Chair of Communication Networks
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Diploma Thesis

# Analysis of Interworking Functions for Heterogeneous Networks

of

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I assure, that this work has been done solely by me without any further help from others except for the offical attendance by the Chair of Communication Networks. The literature used is listed completely in the bibliography.

Aachen, April 15, 2009

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# ABSTRACT

Future cellular radio networks will enable mobile terminals to communicate in environments populated by a multitude of devices, technologies and business actors using several radio interfaces. In this environment, one important task is to develop common control functions for elements in such networks. One of today's challenges is to provide service continuity in those highly heterogeneous networks. The service continuity can be measured in terms of a satisfied user criteria, which consists e.g. of the perceived end to end data packet delay, i.e. transport layer packet delay.

The IEEE 802.21 standard focuses on the support of media independent handover for a broad range of technologies, but with strong emphasis on 802 technologies. The Framework Programme (FP)7 European Project OMEGA investigates the performance of home networks, which consist of technologies like Wireless Local Area Networks (WLAN), Hybrid Wireless Optics (HWO) or Power Line Communications (PLC).

The aim of this work is to investigate in the context of the OMEGA project, which functions of the IEEE 802.21 standard are needed in order to co-operate in heterogeneous home networks. Subsequently, their performance in terms of QoS evaluation are developed. One of the most important functions is the path selection since it establishes the flow between source and destination and simultaneously, deals with the reservation of resources. In this work an approach for the identification and selection of possible paths using signal flow graphs analytically has been evaluated. The scheme is based on ad hoc networks and the proposed algorithm is Bandwidth Guaranteed Source Routing (BGSR). The analysis provides information about the required delay in the selection and helps to evaluate the influence of the route selection in the uninterrupted provision of service. Another concept to be considered is the path re-selection mechanism. A comparative analysis of centralized and decentralized solutions is developed using SFGs as well and basing the evaluation on the latency of both mechanisms.

# KURZFASSUNG

Zukünftige Mobilfunknetze ermöglichen es mobilen Endgeräten mit unterschiedlichen Netzen zu kommunizieren. Dabei kann das Endgerät aus einer Vielzahl von verfügbaren Technologien und Netzbetreibern auswählen. Die Kommunikationsnetze müssen hierzu geeignete Kontrollmöglichkeiten zur Verfügung stellen. Eine der größten Herausforderungen ist es, dass den Nutzern unterbrechungsfreie Dienste angeboten werden, während sich das Terminal in einer heterogenen Umgebung bewegt. Dienstspezifische Dienstgüteparameter geben Information darüber, wann ein Dienst eine Unterbrechung als solche wahrnehmen würde. Daher müssen Dienstgüteparameter wie z.B. Paketverzögerung und Durchsatz betrachtet werden. Das Satisfied User Criteria gibt Auskunft darüber, wie zufrieden ein Nutzer während der Diensterbringung ist.

Der IEEE 802.21 Media Independent Handover Standard bietet ein Rahmenwerk zur Durchführung von vertikalen und horizontalen Handovern mit einer starken Betonung auf 802 Technologien, bietet jedoch auch Unterstützung für andere zellulare Mobilfunksysteme. Das OMEGA Projekt ist ein Projekt im siebten Rahmenprogramm der Europäischen Union und untersucht die Leistungsfähigkeit von heterogenen, vermaschten Heimnetzen. Dort werden verschiedene Technologien betrachtet, u.a. Wireless Local Area Network (WLAN), Hybrid Wireless Optics (HWO) und Power Line Communications (PLC).

Ziel dieser Arbeit ist es, im Kontext des OMEGA Projektes zu untersuchen, welche über die im IEEE 802.21 Standard hinausgehenden Funktionen zur Zusammenarbeit in heterogenen Heimnetzen benötigt werden. Anschließend wird ihre Leistungsfähigkeit hinsichtlich der unterstützten Dienstgüte bewertet. Eine wesentliche Funktionalität ist die Auswahl eines geeigneten Weges zwischen Datenquelle und -senke (Path Selection). Zu diesem Zweck wurde in dieser Arbeit ein Konzept zur Ermittlung und Auswahl von möglichen Pfaden erstellt und mit Hilfe von Signalflussgraphen analytisch bewertet. Das Konzept beruht auf dem von ad hoc Netzen bekannten Bandwidth Guaranteed Source Routing (BGSR) Verfahren. Die Analyse gibt Auskunft darüber, wieviel Zeit die Pfadermittlung und -auswahl benötigt und hilft abzuschätzen, welchen Einfluss die Wegewahl auf die unterbrechungsfreie Diensterbringung hat. Darüber hinaus wird betrachtet, welche Auswirkungen eine zentrale oder dezentrale Wegewahl auf die Diensterbringung besitzt. Dazu werden die beiden Verfahren mit Hilfe von Signalflussgraphen miteinander bezüglich ihrer Signalisierverzögerung verglichen.

# CONTENTS

## CHAPTER 1

# Introduction

## 1.1 Motivation

Nowadays, Wireless Access Networks are widely spread and in a constant development basing on the standards of Wireless Fidelity (WiFi), Worlwide Interoperability for Microwave Access (WiMAX) and 3rd Generation Partnership Project (3GPP). After analyzing benefits of 3G and WLAN, it can be observed that combination of both of them will produce a network with competent features to satisfy users' needs.
A continuous connectivity everywhere and at anytime is becoming one of the required aims within heterogeneous networks. Non heterogeneous networks like GSM or GPRS have already good coverage, however there may be better alternatives available depending on the users' requirements, e.g. higher data rate than available with GPRS needed. For users it is very attractive to have ubiquitous Internet connections especially while on the move. In order to achieve this goal, the deployment of intelligent protocols able to allow transparent handovers between several networks is required.

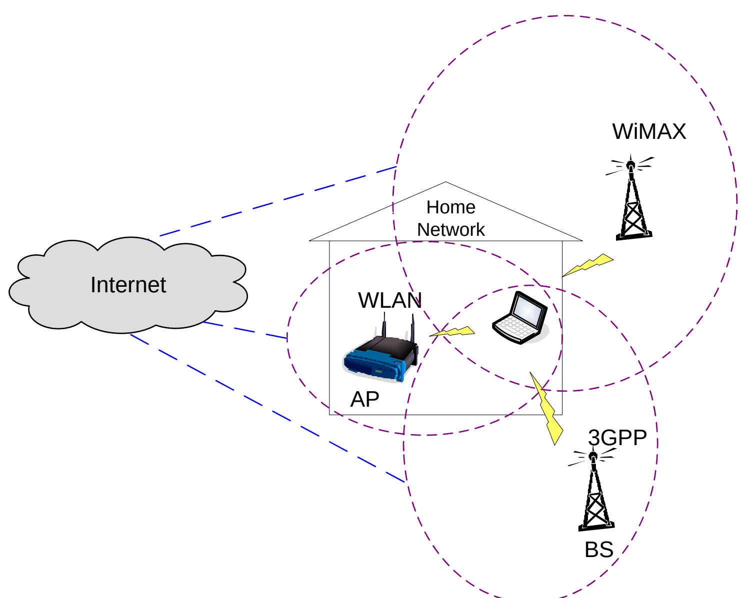


**Figure 1.1:** Heterogeneous Network.

In many cases, a mobile device is capable to support more than one access network technology and it is also possible to have areas where more than one access technology is available, for instance WLAN Access Point, WiMAX and 3GPP network (see Figure 1.1). The ideal situation is to detect all these access networks around the user, being able to identify the best one taking into account QoS criteria in order to avoid the loss of information.
Transparent connectivity requires mobility and compatibility in horizontal and vertical handovers. Heterogeneous one considers the handover between different networks like

WLAN, WiMAX and cellular networks and homogeneous includes handover between PoA (Points of Attachment) like AP (Access Points) in the same WLAN or between BS (Base Stations) WiMAX within the same network.

## 1.2 Problem Description

This work specially focuses on analysing heterogeneous home networks using multiple access technologies, while the connection must continue working. The IEEE 802.21 standard describes the support of media independent handover technologies, but it emphasizes on 802 technologies. The FP7 European Project OMEGA is doing research into home networks like WLAN, HWO or PLC.
The challenge is to analyze the interworking functions in heterogeneous home networks, assuming a mobile user equipped with multiple transceivers for different wireless technology standards. Once defined the scenario, it will be possible to evaluate some QoS parameters through the mathematical tool Matlab.
Some of the analyzed parameters are: packet delay, jitter, throughput and interruption time of multimedia sessions. After the analysis of QoS criteria, it is possible to determine the level of satisfaction of the user, which is the desired concept since this work focuses on the SUC (Satisfied User Criteria).

## 1.3 System Concept

### 1.3.1 System Idea

The system consists of a mobile terminal able to connect to different (radio) access technologies.

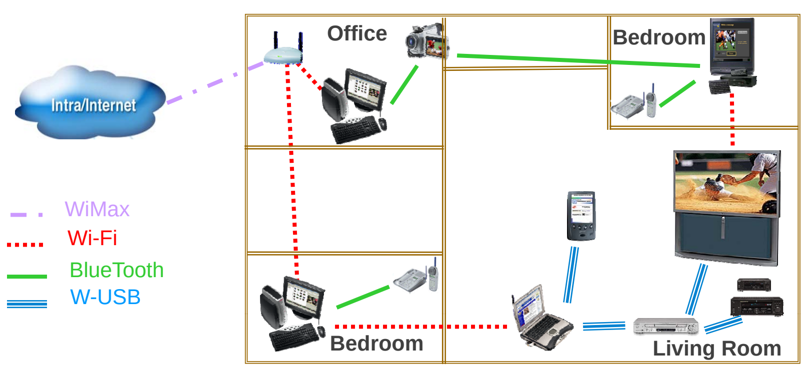


**Figure 1.2:** System Idea.
[1]

Figure 1.2 shows a typical apartment with different devices and wireless technologies which allow the users to communicate with their family reducing any sense of isolation they may have. The present work deals with the analysis of scenarios like this.

### 1.3.2 Goals and Requirements

The development of suitable common control functions in heterogeneous networks has to be carried out. Once defined these functions, some of them will be modelled using SFGs and the quantitative analysis of the SUC of users will be done by means of analytical calculations with Matlab.

## 1.4 Structure

The work is subdivided as follows:
Chapter 1 describes the topic, the motivation and the problem description. It ends with a description of the goals and requirements of this work.
Chapter 2 provides information in order to understand the problem in heterogeneous networks. It starts examining current state of the art IEEE 802.21 standard, afterwards it describes the work of the FP7 European Project OMEGA.
Chapter 3 gives a description of the Convergence Layer. Some Interworking Functions are described by means of use cases and finally, the Path Selector, which will be analysed, is presented in detail.
Chapter 4 contains the development of the analysis of the Path Selector. The Bandwidth Guarantee Source Routing Algorithm is presented, next the signal flow graphs and the delay generation functions for its analysis are shown. The chapter ends with the analysis of a complete scenario and its subsequent evaluation. Also, an analytical comparison between centralized and decentralized path re-selection is included.
Chapter 5 concludes this work and shows a summary. It ends with an outlook for possible future work.

## CHAPTER 2

# Heterogeneous Home Networks

## 2.1 Overview

Today's homes are equipped with a multitude of devices using several wired or wireless communication technologies forming a heterogeneous network environment (see Figure 2.1). These networks usually have a single point of connection to the Internet via simple DSL modems or in most cases DSL routers. However, it is foreseen that those nodes are substituted by nodes with additional capabilities as already proposed by the Home Gateway Initiative (HGI).

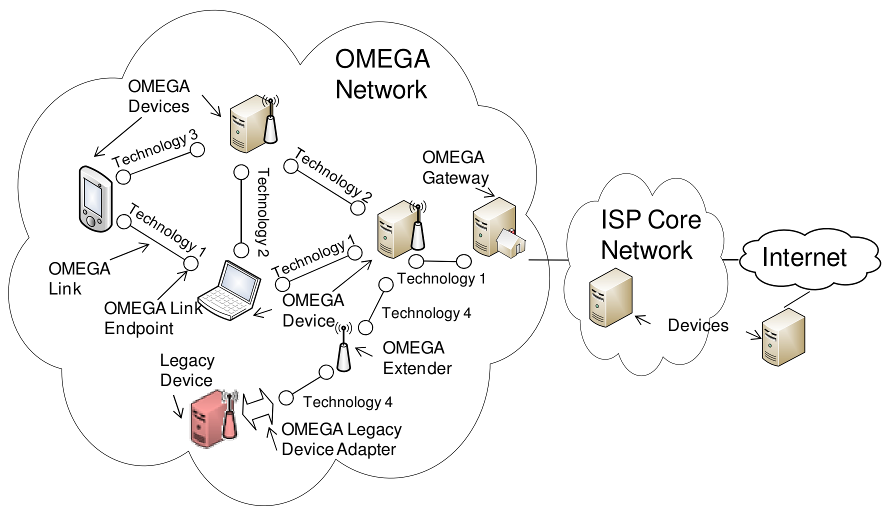


**Figure 2.1:** Heterogeneous network environment.

In Figure 2.1, several OMEGA Devices and OMEGA Links form the OMEGA network. Each link has OMEGA Link Endpoints. Also, an OMEGA network provides interfaces in order to interconnect to legacy devices or other networks (non OMEGA devices in general), inducing an additional functionality which consists in translating the not Inter-MAC frames provided by the legacy device into Inter-MAC frames : that functionality is named here OMEGA Legacy Device Adapter (OLDA). Therefore the OLDA can act as an OMEGA proxy for non OMEGA devices. The OMEGA Extender capability is used to extend the home network coverage and to allow OMEGA the communication between OMEGA devices having different PHY interfaces. The OMEGA Network is connected to the Internet via an OMEGA Device, the OMEGA Gateway.

The HGI proposes a remotely manageable gateway which may also allow traditional network operators to manage the home network gateway as well as the remaining devices which form the whole home network. It elaborated QoS mapping rules especially to guarantee the QoS of managed services (i.e. the user has paid for or would like to prioritize) [2].

A further management aspect is the deployment of devices which form the infrastructure of the home network, so called HNID (Home Network Infrastructure Device). Although

the deployment should be done in a plug-and-play manner and the topology of the network should be discovered autonomously, the system may provide assistance in the planning of appropriate locations for wireless infrastructure components.
Envisaged functionality includes quality of service support for diverse multimedia applications like:

- Video-on-demand or live streaming
- Voice
- Internet browsing
- Interactive multimedia(video conference, etc.)
- Online gaming
- Security and surveillance

## 2.2 IEEE 802.21 Media Independent Handover Standard

### 2.2.1 Overview

802.21 is an IEEE emerging standard. The standard supports mechanisms enabling seamless handover between networks of the same type as well as handover between different network types also called Media Independent Handover (MIH) or vertical handover.
The standard specifies IEEE 802 media access-independent mechanisms that optimize handovers between heterogeneous IEEE 802 systems and between IEEE 802 systems and cellular systems. IEEE 802.21 has the goal to facilitate handovers and to maximize handover efficiency.
The standard gives the upper layer's entities the possibility to control the heterogeneous Data Link Layers by using simple and media-independent primitives called commands. They can be issued after a reception of a layer 2 triggers called events.

### 2.2.2 802.21 Services

Three main services are defined. The Media Independent Event Service (MIES) provides event classification, event filtering and event reporting, corresponding to dynamic changes in link characteristics, status and quality. The Media Independent Command Service (MICS) enables MIH nodes to manage and control link behaviour related to handovers and mobility. It also provides the means to mandate actions to lower layers, in a local or in a remote protocol stack. Lastly, the Media Independent Information Service (MIIS) provides details on the characteristics and services provided by the serving and surrounding networks. Through the use of these services, layer three mobility management protocols control the handover procedure in a more efficient way while enabling seamless handover [3].

#### 2.2.2.1 802.21 Event Service

The MIHF (see Figure 2.2) offers the higher layer entities the possibility to receive event indications from a particular event source by making a subscription, this task is done by using the MIES.
Multiple higher layer entities (local and remote) can be subscribed for event indications at the same time. A local MIHF is the one that is within the entity?s protocol stack. A remote one is in a peer entity protocol stack.
In the protocol stack there are two types of events: Link Events and MIH Events. Link Events originate from the DLL and terminate at the MIHF. They are always local. The

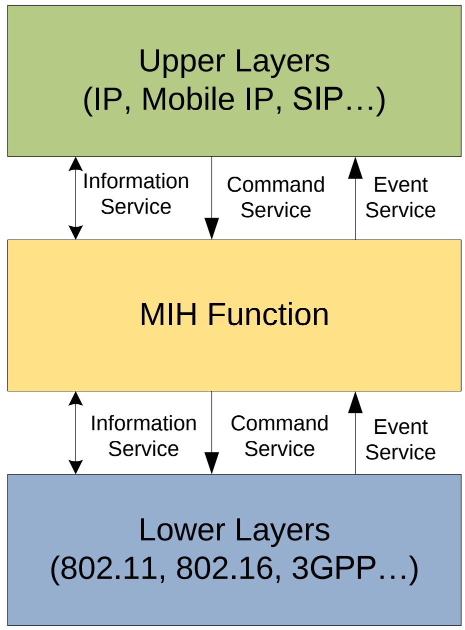


**Figure 2.2:** MIH General Service Architecture.

Link Events may lead to MIH Events. They can be local and remote. Events that are propagated by the MIHF to subscribed MIHF Users are defined as MIH Events. Furthermore the MIHF is capable to notify remote MIHF Users about MIH Events [3].

Event Subscription provides a mechanism for local and remote entities to subscribe themselves and receive events. Subscriptions may be divided into Link Event Subscription and MIH Event Subscription.

Link Event Subscription is performed by the MIHF. The MIHF subscribes itself in the DLLs in order to receive event indications. Therefore the DLL must provide to MIHF what type of event indications they support.

DLLs should periodically check if an event has to be generated. They can do it by using the threshold provided by the user upon registration for each event type and compare the current value to the appropriate threshold. If the threshold is hit, the DLL should indicate the event to the MIHF.

#### 2.2.2.2 802.21 Command Service

MICS allows the higher layers to send media independent commands to the lower layers and thus to control their behavior.

The defined commands allow the MIHF Users to configure, control and get information from the lower layers. Thus the users are supported by the MICS in their job of making a handover decision in a heterogeneous environment.

The commands can be divided into two categories: MIH Commands and Link Commands.

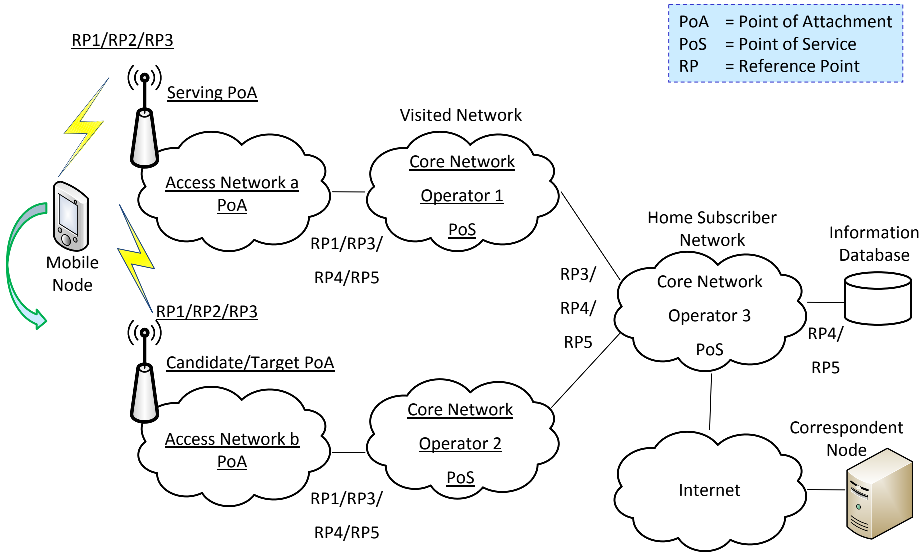


**Figure 2.3:** MIH network architecture.
[5]

### 2.2.3 802.21 Network Architecture

There are two attachment points in the network for a MIH capable device (as seen in Fig 2.3):

- Network Point of Attachment (PoA): network side endpoint of a L2 link which includes a Mobile Node as other endpoint.
- MIH Point of Service (MIH PoS): MIH instance at the network side which is able to exchange MIH messages with a MIHF in the Mobile Node.

PoS and PoA can be in the same node.
Figure 2.3 shows specifically handover between a serving to a candidate PoA.

## 2.3 FP7 European Project OMEGA

OMEGA is an Integrated Project in the ICT area funded by the European Commission under the Seventh Research Framework Programme (FP7). The project is running for three years from January 2008 to December 2010.
OMEGA will develop a user-friendly home area network capable of delivering high-bandwidth services and content at a transmission speed of 1 Gbps. The interdisciplinary project consortium consists of 20 European partners from industry and academia.

### 2.3.1 Project goal

The OMEGA project will set a global standard for ultra broadband home area networks. The new standard will enable transmission speeds of 1 Gbps via heterogeneous communication technologies, including Power Line Communications (PLC) and wireless connections. Thus, OMEGA aims to make home area networks as easy to use as electricity from the socket, putting an end to the coverage limitations as well as the wiring clutter in the home [5].

With OMEGA's gigabit home network, users will get easy access to high-bandwidth information and communication services such as telepresence, 3D gaming, enhanced interactivity, virtual reality, high definition video as well as e-health applications and services for the exchange of user-generated business or multimedia content.
The OMEGA network integrates different heterogeneous telecommunication technologies e.g., PLC, Wi-Fi, Ultra Wideband (UWB) and Hybrid Wireless Optical (HWO) to provide connectivity between OMEGA devices. OMEGA project aims to enable the cooperation of communication technologies by developing an Inter-MAC convergence layer located between layer 2 and layer 3 with the main idea of bridging between wired and wireless access technologies (see Chapter 3).

### 2.3.2 Background

Future home area networks must enrich the lives of users, for example by allowing visual communications with their friends or relatives and by enabling interactive experiences through entertainment. Furthermore, home networks should also support citizens in maintaining their independence as they age, for example by offering remote healthcare and by allowing them to communicate with their family to reduce any sense of isolation they may have. In short, users must have the ability to control their virtual as well as their physical environment via home networks.
Users will require such networks to be simple to install, without any new wiring, and easy enough to use so that information services running on the home area network will be just another utility, like electricity, water, and gas.
An example of OMEGA network is depicted by Figure 2.4 which shows different floor plans of the house with several technologies and devices to satisfy needs of the daily life from the user perspective

### 2.3.3 Technical approach

Different challenges have to be considered in order to achieve the connectivities in OMEGA networks:

- Radio communications. The multitude of systems will create coexistence problems. Improving the coexistence and cooperation is necessary. OMEGA will integrate various appropriate radio devices into a converged heterogeneous radio network, which meets the customer's demands with respect to quality of service, reliability, throughput, ubiquity, and self-configuration.
- Power line communications. OMEGA aims to increase the current frequency range for power line communications up to 100 MHz. An investigation of electromagnetic compatibility in this enlarged spectrum will help to define advanced modulation schemes based on multi-carrier approaches that best fit this wider communication pipe containing a higher number of carriers. As a consequence, this will provide a foundation for new wide-bandwidth power line communication transceivers that can substantially increase the data rates available as well as home coverage for consumer applications
- Optical wireless communications. In order to increase the bandwidth, advanced studies on MAC and physical layers will be required. In addition, a complete hybrid optical-wireless prototype will be incorporated into the OMEGA platform.
- Continuity from the access network. Access network continuity will play a key role. It will require novel methods for managing the interconnection of the home area network with various existing networks.

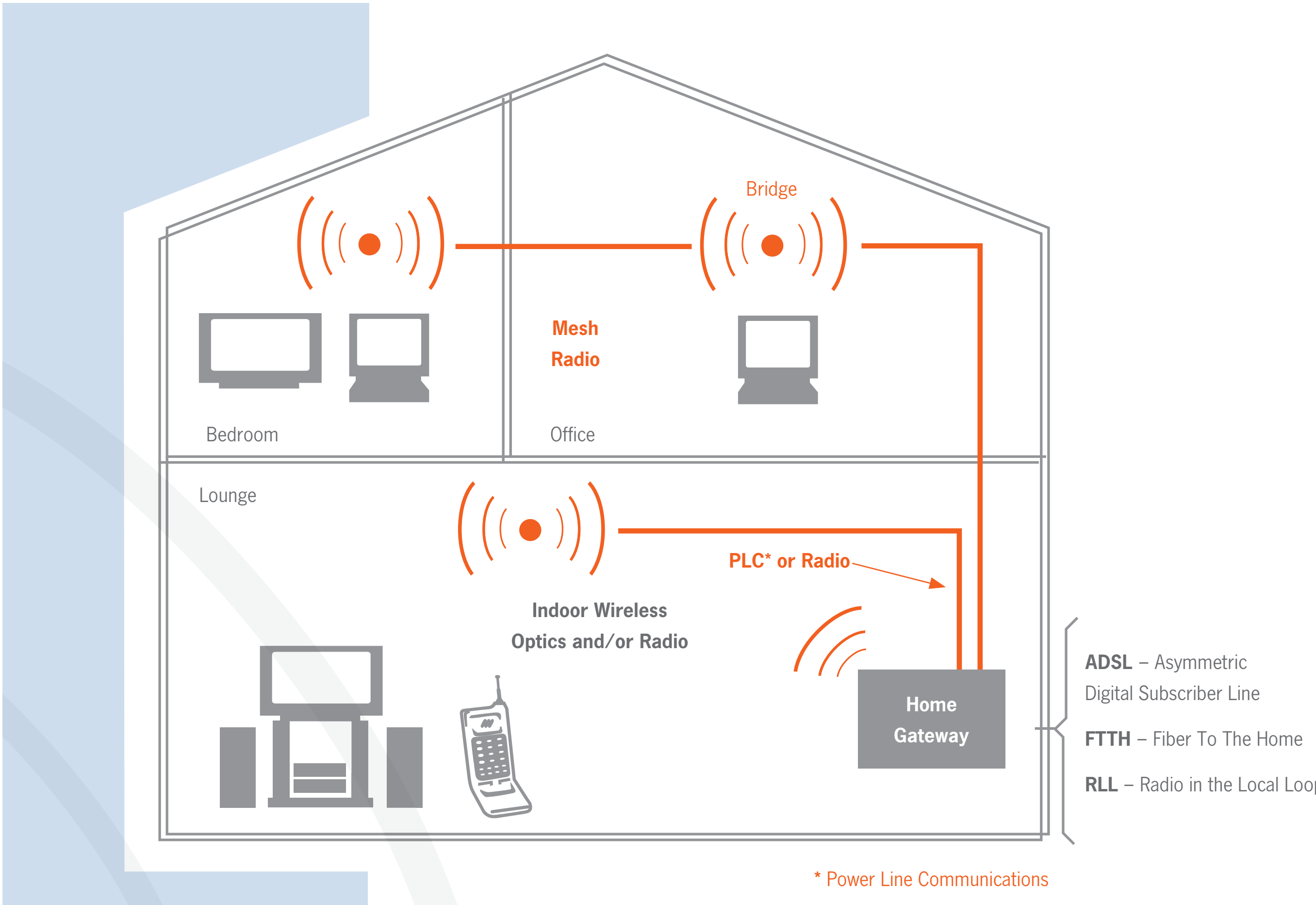


**Figure 2.4:** OMEGA Network.
[5]

### 2.3.4 Expected impact

The OMEGA project will provide contributions to standards, especially in the fields of convergence layer, power line wireless optic communications. The aim is to advance standards to a level that allows the interconnection of all home devices within a gigabit home network.
OMEGA will demonstrate a proof of concept ultra-broadband home area network on the scale of one apartment and will evaluate roll-out scenarios based on actual services. The results of the project should enable and encourage the development of new advanced integrated services to the benefit of Europe's ICT industry and economy.
The adoption of OMEGA's results will give all citizens, independently of their technical knowledge, the opportunity to access advanced information and communication services that will enrich their lives at gigabit-speed. This will be particularly relevant for the growing number of elderly people, who will get easy access to services like, for instance, telemedicine and telepresence.

CHAPTER 3

# Convergence Layer and Interworking Functions

## 3.1 Overview

A multimode mobile has access to different technologies which differ in data rates, modulation schemes and security parameters. If a mobile device is capable of using multiple DLLs, monitoring and control of functionality are required. With this purpose, the OMEGA project aims to enable the cooperation of communication technologies by developing an InterMAC convergence layer between the different DLLs and the upper layers.

After the definition of the InterMAC layer, this chapter shows several Interworking Functions, necessary in order to communicate the InterMAC layers of different devices in heterogeneous networks. Section 3.4 focuses on one of those IWF (path selection) and presents its description.

## 3.2 Convergence Layer (InterMAC)

The InterMAC is the layer that contains adaptation functions both, for data transport and control purposes. It has two main functions: adapting service request from higher layers to the service offered by the Data Link Control and to convert the higher layer packets (PDUs) with variable or possibly fixed size into a fixed size that is used within the DLL. The InterMAC serves as a convergence layer of several link layer technologies for the network layer (IP) as seen in Figure 3.1. In the best case, the user has not more to do than to plug in and/or power on a device.

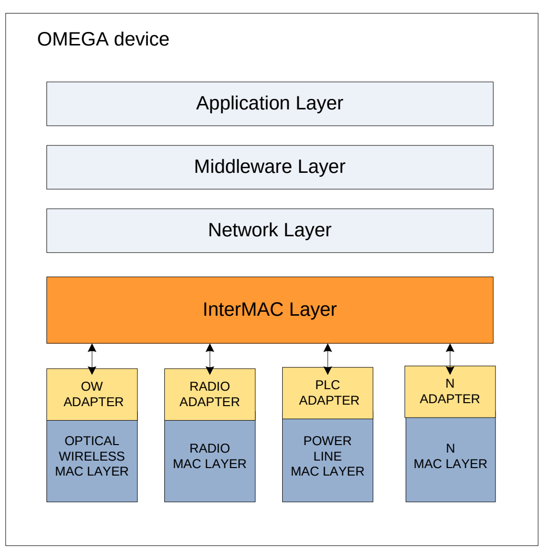


**Figure 3.1:** InterMAC Layer.

It is possible to distinguish between several planes:

- User plane includes functions for transmission of traffic over established connections.
- Control plane includes functions for the control of connection establishment, release, and supervision.
- Management plane includes functions of:
  - Configuration: specifying the management of physical resources and how they are included into the configured network.
  - Accounting: dealing with charging and maintenance costs.
  - Performance: this function must ensure that the network is tuned to meet its performance requirements in terms of user perceived QoS.
  - Fault: this function should aid the planning of future network facilities and enhancements.
  - Security: these functions control access to the network facilities and network management entities.

## 3.3 Use cases of Interworking Functions

In order to communicate the InterMAC layers of OMEGA devices, Interworking Functions are necessary (see 3.2). These functions include QoS support for diverse multimedia applications like video-on-demand or live streaming, online gaming, web browsing, and file exchange. Each of those applications put constraints on the capabilities of the network in terms of acceptable delay, jitter, and throughput.
In some cases, the behavior of the network may change due to additional activation of applications, network devices or other non-network devices in the home, e.g. microwave ovens. A smart network would react to those network changes and would try its best to continue the service provisioning as long as possible according to desired QoS policy. For that reason a set of control functions within the network is necessary to allow making changes to the network state.

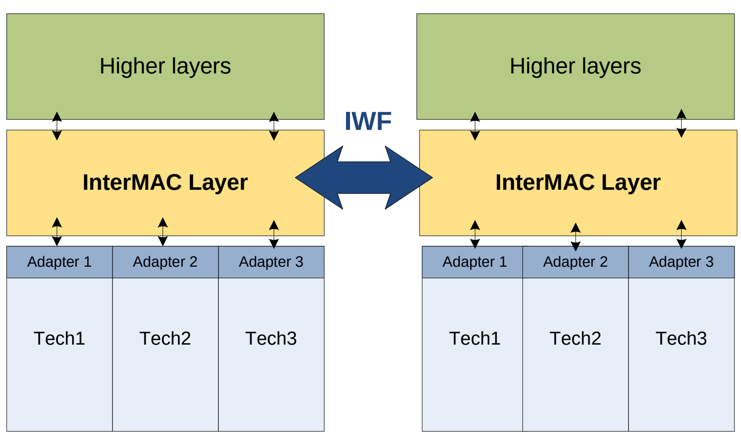


**Figure 3.2:** Interworking Functions.

This section contains the description of some IWF by means of use cases. Use cases are often used in systems engineering as a technique of description due to they overview the functional requirements for a system. Some of its features are mentioned next:

- Visualize the idea of the system with the help of a use case diagram.

- Identify start and end of the use case with the help of triggers and results of the use case.
- Create an essential description for each use case. Define the triggers, pre-conditions, and incoming information as well as the results, post-conditions, and outgoing information for each use case.
- List of actors, triggers and results.

Use cases can be grouped according to the well known architecture of telecommunication networks. Those networks usually consist of a user plane, control plane, and management plane, as it can be noticed in the Figure 3.3. Use cases within the control plane may interact with use cases within the OMEGA management plane.

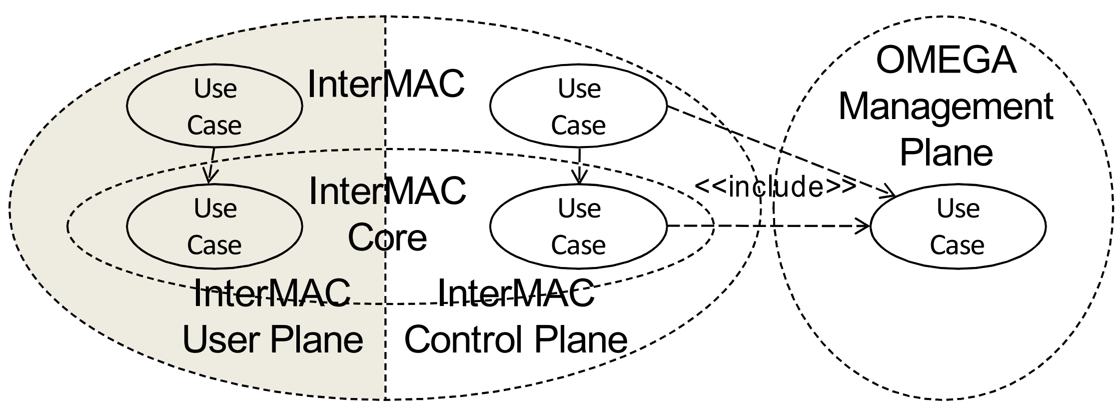


**Figure 3.3:** Architecture of Use Cases.

A use case defines user needs and behaviours that are not likely to change over time. Focusing on OMEGA networks, a use case is defined by some actors, usually represented by family members and there are non-functional requirements like home settings including floor plans of the house and devices in it. Inside a use case, several situations can be developed, each one covered by a single usage scenario sharing the same constraints (house dimensions, actors and devices) imposed by the use case. Next subsections show different IWF described by means of use cases. It should be noted that next IWF are focused on control and user planes.

### 3.3.1 Path Scheduling

Different flows of data arrive at the user plane and each of them has to be scheduled along the best combination of paths depending on its QoS requirements. The scheduler determines which resources to use depending on the descriptors of class of traffic.

### 3.3.2 Load balancing

When the path from a specific source to a destination is not available, an alternative path is the best option. Most of these paths selection deal with the residual bandwidth as a

**Table 3.1:** Path Scheduling

| | |
|---|---|
| **Name of the Use Case** | Path Scheduling |
| **Actors** | Higher layer in the user plane (Data source) |
| **Triggers** | Data arrives at the user plane of the InterMAC |
| **Results** | The best combination of paths is chosen according the class of incoming traffic |
| **Pre-conditions** | There is more than one path between the source and the destination |
| **Post-conditions** | Data is transmitted along the most suitable path depending on QoS |
| **Incoming information** | - Sender Layer 3<br>- Receiver Layer 3 Address<br>- Descriptor of class of traffic |
| **Outcoming information** | The best combination of paths to reach the endpoint |

performance metric. With this function, it is possible to balance the load along links in the network choosing an alternative less utilized path. This is a function which can be understood within the interworking function of path scheduling.

**Table 3.2:** Load Balancing

| | |
|---|---|
| **Name of the Use Case** | Load balancing |
| **Actors** | Higher layer in the control plane (Data source) |
| **Triggers** | A link is close to overload |
| **Results** | The overloaded link supports less data than before. The load is balanced between the rest of the links |
| **Pre-conditions** | Some link is overloaded |
| **Post-conditions** | The load is balanced between several links |
| **Incoming information** | Initial load of the links |
| **Outcoming information** | The best combination of paths to reach the endpoint |

### 3.3.3 QoS classification and marking

Classification and marking is a system of identifying packets assigning certain parameters within the packet headers in order to group them. Once the traffic is identified, it can be marked or 'coloured' into groups so that QoS policies can be applied to them. An end-to-end QoS model requires the ability to mark a traffic stream into one of a group of classifications. Each classification incorporates a QoS service level.

**Table 3.3:** QoS classification marking

| | |
|---|---|
| **Name of the Use Case** | QoS classification marking |
| **Actors** | Higher layer in the control plane (Data source) |
| **Triggers** | Data arrives at the user plane of the InterMAC |
| **Results** | Packets are marked according their priority (SLA) |
| **Pre-conditions** | Packets Parameters of QoS of data |
| **Post-conditions** | Packets arrive at the destination guaranteing QoS (according to to their priority) |
| **Incoming information** | Data.QoS parameters: priority of the traffic |
| **Outcoming information** | Packets are marked according QoS |

### 3.3.4 Roaming to other home networks

When a mobile device is transferred via handover to another HN, the roaming process is required. The new network has to identify which HN belongs to and checking if a roaming agreement between both exists. If it exists, the visited network has to maintain a temporary subscriber record for the device. Table 3.4 shows the use case.

**Table 3.4:** Roaming to other home network

| | |
|---|---|
| **Name of the Use Case** | Roaming to other home network |
| **Actors** | Higher layer in the control plane |
| **Triggers** | The home network has to be changed due to a new location of the device |
| **Results** | Connection to other home network |
| **Pre-conditions** | Device trying to connect to another home network |
| **Post-conditions** | The new home network has to maintain a temporary subscriber record for the device |
| **Incoming information** | - Identifier<br>- Message of request |
| **Outcoming information** | • If the new home network identifies the device and lets the connection:<br>- Internal temporary address to the device<br>• Otherwise:<br>- Rejection to the request |

### 3.3.5 Admission control

The admission control checks if it is possible to establish a path between source and destination with the requested QoS. If it is possible, the new connection can access to the network; otherwise, the request is rejected. Use case is described in 3.5

**Table 3.5:** Admission control

| | |
|---|---|
| **Name of the Use Case** | Admission control |
| **Actors** | Higher layer in the control plane (Data source) |
| **Triggers** | A new connection wishes to use the network |
| **Results** | Acceptance or rejection of the request |
| **Pre-conditions** | An application requests a connection |
| **Post-conditions** | The network accepts or rejects the connection |
| **Incoming information** | - Traffic<br>- Characteristics of the traffic: Qos required |
| **Outcoming information** | - Acceptance of the request<br>- Rejection of the request |

## 3.4 Path selector

The interworking function of path selection has been selected to evaluate its influence in QoS parameters (packet delay, throughput). In order to describe it more detailed, the use-case description in Table 3.6 has been used.

**Table 3.6:** Path Selection

| | |
|---|---|
| **Name of the Use Case** | Path Selection |
| **Actors** | Higher layer in the user plane (Data source) |
| **Triggers** | Load is higher than a threshold ($T_H$), Node is added to a network |
| **Results** | Load of the overloaded link is balanced between the most suitable links |
| **Pre-conditions** | A link is close to overload |
| **Post-conditions** | Load is forwarded by the most suitable links |
| **Incoming information** | Table of links connected to each node and its cost |
| **Outcoming information** | Election of the link with lowest cost |

### 3.4.1 Initial assumptions

Initially, a heterogeneous environment with different technologies has been assumed. The first essential task of the function of Path Selector is to find a suitable path or route through the network between the source and the destination that will have the necessary resources available to meet the QoS constraints for the desired service. Figure 3.4 shows an OMEGA Network in which more than one path to reach a destination can be chosen. The aim of the Path Selector is the selection of the most suitable path, which means, that with the lowest cost and available resources.
In this work, a QoS routing protocol as proposed by [6] is chosen, specially designed for

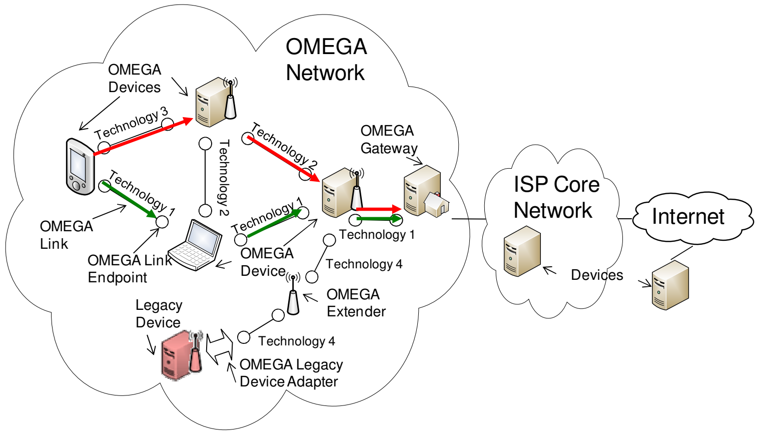


**Figure 3.4:** Path Selection.

ad-hoc networks features (battery life, link stability, node congestion state) in order to provide robustness against mobility and wireless channel fluctuations.

In the mechanism of the protocol, each node computes for each neighbor a cost function including link stability, available bandwidth, link transmission delay and occupied buffers' size. Only neighbors with a cost value less than a fixed threshold forward the RREQ packet. The cost function of a path P is given by the formula 3.1.

$$f(P) = \frac{a}{STAB} + bBW + C_D + (1 - a - b - \theta)BUFFERS \tag{3.1}$$

STAB is relative to stability, BW to the available bandwidth, BUFFERS to occupied buffers's size, $C_D$ to the transmission delay ($C_D =$ -DELAY x log (p) with p the probability that delay constraint is respected). a, b and $\theta$ are fixed parameters; their sum is equal to 1.

### 3.4.2 Bandwidth Guarantee Source Routing Algorithm

The proposed algorithm for the Path Selector is BGSR, based on a widely used routing scheme of Ad hoc networks: DSR (Dynamic Source Routing). In this scheme, with admission control, the flooding overload is effectively decreased and with resource reservation, QoS is guaranteed [7].

A detailed description is given by figure 3.5, where S represents the source node and R, each intermediate node. The source node checks that it has a route to the destination and its resources are sufficient. If these conditions are not satisfied, the source node executes the algorithm and waits for a route reply.

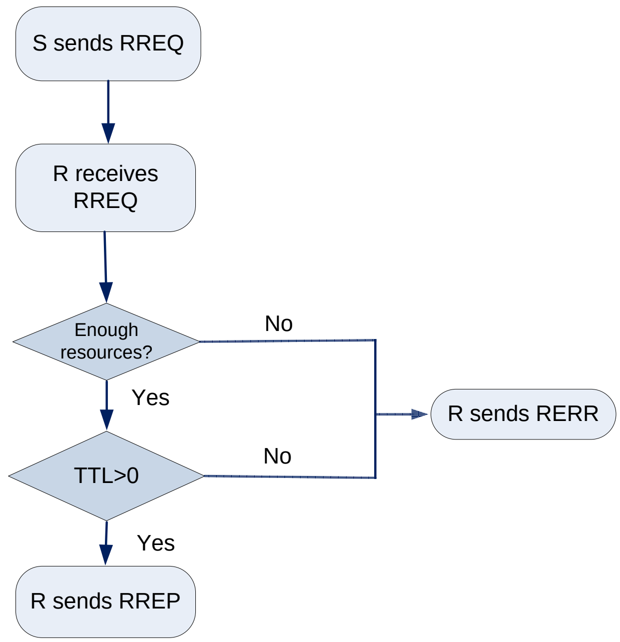


**Figure 3.5:** BGSR algorithm.

BGSR adopts flooding mechanism. The source node will send RREQ to all adjacent nodes, in these RREQs the resource requirements for the traffic are included. Each intermediate node which has received the RREQ, will rebroadcast it until the RREQ reaches the destination. Before sending RREQ out, each intermediate node will check wether its own available bandwidth is equal to or more than the required bandwidth indicated by bandwidth field of RREQ. If there is not enough bandwidth, the intermediate node will quietly discard this RREQ. If there is enough bandwidth, the intermediate node will check whether the resulted number is more than zero after the Time To Live (TTL) got from RREQ is decreased by one. If the resulted number is less than or equal to zero, the intermediate node will discard this RREQ, otherwise it will send RREQ out after attaching its own address to the end of the original route list and filling the resulted number in TTL field.

| | | | | | |
|---|---|---|---|---|---|
| sour_addr | dest_addr | request_id | route_list | bandwidth | TTL |

**Figure 3.6:** BGSR RREQ format.

The RREQ message contains the following entries:

- sour_addr: the source address of the traffic;
- dest_addr: the destination address of the traffic;
- request_id: an ID uniquely representing a request between certain source/destination pair;

- bandwidth: the bandwidth requirement of the traffic;
- TTL: Time to Live, the maximum acceptable number of hops for the traffic

Once the RREQ has reached the destination node, it remains waiting for receiving more messages of request during a timeout. Then, the process of decision will be done: it calculates the total cost of the path, then the lowest cost route is chosen and a RREP carrying this route and the traffic class is unicasted back to the source node. Figure 3.7 shows the entries corresponding to the RREP message.

| sour_addr | dest_addr | request_id | route_list | bandwidth | TTL |
|---|---|---|---|---|---|

**Figure 3.7:** BGSR RREP format.

Considering the mobility of Ad hoc networks, the resource condition might continuously change. The node, which could provide enough resource for the traffic when RREQ passed, might not provide enough resource for the traffic on the arrival of RREP or the next hop to the source along the route list carried in RREP becomes unreachable. Then, this node will send a Route Error (RERR) back to the destination along the coming route of RREP.

When the RREQ does not reach the destination node due to a link failure, an error type 'NEXT HOP UNREACHABLE' is generated. During the checks, if there are not enough resources, 'NO ENOUGH RESOURCE' will be the error type and if the maximum acceptable number of hops is exceeded, also a RERR will be sent to the source node in order to notice the error.

| error sour_addr | error dest_addr | error request_id | error node address | error type |
|---|---|---|---|---|

**Figure 3.8:** BGSR RERR format.

When the RERR is sent back to the destination node, this node will delete all route information items in whose route list field the node indicated by error node address in RERR is included. Then the destination node will check the Route Information Table to select a new route record and resend a RREP with the route information from the first item.

A QoS extension for AODV routing packets [8] is used in QS-AODV, it is added to RREQ, RREP and RERR packets to discover and create routes. This QoS extension includes the application bandwidth requirements and a 'session ID' is used to identify each QoS flow that is established. The session ID and required QoS parameters are recorded in the routing tables to identify different QoS flows. QS-AODV modifies the route discovery and maintenance mechanisms of AODV to provide QoS assurance. QS-AODV limits the broadcast area of the local repair request (see Section 4.6) setting the TTL value to 3.

### 3.4.3 Path selection model

This section shows the model of the path selection by means of the state chart, depicted in Figure 3.9. In this case, the 5 states represent the operation of the path selector.

Node 1 represents the 'good' state in which the path selector works correctly and node 5 represents the 'bad' state, which involves a failure in the operation of the algorithm. After the first execution of the algorithm, if it does not work as it is expected, there are two more attempts. After the first try, the system changes to state 3, in which the algorithm is executed again and after $n$ seconds, the last attempt is carried out. Once reached the state 4, if the path selection does not work, a trigger is executed and it stops its operation.

A HMM model is characterized by the state transition matrix P, which is depicted in Equation 3.2.

$$P = \begin{pmatrix} p_{11} & p_{12} & 0 & 0 & 0 \\ p_{21} & 0 & p_{23} & 0 & 0 \\ p_{31} & 0 & 0 & p_{34} & 0 \\ p_{41} & 0 & 0 & 0 & p_{45} \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \tag{3.2}$$

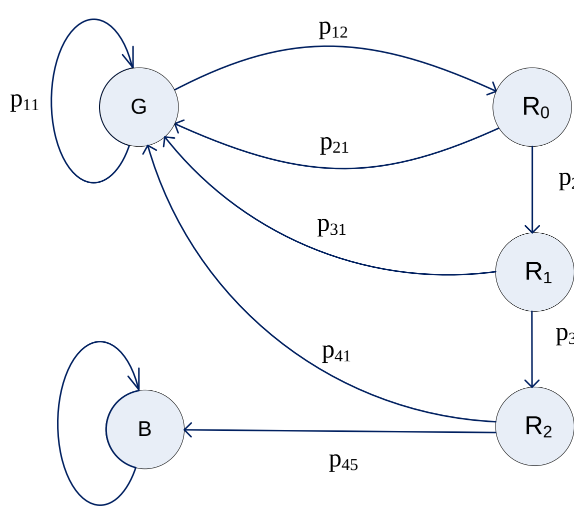


**Figure 3.9:** State chart diagram

The SFG of the path selector is depicted in Figure 3.10. The transmission starts in the state 1 and the receiving state (2) is reached after a delay indicated by the operator $z^{PS}$. States 3 and 4 represent the attempts of retransmission. If the path selection does not work, the failure state (5) is reached after a delay of z. The delay operator $z^{RTO}$ corresponds to the time until the retransmission of the RREQ is done again.

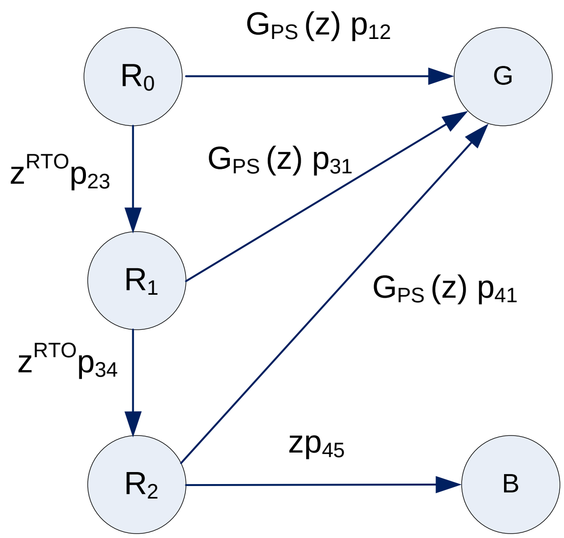


**Figure 3.10:** Matrix Signal-Flow Graph of Path Selector.

### 3.4.4 Modes of operation for path re-selection: centralized and decentralized

The meshed topology of a home network allows choosing alternative paths for a quality of service flow. The establishment and release of flows creates a dynamic environment in which the optimal flow/path combination might require re-selection of paths.

This chapter shows two possible mechanisms which can be used for re-selection of paths: centralized and decentralized also known as local repair. In order to describe them, an example of network topology is shown in Figure 3.11. The gateway is located in node 1 and nodes 2-7 are bridges connected via links with interfaces of different technologies.

Regarding the centralized mechanism, if a failure or degradation in the capacity of link L3 is considered, node 4 broadcasts a message of error to the gateway and BGSR is run again in order to find a new route to the destination. During local repair, when a link break in an active route occurs, the node upstream of that break, node 4, runs the algorithm. The node initiating the repair waits the discovery period to receive RREPs in response to the RREQ. If at the end of the discovery period, the repairing node has not received a RREP for that destination, it proceeds by transmitting a RERR message for that destination. The centralized mechanism involves the error signalling while in the local repair mode, each node reacts automatically to any failure in the network. The detailed analysis of both solutions is described in Chapter 4. Decentralized architectures can use reactive or proactive discovery [9]. Proactive protocols follow an approach similar to the one used in wired routing protocols. By continuously attempting to discover new routes, they try to maintain the most up-to-date topology of the network. This allows them to efficiently forward packets, as the route is known at the time when the packet arrives at the node. In order to maintain the constantly changing network graph due to new, moving or failing nodes, proactive protocols require continuous updates, which may consume large amounts of bandwidth - clearly a disadvantage in the wireless world, where bandwidth is often sparse. Even worse, much of the accumulated routing information is never used, since routes may exist only for very limited periods of time. The family of Distance-Vector protocols, including Destination-Sequenced Distance-Vector Routing, fall into the category

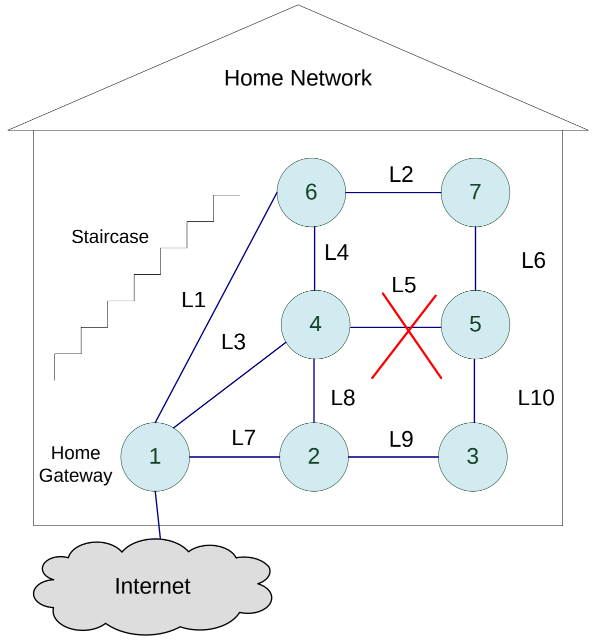


**Figure 3.11:** Home Network with link failure.

of proactive protocols. In contrast, reactive protocols determine the proper route only when required, that is, when a packet needs to be forwarded. In this instance, the node floods the network with a route-request and builds the route on demand from the responses it receives. This technique does not require constant broadcasts and discovery, but on the other hand causes delays since the routes are not already available. Additionally, the flooding of the network may lead to additional control traffic, again putting strain on the limited bandwidth. These reactive (or on-demand) protocols include Dynamic Source Routing (DSR) and Ad-hoc on demand Distance Vector Routing (AODV), as well as the classical flooding algorithms [10].

CHAPTER 4

# The Analytical Model

## 4.1 Overview

This chapter shows the analysis of the Path Selector described in Chapter 3 focusing on a simple scenario. This is done by showing the SFG and the calculation of the delay generation function. Section 4.5 shows the results of the analysis by means of the CDF and PDF. This analytical evaluation obtained using Matlab allows the evaluation of SUC with respect to QoS parameters like the packet delay in this case.
Finally, section 4.6 focuses on path re-selection and shows a comparative analysis of two different techniques: centralized and decentralized, using as well the evaluation of packet delay.

## 4.2 Scenario of analysis

Figure 4.1 shows the scenario that has been analyzed. BGSR is assumed as the protocol of routing and reservation of resources as described in Section 3.4.2.
Conditions of the channels are defined by the delay of retransmission and the BLER defined in Section 4.3.

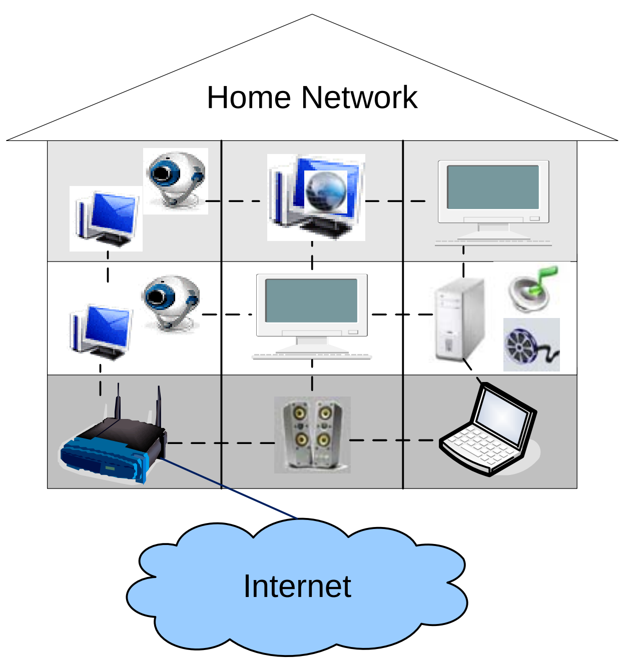


**Figure 4.1:** Scenario of analysis.

## 4.3 Signal Flow Graph Analysis

This section shows the signal flow graph of the system shown in section 4.2.

Performance analysis of communication protocols across different communication layers are in the majority of cases performed by simulations. An analytical analysis is oftentimes only used for calculating mean values. Before starting to model a system it is essential to specify the goal of the analysis, i.e. which performance criteria are considered. SFG models have been used in the last years to model different Automatic Repeat Request protocols amongst others[11].

SFGs provide means to model the statistical time response of communication protocols based on a graphical representation. Statistical states, transition probabilities and probability density functions are used for the parametrization of the SFGs.

Assuming an erroneous channel, the block error rate behavior is modeled by using a Gilbert-Elliott model, which is a HMM with two finite channel states. Each state hides a Block Error Ratio with value $\varepsilon_i$ ($\varepsilon_1 = 0$ for the 'Good' state and $\varepsilon_2 = 1$ for the 'Bad' state). In Figure 4.2, node G represents the good state with minimum error and node B, the bad state in which the error is assumed as maximum. The system switches between these two states according to the transition probabilities.

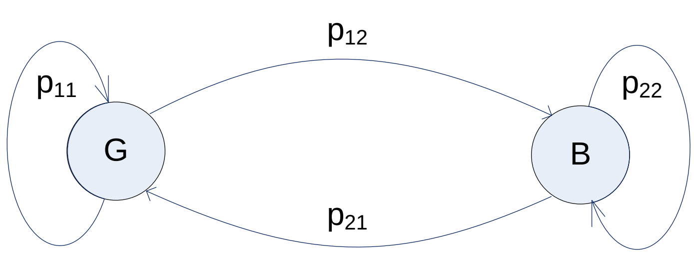


**Figure 4.2:** Structure of the analytical model.

In general a HMM channel model is characterized by the state transition matrix P, the error probability vector $\varepsilon = (\varepsilon_1,\varepsilon_2)$ and the initial probability state vector $\pi_0$. The stationary vector $\pi$ of the canonical HMM is defined by 4.1 [12].

$$\pi = \frac{p_{21}}{p_{12} + p_{21}}, \frac{p_{12}}{p_{12} + p_{21}} \tag{4.1}$$

Focusing on the case of this study, SFG is shown in Figure 4.3. The transmission starts in state S and ends in state A. If the message is not delivered the first time, there are three more retransmissions (state B) and if after the third, the system does not reach the successful state, then the message of error is sent (state F).

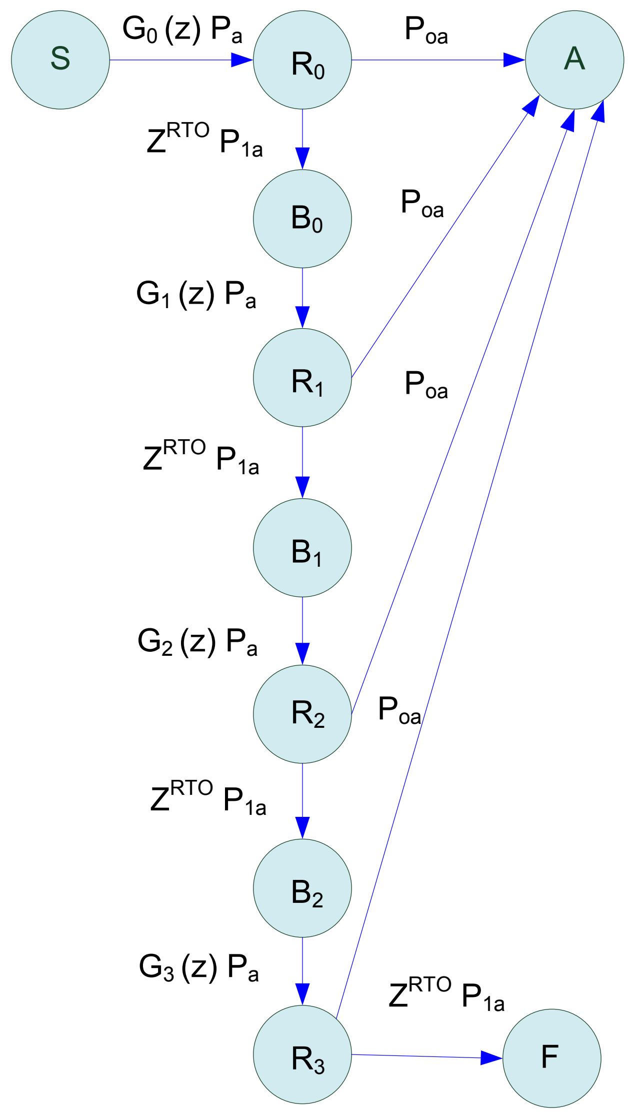


**Figure 4.3:** Signal Flow Graph for one hop and 3 retransmissions attempts.

R represents the receive state; $G_0(z)$, $G_1(z)$, $G_2(z)$ and $G_3(z)$ represent the delay generation function for each of the attempts; $P_a$ represents the channel transition matrix; $P_{1a}$, the probability of retransmission; $P_{oa}$ is the probability of success and $z^{RTO}$, the delay of retransmission. Equations 4.2, 4.3 and 4.4 show the values of these matrixes if considering $\pi = (0.9, 0.1)$.

$$P_{1a} = \begin{pmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{pmatrix} = \begin{pmatrix} 1 - p_{12} & p_{12} \\ p_{21} & 1 - p_{21} \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \tag{4.2}$$

$$P_a = \begin{pmatrix} 0.9 & 0.1 \\ 0.9 & 0.1 \end{pmatrix} \tag{4.3}$$

$$P_{oa} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \quad (4.4)$$

## 4.4 Delay Generation Function

In order to analyze the mean throughput and delay of ARQ mechanisms, SFGs are used to find the Moment Generating Function (MGF) of the transmission time. Data blocks of fixed size are transmitted over a communication channel with a varying delay. Assuming an unreliable channel with the block error probability p (see Eq. 4.5), the data blocks are delayed randomly by the value D characterized with a Probability Mass Function (PMF). The MGF of D is respectively $G_D(z)$ (see Fig. 4.4).

$$p = \frac{p_{12}}{p_{12} + p_{21}} \quad (4.5)$$

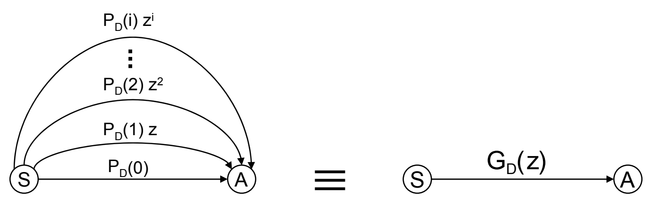


**Figure 4.4:** Signal Flow Graph of delayed segment transmission.

Figure 4.4 illustrates a transmission of a segment over a channel with the varying delay D using a SFG with nodes 'Sending' (S) and 'Arrival' (A). The whole transmission process, from (S) to (A) can be statistically described by the MGF $G_D(z)$.
To sum up, in order to calculate the packet delay, the delay generation function of the system has to be obtained. Next, the required calculations from which the final obtaining of PDF and CDF will be possible are shown.
Equations 4.6-4.9 show the matrix Moment Generating Function (MGF) for Figure .

$$\mathbf{G_0(z)} = G_a(z) P_a P_{oa} \quad (4.6)$$

$$\mathbf{G_1(z)} = G_a(z)^2 P_a z^{-RTO} P_{1a} P_a P_{oa} \quad (4.7)$$

$$\mathbf{G_2(z)} = G_a(z)^3 P_a z^{-2RTO} G_a(z) P_{1a} P_a P_{1a} P_a P_{oa} \quad (4.8)$$

$$\mathbf{G_3(z)} = G_a(z)^4 P_a z^{-3RTO} P_{1a} P_a P_{1a} P_a P_{1a} P_a P_{oa} \quad (4.9)$$

The scalar MGF G(z) is obtained from the corresponding matrix MGF by pre-multiplying with the probability vector of transmitting a new block $\pi_1$ and post-multiplying with the column vector of ones.

$$G(z) = \frac{\pi_1 \mathbf{G(z)} 1}{\pi_1 1} \quad (4.10)$$

with

$$\pi_1 = \pi P_{oa} \quad (4.11)$$

Firstly, a link with $\pi = (0.9, 0.1)$ and $z^{RTO}$ of 1 ms is evaluated. This study includes all possible cases of the Path Selector, which means considering zero, one, two and three retransmissions reaching the successful and the failure state. Table 4.1 shows a summary of it.

**Table 4.1:** Delay generation functions

| **Cases of Path Selector** | **Delay Generation Function** |
|---|---|
| Case 0: 0 retransmissions | $G(z)=\frac{0.9}{z}$ |
| Case 1: 1 retransmission | $G(z)=\frac{0.9z^2+0.09}{z^3}$ |
| Case 2: 2 retransmissions | $G(z)=\frac{0.9z^4+0.09z^2+0.009}{z^5}$ |
| Case 3: 3 retransmissions with success | $G(z)=\frac{0.9z^6+0.09z^4+0.009z^2+9\cdot10^{-4}}{z^7}$ |
| Case 4: 3 retransmissions with failure | $G(z)=\frac{0.9z^7+0.09z^5+0.009z^3+10^{-4}}{z^8}$ |

Once analyzed this simple model, the scenario shown in 4.5 (corresponding to the Home Network shown in Section 4.2) is considered. $M_S$ represents the gateway; $M_D$, the destination node and $M_1$ - $M_5$ represent the intermediate nodes of the Home Network. Regarding the path selection, different combination of paths from $M_S$ to $M_D$ are possible, however this work considers two possibilities: $Path_1$ and $Path_2$, where $Path_1$ corresponds to the path $M_S$-$M_1$-$M_2$-$M_3$-$M_D$ and $Path_2$ consists of $M_S$-$M_4$-$M_2$-$M_5$-$M_D$ from source to destination.

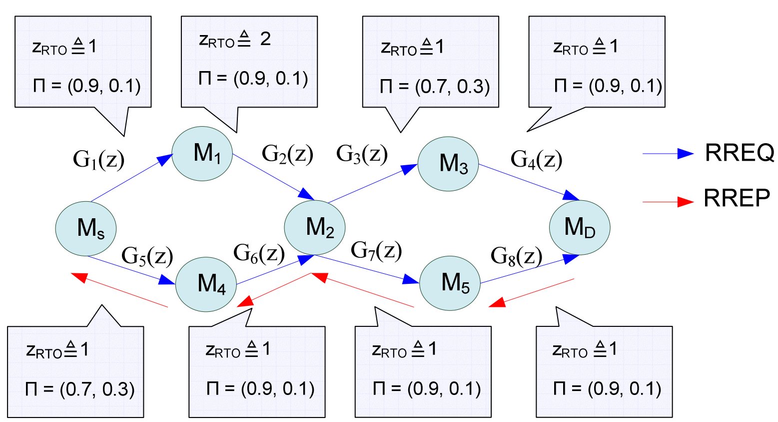


**Figure 4.5:** Scenario of evaluation.

Given this situation, the aim is obtaining the maximum total time that takes to run the algorithm, which includes:

- Time to send the request to the destination
- Timeout which corresponds to the time during the destination is waiting for receiving more possible requests. This value has been defined as the estimation of time corresponding to the 90% of the CDF of delay in the longest path, due to in case of being

higher, one can consider that the path is not good enough to transmit information through it (see Section 4.5).

- Time to send the message of reply to the source.

Since the maximum time is being contemplated, next calculations are based on the worst case, this is when each of the links are assumed to be in case 3. Focusing on the scenario of analysis shown in Section 4.2, uncorrelated links are assumed since the hops use different layer 2 tecnhologies. Equations 4.12 and 4.13 show the calculation of the delay generation function corresponding to each of the possible paths from source to destination that have been considered.

$$G_{Path_1}(z) = G_1(z) \cdot G_2(z) \cdot G_3(z) \cdot G_4(z) \tag{4.12}$$

$$G_{Path_2}(z) = G_5(z) \cdot G_6(z) \cdot G_7(z) \cdot G_8(z) \tag{4.13}$$

where $G_1$(z), $G_2$(z),$G_3$(z), $G_4$(z), $G_5$(z), $G_6$(z), $G_7$(z) and $G_8$(z) are the delay generation functions of each of the links.

After the analysis, values shown in Equation 4.14 have been obtained, where $G_{RREQ}$ is the delay for the request, $G_{RREP}$ represents the delay for the reply and $G_{PS}$, the delay for path selection. More details about the results are explained in Section 4.5.

$$G_{RREQ} = 31ms;\ G_{RREP} = 28ms;\ G_{PS} = 67ms \tag{4.14}$$

## 4.5 Results of analysis

This section shows the statistical functions of PDF and CDF corresponding to the delay generation functions after the calculations with Matlab. PDF is used in order to analyze how probabilities of an event are distributed, whereas CDF represents the probability of receiving an outcome or a lower one. Firstly, the results obtained from a simple model consisting of a link with a BLER of 0.1 and $z^{RTO}$ of 1 ms are analyzed.

The distribution of probabilities is shown in Figure 4.6. After the first try, the probability of success is 0.9 as it can be foreseen by the transition probability $p_{21}$. If the packet does not reach the destination, a first retransmission is executed 1 ms later, being the probability of success of 0.09 and likewise, for a second retransmission in which case, probability is 0.009. Finally, whether the successful state is reached after the third retransmission the expected probability is 0.0009. After all the possible retransmissions, the failure state is reached with a delay of 8 ms and a probability of 0.0001.

As it can be observed, the probability of success is $(p_{12})^n \cdot p_{21}$ where $n$ is the number of attempts and in case 4, $(p_{12})^n \cdot p_{12}$.

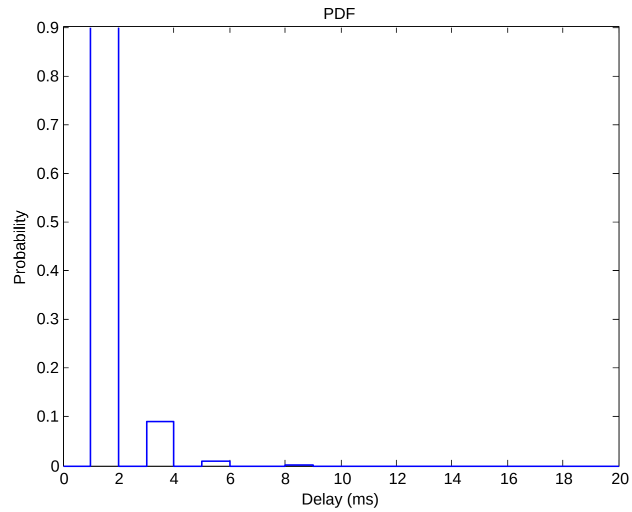


**Figure 4.6:** PDF of delay for a single link.

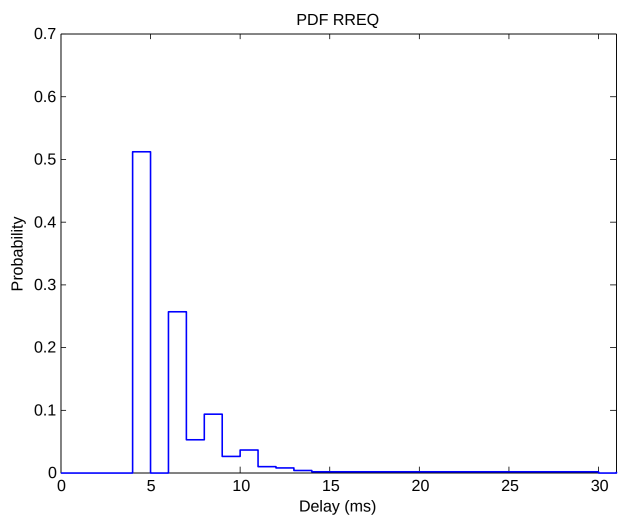


**Figure 4.7:** PDF of delay for RREQ via $Path_1$.

Figures 4.7 and 4.8 correspond to the PDF of each of the paths analyzed in section 4.4 (related to the scenario of analysis) considering all the links in case 3. As it can be noticed, the addition of probabilities is one as expected, and probabilities are distributed according to the quality of channel defined by the parameters previously shown.

Probability of success delivering RREQ from $M_S$ to $M_D$ along the $Path_1$ path is distributed as seen in Figure 4.7. The maximum value is 0.51. The distribution starts at the instant of 4 ms since $G_0(z) = 1$ms and the path consists of four links. At the instant of 31 ms, PDF takes the value of 0.

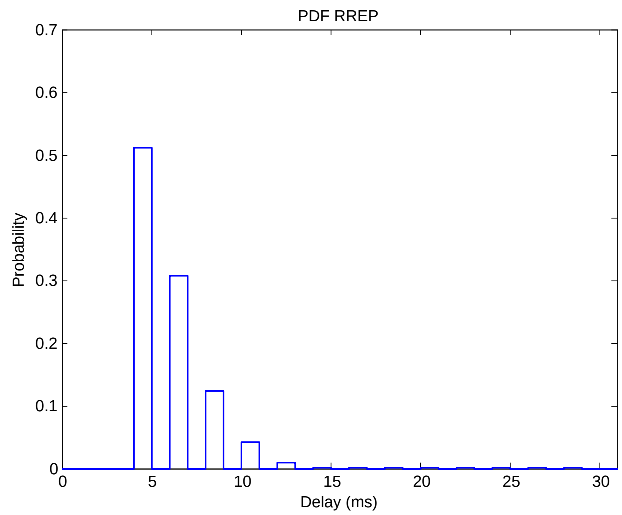


**Figure 4.8:** PDF of delay for RREP.

This PDF corresponds to the delay which takes forwarding RREP from $M_D$ to $M_S$. The maximum value is 0.51. 28 ms is the maximal time.

CDF are depicted by Figures 4.9 and 4.10. The value of time belonging to the maximal CDF is the delay to send a RREQ message, and similarly for the RREP. The maximal value of the CDF is not exactly one for the shown interval due to the maximum of 3 retransmissions which cause infinite delay for some packets.

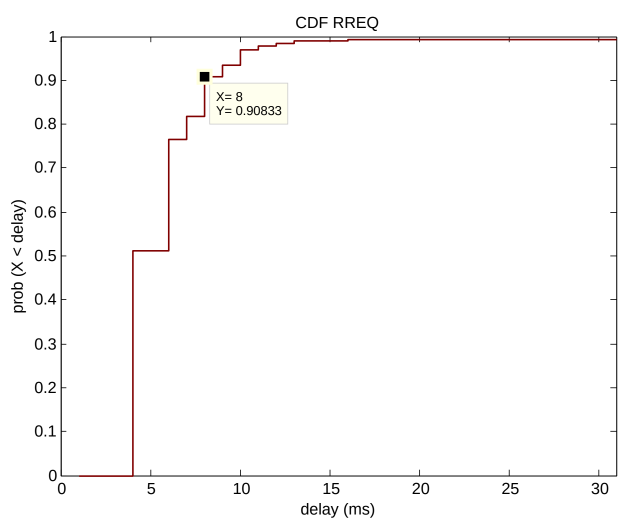


**Figure 4.9:** CDF of delay for request.

Cumulative Distribution Function corresponding to the delay for request takes a maximum value of 0.9916 for a delay of 31 ms.

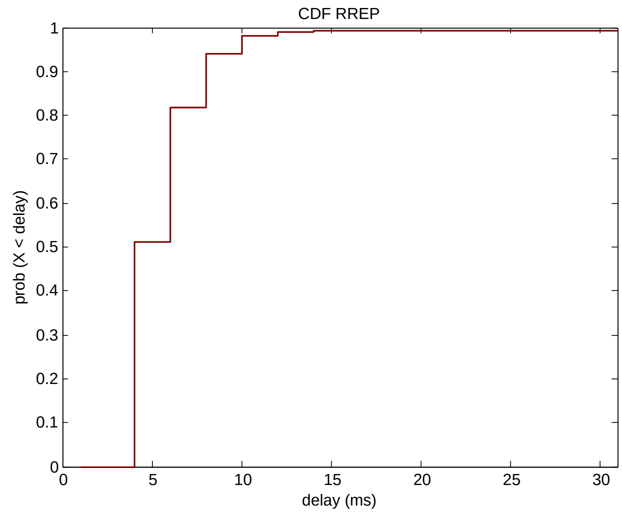


**Figure 4.10:** CDF of delay for reply.

The maximal value of the CDF of delay for reply is similarly, 0.9916.
After the graphical analysis, the aim of this work can be fulfilled with the calculation of the total time. Equation 4.15 shows the time of request and the time of reply, taking into account that each of the messages is transmitted through different paths.

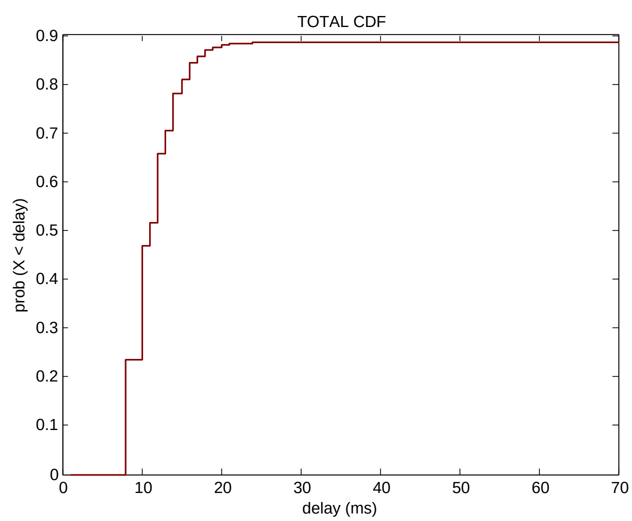


**Figure 4.11:** CDF of delay for path selection.

$$T_{RREQ} = 31ms; T_{RREP} = 28ms \quad (4.15)$$

As explained in Section 3.4.2, once the RREQ has reached node $M_D$, it waits for a time during which more requests from other paths can be received. This concept has been defined in Section 4.4 and Figure 4.9 shows graphically the origin of this value (8 ms). Equation 4.16 shows the total time and Figure 4.11 illustrates it.

$$T_T = T_{RREQ} + T_{TO} + T_{RREP} = 31ms + 8ms + 28ms = \mathbf{67ms} \tag{4.16}$$

## 4.6 Comparison between centralized and local repair path re-selection

As explained in Chapter 3, two modes of operation for path re-selection can be defined. This section analyzes and compares both of them in terms of delay.
Focusing on the scenario shown in Figure 3.11 (Section 3.4.4) and assuming the following parameters: $z^{RTO} = 1$ms, $\pi = (0.9, 0.1)$ and hop limit set to 3, a fail in link L5 is considered. If a connection between node 1 and node 7 is required, three paths are possible as shown in Figure 4.12. However, only paths P1 and P2 would be available after the failure; P1 is the path which has been analyzed.

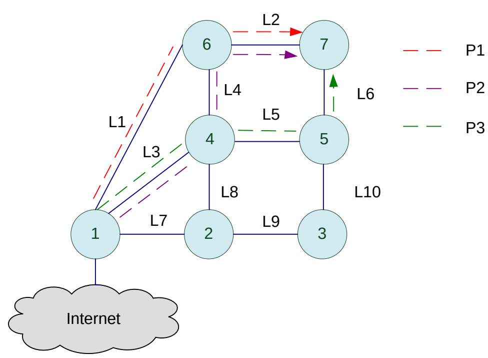


**Figure 4.12:** Home Network with possible paths.

As mentioned in Section 3.4.4, the centralized mechanism needs a time required for the error signalling, which involves that node 4 will send a message of error to node 1 in order to notice the failure. Once again, signal flow graph is modelled as seen in Figure 4.13 in order to obtain the value of $T_{RERR}$.

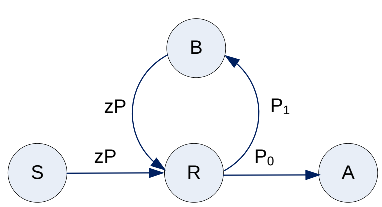


**Figure 4.13:** Signal flow graph for the error signalling.

Equation 4.17 shows the delay generation function corresponding to the error signalling delay.

$$G(z) = \frac{0.9}{z - 0.1} \tag{4.17}$$

In figure 4.14, PDF of $G(z)$ is depicted, the delay of error signalling can be noticed as 4 ms.

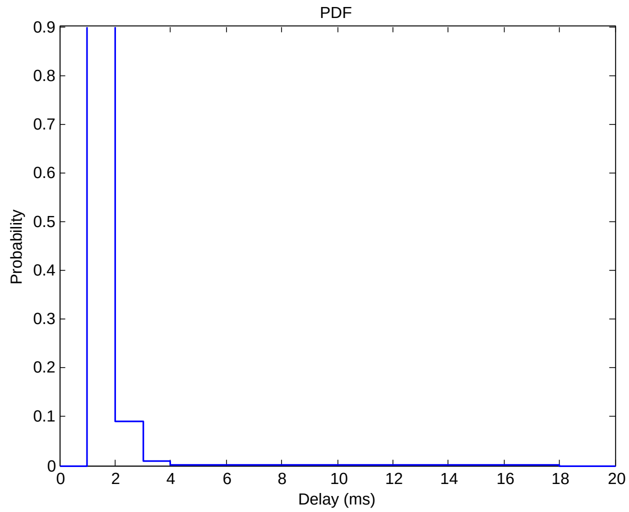


**Figure 4.14:** PDF of delay in error signalling.

Once the RERR message has reached the gateway (node 1), the flooding of RREQ messages can be initiated. In this case, this message will be forwarded through P1 and P2 due to the failure of L5. Figure 4.15 shows the PDF of the delay generated through path P1 while forwarding messages of request and reply, whereas Figure 4.16 corresponds to the CDF. As previously explained, timeout is defined as the 90% of the CDF, so that in this case it takes the value of 3.5 ms. After the timeout, node 7 sends the RREP to node 1 through P1 assuming that its cost is lower than the cost of P2. Similarly, Figure 4.16 illustrates the delay referred to the RREQ and RREP message (14 ms), in this case also valid for the local repair. Equation 4.18 shows the total time required using the centralized mechanism.

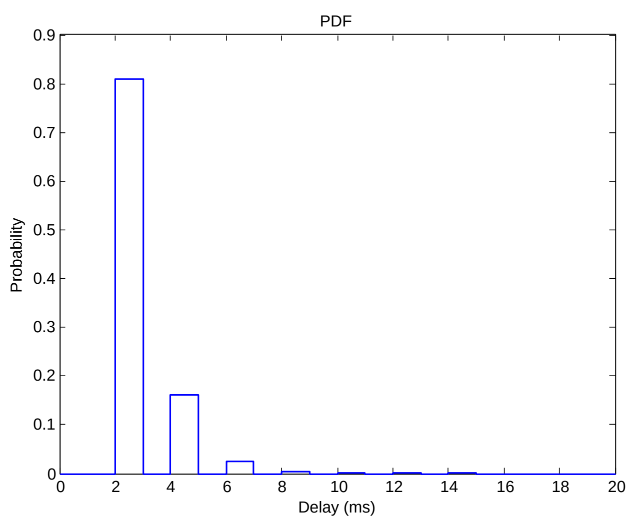


**Figure 4.15:** PDF of delay in request and reply in centralized mode.

Probability of success delivering RREQ and RREP is distributed as seen in the figure 4.15.

The maximum value is 0.81. The distribution starts at the instant of 2 ms since $G_0(z) =$ 1ms and the path consists of two links. At the instant of 14 ms, PDF takes the value of 0.

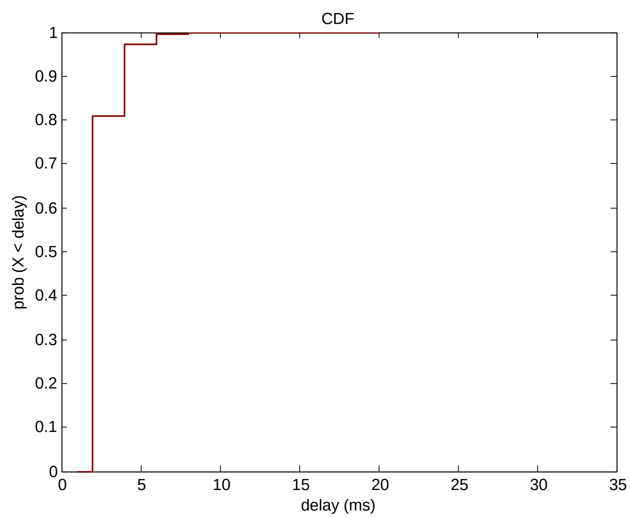


**Figure 4.16:** CDF of delay in request and reply.

CDF takes the maximum value (0.9998) when time is 14ms, therefore this is the delay of request and analogously, of reply.

$$T_T = T_{RERR} + T_{RREQ} + T_{TO} + T_{RREP} = 4ms + 14ms + 3.5ms + 14ms = \mathbf{35.5ms} \quad (4.18)$$

Regarding the decentralized mode, node 4 (upstream node) starts the flooding directly without notifying the failure state to the gateway. Therefore, the total delay for the path re-selection includes the request, timeout and reply processes. The reply is executed via P2 (and not P1) due to the node that initiated the request is included in this path and if it does not receive a RREP after a certain period of time, the local repair request fails and a RERR packet is sent to the source node. Details about corresponding analysis are summarized in Equation 4.19. Figure 4.16 is also valid for the request and reply of the local repair solution since both paths consist also of two links with the same assumed conditions as in the centralized case. Figures 4.17 and 4.18 show the total CDF for both situations.

$$T_T = T_{RREQ} + T_{TO} + T_{RREP} = 14ms + 3.5ms + 14ms = \mathbf{31.5ms} \quad (4.19)$$

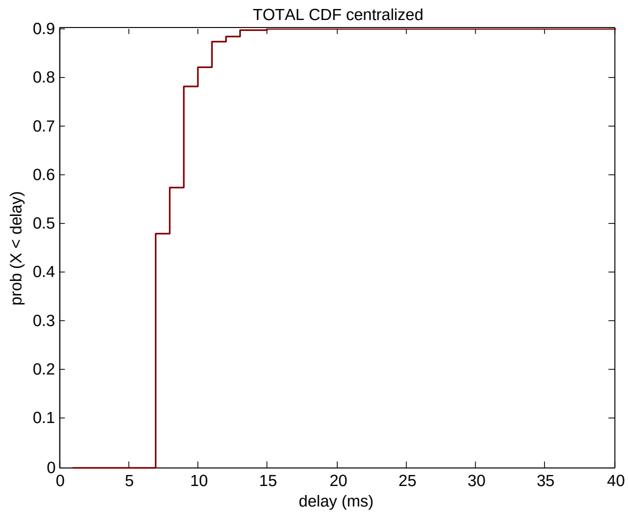


**Figure 4.17:** CDF of delay for centralized path re-selection.

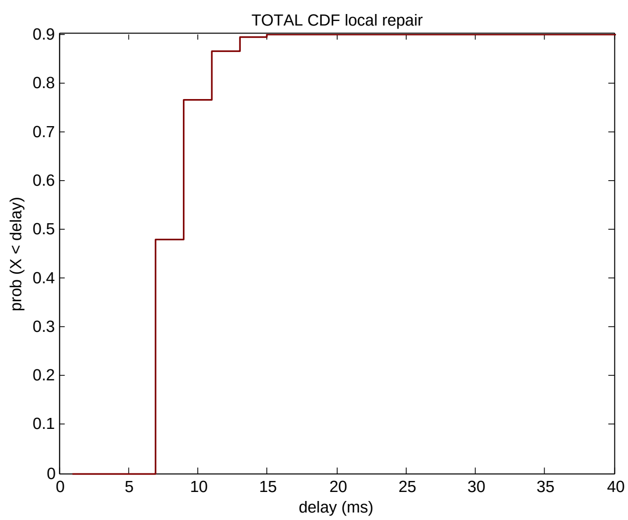


**Figure 4.18:** CDF of delay for local repair.

In this analysis, three parameters have been considered: the delay of retransmission, the number of retries and the hop count. As it has been shown, the value of the total delay (Qos parameter evaluated) is function of these conditions, therefore the QoS needs of the different applications can be adapted setting the mentioned parameters.

CHAPTER 5

# Conclusions and Outlook

## 5.1 Theses

The result of this work gives answer to the following theses:

- It represents a framework for the setup of retransmissions according to the QoS of the required applications.
- The SFG analysis is suitable to model IWF, like the path selection, and provides results in order to evaluate the SUC parameters.
- Regarding the path re-selection, the latency of a centralized mechanism is higher than in decentralized solutions due to the delay includes the time necessary for the error signalling while in the decentralized, path re-selection involves directly the discovery of a new path.

## 5.2 Summary

During this work, Convergence Layer and Interworking Functions have been evaluated. In order to get a descriptive model of the most important functions, the concept of use case has been applied.

After describing some of the main IWF for the InterMAC layer, the path selector has been developed in detail. Its functions deal with finding a suitable path between the source and the destination (flow establishment) within a heterogeneous network and providing simultaneously with the required resources. For this purpose, the research of routing algorithms in ad hoc wireless networks has been required, leading the study to a protocol based on the BGSR algorithm.

Once defined the mechanism used by the protocol, the analytical evaluation has been carried out. The analysis of the selected IWF has involved an evaluation based on SFG and a subsequent one with Matlab. Both analysis are focused on the delay generation function derived from the exchange of messages which flow establishment and reservation of resources require. All investigations assume the worst case in the operation of the algorithm since the calculation of the maximum delay has been the considered goal.

In order to model the path selector, several assumptions about the network have been made; these are related to the link conditions defined by the BLER and the delay of retransmission. The statistical tools obtained and analyzed in this work have been PDF and CDF due to they give information about the delay and the distribution of probabilities.

The next step has focused on the study of path re-selection mechanisms. Since mobile ad hoc networks do not rely on any fixed infrastructure, an optimal re-selection of paths might be a topic of special interest. The analysis has consisted of comparing between two possible solutions: centralized, in which any failure has to be notified to the gateway of the network; and decentralized, characterized by the lack of error signalling. Centralized solutions imply that the load in the central node can increase strongly when the number of nodes that need services increases, whereas in decentralized solutions the network load will be more equally spread over the network. In terms of scalability, both solutions are using broadcasting messages since the algorithm of BGSR is based on flooding mechanism

(although in the centralized mechanism, the message of error is unicast) so assuming the same situation both in centralized and decentralized, the burden on the network does not make a big difference.
To sum up, the result of this work gives answers to the identification of interworking functions for heterogeneous networks providing an analytical evaluation of the path selection and a comparison between centralized and decentralized solutions for the path re-selection.

## 5.3 Outlook

This thesis has shown an analytical study of path selection using SFG and the simulation of home networks' scenarios. The evaluation of QoS parameters has provided results which might be useful in order to consider de satisfied user criteria.
Future works could focus on the study of other parameters different from the delay generation function which could also evaluate several QoS criteria. Keeping on the same line, another algorithm could be considered in order to improve the selection of path and analyzing its delay and other parameters as well.
Another possibility would be developing a similar study with other IWF belonging to the InterMAC layer, some of which have already been described in this work. Performing an analysis of the main functionality for heterogeneous networks is an essential task for the evaluation of OMEGA technologies and this investigation represents part of the work.

# LIST OF FIGURES

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| 3GPP | 3rd Generation Partnership Project |
| AP | Access Point |
| BGSR | Bandwidth Guarantee Source Routing |
| BS | Base Station |
| CDF | Cumulative Density Function |
| CL | Convergence Layer |
| DLC | Data Link Control |
| DLL | Data Link Layer |
| DSR | Dynamic Source Routing |
| DSL | Digital Subscriber Line |
| FP7 | Seventh Research Framework Programme |
| IP | Internet Protocol |
| IWF | Interworking Function |
| HGI | Home Gateway Initiative |
| HMM | Hidden Markov Model |
| HN | Home Network |
| HNID | Home Network Infrastructure Device |
| HWO | Hybrid Wireless Optical |
| ICT | Information and Communication Technologies |
| L2 | Layer 2 |
| LTE | Long Term Evolution |
| MAC | Medium Access Control |
| MFG | Moment Generation Function |
| MICS | Media Independent Command Service |
| MIES | Media Independent Event Service |
| MIH | Media Independent Handover |
| MIHF | Media Independent Handover Function |
| MIIS | Media Independent Information Service |
| MN | Mobile Node |
| OLDA | OMEGA Legacy Device Adapter |
| PDF | Probability Density Function |
| PDU | Packet Data Unit |
| PLC | Power Line Communications |
| PMF | Probability Mass Function |
| PoA | Point of Attachment |
| PoS | Point of Service |
| QoS | Quality of Service |
| RREQ | Route Request |
| RERR | Route Error |
| RREP | Route Reply |
| SFG | Signal Flow Graph |
| SUC | Satisfied User Criteria |
| UWB | Ultra-Wideband |
| WiFi | Wireless Fidelity |
| WiMAX | Worldwide Interoperability for Microwave Access |
| WLAN | Wireless Local Area Network |

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