Current Trends and Perspectives in Wireless Virtualization

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***Abstract*—The objective of this paper is to survey and compare recent works in the field of wireless virtualization in order to identify potential applications, common trends and future research directions. First, this paper briefly summarizes different wireless virtualization architectures as well as both enabling and enabled technologies related to wireless virtualization. Then, this paper proposes a wireless virtualization classification based on the type of virtualized resources and the depth of slicing. The three main perspectives identified are data and flow-based perspective, protocol-based perspective and spectrum-based perspective. A hypothetical ecosystem scenario of a future virtualized wireless infrastructure in which these perspectives coexist is explored. Finally, the challenges and requirements of a sustainable wireless virtualization framework are discussed.**

Keywords*—*Wireless virtualization, software-defined networking, software-defined radio, cloud infrastructure.

I. Introduction

Cloud computing and computer virtualization have maintained strong foothold in the IT industry for the past few years. The idea of network virtualization, which is the virtualization of routers and switches, is gaining momentum in both the industry and the academia. In the wake of widespread adoption of virtualization in the computing and networking domains, the virtualization of wireless access infrastructure has also become an active area of interest. Wireless standards and mobile device technologies are progressing at a rapid pace such that the future of digital communication will be dominated by a dense, ubiquitous and heterogeneous wireless network. In such a rich wireless ecosystem, the issue of technological compatibility and smooth handover among different wireless technologies arises. The development, deployment and management of such diverse and rich wireless systems will become more complex. Thus, the future is about the *convergence* of different technologies. Wireless virtualization is one possible solution to simplify the management and allow the co-existence of different technologies [1] [2].

In fact, wireless virtualization has a wide range of potential benefits in both commercial and academic contexts by enabling a *flexible reuse* of existing infrastructure. Commercially, it can lower the capital expenditures and the barrier to entry for emergent Internet or cellular service providers [3]. Additionally, wireless virtualization allows telcom operators to leverage from cloud services. Various network and control & management (C&M) functions can be decoupled from the hardware and implemented in the cloud, harnessing its high-volume processing capabilities [4] [5]. This decoupling and centralization of C&M allows the service providers to offer fully-differentiated services to the clients without having to own the infrastructure. Hence, a more integrated, immersive, diverse and competitive environment can be offered to the network customers [1]. In a sense, virtualization allows new applications that require highly-customized network capabilities to share the *same* infrastructure. In terms of academic research, virtualization is extensively applied in the research themes such as *Future Internet* [6] and *clean-slate design* [7]. The main reason for virtualization to be used in research is the level of flexibility that can be achieved with virtualized experimentation testbeds. Virtualization can shorten the research and development life cycle of new wireless technologies by providing a more open and flexible infrastructure [2]. Since the virtualized infrastructure can be shared among multiple virtual instances (similar to guest virtual machines in host virtualization) isolated from each other, it can enable the testing and deployment of experimental functionalities on a real production infrastructure without disturbing its regular operations.

In practice, the level of programmability and granularity of control over the virtualized infrastructure can vary from one application to another. Thus, there exist different approaches to wireless virtualization to suit different services and applications. So far, an overwhelming amount of literature has been published to introduce diverse wireless virtualization approaches. This paper is an attempt to summarize some of these techniques and approaches. One goal of this paper is to identify fundamental perspectives of wireless virtualization based on the extent and depth of resource sharing. This paper envisions that the identification of the fundamental perspectives of wireless virtualization will eventually lead to a unifying and long-term wireless virtualization and management framework. The rest of the paper is organized as follows. Section II summarizes different wireless virtualization trends. Section III discusses about the coexistence of different virtualization domains and the three main wireless virtualization perspectives identified from literature. Section IV provides a futuristic scenario with different actors on a hypothetical virtualized wireless infrastructure. Section V identifies the challenges and the requirements of a unified framework for wireless virtualization. Finally, Section VI concludes the paper and outlines the future works.

II. Current Trends in Wireless Virtualization

The common goal between wireless virtualization and the recent trends in future next-generation networks is to create a more flexible and sustainable infrastructure. The survey [7]

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provides a comprehensive compilation of emerging computer networking technologies, including network virtualization, an extremely active but relatively young area of research. Exclusive surveys on advancements in network virtualization are found in [8] and [9]. It is interesting to draw a parallel between network and wireless virtualization. The survey [9] identifies wireless virtualization as one of the *frontier* emerging research areas in network virtualization. However, while the fundamental concept of both network and wireless virtualization remains the same, there are significant differences between their approaches. For instance, due to the probabilistic and shared nature of the wireless transmission channel, different problems unique to the wireless medium arise. The term *wireless virtualization* refers to many different approaches aimed at addressing these issues. Wireless virtualization is defined in this paper as the *abstraction* and *sharing* of wireless hardware equipments by multiple virtual owners, referred to as *tenants*. The virtual instance of a set of shared resources is called a *slice*. Each tenant is given the illusion of ownership over its slice defined by a *service-level agreement* (SLA). However, the degree of sharing can vary from high-level mobile network management to low-level spectrum and RF frontend slicing. This section provides a glimpse on some of the recent wireless virtualization trends. A more detailed overview of these technologies can be found in [10].

A. Wireless Virtualization and Software-Defined Networking

The wireless access network can be considered as an extension of the (wired) core network. Thus, existing concepts and techniques used in network virtualization have also been applied to the wireless domain. General requirements for the management of a future virtualized network infrastructure identified in [6], such as service-awareness and functions modularity, are equally relevant in a wireless access network. Decoupling and management protocols such as CAPWAP [11] can consolidate wireless functions in a centralized *software* controller, making virtualization at the infrastructure-wide level easier to implement. Software-defined networking (SDN) enablers such as the OpenFlow standard [12] allow an external centralized software controller to access the switching functions of the network fabric using flow-based action rules. While OpenFlow is not a virtualization technology by itself, auxiliary tools such as FlowVisor [13] provide the isolation needed for virtualization. OpenFlow has been extended to wireless access points (APs) in OpenRoads [1] in which the forwarding plane of a mobile network is virtualized through FlowVisor [13] while the wireless AP configurations are remotely controlled using SNMP.

B. 802.11 WLAN Virtualization

Virtualization can be applied to specific wireless technologies, such as the WLAN and the cellular network. For the virtualization of 802.11 WLAN APs, [14] uses the existing 802.11 PSM and PCF functions to allow a single wireless network interface card (NIC) to simultaneously participate in multiple networks by seamlessly switching between different modes. This technique takes advantage of the sleep state of PSM to maintain the virtual connectivity. Virtual Wi-Fi [15] uses similar techniques in conjunction with augmented drivers in order to extend host virtualization with virtual wireless NICs. For heterogeneous networks with 802.11 technologies, carrier-grade mesh network [16] proposes a generic interface management function (IMF) and a MAC abstraction layer extension to the IEEE 802.21 interoperability standard to allow multiple standards to be managed through a common mesh functions management layer. On the other hand, CloudMAC [17] attempts to decouple the 802.11 MAC processing of APs by using OpenFlow to forward the tunnelled MAC frames to the cloud. These MAC frames are then processed in virtual server machines acting as virtual APs.

C. Cellular Basestation Virtualization

For cellular networks, basestation virtualization is achieved when the BS hardware can be shared across isolated network instances. Basic cellular technologies already have more advanced scheduling capabilities compared to WLAN technologies. However, basestation virtualization can also allow each tenant to have its own customized schedulers over their slice. The following architectures are mainly based on modifying multiple access techniques to provide slice isolation at the basestation, as suggested in [18]. The virtual base transceiver system (vBTS) in [19] is a WiMAX virtualization architecture that uses full instances of the BS firmware on virtual machines. However, it treats the physical basestation as a black box, being only able to control the multiplexing of data flows through a modified access service network (ASN) gateway. The network virtualization substrate (NVS) [20] takes one step further and integrates virtualization into the WiMAX basestation OFDM-A downlink scheduler software. In order to achieve this, NVS separates the scheduling process into two steps: the *flow scheduler* controlled by each tenant and the *slice scheduler* managed by the virtualization layer. Then, NVS provides a library of flow scheduling algorithms with different scope and granularity that can allow each tenant to customize the scheduling algorithm in their own slice, effectively allowing different scheduling algorithms to coexist across slices. Similarly, for LTE virtualization, the architecture proposed in [3] modifies the MAC scheduler of the eNodeB (LTE basestation) to isolate the traffic of different slices based on slice SLAs. Then, each slice can have its own scheduling implementation with the resources allocated to them.

D. Wireless Virtualization Using Software-Defined Radio

The concept of software-defined radio (SDR) is to allow traditionally hardware-integrated wireless functionalities to be controllable and customizable from software. Just like how SDN technologies can play a key role in the implementation of network virtualization, SDR technologies can be used to implement wireless virtualization. The OpenRadio platform [21] separates the wireless baseband processing into the decision and processing planes, both software-programmable. This allows the same set of DSP processing resources to be shared among different protocols, increasing the flexibility and reuse factor of the hardware. On the other hand, the Sora SDR [22] uses a radio control board (RCB) to forward digitized RF samples to general-purpose processors (GPPs) in order to performs real-time baseband processing in software. As such, by providing full software control over the baseband processing, Sora enables the implementation of wireless virtualization through software programming instead of hardware modifications. Different implementations of wireless virtualization can then be executed as a software application over the SDR platform. For instance, multi-purpose access point (MPAP) [23] uses Sora to share the same RF frontend for both 802.11g and 802.15.4 communication.

E. Sub-PHY Wireless Virtualization

The virtualization of wireless resources can be performed at the spectrum and RF frontened level, even beyond the PHY layer of wireless protocols. The spectrum virtualization layer (SVL) [24] architecture considers a *spectrum layer* beneath the PHY layer that uses dynamic spectrum allocation/access (DSA) and intermediate spectrum reshaping techniques to multiplex the baseband signals of different PHY layers, allowing them to share the same RF frontend on different portions of the spectrum. The SVL is implemented with the help of Sora [22]. On the other hand, the RF frontend circuit itself can be enhanced. For instance, Picasso [25] can support full-duplex transmission in adjacent or closely located frequency bands. In Picasso, RF circuit cancellations are combined with digital filtering in order to provide better isolation between transmit and receive signals, giving more flexibility and degrees of freedom for virtualization and cognitive radio technologies [25].

F. General Wireless Virtualization Testbed Architecture

The integration of different wireless virtualization technologies in a future infrastructure is considered in [26], in which different control schemes to jointly manage wireless and wired resources are presented. A distinction is made between the control among similar resources (*horizontal* control) and the control across different resources (*vertical* or *cross-domain* control). In [26], the hypervisor layer acts as a resource broker inside a heterogeneous infrastructure (i.e. with different types of resources). Similarly, Virtual Radio [2] describes a generic virtualization management interface (VMI) that brokers the allocation of radio resources among *virtual nodes*. This idea of intermediary resource brokering is further explored in VANI [27], a heterogeneous testbed that supports wireless and other non-computing resources through a *localized* virtualization agent connected to a central control and management (C&M) framework. Finally, the Smart Applications on Virtual Infrastructure (SAVI) [28] testbed, an extension to VANI, provides a unified cloud-based C&M framework for an application and service-oriented virtualized infrastructure. In SAVI, wireless technologies are designated to be one of the primary and preferred modes of access.

III. Coexistence and Convergence of Virtualization Perspectives

The benefits of wireless virtualization are often clouded by different arising concerns on its role in the Future Internet infrastructure. Due to the fact that its implementation is still in its infancy stage, it is difficult to concretely evaluate its true potential. At the same time, alternative concepts and technologies attempt to solve similar problems. For instance, LTE network sharing [29] already allows multiple operators to share the same infrastructure, despite not to the same extent as a fully virtualized system [2]. However, not all levels of wireless virtualization are necessary depending on the intended application. This section presents a view in which different

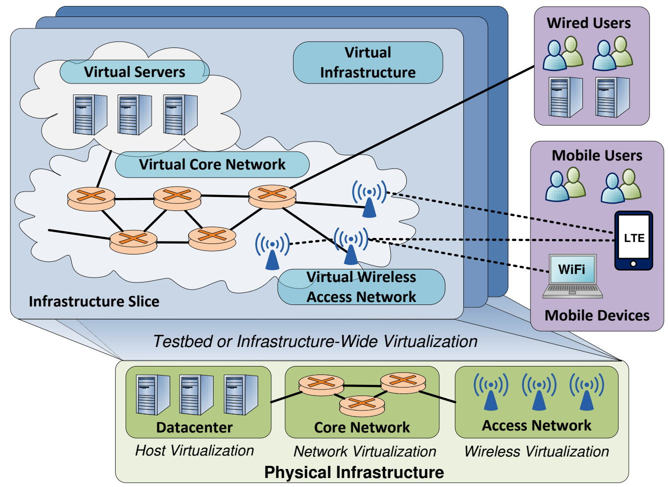

Fig. 1. Integration of Wireless Virtualization in a Cloud Infrastructure

forms of wireless virtualization can coexist with each other and within the overall infrastructure.

A. Coexistence of Virtualization Domains

In practical applications, the wireless access network is always connected to the core network. The interaction between mobile devices, wireless transmission points, host computers, routers and other network equipments form the modern Internet infrastructure. This brings out an interesting question on the degree of integration between different technological *domains* in the future. In this case, a *domain* refers to a set of infrastructure components sharing similar types of resources and performing similar functionalities. For instance, wireless virtualization can be integrated with other virtualized domains in order to form a *cloud infrastructure*. In such a scenario, the wireless access network can be offered as an extension to the concepts of IaaS and *network-as-a-service* (NaaS) borrowed from cloud computing. This extension is illustrated in Figure 1 where a single slice can span across the entire infrastructure, including virtualized computing, networking and wireless resources. In such an infrastructure, a given application or service is no longer bound to a particular domain or layer.

B. Main Wireless Virtualization Perspectives

In reality, simultaneous use of the same resource is but an illusion provided by the abstraction of the resource. In other words, high-level infrastructure sharing usually translates into low-level *resource partitioning*. In this subsection, different aspects of wireless technologies are addressed in different virtualization perspectives. The different perspectives also attempt to solve different issues and provide different advantages. Three main perspectives are identified based on the type of virtualized resources and the depth of sharing that is supported. Many architectures and technologies surveyed in Section II can incorporate multiple perspectives. The presence of multiple perspectives that complement each other can lead to a highly flexible infrastructure.

1) Data and Flow-Oriented Perspective: The flow-oriented perspective is inspired by flow-based SDN technologies such as OpenFlow and the need for differentiated service. This perspective views the wireless access network as a data exchange and distribution network. Thus, it focuses on providing isolation, scheduling, management and service differentiation between both uplink and downlink data flows from different slices. This is the most common perspective on wireless virtualization and is often referred to as *mobile network virtualization* due to its close relationship and integration with network virtualization concepts. However, it can still involve wireless-specific functionalities such as the scheduling of radio resource blocks in order to reinforce SLAs. It can be implemented as an overlay over the wireless hardware. In that case, it acts as a filter and software switch module, such as in OpenRoads [1] and vBTS [19]. It can also be integrated within the internal scheduler of the wireless hardware, such as in NVS [20] and virtual LTE [3].

2) Protocol-Oriented Perspective: Unlike the flow-oriented perspective which originated from network virtualization, the protocol-oriented perspective is unique to wireless virtualization. It focuses on the isolation, customization and management of multiple wireless protocol instances on the same radio hardware. Here, the type of resources being sliced can vary depending on how the wireless protocol is being processed on a given hardware platform. For instance, if the protocol layers are purely implemented through software, software-based resources must be sliced to provide the processing support. On the other hand, hardware resources such as DSP blocks must be sliced if protocol processing is performed in hardware. This perspective is supported by the architecture in [2]. A partial implementation allows multiple instances of the same protocol stack to share the radio with different sets of configuration, as in [14] with 802.11. It can also involve modifications and enhancements to existing protocols to support virtualization, such as in [20] with WiMAX and [3] with LTE. A full implementation potentially allows different protocols to operate on the same radio hardware, making the radio hardware fully customizable. This is possible using SDR technologies such as OpenRadio [21] and Sora [22].

3) RF Frontend and Spectrum-Oriented Perspective: The RF frontend and spectrum-oriented perspective is based on the application of cognitive radio concepts in wireless virtualization in which the RF circuit and the raw spectrum (i.e. before baseband processing) are respectively the resources being sliced. It involves novel sub-PHY layer techniques discussed in Section II such as dynamic spectrum allocation and full-duplex RF transmission. This perspective can overwrite the basic spectrum scheduling performed in the flow-oriented and protocol-oriented perspectives by reshaping the signal as in SVL [24]. This perspective also completely decouples the RF frontend from the protocols, allowing a single frontend to be used by multiple virtual wireless nodes or multiple frontends to be used by a single node. This perspective also includes enhancements to the RF frontend circuit itself in order to virtualize the radio hardware, such as in Picasso [25].

IV. A Hypothetical Virtualized Infrastructure

A hypothetical futuristic virtualized infrastructure is envisioned as shown in Figure 2. The hypothetical scenario predicts how the roles of different actors can change with the introduction of a *fully virtualized* and *integrated* wireless infrastructure.

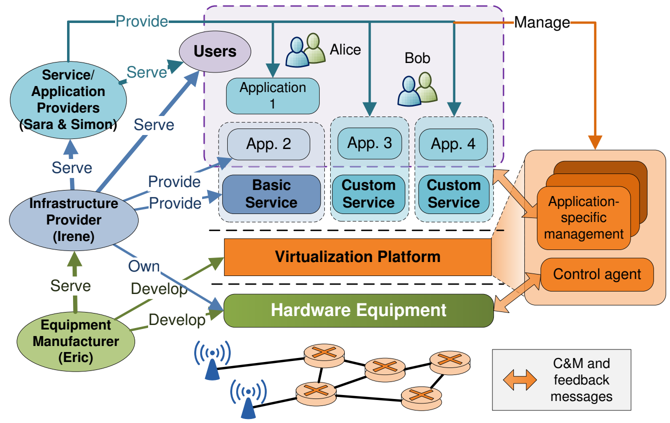

Fig. 2. Interaction among Different Actors in a Hypothetical Virtualized Infrastructure

First, let's consider an industrial or commercial scenario. In this scenario, Eric, the equipment manufacturer, provides a *control agent* that acts as an abstraction and management interface to his high-performance hardware. Eric also has the choice of providing a *virtualization platform*, a software suite of virtualization management tools. Otherwise, third-party companies can develop these platforms by accessing the control agents. Irene, the infrastructure provider, owns the hardware infrastructure. Irene can then offer virtual instances of the infrastructure to the application and service providers Sara and Simon. Of course, Irene herself can act as a basic service provider. However, she also sells to Sara and Simon the right to provide their services over the same infrastructure without having to own it. Sara and Simon, who traditionally might not have control over the infrastructure, are now able to use customized network topologies and optimized protocols to accompany their services. They will be able to manage their slice via an *application-specific management* without being affected from each other. This application-specific management will typically be implemented in the cloud as predicted by [4] and [5]. Ultimately, the users Alice and Bob are unaware of the interaction between the providers. Alice and Bob simply use customized applications and services that take advantage of the full infrastructure. On the other hand, in terms of research scenarios, researchers and developers interested in the development of novel services, applications and technologies can be allocated a slice of the already-deployed infrastructure through a *testbed-as-a-service* framework. This can be achieved without disturbing the regular production slices, as suggested in [1] and [12].

While these scenarios might sound similar to the current practice of network sharing, the differences can be better highlighted with the help of some futuristic applications. For instance, since the service requirements for wireless smart grid communications are different from regular traffic [30], the scheduling and management of the network is best handled by the utility provider instead of the infrastructure provider. A virtualized infrastructure can enable a power utility provider to have full control over a secure relay network for smart grid communications while sharing the same wireless infrastructure with the public access network (i.e. cellular network). Thus, utility providers do not need to invest in their own private and potentially under-utilized wireless network infrastructure. Virtualization can also enable new approaches to the development and deployment of advanced wireless communications applications and techniques. For instance, in terms of PHY processing techniques, the service quality offered to the users in a cellular network can be improved by using coordinated multi-point (CoMP) assisted by PHY virtualization as suggested in [31]. In terms of new applications, services such as a *cloud-based mobility management* will be possible. Similar to cloud storage services accessible anywhere at any time, a cloud connectivity service can guarantee an always connected state no matter where the user is located. The concept of *mobile personal grid* (MPG) [32] would be an example of such service that can be deployed over a virtualized wireless infrastructure. Those are examples of applications that cannot be easily implemented without a virtualized wireless infrastructure.

V. Challenges and Requirements of Virtualized Wireless Infrastructure

A. Challenges of Wireless Virtualization

The virtualization of wireless infrastructure imposes different challenges and practical design difficulties. Some of these challenges are implementation-specific, often caused by limitations in the technologies in terms of speed and complexity. On the other hand, the level of functional decoupling and the granularity of control over wireless resources cast dilemmas on a more conceptual level. Some of the main challenges are identified as follows.

1) Flexibility-performance trade-off: Wireless technologies are inherently specialized and optimized, making it hard to apply the same virtualization approach to diverse wireless access technologies without losing their respective benefits. Thus, there is a flexibility-performance trade-off. The virtualization framework should have the flexibility of running and managing applications over diverse wireless technologies in a converged and seamless operation. However, over-generalization can lead to a reduced efficiency in the performance of a given wireless technology. Furthermore, high granularity of programmability and control of wireless resources can add overhead latency to the time-sensitive functionalities. On the other hand, a deeply integrated and specialized virtualization of a specific technology can lead to a more efficient design, albeit a less flexible and portable one. One potential take on the flexibility-performance trade-off is the combined use of local virtualization agents, as in VANI [27], and semi-persistent rules and policies, as in OpenFlow [12].

2) Scalability: When wireless functionalities are pushed to an external controller, the scalability of the virtualized network becomes dependent on the processing capabilities and the link capacity between the controller and the wireless devices. The extreme case of such dependence is present in Sora SDR [22], which pushes the entire baseband processing of the radio into a GPP. As the virtualized wireless network is scaled and the physical controller-node distance is increased, time-sensitive functionalities can get adversely affected and start to experience longer delays. One potential way to tackle this challenge is the use of high-throughput and low-delay optical links such as in *radio over fiber* technologies.

3) Extensibility and Complexity of Implementation: Depending on the depth of slicing, virtualization can add complexity to the implementation and operation of the infrastructure. Virtualization potentially require modifications to high-performance hardware such that they can be abstracted and remotely managed. Similarly, the modification of the client devices and user equipments may also become necessary as in case of SplitAP [33]. From the management perspective, a generic high-level management rule has to be accurately translated into different hardware-specific control messages within strict timing restrictions. Thus, management isolation and co-ordination among multiple slices can cause overly-complex interactions among different components.

B. Requirements of Future Wireless Virtualization Framework

In order to solve some of these challenges, a sustainable and unifying wireless virtualization framework has its own general requirements. In addition, in order to be sustainable, flexibility and open access are some of the desired features of the architecture design of the framework. Some of these requirements are outlined as follows.

1) Generic and modular external interface: One basic requirement of a *unified* wireless virtualization framework is to have generic, common and technology-independent interfaces for different hardware devices. This essentially results in decoupling of the C&M functions of the framework from its virtualization mechanisms. An intermediary component such as the *local virtualization agent* in VANI [27] can help to satisfy this requirement. Common functionalities among different wireless technologies and virtualization perspectives should be incorporated into a basic library of functions accessible through the local virtualization manager. The modularity of the components is a key in order maintain a healthy and sustainable development of the framework.

2) Evolvability of the framework: Since the wireless ecosystem is constantly evolving, a *sustainable* wireless virtualization framework is required to leave possibilities for extensions. As the depth of virtualization evolves, new extension modules and plug-ins should be addable to the framework. The potential integration and federation of emerging virtualization architectures should be considered. The C&M should be scaled accordingly to support new management functionalities associated with new perspectives and new technologies. The overhead and latency incurred from the increased complexity of the framework should be mitigated.

3) Management isolation and resource abstraction: The framework should provide a mechanism for customizable and isolated control among tenants. In the ideal case, each tenant should have maximum degree of freedom to apply their own C&M over their slice without having to worry about conflicts from other slices. *Management autonomics* is another desirable feature to allow each slice to automatically maintain service parameters through a feedback system. A maximal autonomic management should provide self-organizing, self-configuring and self-healing functionalities to each slice.

VI. Conclusion and Future Works

The panorama of wireless virtualization is diverse in both scope and depth. Different wireless virtualization approaches are required for different applications. Specific wireless virtualization perspectives present in literature are rewarding in that they efficiently carry out the applications they are designed for. However, this paper explored the possibility that different virtualization architectures and technologies can actually complement and co-exist with each other to form a virtualization ecosystem. This will eventually lead to a sustainable and evolvable wireless virtualization framework in the future. To this end, three wireless virtualization perspectives were identified. Different virtualization techniques pertaining to these perspectives can be brought together in order to form a multi-dimensional virtualization framework. For instance, different technologies such as SDN, SDR and cognitive radio can each solve different aspects and challenges of virtualization. Future works include the design of a generic and modular wireless virtualization meta-architecture that considers the integration of multiple wireless virtualization perspectives, including flow-based, protocol-based, and spectrum-based virtualization.

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