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SDN@home: A Method for Controlling Future Wireless Home Networks

Pierluigi Gallo, Katarzyna Kosek-Szott, *Member, IEEE,* Szymon Szott, *Member, IEEE,* and Ilenia Tinnirello

***Abstract*—Recent advances in wireless networking technologies are leading toward the proliferation of novel home network applications. However, the landscape of emerging scenarios is fragmented due to their varying technological requirements and the heterogeneity of current wireless technologies. We argue that the development of flexible, software-defined wireless architectures, including such efforts as the Wireless MAC Processor, coupled with software defined network (SDN) concepts, will enable the support of both emerging and future home applications. In this paper, we first identify problems with managing current home networks being composed of separated network segments governed by different technologies. Second, we point out the flaws of current approaches to provide interoperability of these technologies. Third, we present a vision of a software-defined multi-technology network architecture (SDN@home) and demonstrate how a future home gateway (SDN controller) can directly and dynamically program network devices. Finally, we define a new type of flexibility enabled by SDN@home. Wireless protocols and features are no longer tied to specific technologies but can be used by general-purpose wireless SDN devices. This permits to satisfy requirements demanded by home owners and service providers under heterogeneous network conditions.**

***Index Terms*—Control protocol, software-defined networking, interoperability of networking technologies, Wireless MAC Processor, wireless networks.**

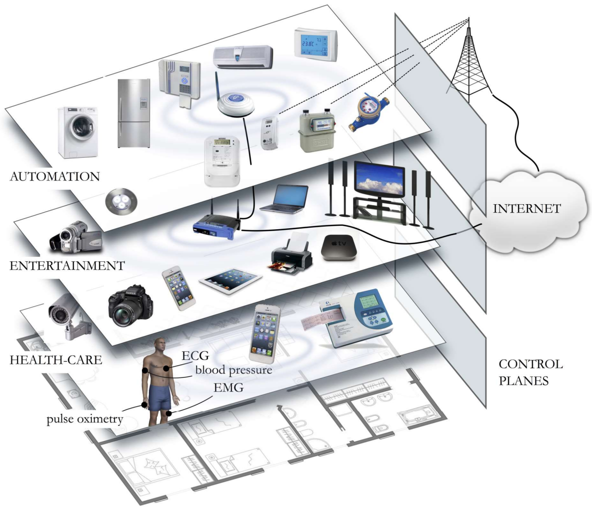

Fig. 1: Current status of home wireless networking: applications are tied to technologies with one gateway per technology/application leading to separated data and control planes.

I. Introduction

We are witnessing an impressive evolution in the use of home network applications. Previously, the main driver has been Internet access, with an access point (AP) used to wirelessly connect user devices, now it is becoming common to use home networks for sharing information between computers and other multimedia devices in the home, e.g., multimedia servers, smart TVs, and cameras, all equipped with a Wi-Fi interface. In parallel, ad-hoc network deployments, based on heterogeneous technologies such as ZigBee or Bluetooth, are becoming popular for monitoring-based applications, including home automation (remote control of electric appliances, smart metering) and providing healthcare services. As a result, current home networks are composed of several segments, such as the *automation* network, the *entertainment* network, and the *healthcare* network – in which tens of devices are independently managed by network administrators, service providers and even home owners (Fig. 1). This may lead to error-prone configurations and severe coexistence problems between *heterogeneous technologies* and *different network actors*, which may impair the quality of service (QoS) for emerging and future home applications [1]. The adoption of *heterogeneous technologies* for managing home network segments is motivated by the lack of a single flexible technology able to effectively work under different application scenarios and, sometimes conflicting, requirements, e.g., low power, high bandwidth. This heterogeneity of standards implies the need of inter-networking solutions for providing service federation in residential networks. Currently, a typical inter-networking scenario is based on a central node, called the *home gateway* (HGW) and classical IP solutions. Alternatively, an abstraction layer is added or a one-for-all technology is proposed (Section II). The existence of *different actors*, independently configuring sub-sets of home devices, is due to the lack of a clear separation between control and data planes. Indeed, in current deployments each service provider is ultimately responsible of creating and maintaining the network segment used by its relevant applications.

In such a scenario, we argue that the paradigm of software defined networking (SDN), recently emerged in the wired domain, can also be beneficial for dealing with the complexity of wireless home networks. In our vision, which we refer to as SDN@home (Fig. 2), the control plane of diverse wireless

P. Gallo and I. Tinnirello are with the Università di Palermo, viale delle Scienze ed. 9, 90128 Palermo, Italy, e-mail: pierluigi.gallo@dieet.unipa.it, ilenia.tinnirello@tti.unipa.it

K. Kosek-Szott and S. Szott are with the AGH University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, al. A. Mickiewicza 30, 30-059 Krakow, Poland, email: {kosek, szott}@kt.agh.edu.pl

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home networks (e.g., entertainment, automation, healthcare) is separated from the data plane – similarly to the approach proposed by OpenFlow [2]. The control plane is managed by a specialized *network administrator* who manages the HGW by installing software provided by *network programmers*, which allows avoiding conflicts and performance impairments between different *service providers* as well as satisfying *home owner* expectations. Consequently, in SDN@home, the multi-technology HGW acts as a central controller. The centralized control of wireless home networks is made possible with the help of a common control protocol and a common programming language understood by all wireless devices (cf. Section III-C).

HGWs are already exploited for facilitating the coexistence of wireless devices operating on the same bandwidth and optimizing relevant radio settings, or for providing context information (e.g., spectrum availability) and facilitating the coordination among neighboring home networks [3]. However, current optimizations are restricted to the tuning of a limited number of technology-specific network parameters, i.e., *parametric network control*. Additionally, in the wired SDN, network control mainly consists of diverting flows over a fixed physical topology, which is not enough for wireless SDN which must also involve the configuration of the physical links. Our idea is based on empowering the HGW's control role by means of a southbound interface (using the SDN terminology) able to drive the home devices through the loading, configuring, enabling and disabling of key configuration elements such as radio settings, queuing policies, per-flow rate limiters and even medium access policies, i.e., *flexible network control* (Fig. 2).

The contributions of this article include presenting a novel vision for a wireless SDN in a new context extending our previous work [4] to heterogeneous networks (Section III-A); presenting a generic architecture of programmable wireless devices (Section III-B) with a unified control protocol and centralized management (Section III-C); and presenting examples in which wireless device programmability has clear advantages over parametric control (Section IV). We conclude the paper with open research areas (Section V).

II. Interoperability of Network Technologies

As shown in Table I, home network scenarios are subject to specific requirements, which can be met by one of many heterogeneous wireless technologies. A detailed overview of these technologies can be found in [5], while [6] provides a quantitative comparison of the most prominent ones. Because of their key characteristics, some technologies are designed for certain applications [5] (cf. Table I). Therefore, interoperability of different network technologies is an important challenge for future home networks [7], [8]. Currently, this challenge can be handled using one of three approaches described below.

A. Traditional IP-based Approach

According to the OSI model, adopting an all-IP approach ensures the end-to-end exchange of data irrespective of the underlying network technologies. Specialized services can

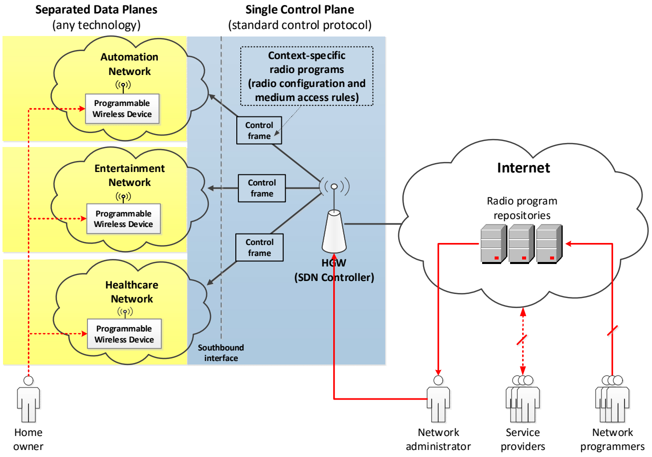


Fig. 2: The SDN@home architecture.

then operate in the network. A good example is Universal Plug and Play which facilitates the discovery and delivery of multimedia content in home networks [8].

Although this solution is common in core next-generation networks, it is less suitable for home networks. First, all devices are required to support IP routing and forwarding which may not be the case for low-power devices. Second, network management may be difficult if the routing protocol does not consider the properties of the wireless technologies used.

B. A Unifying Technology

A unifying technology, in order to support network interoperability, should be: *adaptable* – to achieve the best performance in common use cases; *extensible* – to operate in highly specialized use cases; and *compatible* – to allow easy integration with existing and future technologies.

Wi-Fi is a good example of a unifying technology since the 802.11 standard is constantly upgraded with new functionalities (Table II) [9]. However, there are some challenges that cannot be easily solved for a technology working on unlicensed bands without a central coordinator, such as: *lack of hard QoS guarantees* especially required in emergency situations [10]; *isolation between coexisting networks*, including home networks dedicated to different applications or neighboring networks; and *lack of support for simultaneous multi-home connections*, which prevents a station from maintaining more than one connection at a time.

C. A Unifying Interface

The abovementioned issues have driven the development of network models based on a single, unifying interface. One example is the IEEE 1905.1 standard [11], which defines a "2.5 abstraction layer" to hide the underlying network technologies from higher layers. Together with its recent amendment 1905.1a-2014, it provides a common interface to different home networking technologies (e.g., Wi-Fi, Ethernet) and allows selecting the best network technology for each transmission. Unfortunately, it does not provide the flexibility

TABLE I: Home network scenarios – current vision

Scenario	Example applications	Requirements	Exemplary technologies
Healthcare	Reactive (acute conditions)	Real-time, high priority, low range, low power, low rate	802.15.1 (Bluetooth), 802.15.6 (BAN), 802.11ah (Low-power Wi-Fi)
	Proactive (long-term observations, data collection)	Background, low priority, low range, low power, low rate	
Automation	Monitoring, control, energy management, security	Large range, low data rate, low power	802.15.4 (ZigBee), 802.11ah (Low-power Wi-Fi)
Entertainment	Multimedia streaming	High data rate, low range, QoS support (if real-time), possibly no energy requirements (for TV, NAS, etc.)	802.11 (Wi-Fi), 802.15.1 (Bluetooth)
Internet-based services	VoD, VoIP, music streaming, social media	As for *Entertainment* plus location awareness, moderate energy requirements (laptops, smartphones, tablets), support for nomadic access (visiting friends/relatives)	

TABLE II: Recent and upcoming IEEE 802.11 amendments

Amendment	Release date (expected in italics)	Title	Scope	Home networking scenario
802.11aa	2012	Robust streaming of Audio Video Transport Streams	Group-addressed transmission service, stream classification service, intra-access category prioritization, overlapping basic service set (OBSS) management, support for the IEEE 802.1Q Stream Reservation Protocol.	Entertainment
802.11ac	2013	Very High Throughput $<$ 6 GHz	Improvement of user experience by providing significantly higher basic service set (BSS) throughput (up to almost 7 Gbps). Operation below 6 GHz including distribution of multiple multimedia/data streams.	Entertainment
802.11ad	2012	Very High Throughput 60 GHz (Wireless Gigabit Alliance, WiGig)	Operation in frequencies around 60 GHz. Support of very high throughput (up to almost 7 Gbps). Fast session transfer among 2.4GHz, 5GHz and 60GHz.	Entertainment
802.11ae	2012	Prioritization of Management Frames	Policy-based prioritization of management frames.	Entertainment
802.11af	2013	TV Whitespace	Channel access and coexistence of IEEE 802.11 networks in the television (TV) white space.	General-purpose
802.11ah	*2016*	Sub 1 GHz sensor network, smart metering	Operation of license-exempt IEEE 802.11 wireless networks in frequency bands below 1 GHz excluding the TV white space bands.	Automation and healthcare
802.11ai	*2016*	Fast Initial Link Setup	Fast initial link set-up methods which do not degrade the security offered by robust security network association (RSNA) defined in IEEE 802.11.	General-purpose
802.11ak	*2016*	General Link (GLK)	Possible enhancement of IEEE 802.11 links for transit use in bridged networks. Support of home entertainment systems, industrial control equipment and other products/applications that have IEEE 802.11 and IEEE 802.3 capability.	General-purpose
802.11aq	*2016*	Pre-association Discovery	Mechanisms that assist in pre-association discovery of services. Access to one or more frequency bands for the purpose of local area communication.	General-purpose
802.11ax	*2019*	High Efficiency WLAN	Improvement of spectrum efficiency to enhance the system throughput in high density scenarios.	Entertainment

and reconfigurability required by home networking scenarios, because it permits only switching between data link technologies, with limited configuration options for the radio links.

In the same directions, several research projects (such as the European H2020 Project WiSHFUL[1]) are in the process of designing a unifying control interface for existing wireless technologies, to allow tuning of selected operating parameters by avoiding the technology-specific and even vendor-specific configuration interface. The concept of a unified interface is closely related to the emerging concept of programmable networks, in which the programming model of the devices evolves from parametric control to more powerful abstractions. Examples of such abstractions can be found within the ETSI architecture for configurable mobile devices [12] and OpenFlow [2]. Comparing these approaches to a unifying technology (Section II-B) is analogous to the difference between a dedicated device (with its associated technologies) and a programming language. A unified interface enables the paradigm shift from designing closed systems to an open system approach. This speeds up development by reducing the time required for new features to become available on the market. Additionally, it allows vendors to compete by having different implementations (algorithms) running within a device while maintaining interoperability between devices and enabling greater control. Therefore, a unified interface is a key enabler for programmable technologies.

III. From one-for-all to a Programmable Technology

SDNs, recently emerged in the wired domain, have shown that different network operations can be defined in software by means of abstractions that expose simple and effective programmable interfaces. Although this approach is still underexplored in the wireless domain, it is beneficial for simplifying the coexistence and management of devices, working on the same unlicensed bands, that are usually vertically integrated and application-specific such as the ones used in home networks.

The SDN concept has been considered for home networks but from the perspective of service providers willing to improve the *management of the Internet access network* [13]. Conversely, we propose to apply the principle of a logically centralized control for the *management of wireless home networks*. This could introduce several benefits due to the network-wide optimization of hardware, radio, storage, and energy resources that can be allocated for supporting home applications, such as the collection of metering data on the home gateway, the storage of video surveillance traffic, and the transport of entertainment traffic between smart TVs and hard disks.

Our idea is to enable the opportunistic configuration of domestic wireless devices as a function of the specific interference context and running applications. For this purpose, it is necessary to abstract the internal architecture of wireless devices and to clearly define the programming interfaces. Therefore, the proposed wireless SDN is somewhat similar to the wired SDN (Fig. 2): the data plane is separated from the control plane, the HGW acts as the SDN controller, there is a southbound interface which supports a customized control protocol described in Section III-C. However, differently from SDN in wired networks, where device configuration is basically given by a processing table specifying the rules for forwarding packets, in the wireless domain SDN is more complex because the physical links between the devices are not deployed *a priori*, but depend on radio configuration (frequency, modulation, etc.), mobility, and interference. Therefore, network programming is strictly tied to radio and medium access control.

A. The SDN@home Architecture

In the SDN@home architecture (Fig. 2), the behavior of devices forming the *automation*, *entertainment*, and *healthcare* networks are managed by a single control plane. The HGW acts not only as a connection to an external public network but also as a centralized *SDN-enabled home network controller*. This approach allows general-purpose wireless devices to be programmed on-the-fly by installing *radio programs* according to different application scenarios and changing conditions affecting the home network.

We expect the HGW to be controlled by a single entity – the *network administrator*. It is the network administrator's role to configure the HGW's control logic, while the service providers (e.g., ISPs, healthcare service providers, electrical power companies) or vendors can advocate the installation of their radio programs to the network administrator (Fig. 2). Ultimately, it is the network administrator's role to ensure optimal network performance, e.g., that only trusted radio programs are loaded on home devices and that fairness is ensured in the network. This approach provides more flexible manageability of home networks and simplifies adding new services to such networks. Additionally, the network administrator can delegate third parties to control specific network functions. This makes SDN@home aligned with commercial trends that allow sharing airtime and back-haul resources with people outside the home[2]. However, SDN@home permits much more than just controlling who can access the home network, by providing flexibility also at the data link and physical layers.

The envisioned evolution of home networks, leading toward the adoption of wireless SDNs, can be incremental, i.e., having both SDN-enabled and legacy devices operating concurrently (Fig. 3). Even today wireless devices expose some configuration capabilities (such as the operating channel and the transmission power) that can be exploited for global optimization. Fig. 3b shows an architectural view of programmable wireless devices in case of SDN-enabled devices and standard technology devices. The radio manager is responsible for configuring the radio link by tuning the available settings; for SDN-enabled devices, it can also specify the medium access rules. The queue manager is responsible of specifying the radio and access parameters of different traffic flows and mapping the flows onto the radio interfaces. A control process interacts

[1] http://www.wishful-project.eu

[2] https://corp.fon.com/en

with the central SDN controller by means of a control protocol, for coordinating the device configurations.

Note that by programmable wireless interfaces we do not mean Software-Defined-Radio (SDR) platforms, where every functionality, including modulation and coding, can be programmed from scratch. Conversely, we mean general-purpose devices based on an abstract architecture and programming model (similar to the general-purpose OpenFlow switches) that can work according to different operation modes (short-range communications, directional links, etc.), while maintaining a limited complexity, suitable for global control. Examples of architectures for programmable wireless interfaces have been recently proposed for sensor networks [14] and for Wi-Fi networks with the Wireless MAC Processor (WMP) [4] described in the following subsection.

B. A Programmable MAC Engine

The WMP architecture [4] is an example of a programmable MAC engine that allows devices to run the radio programs provided by the HGW. It responds to the technical hurdle of designing a general-purpose wireless device and a high-level programming language for configuring its behavior. The device hardware capabilities, which cannot be reprogrammed, are abstracted by the following sub-systems: *i*) the *transceiver*, dealing with the reception and the transmission of the frames, according to a predefined set of modulation and coding schemes; *ii*) the *transmission queues*, in which traffic flows or control and management frames can be separately enqueued for achieving different MAC performance; *iii*) the *reception queue*, in which incoming packets can be stored before being forwarded to the host. Rather than be controlled by a given protocol, these sub-systems can be governed by a generic execution engine able to run programs defined in terms of Extended Finite State Machines (XFSMs). The XFSMs are composed by reusing a set of signals provided by the hardware subsystems by means of an interruption block, a set of elementary primitives implemented into an operation block, and a set of registers for saving the system state and configuration parameters. These signals, primitives and configuration registers represent the device's application program interface. A *memory block* is dedicated to the storing of the MAC programs, while a *control interface* is available for loading the programs and tuning the configuration parameters. The method of exchanging control information between network devices is described in Section III-C.

According to the SDN@home architecture, a wireless device does not implement a standard-specific predefined protocol, but it acts as a generic executor of state machines reacting to internal events of the system (e.g., the arrival of a new packet from the host) or external events of the channel (e.g., the reception of a new packet from the air interface) as shown in the example in Fig. 4a. The reactions to the same signals may vary according to the system state, which includes the state of the hardware and the logical state of the programmed protocol, which in turn is given by the program state and global variables. This programming model allows to define radio programs in a compact form.

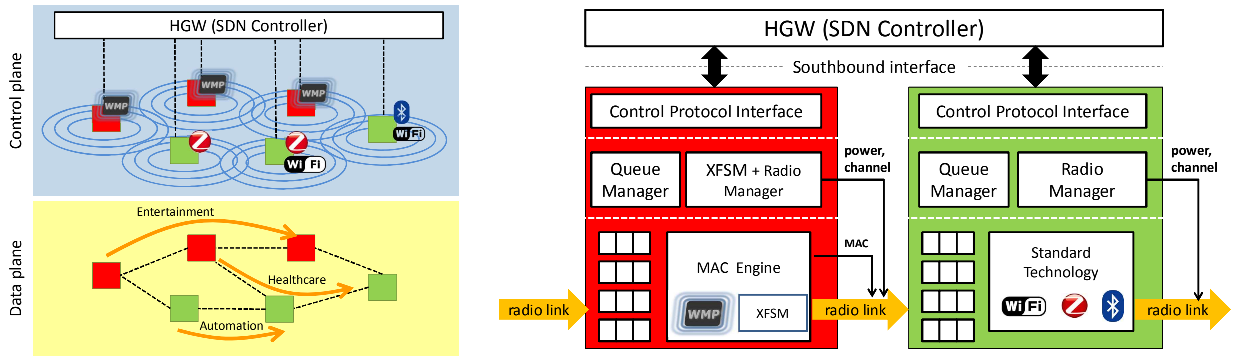
The presented approach allows to re-purpose the same hardware for supporting different medium access rules and networking models by providing a trade-off between flexibility and ease of programming. It clearly decouples the role of the device manufacturer from that of the network programmer (Fig. 2). *Manufacturers* remain in charge of providing hardware signals as well as radio primitives which may change according to the device complexity, while *programmers* are free to define the protocol states and relevant transitions which orchestrate such primitives according to their desired logic.

C. Control Protocol and Control Channel

In order to exploit programmable wireless interfaces for adapting the home network behavior to different radio contexts and applications, a control protocol is required for communication between the SDN controller and the network devices. The control protocol envisioned in SDN@home is based on a client-server model, where the central controller implements a programmable control logic for deciding the radio configuration of the devices and the client process, running on the devices, makes the device programming interface remotely available for triggering reconfiguration actions. The control protocol collects device statistics and estimates the network state and then dynamically injects and activates the radio programs in each device. The radio programs are specified as a set of initialization parameters of the transceiver settings and an (optional) table of transitions coding the MAC state machine, that can be conveniently transported in special control packets [4].

Control messages require a *physical transport network* that can be realized in different ways. Currently, we consider the following three approaches for SDN@home: (*i*) coexistence of control and data channels as in-band signaling; (*ii*) setting the control network on a separate physical channel, possibly with a smaller bandwidth (e.g., 5 MHz instead of 20 MHz); (*iii*) virtualization of the control and data channels over the same physical channel (e.g., a portion of the beacon interval can be allocated to the control network with legacy access rules). In-band signaling can be exploited for configuring devices based on legacy technologies: a multi-technology HGW can reach each device by opportunistically selecting the appropriate interface. Out-of-band signaling or virtualization solutions require more advanced devices, in which a real or virtual network interface is dedicated to the control network. The selection of the best approach is left for the network administrator. Additionally, since hardware devices provide primitives to change the modulation and coding scheme (MCS), the SDN controller coordinates the selection of appropriate MCSs for the control and data planes based on the device types present in the household and their supported capabilities.

Many standard extensions recently proposed for Wi-Fi (e.g., 802.11n reverse path, 802.11z direct link, 802.11ah directional links) mimic our approach, because they use the legacy distributed coordination function (DCF) channel access for sending signaling messages responsible of activating predefined enhanced access operations. Our architecture avoids having these enhanced operations preliminarily standardized



(a) (b)

Fig. 3: Coexistence issues in SDN@home when SDN-enabled (red) and legacy devices (green) are used: (a) management by a centralized controller, (b) internals of the devices.

and implemented into the cards, but keeps the possibility of using standardized technologies for activating new features on demand.

Although the specific definition of the control protocol is out of the scope of the present work, we envision the definition of some core messages to be used for centralized control: *management messages*, for the creation and maintenance of the control network, such as associating the client process of each device to the HGW, estimating the latencies between the controller and the devices and verifying the operation of the control link; *controller-to-device messages* for specifying, modifying, or deleting radio programs for different traffic flows, synchronizing the reconfiguration of multiple devices, and requesting information on device capabilities; as well as *device-to-controller messages*, for informing about device statistics and the state of the data links. While in our initial experiments we implemented a simplified (customized) control protocol, we are currently considering the adaptation of other well established protocols (such as CAPWAP [15] or OpenFlow [2]) for supporting the above mentioned messages and in particular the synchronization of reconfiguration commands.

IV. Use Case Analysis

In this section we discuss examples in which the centralized control of home wireless devices can improve the QoS perceived by home owners.

We categorize our examples in two different groups: in the first, labeled *flow-level device control*, the controller is mainly responsible for diverting traffic flows across the technologies available in each device and configuring the relevant parameters; in the second, labeled *link-level device control*, the controller is additionally responsible for configuring the behavior of the links, where the traffic flows have been diverted, by defining the medium access rules employed by each device. For both groups, where appropriate, we provide the roles of the main actors (Fig. 2).

A. Flow-level Device Control

In a typical home network there is a redundancy of functionalities and technologies provided by different devices, due to the coexistence of multiple similar devices owned by family members (e.g., smartphones, tablets) and the availability of multiple wireless interfaces in the same device (e.g., Bluetooth, Wi-Fi, 4G). In such a scenario, the perceived QoS can be significantly improved by selecting the most appropriate device or interface for each traffic flow. We provide three examples of how flow-level device control can alleviate this problem.

1) Multi-device Services: The availability of multiple home devices with similar capabilities can be exploited for improving services which are currently designed for working on specific devices. For example, voice calls directed to cordless DECT phones could be forwarded to local smartphones (through Wi-Fi), which may be closer to the home owners. SDN@home allows dynamic monitoring of devices supporting each specific service and defining the per-flow forwarding technologies and multicasting rules accordingly.

2) Multi-homing: The backhaul resources of domestic APs may be underused, e.g., when the home owners are not present. SDN@home allows central control of customers' home access networks and sharing unused resources. For example, the network administrator can request continuous monitoring of the aggregate backhaul bandwidth required by each neighbor AP. When an AP is overloaded while one or more neighboring APs are underloaded, selected traffic flows can be diverted from the serving AP to the neighboring one.

3) Wi-Fi Offloading: Offloading mobile traffic over Wi-Fi networks is a very promising solution for increasing the capacity of 5G cellular networks. IEEE 802.11 extensions are proposed to permit Wi-Fi offloading (802.11u, 802.11ah, 802.11ax), but the heterogeneity of platforms, technologies, and channel conditions of domestic wireless networks leave many open issues. SDN@home can support this functionality by locally monitoring the congestion of ISM bands and setting up a Wi-Fi link between the smartphone and the HGW for traffic offloading in a secure manner. These operations can be performed by intermediate network administrators offering services to the cellular provider.

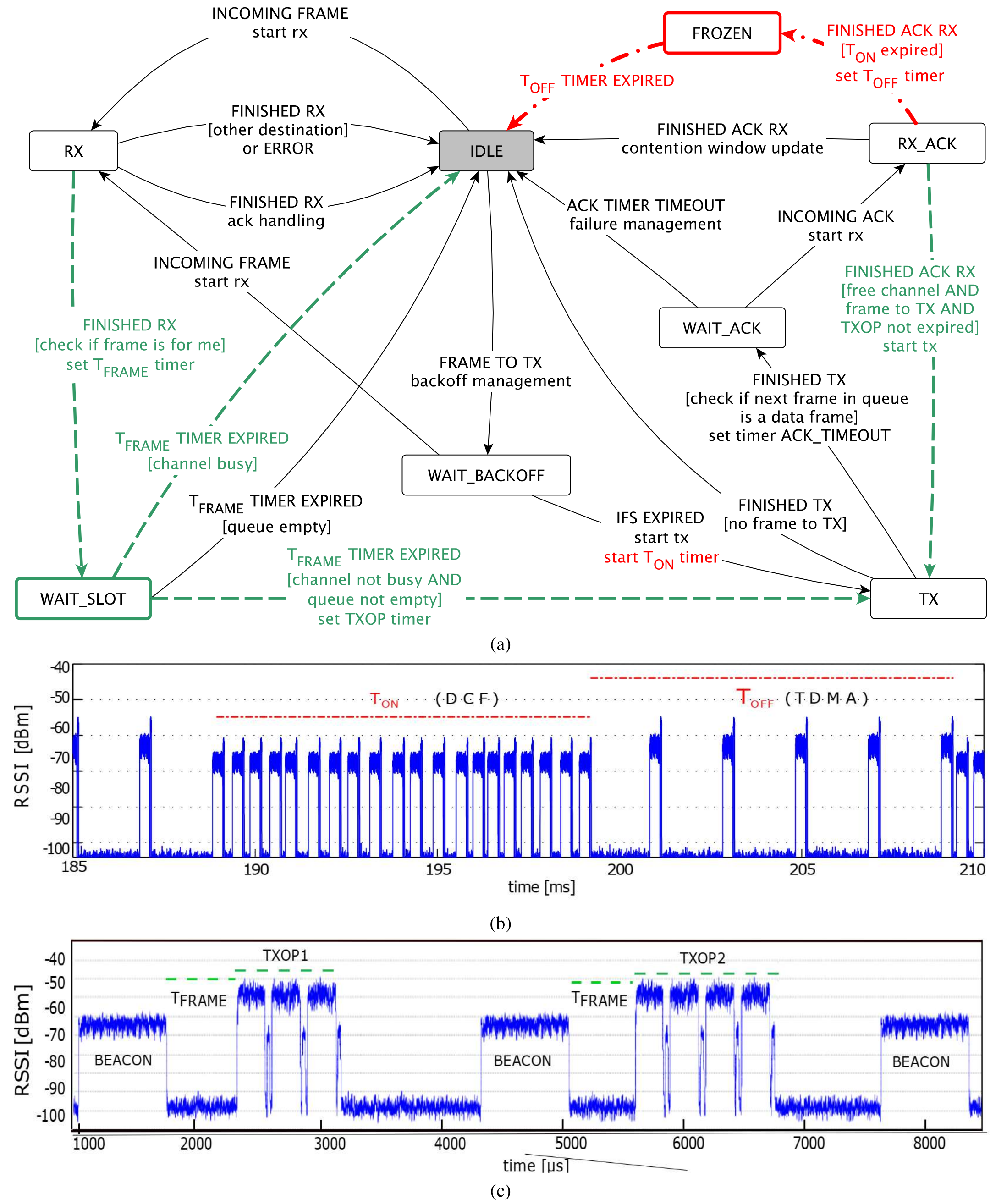


Fig. 4: SDN@home applications: (a) the XFSM implementing DCF and differential changes to support healthcare services (red dot-dashed lines) and monitoring applications (green dashed lines), (b) trace with healthcare traffic protection during T_{OFF}, and (c) trace with power-saving by tuning TXOP.

B. Link-level Device Control

In home networks multiple wireless links, each transporting traffic flows of varying characteristics, are likely to coexist. Since the performance of each link is affected by the interference created by the other links (as well as by external interference), it is possible to exploit the central controller for introducing coordination mechanisms among these links, by acting on PHY and MAC settings of the relevant interfaces. In SDN@home, the SDN controller loads the desired radio program on the home devices and links each state machine with the relevant traffic flow. Fig. 4a shows a simplified representation of three radio programs, in which state labels indicate the meaning of the protocol logical state, while transitions include their triggering hardware signals (in capital letters), conditions to check (in square brackets) and primitives to be executed before entering into the destination state. The reference DCF program is shown in black, while service-specific adaptations are marked in dot-dashed red lines (for healthcare services) and dashed green lines (for home automation).

1) Healthcare Services: Current healthcare services are based on monitoring of medical parameters by means of dedicated sensors communicating via Bluetooth. Reliability is one of the main application-specific requirements in this scenario, which can be achieved by programming coexisting devices to avoid interference with healthcare data. To this purpose, a FROZEN state was added to the MAC protocol by the network programmer to periodically prevent the interfering devices from channel access. Additionally, dynamical tuning of T_{ON} and T_{OFF} parameters was added in order to permit the network administrator to achieve the best channel utilization as a function of the protected monitoring traffic. The device transmitting healthcare data was programmed by the network administrator through HGW to use TDMA (the differences in the XFSM are not reported in the figure). Fig. 4b shows the resulting channel access trace in terms of the received signal strength indication (RSSI) in case of one device programmed with CSMA and another with TDMA. The channel is slotted in orthogonal channel portions to be used exclusively by each device to avoid interference and improve the QoS perceived by the home owner.

2) Home Automation: Applications for home automation usually require low-rate and low-power transmissions. SDN@home allows dynamically programming such devices (set by the network administrator through the HGW) to save energy by switching off the wireless interface at regular temporal intervals. This tunable behavior uses an additional synchronization mechanism based on the reception of a reference signal (e.g., a beacon frame) and permits to restore high responsiveness on demand. Fig. 4c shows the resulting channel trace. Each device waits for a different T_{FRAME} when its time slot starts and transmits during tunable TXOPs. The first transmission opportunity lasts three frames. During the next beaconing period, the controller tunes the TXOP parameter to last four frames in order to optimize the activation and sleeping intervals according to expected traffic, which may vary as a function of the time of day, user presence, weather conditions, etc.

V. Conclusions and Research Challenges

In this paper, we have described the shift from *inflexible* multi-technology home networks to *programmable (software-defined)* multi-technology home networks and proposed the novel SDN@home architecture. We have also identified four key actors (home owners, network administrators, network programmers, and service providers) and described their responsibilities within this architecture.

Unlike with the current paradigm where capabilities of wireless devices are only selectable among a predefined list of MAC policies, with SDN@home future home devices will be aware of their surroundings and dynamically programmable by SDN controllers in accordance to the radio conditions, traffic requirements, home network scenarios, etc. The only requirement is that all wireless home network devices use a dedicated control plane, i.e., they are able to change their configurations according to information received in control frames. With this approach, the flavors of the existing wireless technologies can be used to precisely tailor home network performance to different applications, scenarios, and needs. In other words, the advantages of, e.g., Wi-Fi (such as high throughput provided by 802.11ac) can easily be coupled with the advantages of other application or scenario-specific wireless technologies (e.g., ZigBee, Bluetooth) providing optimized home network performance. This also means that with SDN@home different protocols and features can be shared across network technologies in order to increase home owner experience and satisfaction (i.e., a new type of flexibility is achieved, since different protocols/features are no longer tied to specific network technologies).

The full programmability of wireless devices and their control through the SDN@home architecture provides the opportunity to overcome many existing problems. However, further research is required in providing optimization frameworks for:

- the coexistence of heterogeneous wireless technologies (spectrum sharing, interference management, transmission power allocation, carrier sense threshold adoption),
- the coexistence of homogeneous wireless networks (medium access rules for optimizing channel utilization and ensuring compatibility with legacy devices),
- the coexistence of SDN-enabled and legacy wireless devices,
- the management of coexisting (overlapping) networks (governed by single or multiple operators).

A separate area of future work is the development of security methods to counter the risks introduced by the programmability of wireless devices. Signature-based cryptographic methods can guarantee that malicious code is not allowed execution on home owner devices. Other solutions are required to guarantee fairness in networks with selfish users: either by implementing inherently robust mechanisms or by stimulating cooperation through specific policies. Furthermore, regulatory restrictions and protective solutions can be implemented at the MAC engine level rather than at the protocol (e.g., the engine refuses to execute consecutive transmissions under a specific inter-frame space or implements a carrier sense that cannot be bypassed or switched off). In this sense, flexibility does not mean complete deregulation. Despite these potential risks and still undefined solutions, which are mostly a result of the early development stage of this technology, the benefits of wireless SDN outweigh the costs to implement countermeasures.

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References

[1] K. Papagiannaki, M. Yarvis, and W. Conner, "Experimental characterization of home wireless networks and design implications," in *INFOCOM 2006. 25th IEEE International Conference on Computer Communications. Proceedings*. IEEE, 2006, pp. 1–13.

[2] N. McKeown, T. Anderson, H. Balakrishnan, G. Parulkar, L. Peterson, J. Rexford, S. Shenker, and J. Turner, "OpenFlow: enabling innovation in campus networks," *ACM SIGCOMM Computer Communication Review*, vol. 38, no. 2, pp. 69–74, 2008.

[3] R. Ferrus, O. Sallent, J. Perez-Romero, and R. Agusti, "A solution framework to provide management services for wireless communications in the digital home," *Communications Magazine, IEEE*, vol. 50, no. 11, pp. 132–141, 2012.

[4] G. Bianchi, P. Gallo, D. Garlisi, F. Giuliano, F. Gringoli, and I. Tinnirello, "MAClets: active MAC protocols over hard-coded devices," in *Proc. of CoNEXT*, 2012.

[5] A. Aragues, I. Martínez, P. Del Valle, P. Munoz, J. Escayola, and J. D. Trigo, "Trends in entertainment, home automation and e-health: Toward cross-domain integration," *Communications Magazine, IEEE*, vol. 50, no. 6, pp. 160–167, 2012.

[6] J.-S. Lee, Y.-W. Su, and C.-C. Shen, "A comparative study of wireless protocols: Bluetooth, UWB, ZigBee, and Wi-Fi," in *Industrial Electronics Society, 2007. IECON 2007. 33rd Annual Conference of the IEEE*. IEEE, 2007, pp. 46–51.

[7] A. Brush, B. Lee, R. Mahajan, S. Agarwal, S. Saroiu, and C. Dixon, "Home automation in the wild: challenges and opportunities," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 2011, pp. 2115–2124.

[8] S. Palm, "Home Networks: From Bits to Gigabits: Lessons Learned from the Evolution of Home Networking," *Consumer Electronics Magazine, IEEE*, vol. 1, no. 3, pp. 29–35, 2012.

[9] G. Hiertz, D. Denteneer, L. Stibor, Y. Zang, X. P. Costa, and B. Walke, "The IEEE 802.11 universe," *Communications Magazine, IEEE*, vol. 48, no. 1, pp. 62–70, 2010.

[10] K. Kosek-Szott, M. Natkaniec, S. Szott, A. Krasilov, A. Lyakhov, A. Safonov, and I. Tinnirello, "What's new for QoS in IEEE 802.11?" *Network, IEEE*, vol. 27, pp. 95–104, 2013.

[11] "IEEE Standard for a Convergent Digital Home Network for Heterogeneous Technologies," *IEEE Std 1905.1-2013*, pp. 1–93, April 2013.

[12] Y. Jin, K. Kim, D. Kum, S. Choi, and V. Ivanov, "The ETSI standard architecture, related interfaces, and reconfiguration process for reconfigurable mobile devices," *Communications Magazine, IEEE*, vol. 53, pp. 38–46, 2015.

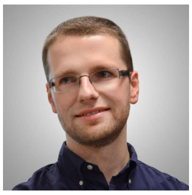
[13] H. Kim and N. Feamster, "Improving network management with software defined networking," *Communications Magazine*, vol. 51, pp. 114–119, 2013.

[14] P. De Mil, B. Jooris, L. Tytgat, J. Hoebeke, I. Moerman, and P. Demeester, "snapMac: A generic MAC/PHY architecture enabling flexible MAC design," *Ad Hoc Networks*, vol. 17, pp. 37–59, 2014.

[15] P. Calhoun, M. Montemurro, and D. Stanley, "RFC 5415: Control And Provisioning of Wireless Access Points (CAPWAP) Protocol Specification," 2009.

Pierluigi Gallo has been an Assistant Professor at the University of Palermo since November 2010. He graduated with distinction in Electronic Engineering in July 2002 and worked at CRES (Electronic Research Center in Sicily) until 2009. His work there was dedicated to QoS in IP core routers, IPv6 network mobility and Wireless Networks. His research activity has focused on wireless networks at the MAC layer and 802.11 extensions, localization based on the time of arrival and cross layer solutions. P. Gallo has contributed to several national and European research projects: ITEA-POLLENS (2001-2003) on a middleware platform for a programmable router; IST ANEMONE (2006-2008) about IPv6 mobility; IST PANLAB II on the infrastructure implementation for federating testbeds; ICT FLAVIA (2010-2013) on Flexible Architecture for Virtualizable future wireless Internet Access; CREW (2013-2014) Cognitive Radio Experimental World.

Katarzyna Kosek-Szott received her M.Sc. and Ph.D. degrees in telecommunications (both with honors) from the AGH University of Science and Technology, Krakow, Poland in 2006 and 2011, respectively. Currently she is working as an assistant professor at the Department of Telecommunications, AGH University of Science and Technology. Her general research interests are focused on wireless networking. The major topics include wireless LANs and quality of service provisioning within these networks. She is a reviewer for international journals and conferences. She has been involved in several European projects: DAIDALOS II, CONTENT, CARMEN, FLAVIA, PROACTIVE, RESCUE as well as grants supported by the Polish Ministry of Science and Higher Education. She has also co-authored a number of research papers.



Szymon Szott received his M.Sc. and Ph.D. degrees in telecommunications (both with honors) from the AGH University of Science and Technology, Krakow, Poland in 2006 and 2011, respectively. Currently he is working as an assistant professor at the Department of Telecommunications, AGH University. In 2013, he was a visiting researcher at the University of Palermo (Italy) and at Stanford University (USA). His professional interests are related to wireless local area networks (medium access, QoS provisioning, security). He is a reviewer for international journals and conferences. He has been involved in several European projects (DAIDALOS II, CONTENT, CARMEN, MEDUSA, FLAVIA, PROACTIVE, RESCUE) as well as grants supported by the Ministry of Science and Higher Education and the National Science Centre. He is active in the ETSI NTECH Working Group on Evolution of Management towards Autonomic Future Internet (AFI) as well as the Association of Top 500 Innovators where he is a member of the management board. He is the author or co-author of over 40 research papers and four book chapters.

Ilenia Tinnirello has been an Assistant Professor at the University of Palermo since January 2005. She received her Laurea degree in Electronic Engineering and the Ph.D. in Communications in April 2000 and February 2004 respectively. She was also a Visiting Researcher at Seoul National University, Korea, in 2004, and Nanyang Technological University of Singapore in 2006. Her research has focused mainly on wireless networks particularly on multiple access algorithms with quality of service provisioning, cross-layer interactions between access solutions and physical layer; and mobility management and load balancing in wireless packet networks. I. Tinnirello has been involved in several international and national research projects, which include the bilateral Italian-Korean research project INFINITY and the national research project PRIN MIMOSA, as a scientific coordinator for the research unit of Palermo, and the European project FP7 FLAVIA, as technical coordinator.