain support.

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