Wireless Software and Hardware platforms for Flexible and Unified radio and network controL

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***Abstract*—Wireless networks have recently evolved to very complex systems, due to the increasing diversity of competing radio technologies, applications and service providers which coexist in the same environments. In such a scenario, we argue that performance optimization cannot only rely on advanced hardware platforms and radio capabilities, but mainly depends on the availability of suitable software platforms for controlling and coordinating radio communication and network protocols within the complex wireless ecosystems. The WiSHFUL project addresses these issues by proposing a flexible and unified radio and network control framework for standardized technologies as well as Software Defined Radios.**

I. Introduction

Recent trends in the development of information systems require innovative wireless solutions. In addition to the existing and ever increasing human generated data traffic, machine generated traffic from the Internet of things, the Industry 4.0, the Tactile Internet and the ambient assisted living are quickly adding to the pressure. Wireless communication networks supporting these trends will have to simultaneously support time-critical as well as delay tolerant traffic, high as well as low data rate traffic, highly dynamic and ad-hoc networks, and should furthermore be capable to scale according to temporal demand fluctuations on different time-scales. This emerging ecosystem can be compared to existing ad-hoc network scenarios for large public events or emergency situations, albeit at a different scale and complexity.

The 5G mobile wireless communications already address these emerging challenges by proposing complex systems that comprise multi-spectral band communication including NFC (Near Field Communication), Bluetooth, mmWave, GSM macro-cells and sub-GHz [1]. Such emerging infrastructure has to be a) sufficiently open to allow the gradual integration of technologies and b) sufficiently flexible and dynamic to quickly respond to highly fluctuating and varying traffic demands.

The widely available off-the-shelf hardware and software comes in the form of radio chips which implement only the obligatory parts and some arbitrarily selected optional parts of wireless standards, offering poorly documented interfaces and restricted drivers, being either closed or limited in functionality. Consequently, the openness and flexibility of these hardware platforms are very limited. Both wireless system developers (in particular in smaller companies) and researchers see that even minor tweaks or adaptations generally require huge effort and corresponding cost. On the other hand, powerful Software Defined Radio (SDR) platforms are available which offer excellent flexibility at the physical layer (waveform, modulation and coding schemes, spectral range, centre frequency, etc.). The problem with these platforms is that they typically lack high-level specifications and programming tools as well as standard APIs for embedded code development.

Currently, solutions for wireless provisioning on large public events or in emergency scenarios mostly rely on closed systems in which the entire wireless infrastructure –consisting of access points and/or base stations, and control network– is optimised as a proprietary black-box. It is not clear, however, how well such solutions perform in case of heterogeneous networks, especially when a multi-vendor approach is adopted. The effect of Bluetooth on the performance of the WiFi network on large events, for example, is hard to predict and generalize into an interference model. Also the openness and flexibility of the control network of these systems is very limited today, while a 5G scenario as described in [1] is hard to imagine without an open network control interface.

In this paper, we propose unified radio and network control interfaces for off-the-shelf as well as advanced SDR equipment that allow customizing wireless access solutions for specific networking and traffic contexts. The proposed unified radio control abstracts hardware specific instructions and thus enables full, vendor-independent radio control, while the unified network control allows rapid prototyping and adaptations of network protocol stacks in a heterogeneous, multi-vendor environment. These abstractions allow experimenting with flexible control of radio communication and network stacks, in turn enabling intelligent, node-level and network-wide decisions on radio and network operation modes and settings, driven by higher-level domain-specific application demands and taking into account external policies (e.g, policies for dynamic spectrum access). The proposed concepts will be realized and demonstrated on readily available public wireless experimentation infrastructures developed within FIRE[1], which allow to quickly prototype and test innovative solutions in real environments, thus speeding-up the development cycles.

Section II of the paper introduces the driving scenario behind the WiSHFUL vision on future-proof wireless solutions. Section III introduces the WiSHFUL concept, deriving a set of necessary requirements from the wireless network architecture to increase its flexibility and thus enable the measures identified previously. Section IV explains how these concepts will be validated on existing wireless testbeds. A summary and a brief look on the future conclude this paper.

II. Driving Scenario

The scenario considered in our work refers to the emerging wireless ecosystem, where multiple technologies, operators and service providers coexist in the same environment characterized by a high-density deployment of wireless devices. Because of the heterogeneous capabilities of the devices (in terms of spectral bands, coverage, management functionalities, networking models, etc.), the lack of open vendor-independent configuration interfaces, and the conflicting goals of independent providers, the integration of these technologies is currently very limited.

Indeed, wireless devices employ one or more radio interfaces implementing specific wireless standards (such as LTE, WiFi, Bluetooth), while in niche contexts more advanced programmable interfaces, based on SDR, may also be available. These devices are generally organized into coexisting wireless systems, including: 1) peoples' body area networks (BAN), 2) their gateways to the Internet (i.e, typically tablets and mobile phones) and the relevant access network, 3) smart buildings, smart cities or more generally speaking, smart environments.

The BAN is usually composed by wearable well-being or health related sensors, micro-cameras or implants, cognitive and physical augmentation devices (as glasses and retina displays), etc., which are connected to a gateway or mobile device and possibly interact with a robot companion or assistant (particularly in case of elderly or disabled people). The access technologies are mainly represented by cellular technologies and WiFi, while building and city automation systems are equipped with massive low-cost/low power devices, intelligent cameras, and pervasive access points.

Different wireless services with heterogeneous requirements can be simultaneously active in the ecosystem, such as access to the Internet, collection of monitoring or metering data, support of mission-critical machine-type communications (MTC) and other reliable services for security and business purposes. Each service may depend on the specific context of daily life. First, one rather static and controlled context is the home environment (the same scenario can also be applied in most small office environments). Second, a mostly mobile and dynamic context is given by a smart city where users move by foot or vehicles (the same scenario could be considered for large working environments such as certain factories and production environments). Third, a very dense and somewhat ad-hoc scenario is represented by the participation at a large public event.

A. Home usage scenario

Despite their apparent simplicity, the manageability of home networks is compelling. First, since several wireless technologies operate on the same frequency bands and several home networks interfere each other, it is necessary to consider coexistence and coverage problems. Adopting different spectrum portions for different applications (licensed cellular frequencies, 5 GHz, 2.4 GHz or lower frequencies as the TV white-spaces)

[1]FIRE facilities: http://www.ict-fire.eu/home.html

can help in mitigating coexistence problems. Second, devices operating in the home belong to different actors: the user (i.e., the home owner), who wants to configure its monitoring and automation system according to personal preferences; the Internet service provider (ISP), that installs its gateway at the users home for offering its services; other service providers (e.g., IP-TV, heath-care service), that provide a service from outside the home to user devices; other utility providers (e.g., the electricity provider), that install smart meters at the users home for performing remote readings. Every actor may access a limited fraction of devices and, even when allowed to modify the device configuration, it has a limited control on the device positioning (which is ultimately decided by the users). Third, environment and interference conditions are time-varying, because they depend on the presence of users at home. Critical co-existence problems and capacity issues may occur at evening or during the holidays, when the boosting of traffic generation can significantly degrade performance.

B. Smart city usage scenario

Apart from cellular access networks, we assume that a smart city is equipped with a pervasive wireless infrastructure offering local connectivity. We can distinguish two situations: one in which a person walks and one in which a person drives (or is driven in) a vehicle along the city.

Walking in places that are not crowded poses no particular challenges, however walking in very crowded environments such as subway stations, shopping streets, historical centres, etc. can result in low data-rates, intermittent connections with the infrastructures, and serious inter-BAN interference. The overloaded network can, however, be optimised by applying a mix of frequency diversity, channel allocation, power control, etc. techniques. When driving a vehicle, the typical user has limited needs for data. However, when people drive alone in self-driving vehicles, they will likely behave similarly as they do on trains when commuting nowadays. This involves working possibly over a VPN connection to the corporate network, surfing the web, using social networking apps and watching (streaming) videos. Some of these activities may require a reliable data connection of relatively high bandwidth. Additional services may include consumption of multimedia (including 3D visualizations) information about landmarks retrieved based on the position may be particularly relevant for tourists.

The smart city also has wireless sensors in trash-bins, traffic lights, light poles, parking spaces, etc. These can be optimised geographically not to interfere with each other and mostly use lower frequencies to increase coverage.

C. Public event usage scenario

In case of public events, a dedicated wireless infrastructure (based on WiFi technology or LTE-A in unlicensed bands) is pre-installed in the hosting venues or public spaces.

Typical participants to the event want to Tweet their experience, upload photos and videos, check what other friends share, and possible check also news. A class of users represented by the staff manning the venue or some special service staff need reliable wireless services for security or business applications. Emergency applications, which require to be served with the highest possible priority and reliability, may also take place at large public events.

In this context, the design of the wireless infrastructure is very complex because of the high-density of users and significant variability of capacity requirements (that can be strongly dependent on location and time). The high density of devices can create serious interference problems between neighbour BANs or BANs and environmental MTC/IoT technologies, which require some coordination strategies for selecting the channels, transmission powers and operating intervals of different network segments. The variability of the capacity demand can be faced by deploying a dynamic network infrastructure, in which access points can be switched on and off, can work on different bands, and can tune their coverage range according to the network status and performance. To this purpose a control network has to be deployed for monitoring and configuration purposes.

III. The WiSHFUL Concept

From the description of the previous scenarios, it is evident that the static planning and configuration of wireless infrastructures and devices (today still faced with intense manual work) can be significantly inefficient. Moreover, performance optimization cannot be just a matter of the availability of advanced hardware platforms and radio capabilities (such as MIMO, beamforming, spectrum agility, etc.), but mainly depends on the availability of suitable software platforms for controlling and coordinating radio communication and network protocols within the complex wireless ecosystems.

In this direction, the WiSHFUL project proposes an architecture for wireless systems devised to enable the definition of cognitive adaptations of radio operation and automated run-time network intelligence, by means of flexible and unified radio and network control. With flexible control we mean the possibility to maximize the configuration space of the devices, exploiting all the radio functionalities and programmable protocol logics supported by the radio and platform hardware. With unified control we mean the possibility to expose platform-independent programming interfaces over very

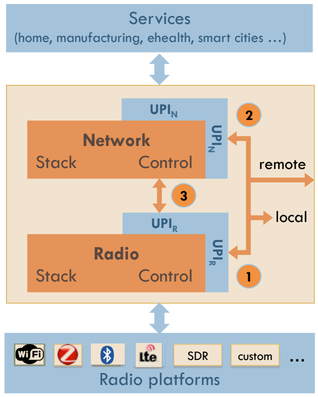

Fig. 1. Illustration of the functional blocks and the Unified programming interfaces.

heterogeneous hardware platforms, including standardized technologies and SDR platforms. WiSHFUL adopts the general idea of software defined networking (SDN), implemented in core IP networks, and applies it to the more heterogeneous access networks.

Figure 1 summarizes this general project vision. The figure provides a conceptual view of the blocks foreseen for the resulting architecture. Existing devices feature radio driver software comprising PHY and some low-level MAC functionality and a network stack comprising some higher-level MAC and upper layer functionality depending on the implementation [2]. In our vision, the radio and networking software can be extended with control functionality (i.e, radio and network control blocks in the figure) and the extension also exposes the corresponding configuration interfaces that can be used for interaction with both local and global (network-wide or cross-network) entities, such as intelligent control engines or application layer services. The intelligence engines are not shown in this figure. The clean separation between radio control functions and network protocol functions is envisioned to break the current monolithic implementation of wireless stacks, thus alleviating future radio driver and networking software development efforts drastically, while preserving reliability and time accuracy constraints of radio and networking operations.

A. Flexibility Requirements

In order to design the WiSHFUL software components for different radio platforms, we started from the analysis of the flexibility requirements emerged in the driving scenarios. The requirements have been categorized into three groups, which refer to configuration options desirable for wireless infrastructures, end user devices, and SDR platforms.

Wireless Infrastructures. The following, non exhaustive, set of requirements have been identified for improving the coverage and the capacity of wireless infrastructures.

- Activate more Access Points (APs) while lowering the transmit power of the already active ones (i.e, increase capacity in the space domain).
- Switch to a higher EM frequency, increasing the capacity while lowering the coverage of a single AP (i.e, increase capacity in the space domain).
- Increase the number of EM frequencies that are used (i.e. increase capacity in the frequency domain).
- Avoid interference by optimizing the frequency selection so that the APs within the same collision domain use different EM frequencies.
- Downlink optimization: by prioritizing certain application streams the capacity of high priority traffic can be ensured while low priority traffic is best-effort.

Users' end devices. This set of requirements has been identified for improving the utilization of the wireless resources and coordinating multiple technologies available on the user side. Examples of these requirements are:

- Traffic shaping on the users' end devices allows a more fine-grained planning of the required bandwidth (i.e, demand side control).
- Dynamic frame aggregation allows increasing the number of aggregated frames when the channel is stable. Frame aggregation reduces the protocol overhead and increases the good-put.
- Use a cross-technology TDMA protocol to increase the capacity in the time domain by coordinating the transmissions between different technologies within the same collision domain.
- Incorporate seamless handover to reduce control traffic necessary for roaming from one technology to another. Hard hand-overs (WiFi = break and make) can be replaced with soft hand-overs (UMTS = make and break).
- Based on the type of application stream the most optimal technology can be selected (i.e, automatic technology selection).

SDR platforms. SDRs can offer even more fine-grained control by extending the possible reconfiguration options, which are typically shielded from the end-user in COTS network interfaces:

- By re-aligning the centre frequencies of each wireless channel more channels can be co-located in the same ISM band.
- By adjusting (e.g, decreasing) the guard bands between wireless channels, more of them can be squeezed into the same ISM band, OFDM and Filter Bank Multi-carrier (FBMC) providing an upper limit in terms of spectral density

[2]Linux wireless subsystem: https://wireless.wiki.kernel.org/en/developers/documentation

- By dynamically selecting the (de)modulation techniques based on the channel quality, the optimal data rate can be obtained for a given channel quality. Combining this with OFDM, yields DMT, a technique well known in xDSL systems, with opportunities in the wireless domain

B. Unified Programming Interfaces

The Unified Programming Interfaces (UPIs) proposed in WiSHFUL enable easy and flexible radio and network control both for standardised technologies and SDRs. Using the UPIs, intelligent engines can optimize towards specific network requirements and fine-tune the behaviour of any networking layer. We distinguish two types or UPIs: one for radio control (UPI_R) and one for network control (UPI_N) as depicted in Figure 1.

UPI for Radio Control The UPI_R enables intelligent engines (both local and external) to retrieve information from the radio as well as controlling its behaviour. For instance, the intelligent engine is able to retrieve information such as binary spectrum occupancy value, raw I/Q samples, RSSI, LQI, duty cycle info and error statistics. The engine can also control the behaviour of the radio such as setting modulation and coding type, power levels, beam forming parameters, transmission timings, etc. Apart from the utilization of a simple parametric control model, we also envision the possibility to define more advanced configurations based on novel abstractions of the radio. In this case, the UPI_R allow to program the radio behaviour according to the supported abstractions and domain-specific programming languages. For example, the radio behaviour can be described in terms of state machines [2] or time-annotated chains of radio instructions [3], which are programmed by specifying the hardware primitives to be called when hardware signals are detected in a given logical state.

UPI for Network Control The UPI_N enables intelligent engines (both local and external) to retrieve and aggregate information from the network as well as controlling its behaviour. Examples of network information are the topology, the congestion level of links or paths, the selected routing algorithm, the available traffic classes and flow-level statistics. Network configurations enabled by UPI_N involve the set-up of logical associations/links among the nodes, mapping of traffic flows into queues with different priorities and specific radio configurations, flow control among multiple real/virtual radio interfaces, network coding of different traffic flows, etc. Also for network control, we envision the possibility to introduce behavioural abstractions devised to specify the network configuration in a compact domain-specific language. For example, the rules for forwarding the packets belonging to different traffic flows across different links and radio interfaces can be specified in terms of tables with conditions to be matched and relevant actions.

C. Intelligence

The UPI_R and UPI_N interfaces can be used by local and global intelligent engines to gather node-local or network-wide information and to dynamically select the most optimal radio and network configurations. For supporting network-wide dynamic configurations, it also required to enable some basic control services, such as synchronisation, monitoring and triggering of synchronised actions at multiple devices (for example for interference coordination).

Intelligent engines can work on different models and scopes such as local, global or hybrid (with some forms of central or distributed control). Moreover, they can work separately on the network stack and radio stack, or they can work on the whole device configuration. As an illustrative example, in the following we briefly describe how the typical problem of WiFi and ZigBee coexistence can be faced under the three different optimization scenarios.

Case 1. Assume that traditional network stacks are deployed on a WiSHFUL cognitive radio, able to implement the WiFi and ZigBee transceiver and to expose the UPI_R interface. In case WiFi nodes are involved in a low-rate traffic flow, the intelligent engine can reduce the operation bandwidth of WiFi nodes (e.g, by down-clocking the OFDM modulator) in order to avoid interference with the overlapping ZigBee channel.

Case 2. Assume that WiSHFUL cognitive network stacks, exposing the UPI_N interface, are deployed on traditional off-the shelf WiFi devices. In case the WiFi devices interfere with low-power ZigBee nodes and no orthogonal channel is available, the intelligent engine can configure the WiFi legacy MAC for working with a portion of the WiFi beacon interval in contention-free mode. This configuration prevents WiFi nodes from periodically contending for the channel, thus leaving some channel resources to low-power ZigBee nodes.

Case 3. When the devices are based on a full WiSHFUL cognitive stack, exposing both UPI_N and UPI_R interfaces, more advanced optimizations are possible. The intelligent engine can configure all the devices (either the ones implementing the WiFi transceiver and the ones implementing the ZigBee one) for recognizing a common synchronization signal and employing a cross-technology TDMA (as demonstrated in [4]). Since different technologies work on independent time intervals, the same cognitive radio can support two virtual radio interfaces and switch from one mode to another according to the traffic type. This requires an opportunistic configuration of the radio and lower (i.e, time critical) MAC operations, as well as a configuration of the flows classification and forwarding policies.

IV. Realization

The WiSHFUL concept will be demonstrated by: i) developing the software components described in Figure 1 for different standard technologies and SDR platforms; ii) implementing some exemplary intelligent engines for demonstrating the set-up of the control network and the utilization of the unified programming interfaces in specific use cases; iii) offering the enhanced hardware and software platforms to external experimenters willing to speed-up the design and validation of novel wireless services. Regarding the hardware facilities, we will work on publicly available infrastructures, such as the existing facilities at w-iLab.t, IRIS, TWIST and ORBIT. These facilities make available a wide range of devices and supporting control infrastructures.

The w-iLab.t Zwijnaarde facility [5] consists of 70 embedded PCs, 15 of which are mobile, located in a pseudo-shielded environment of size 66 by 20 meters. These PCs have attached various radio equipment such as: 80 sensor nodes operating in 2.4-2.48 MHz, 17 software defined radios operating at 2.4 - 2.5 and 4.9 - 5.85 GHz and 100 MHz - 6 GHz, 2 LTE small cells (LTE245F) and 2 dongles (Huawei LTE E398). It also includes an open LTE EPC (SIRRAN EPC LTEnet).

The IRIS facilities are organized into 16 experimentation units, each consisting of three parts: a Linux (Ubuntu 14.04 LTS) virtual machine,

Iris SDR software, and Universal Software Radio Peripheral (USRP) radio hardware. The radio hardware is housed on the ceiling of our dedicated indoor testing space.

The TWIST testbed [6] spans the three floors of a building resulting in more than 1500 m2 of instrumented office space. It is equipped with 200 wireless sensor nodes, working in 868 MHz or 2.4GHz ISM bands. The testbed is also instrumented with 23 commercial off-the-shelf wireless routers working in 2.4GHz and 5GHz bands and mobility can be tested using two robotic-based autonomous mobility platforms.

The ORBIT radio grid, finally, is the de-facto community resource in the US for evaluation of emerging (wireless) network architectures and protocols. The ORBIT testbed at WINLAB [3] is a 20-by-20 array of programmable nodes, with range of wireless (commercial 802.11 a/b/g/n/ac/ad WiFi, Bluetooth, Zigbee, WiMAX and LTE radios, a variety of cognitive radio and SDR platforms such as USRPs, Nutaq, WARP, Avnet and WINLAB engineered cognitive radio platforms) and wired SDN enabled interfaces.

[3]Open-access research testbed for next-generation wireless networks (orbit). [Online]. Available: https://www.orbit-lab.org/

V. Summary and Future Work

We briefly described the WiSHFUL approach to improve the coexistence of standard and advanced wireless technologies, for enabling the development of novel wireless services and highly-customized wireless access infrastructures. The research challenges addressed by the project are mainly related to the design of the control interfaces for driving radio and network stack configurations. Indeed, for trading off easy of configuration and flexibility requirements, it is important to identify suitable abstraction models of wireless devices and compact programming languages. Moreover, for minimizing the signalling overheads on the control network (that it is likely to be wireless, in many practical scenarios), novel control models, mixing centralized and localized decisions, will be evaluated.

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