Wireless Network Virtualization: A Survey, Some Research Issues and Challenges

Chengchao Liang and F. Richard Yu
*Depart. of Systems and Computer Eng., Carleton University, Ottawa, ON, Canada
Email: chengchaoliang@sce.carleton.ca; richard.yu@carleton.ca

***Abstract*—Since wireless network virtualization enables abstraction and sharing of infrastructure and radio spectrum resources, the overall expenses of wireless network deployment and operation can be reduced significantly. Moreover, wireless network virtualization can provide easier migration to newer products or technologies by isolating part of the network. Despite the potential vision of wireless network virtualization, several significant research challenges remain to be addressed before widespread deployment of wireless network virtualization, including isolation, control signaling, resource discovery and allocation, mobility management, network management and operation, and security as well as non-technical issues such as governance regulations, etc. In this paper, we provide a brief survey on some of the works that have already been done to achieve wireless network virtualization, and discuss some research issues and challenges. We identify several important aspects of wireless network virtualization: overview, motivations, framework, performance metrics, enabling technologies, and challenges. Finally, we explore some broader perspectives in realizing wireless network virtualization.**

***Index Terms*—Wireless network virtualization, abstraction and sharing, isolation, cognitive radio and networks, cloud computing.**

I. INTRODUCTION

In the information and communications technology (ICT) sector, *virtualization* has become a popular concept in different areas, e.g., virtual memory [1], virtual machines [2], virtual storage access network [3] and virtual data centers [4]. Virtualization involves abstraction and sharing of resources among different parties. With virtualization, the overall cost of equipment and management can be significantly reduced due to the increased hardware utilization, decoupled functionalities from infrastructure, easier migration to newer services and products, and flexible management [1]–[4].

In wired networks, virtualization has occurred for decades, e.g., virtual private networks (VPNs) over wide area networks (WANs) and virtual local area networks (VLANs) in enterprise networks [5], [6]. Recently, network virtualization has been actively used in Internet research testbeds, such as G-Lab [7] and 4WARD [8], and applied in the cloud computing environment [9]. It aims to overcome the resistance of the current Internet to fundamental architecture changes. Network virtualization has been considered as one of the most promising technologies for the future Internet [10].

With the tremendous growth in wireless traffic and services, it is natural to extend virtualization to wireless networks. With wireless network virtualization, network infrastructure can be decoupled from the services that it provides, where differentiated services can coexist on the same infrastructure, maximizing its utilization [11]. Consequently, multiple wireless virtual networks operated by different service providers (SPs) can dynamically share the physical substrate wireless networks operated by mobile network operators (MNOs). Since wireless network virtualization enables the sharing of infrastructure and radio spectrum resources, the capital expenses (CapEx) and operation expenses (OpEx) of wireless (radio) access networks (RANs), as well as core networks (CNs), can be reduced significantly. Moreover, mobile virtual network operators (MVNOs) who may provide some specific telecom services (e.g., VoIP, video call, over-the-top services) can help MNOs attract more users, while MNOs can produce more revenue by leasing the isolated virtualized networks to them and evaluating some new services [12]. Meanwhile, wireless network virtualization provides easier migration to newer products or technologies while supporting legacy products by isolating part of the network [12], [13]. In addition, the emerging heterogeneous wireless networks need a convergent and powerful network management mechanism, which can be provided by wireless network virtualization [14].

Despite the potential vision of wireless network virtualization, several significant research challenges remain to be addressed before widespread deployment of wireless network virtualization, including isolation, control signaling, resource discovery and allocation, mobility management, network management and operation, and security as well as non-technical issues such as governance regulations, etc. Particularly, unlike wired networks, where bandwidth resource abstraction and isolation can be done on a hardware (e.g., port and link) basis, radio resource abstraction and isolation is not straightforward, due to the inherent broadcast nature of wireless communications and stochastic fluctuation of wireless channel quality. Another significant challenge of wireless network virtualization is resource allocation, which decides how to embed a virtual wireless network on physical networks. In addition, a large number of intelligent devices/nodes with self adaptation/context awareness capabilities induce non-trivial security challenges to wireless network virtualization. These challenges need to be tackled broadly by comprehensive research effort.

In this paper, we provide a brief survey on some of the works that have already been done to achieve wireless network virtualization, and discuss some research issues and challenges. A taxonomy graph of our approach towards the

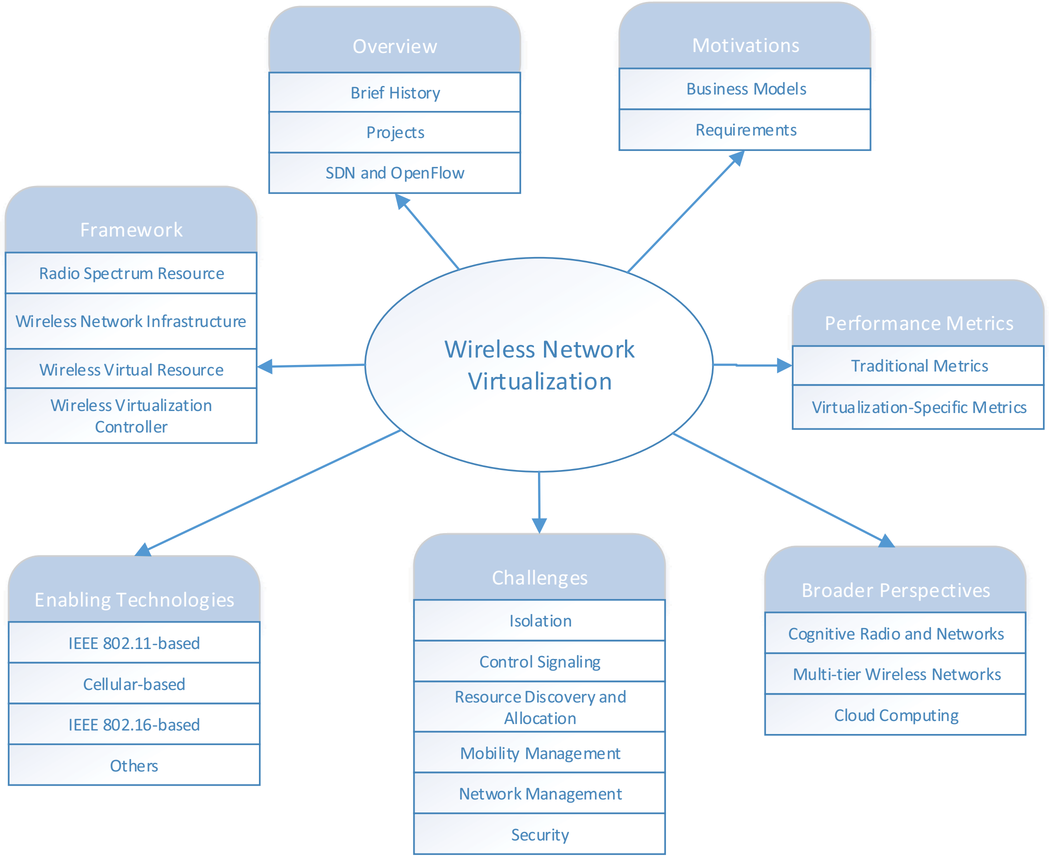


Fig. 1. Road map of wireless network virtualization.

design of wireless network virtualization is given in Fig. 1. As shown in the figure, we identify seven important aspects of wireless network virtualization where we would like to focus: overview, motivations, framework, performance metrics, enabling technologies, challenges, and broader perspectives.

In the following sections, we elaborate on each such aspect and discuss the related issues. Section II presents a brief history of wired network virtualization. Then some projects on network virtualization are introduced. Software defined networking and OpenFlow are also presented. In Section III, we will present the business models and the involved parties. The motivations and requirements of wireless network virtualization are also discussed. A framework is summarized in Section IV with four main components: radio spectrum resource, wireless network infrastructure, wireless virtual resource, and wireless virtualization control. Section V presents some performance metrics that are necessary to evaluate the performance and quality of a virtualized wireless networks. Some enabling technologies for wireless network virtualization are discussed in Section VI according to different radio access technologies. Section VII presents research issues and challenges. Some broader perspectives are also presented. Finally, we conclude this study in Section VIII.

II. OVERVIEW OF NETWORK VIRTUALIZATION

In this section, we first present a brief history of wired network virtualization. Then, some projects on network virtualization are presented. Software defined networking (SDN) and OpenFlow are also introduced in this section.

A. *Brief History of Wired Network Virtualization*

Virtualization has occurred in wired networks for decades. Some examples of wired network virtualization include virtual local area networks (VLANs), virtual private networks (VPNs), active and programmable networks, and overlay networks, which are described in the following.

1) VLAN: A VLAN refers to a domain where a group of hosts with a common interest are allowed to be logically brought together under a single broadcast domain regardless of their physical connectivity [15].

2) VPN: In a VPN, a private network, whose hosts are distributed in multiple sites, connects through private and secured tunnels (links) over public communication networks (e.g., the Internet or PSDN) [16]–[18]. Depended on different layers, VPNs can be classified into four classes: Layer 1 VPNs [19], Layer 2 VPNs [20], Layer 3 VPNs [21] and higher layer VPNs [22]. It should be noted that Layer 1 VPNs have no guarantee between data plane connectivity and control plane connectivity, which means that each service network has independent address space and L1 resource view, separating policies and completing isolation from other VPNs. This is the main difference between Layer 1 VPNs and Layer 2/3 VPNs.

3) Active and programmable networks: In response to user demands, the need of creating, deploying, and managing novel services on the fly drives the research of active and programmable networks. The fundamental discussion of programmable networks is that separating communications hardware from control software and allowing multiple parties to run possibly totally different protocols on the same network elements without any conflict. The open signaling approach and the active networks approach are the two kinds of implementations of active and programmable networks [23].

4) Overlay network: A virtual network that creates a virtual topology based on the physical topology of another network can be considered as an overlay network where nodes are connected through virtual links, which correspond to paths in the underlying network. Overlays are typically implemented in the application layer [6].

In the above four examples of wired network virtualization, the scope of virtualization is limited to one or two layers. However, to exploit the full benefits of virtualization, the network needs to be fully virtualized, and services are clearly separated from their underlying infrastructure.

B. Projects on Network Virtualization

Recently, several research projects have been started around the world in the area of network virtualization, including X-Bone [24] and Tempes [25] focusing on networking technology; UCLP [26], VNET [27], AGAVE [28] and VIOLIN [29] focusing on layers of virtualization; VNRMS [30], NetScript [31], Genesis [32] and FEDERICA [33] focusing on architectural domain and management; and PlanetLab [34], GENI [35], VINI [36], CABO [37], 4WARD [8] and NouVeau [38] focusing on the granularity of virtualization; and VITRO [39] focusing on virtualization of wireless sensor networks. Due to the space limitation, we only give a brief introduction to CABO, GENI, 4WARD and PlanetLab, which are important projects on network virtualization.

1) CABO: In CABO, the concept of separation between infrastructure providers (InPs) and SPs is promoted and improved by an integrated project to support full virtualization that allows SPs to provide end-to-end services over multiple InPs' infrastructure. CABO is also the first full virtualization project in which virtual routers can move (are mapped) from one physical node to another. It also provides guarantees and customization to service providers to support end-to-end services to the end users.

2) 4WARD: In 4WARD, more detailed business models are introduced in addition to InPs and SPs, including virtual network providers (VNPs) and virtual network operators (VNOs). This business model gives more opportunities to the market. The project also includes substantial work on resource allocation and resource discovery of network virtualization. Moreover, 4WARD also supports virtualization of heterogeneous networking technologies. Another significant contribution is that 4WARD implements network virtualization not only in experimental networks and testbeds but also in realistic networks.

3) PlanetLab: PlanetLab proposes a concept of slice-ability, in which each application acquires and runs in a slice of the overlay. Slice-ability is a crucial ability and design principle in network virtualization, which dominates the realization of both wired and wireless network virtualization.

4) GENI: GENI introduces network virtualization to the wireless area. In GENI, virtualization techniques and slicing techniques are proposed by utilizing TDMA, FDMA and SDMA. Moreover, GENI gives researchers the opportunity to create customized virtual networks unfettered by assumptions or requirements of the existing Internet.

5) VITRO: VITRO proposes an integrated architecture of enabling virtualization in wireless sensor networks while providing advanced services. The approach in VITRO realizes the decoupling of the applications running on physical nodes from the physical sensor deployment. This concept of virtual sensor networking allows the dynamic cooperation among sensor nodes, helping the proliferation of new services and applications beyond the scope of the original deployment.

C. Software Defined Networking and OpenFlow

SDN is an emerging network architecture where network control is decoupled from forwarding and is directly programmable [40]. It is considered as one of the most promising technologies to realize virtual networks, especially in network control. SDN focuses on four key features [41]:

- Separation of the control plane from the data plane.
- A centralized controller and view of the network.
- Open interfaces between the devices in the control plane (controllers) and those in the data plane.
- Programmability of the network by external applications.

By separating a network's control logic from the underlying physical routers and switches that forward traffic, network operators can write high-level control programs that specify the behavior of an entire network. This is different from conventional networks, where network operators must codify functionalities in terms of low-level device configurations. SDN allows network administrators to have programmable central control of network traffic via a controller without requiring physical access to the network's switches. A configuration of SDN can create a logical network control plane where hardware is physically decoupled from the data forwarding plane hardware, i.e., a network switch can forward packets and a separate server can run the network control plane. The decoupling allows for the control plane to be implemented using a different distribution model than the data plane. Control plane development and runtime environment tasks can then be run on a different platform (other than the low-powered management CPUs found on hardware switches and routers).

OpenFlow is a standard communications interface defined between the control and forwarding layers of an SDN architecture [42]. The standard is managed by Open Networking Foundation (ONF). OpenFlow allows direct access to and manipulation of the forwarding plane of network devices, such as switches and routers. With OpenFlow, the path of network packets through the network of switches can be determined by software running on multiple routers. A number of network switch and router vendors have announced intent to support OpenFlow standard.

III. MOTIVATIONS, BUSINESS MODELS & REQUIREMENTS OF WIRELESS NETWORK VIRTUALIZATION

In this section, we will discuss the motivations of wireless network virtualization. Business models with different roles in the wireless network market and the functions of these roles will be presented. Moreover, we will discuss the requirements that need to be met to implement wireless network virtualization.

A. What is Wireless Network Virtualization?

Wireless network virtualization can have a very broad scope ranging from spectrum sharing, infrastructure virtualization, to air interface virtualization. Similar to wired network virtualization, in which physical infrastructure owned by one or more providers can be shared among multiple service providers, wireless network virtualization needs the physical wireless infrastructure and radio resources to be abstracted and isolated to a number of virtual resources, which then can be offered to different service providers. In other words, virtualization, regardless of wired or wireless networks, can be considered as a process splitting the entire network system [13]. However, the distinctive properties of the wireless environment, in terms of time-various channels, attenuation, mobility, broadcast, etc., make the problem more complicated. Furthermore, wireless network virtualization depends on specific access technologies, and wireless network contains much more access technologies compared to wired network virtualization and each access technology has its particular characteristics, which makes convergence, sharing and abstraction difficult to achieve. Therefore, it may be inaccurate to consider wireless network virtualization as a subset of network virtualization [11].

In this paper, we consider wireless network virtualization as the technologies in which *physical wireless network infrastructure resources* and *physical radio resources* can be *abstracted* and *sliced* into *virtual wireless network resources* holding certain corresponding *functionalities*, and *shared* by multiple *parties* through *isolating* each other. In other words, virtualizing wireless network is to realize the process of abstracting, slicing, isolating and sharing the wireless networks. Since wireless network resources are sliced into multiple slices, the terms of virtual slice and virtual network have the similar meanings of virtual wireless network resources. We may use them alternatively in this paper

B. What are the Business Models of Wireless Network Virtualization?

In wireless network virtualization, physical resources are owned by some parties, and virtual resources are utilized by some other parties. The question is who these parties are. Business models can describe the constitution of the roles in the wireless network market and the main functions of these roles. As shown in Fig. 2(a), generally, after wireless network virtualization, there are two logical roles, MNO and SP [12], [37], [43]. All of the infrastructures and radio resources of physical substrate wireless networks, including the licensed spectrum, radio access networks (RANs), backhaul, transmission networks (TNs), and core networks (CNs), are owned and operated by MNOs. MNOs execute the virtualization of the physical substrate networks into some virtual wireless network resources. For brevity, we use virtual resources to indicate the virtual wireless network resources. SPs lease these virtual resources, operate and program them so that to offer end-to-end services to end users. In some papers (e.g., [5]), the MNO becomes InP, which is only responsible for owing and leasing wireless network resources to SPs. SPs will create and deploy the virtual resource by themselves based on the leased and allocated resource to satisfy the requirements of end-to-end services.

The roles in in the above business models can be further decoupled into more specialized roles, including InP, mobile virtual network provider (MVNP), mobile virtual network operator (MVNO) and SP [44]–[46], as shown in Fig. 2(b). The functions of them are describing as follows.

a) InP: owns the infrastructure and wireless network resources. In some cases, the spectrum resources may or may not be owned by InP.

b) MVNP: leases the network resources and creates virtual resources. Some MVNPs may have some licensed spectrum such that they do not need request spectrum resources from InP. In some papers (e.g., [47]), MVNP is called mobile virtual network enabler (MVNE).

c) MVNO: operates and assigns the virtual resources to SPs. Meanwhile, in some approaches, MVNOs consists of the roles of both MVNOs and MVNPs. Actually, this model is fit for the emerging concept of so called XaaS [48] in cloud computing. What provided in InPs is infrastructure-as-a-service (IaaS) while what provided in MVNOs is network-as-a-service (NaaS).

d) SP: concentrates on providing services to its subscribers based on the virtual resources provided by MVNOs.

In other words, virtual resources are requested by SPs, managed by MVNOs, created by MVNPs, and running at InPs physically. Obviously, this four-level model can create more opportunities in the market and simplify the functions of each role intuitively. Nevertheless, more coordination mechanisms and interfaces should be used, which may increase the complexity and latency significantly.

Here, we give a short discussion on the role of MVNOs. The definition of MVNOs is different in different countries and communities [47]. The authors of [13] argue that MVNOs do not own any spectrum and radio access networks for its subscribers to access. However, in [47], MVNOs may or may not own infrastructure, or may only own other parts of wireless networks (e.g., CNs) except RANs and spectrum licenses. The authors of [47] consider that MVNOs are the key players who can break the value chain of telecommunications both wired and wireless in the future mobile network markets. This claim is based on the existence of pure InPs, which means

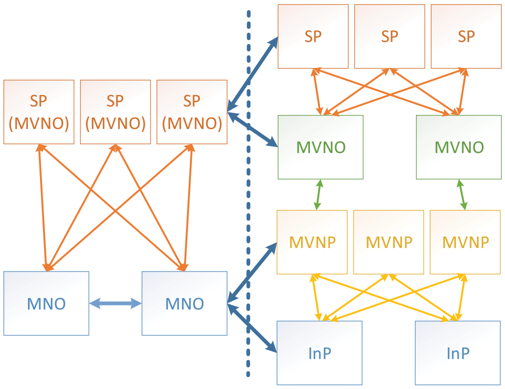


Fig. 2. Business models of wireless network virtualization. (a) A two-level model; (b) A four-level model. SP - service providers; MNO - mobile network operator; MVNO - mobile virtual network operator; MVNP - mobile virtual network provider; InP - infrastructure provider.

MVNOs (including MVNPs and MVNOs) are the entities responsible for providing virtual resources to SPs [10], [46]. In the XaaS concept, IaaS can be provided to MVNOs, and MVNOs can provide NaaS to SPs. However, up to now, most of the infrastructures and radio resources are owned by the MNOs who do not want to share too much revenues to potential MVNPs and MVNOs. Unlike this judgement, some approaches (e.g., [49]) consider the MVNO as a special SP, which provides enhanced services to focused customers. In this situation, both MVNOs and MNOs are in a win-win situation, since MVNOs help MNOs attract/retain greater number of customers, and MVNOs may provide services including VoIP, video telephony, live streaming, etc. [12].

The above business models can also be used for IEEE 802.11-based wireless networks. In commercial cellular networks, 802.11-based access technologies can be used as an efficient supplement to cellular networks for the data traffic in hot spots. In this case, as part of the whole wireless network, 802.11-based networks can follow the business models discussed above. In another model with 802.11-based networks, called "Testbed as a Service" (TaaS) [50], [51], MNO and SPs may be the equipment providers (administrators) and research institutions (groups) separately instead of being commercial entities.

C. *Why Need Wireless Network Virtualization?*

The motivations for wireless network virtualization range from academic and industrial research to commercial markets. In wireless networks, a significant connection between theoretical research and practical implementation is the infrastructure-based testbed used for identifying and evaluating new technologies and proposed ideas. Wireless network virtualization can support powerful and efficient testbed systems that can shorten the process of R&D of innovated technologies in two folds. First, due to the flexibility, programmability and customization of virtual networks, the proposed new networking technologies and services can be implemented in infrastructures for easier and faster evaluation without considering the complicated interfaces and characteristics of physical infrastructures. Second, due to the isolation between virtual networks, multiple experiments can be run and operated simultaneously, which means, even in the real infrastructure, experimental functions can be tested and deployed without disturbing the normal services [14].

In commercial markets, CapEx and OpEx can be lowered significantly due to the sharing enabled by wireless network virtualization. The authors of [49] estimate that up to 40% of $60 billion used for OpEx and CapEx can be saved by operators worldwide over a five-year period. A very detailed analysis of OpEx and CapEx in sharing wireless network is given in [52]. It is estimated that the sharing of sites and antennas can reduce 20-30% of CapEx, 25-45% of CapEx can be saved if the whole radio network is shared, and the sharing of all the assets would decrease CapEx by an additional 10%. Although OpEx varies largely in different countries, in general, there is big space to reduce OpEx and CapEx by deploying network sharing.

Over the past years, MVNOs and over-the-top (OTT) SPs have become strong players in mobile network markets and brought their featured services to impact the ecotope of the traditional market dominated by MNOs. Fortunately, wireless network virtualization brings a win-win situation for both MVNOs and MNOs [12]. MVNOs or other types of SPs can lease virtual networks from MNOs, and MNOs can attract greater number of customers from MVNOs and SPs. For MNOs themselves, since the network can be isolated into several slices, any upgrading and maintenance in one slice will not affect other running services. For SPs, leasing virtual networks helps them "get rid of" the control of MNOs, so that customized and more flexible services can be provided more easily and the quality of service (QoS) can be enhanced as well. This also brings impressive revenues to MNOs, because SPs needs to pay more to the MNOs and reduces the undying arguments between MNOs and SPs.

D. *What are the Requirements of Wireless Network Virtualization?*

Wireless network virtualization can be developed based on a specific business model. There are some requirements that need to be met to implement wireless network virtualization. Depending on the scope of virtualization, these requirements can be classified as basic requirements and additional requirements.

1) *Basic requirements:*

a) Coexistence: In wireless network virtualization, physical infrastructures should allow that multiple independent virtual resources coexist on substrate physical networks [46]. Actually, it is clear that the purpose of virtualizing network is to make multiple systems to run on the same physical resources.

Moreover, since virtual slices are created according to the requirements of SPs, they are different among virtual slices. Virtualization systems have to bear multiple virtual slices who hold various QoS requirements, topology, services type, security level, user behaviour, and etc.

b) Flexibility, manageability and programmability: Freedom in different aspects of networking needs to be provided in wireless network virtualization through the decoupling customized control protocols from the underlying physical networks and other coexisting virtual networks. [5]. However, since different virtualization may have different levels, ranging from flow level, sub-channel or time-slot level, to antennas level [12], flexibility depends on the level of virtualization. Higher level virtualization may reduce the flexibility of virtualization while better multiplexing of resources across slices (and hence increased utilization with fluctuating traffic) and simplicity of implementation, but can reduce the efficacy of isolation and the flexibility of resource customization, whereas virtualization at a lower level leads to the reverse effects.

Manageability and programmability are other two basic requirements. Since virtual slices or virtual networks are assigned to SPs and the management of these virtual wireless resources are decoupled from substrate networks, wireless network virtualization needs to provide complete end-to-end control of the virtual resource to the SPs [5]. SPs are able to manage configuration, allocation of virtual networks, e.g., routing table, virtual resource scheduling, admission, and even modifying protocols, etc.

To realize manageability, programmability needs to be integrated in wireless network virtualization to help SPs implement customized diverse services, protocols and networks. Programmability needs MNOs to provide appropriate interfaces, programming language and enabling a secure programming paradigm with considerable level of flexibility [6].

c) Isolation: Isolation ensures that any configuration, customization, topology change, mis-configuration and departure of any specific virtual networks will be not able to affect and interfere other coexisting parts. In other words, isolation means that any change in one virtual slice, such as the number of end users, mobility of end users, fluctuating of channel status, etc., should not cause any change in resource allocation for other slices [12]. Indeed, virtual slices or virtual networks are transparent to each other, or we can say that they never know the existence of other virtual slices. It is similar to the multiplexing among users in modern mobile networks but not the same. Since many virtual networks should coexist, isolation is the basic issue in virtualization that guarantees fault tolerance, security, and privacy [5]. In addition, in wireless networks, especially cellular networks, any change in one cell may introduce high interference to neighbor cells, and the mobility of end users may create instability of a specific area [53]. Therefore, isolation becomes more difficult and complicated in wireless networks compared to the wired counterparts.

2) Additional requirements:

a) Heterogeneity: Since there are many coexisting radio access technologies, wireless network virtualization should allow heterogeneity. And the substrate physical networks should be composed of not only heterogeneous wireless networks but also wired networks. Moreover, the authors of [46] point out that virtual networks on top of them could be heterogeneous (e.g., by using different protocols).

b) Revisitation and scalability: The infrastructures in wireless network virtualization should provide the capability that supports an increasing number of coexisting virtual networks or some sliced virtual resources;

c) Stability and convergence: For virtual wireless networks, stability decreases the effects of errors and misconfigurations in the underlying physical network. Also, convergence allows virtual wireless networks to be stable in case of any instability happening.

d) Mobility: Virtual wireless networks should support not only traditional mobility but also mobility between MVNOs or SPs. Mobility management should allowed virtual mobility that is between WVNs or SPs and geographical mobility at the same time.

e) Resource utilization: Wireless network virtualization should guarantee the efficient use of physical radio resources, computing resources and other resources. The architecture needs to cope with the tradeoff between complexity and efficiency in dynamic resource scheduling.

IV. FRAMEWORK OF WIRELESS NETWORK VIRTUALIZATION

In this section, a framework is summarized for wireless network virtualization. This framework is based on the architectures proposed by existing studies, and reflects the basic ideas, components and relationship in wireless network virtualization; but, unfortunately, this framework may not represent all of the architectures, because each architecture has special purposes, original intension and ideas. Generally, the framework of wireless network virtualization can be composed of four main components: *radio spectrum resource*, *wireless network infrastructure*, *wireless virtual resource*, and *wireless virtualization controller*, as shown in Fig. 3.

A. Radio Spectrum Resource

Radio spectrum resource is one of the most important resources in wireless communications. Usually, radio spectrum resource refers to the licensed spectrum or some dedicated free spectrum (e.g., IEEE 802.11). As cognitive radio [54] emerges, radio spectrum extends its range from dedicated spectrum to white spectrum, which means idle spectrum unused by the owner can be used by others.

We separate radio spectrum as a single component of wireless network virtualization due to the improvement of cognitive networks [55], deployment of heterogeneous networks (e.g., femtocells and small cells) [56] and implementation of network sharing [47]. Cognitive radio technology makes the usage of spectrum more flexible compared to current relatively fixed spectrum access, while heterogeneous networks change the traditional frequency reuse planning in cellular networks. These two technologies will be discussed in Section VII. Network sharing introduces cooperation into the relationship among telecommunication operators. Roughly speaking, *network sharing* includes *spectrum sharing*, *infrastructure sharing* and *full network sharing*. The later two parts and the definition of network sharing will be discussed in the next subsection.

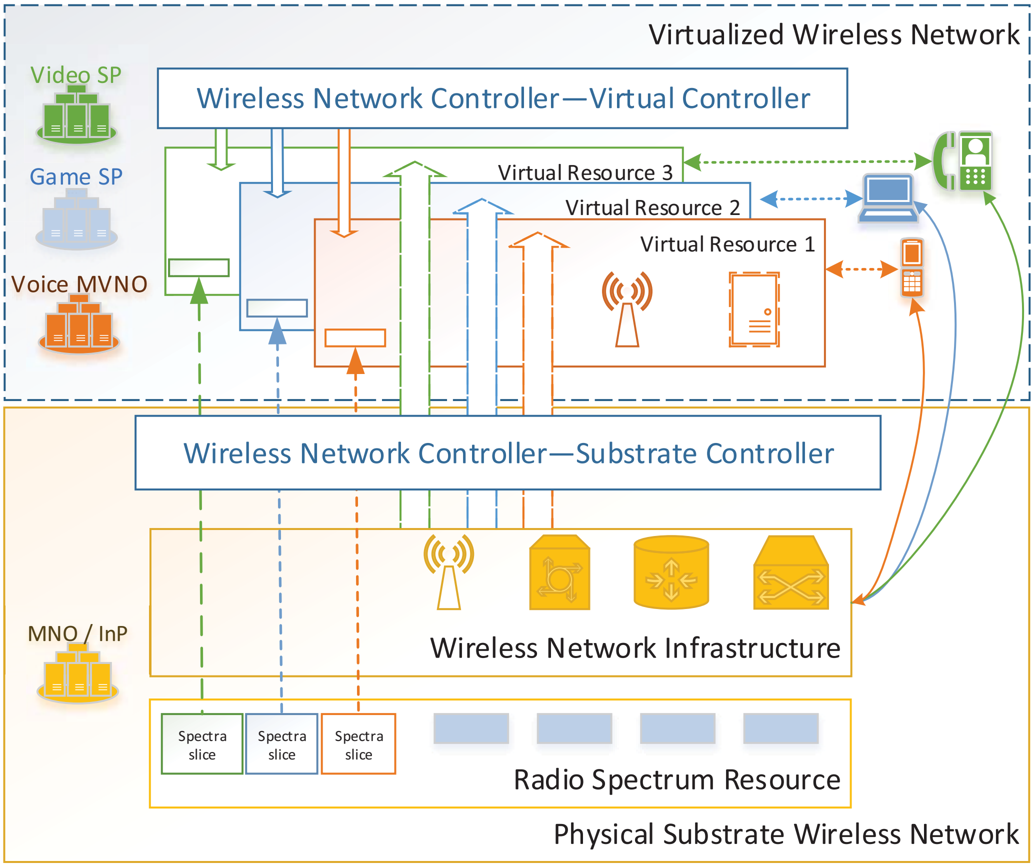


Fig. 3. A framework of wireless network virtualization.

Spectrum sharing refers to that all or part of the licensed spectra owned by operators can be utilized by multiple contracted operators (usually the operators who have contributed to the shared spectra) based on agreements. For example, operator A and operator B have a contract to share both of their spectra with each other so that they have more flexible frequency scheduling and diversity gain that can improve the efficiency and capacity of networks. Actually, inter-operator spectrum sharing has been proposed for many years, e.g., [57] and [58]. However, due to the reasons of policies and markets instead of technology, spectrum sharing is not popular in current cellular networks. Fortunately, wireless network virtualization is recalling spectrum sharing to promote full virtualization, which means to consider the total available radio spectra as a whole resource and to virtualize them as the abstracted access medium.

B. *Wireless Network Infrastructure*

Wireless network infrastructure refers to the whole wireless physical substrate network, including sites (towers and antennas), base stations (macrocell, smallcell, relay, RF, baseband processors, radio resource controllers, etc. in cellular networks), access points (in wireless local area networks (WLANs)), core network elements (gateway, switchers, routers, etc.), transmission networks (backhaul and links between RANs and CN).

These infrastructure components implemented physically are the "foundation" of wireless networks and occupy the majority of the investment of MNOs. In modern wireless networks, a single whole wireless network (including RAN, CN and TN) may be possessed by one MNO, or some parties may own part of the whole wireless network, e.g., some parties own the CN while some parties only have the TN. However, in a certain geographical area, the relationship among MNOs or InPs who operating the same part of the network is in competition, which means no sharing or limited sharing (e.g., roaming) exists. Therefore, any virtualization in this paradigm is the so called *limited intra-infrastructure virtualization*, which means virtualization within a single MNO or InP [13].

Obviously, as we discussed above, since MNOs need to attract more customers and satisfy the various requirements from SPs, the cooperation and sharing of resources among MNOs have been becoming a new paradigm when planing and operating wireless network infrastructure, which leads to the improvement of network efficiency and utilization. Network sharing refers to that multiple MNOs who share the capacity and infrastructure of a physical network with each other. From the business perspective, network sharing can be considered as an agreement that two or more MNOs pool their physical network infrastructure and radio resources together and share with each other. From the technology perspective, network sharing is from the sharing of towers and other infrastructure facilities to sharing an entire mobile network [52]. From the view of the concept of cloud, to realize virtualization in wireless networks, network sharing can be considered as an important step to enable IaaS. Meanwhile, network sharing can reduce the CapEx and OpEx of operators significantly [59]. In commercial networks, some initial approaches and promotion of network sharing have been done by several standardization organizations (e.g., 3GPP [60]), vendors (e.g., NEC [61] and Nokia Siemens Networks [62]) and operators (e.g., China Mobile [63]). In the UK, Vodafone and O2 have started their network sharing by pooling their network infrastructure. This network sharing partnership enables better coverage for mobile users and fewer masts to build [64]. One of the network sharing approaches, spectrum sharing, has been introduced in the previous subsection. Thus, the other two approaches, *infrastructure sharing* and *full network sharing*, are discussed as follows.

1) Infrastructure sharing: Unlike spectrum sharing, only infrastructures are shared in this case. Infrastructure sharing can be classified into two categories: (a) *passive sharing* and (b) *active sharing*. Passive sharing refers to that operators share the passive infrastructures, such as building premises, sites and masts. Currently, passive sharing is operated by some third parties called “tower companies” that have agreements with operators to provide passive RAN infrastructures [65]. Active sharing refers to sharing of the network elements of a whole mobile network, such as (a) RF antennas and eNodeBs included in RANs, (b) backhaul and backbone transmission included in transmission networks and (c) routers, switches and register (e.g., visitor location register (VLR)) included in the core network.

In [62], an architecture of network sharing called multi-operator RAN (MORAN) is proposed to allow multiple MNOs to share the RANs. Meanwhile, 3GPP proposes two scenarios where infrastructure sharing is used [66]. In scenario 1, the MNOs connect to the shared RAN directly and serve the respective end users by using their own dedicated licensed spectrum. Scenario 2 is based on geographically split, which means MNOs (usually more than two) will use their respective radio access networks to cover different parts of a country but together provide coverage of the entire country. This scenario can be divided to two cases, which are national roaming between operators (using both the RAN and CN owned by other MNOs) already deployed today and shared radio networks by using their own spectrum (using dedicated or common CNs), respectively.

Virtualization-based infrastructure sharing can be called *cross-infrastructure virtualization*, which means wireless network virtualization is possible both across MNOs (InPs) and within MNOs (InPs) [13].

2) Full network sharing: Full network sharing is the combination of spectrum sharing and infrastructure sharing, which means both radio resource and network infrastructure are able to be shared among multiple MNOs based on agreements.

In 3GPP specification [60], full network sharing supports two identified architectures, which are multi-operator core network (MOCN) configuration and gateway core network (GWCN) configuration. In MOCN, the shared parts are only the RANs including radio resources themselves. GWCN allows sharing not only the RANs but also MSCs and SGSNs, which can be considered as the entities in core networks. Three scenarios are given in [66] where full network sharing is used. In scenario 1, some operators are allowed to access a RAN, which covers a specific geographical area hosting by a third-party (may be another operator except previous operators). Scenario 2 is called common spectrum network sharing where one operator shares its licensed spectrum to other operators, or a group of operators gather their licensed spectrum to a pool and share the total spectrum together. In this scenario, all operators in the group may first connect to a controller called radio network controller then to the shared RAN or may combine with each other to form a common core network then connect to the shared RAN. In scenario 3, multiple RANs may share a common core network, where the elements or nodes have different functions but belong to different RAN operators. Several requirements should be satisfied to deploy the above scenarios in terms of user, network, requirements, security and charging [66]. In [61], specific to long term evolution (LTE)-based mobile networks, NEC provides a solution supporting both of MOCN and GWCN in the 3GPP architectures.

Performance comparisons on inter-operator sharing are studied in [67] in terms of capacity, spectrum and base stations. They evaluate and compare the performance of (a) no-sharing (NS), (b) capacity sharing (CS), which can be considered as a extension of the roaming-based sharing [66] and (c)spectrum sharing (SS), which means operator 1 may share its part of spectrum to heavy loaded operator 2 on traditional infrastructure. Based on their results, it is shown that CS performs the best compared to the others.

Therefore, full network sharing gives virtualization more efficient and flexible physical substrate networks, which leads to the so called *universal virtualization*, where virtualization can be pervasive [13].

C. Wireless Virtual Resource

Wireless virtual resources are created by slicing wireless network infrastructure and spectrum into multiple virtual slices. Ideally, a single slice should include all the virtual entities sliced by each element in the wireless network infrastructure. In other words, a completed slice is a universal wireless virtual network. For example, an SP requesting a slice from a MNO means that this SP wants to have a virtual network from CN to air interface and is able to customized all the virtual elements in this slice. However, in reality, this ideal slice may not be always necessary. Specifically, some MVNOs who may have their own CN or be lake of whole coverage [60] only need RAN slices, while some SPs only need the slices at a specific area or time. Given a more abstract scenario, some emerging over-the-top (OTT) SPs pay more to MNOs only to ensure a guaranteed QoS service to their end users. The MNOs must allocate a certain number of resource slices [12] to these OTT SPs if a contract exists, and these resource slices can be customized by OTT SPs according to their own requirements. Thus, based on different requirements, wireless virtual resource implies various degrees of virtualization level. Here we present the main four levels of wireless virtual resources in the following.

1) Spectrum-level slicing: Spectrum-level slicing can be considered as an extension of dynamic spectrum access and spectrum sharing. In this paradigm, spectra are sliced through time multiplexing, space multiplexing or overlaid access, which are the same as dynamic spectrum access and assigned to MVNOs or SPs. In addition, in wireless network virtualization, spectrum virtualization is link virtualization where the emphasis is the data bear in this link instead of physical layer technology. Roughly, we can say that spectrum-level slicing is an application of spectrum sharing and dynamic access in the virtualization environment.

2) Infrastructure-level slicing: In infrastructure-level slicing, the physical network elements, e.g., antennas, BSs, processor hardware and routers, are virtualized to support sharing by multiple operators. When multiple MVNOs who only own spectrum or multiple MNOs who have limited coverage want to lease infrastructure and hardware from an InP in a certain area, the InP has to virtualize this physical resources into slices of virtual infrastructure and virtual machines. For example, as shown in Fig. 4, the physical network of InP covers area 0; MNO1 has the licensed spectrum and network infrastructure, which covers area 1 and MNO2 has the licensed spectrum and network infrastructure, which covers area 2, while MVNO has the licensed spectrum but without any infrastructure to cover. MNO1, MNO2 and MVNO want to cover the whole areas including area 0, area 1 and area 2. Therefore, for area 2, MNO2 virtualizes the infrastructure and slices them to two slices, assigning each to MNO1 and MVNO. The same situation is true with area 1, where MNO2 and MVNO wants to cover. In area 0, InP virtualizes the physical infrastructure and hardware to three virtual parts, called virtual infrastructure1 (VI1), VI2 and VI3, and lease them to MNO1, MNO2 and MVNO, respectively. MNO1, MNO2 and MVNO control VI1, VI2 and VI3 through the controller who takes the responsibility of resource management (e.g. allocation, scheduling and access admission). Some mechanisms employed this architecture have been approached in network sharing [52], [60], [61], which have been discussed in the previous subsection. In some network situation where an agreement is existing between MNOs, a MNO can share part of its resource to other MNOs. However, from pure network virtualization aspect, the basic difference between networks sharing and infrastructure-level virtualization is that MNOs and MVNOs can manage the virtualized infrastructure and virtual machine sufficiently through controller.

3) Network-level slicing: Network-level slicing is the ideal case as mentioned above. Here we give an example as follows. A BS (e.g., nodeB in UMTS systems or eNodeB in LTE systems) is virtualized to multiple virtual BSs, then the radio resources (e.g., time slots, spectrum and signal processors) are also sliced and assigned to the virtual BSs. To enable virtual CNs, the entities in the CN domain (e.g., routers and switches) have to be virtualized to virtual machines. Specifically, in 3G networks, SGSN and GGSN need to be virtualized; in 4G networks, MME, SGW and PGW need to be virtualized to their multiple virtual counterparts [68]. In [69], the authors introduce an integrated network-level virtualization architecture including all three domains specific to LTE networks. [70] and [71] focus on the RAN domain while [72] focuses on the CN domain. Fig. 5 gives an example of 4G LTE network virtualization, which is based on the architecture proposed in [69].

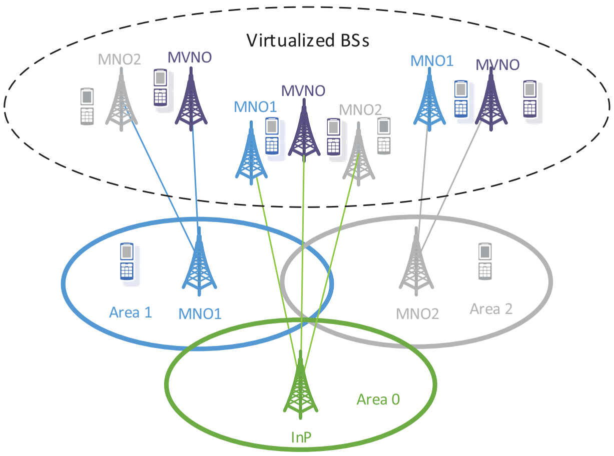


Fig. 4. An example of infrastructure slicing.

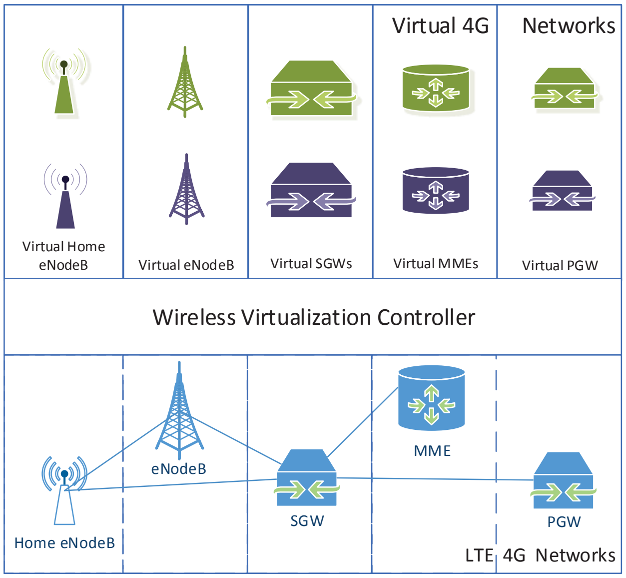


Fig. 5. An example of network-level slicing [69].

4) Flow-level slicing: The main idea of flow-level slicing virtualization is first proposed in FlowVisor [73]. In flow-level virtualization, the definition of slice can be different, but usually it should be a set of flows belonging to an entity that requests virtualized resources from MNOs [12]. Some works

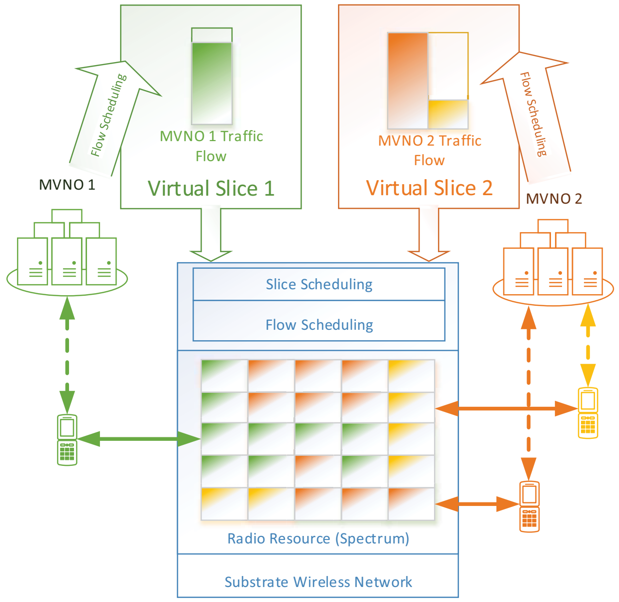


Fig. 6. An example of network-level slicing [61].

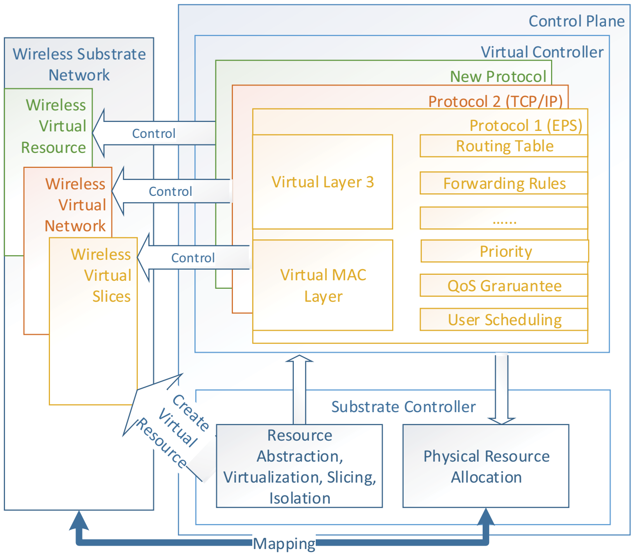


Fig. 7. The architecture of wireless virtualization controller.

have been done towards this architecture, such as [12], [49], [74]. In this architecture, the physical resources that belong to one or more MNOs are virtualized and split into virtual *resource slices*. The resource slices can be bandwidth-based, e.g., data rate, or resource-based, e.g., time slots [12]. A typical example is an MVNO who does not have physical infrastructures and spectrum resource (but has its own customers) to serve video calls to its customers. This MVNO may request a specific slice based on certain data rate (bandwidth) from the MNO who actually operates the physical networks. This scenario is very similar to the example of infrastructure-level slicing except the spectrum resource and other resources. Fig. 6 gives an example of flow-level network virtualization, which is based on the architecture proposed in [61].

D. Wireless Virtualization Controller

Wireless virtualization controller is used for realizing customability, manageability and programmability of virtual slices available to SPs. Through wireless virtualization controller, the control plane is decoupled from data plane and SPs can customize the virtual resource within their own virtual slices. As shown in Fig. 7, there are two parts in wireless virtualization controller, *substrate controller* and *virtual controller*. Substrate controller is used for MNOs or InPs to virtualize and manage the substrate physical network. Virtual controller is used for MVNOs and SPs to manage the virtual slices or networks. Specifically, MNOs use wireless virtualization controller to create virtual slices and embedding the virtual slices onto wireless physical substrate networks, while SPs use it to customize their own end-to-end services, such as scheduling and forwarding. A brief description of network management in virtual networks can be found in [75]. Since SDN and OpenFlow have been considered as the most promising and effective technology in the network management domain, applying SDN in wireless networks has attracted some attentions [68], [76]. The functions and components of wireless virtualization controller is summarized in Fig.7.

V. PERFORMANCE METRICS OF WIRELESS NETWORK VIRTUALIZATION

Before the discussion of enabling technologies for wireless network virtualization, in this section, we present some performance metrics that are necessary to evaluate the performance and quality of a virtualized wireless network. These performance metrics can be used to compare different architectures, virtualization mechanisms, resource allocation algorithms, management systems, customization flexibility, energy saving, interfaces, etc. According the requirements of wireless network virtualization, we classify the metrics into two categories: *performance metrics of traditional wireless networks* and *wireless-virtualization-specific metrics*. These metrics are summarized in Table I.

A. Performance Metrics of Traditional Wireless Networks

In traditional wireless networks, several metrics are used to evaluate the performance of a network. Obviously, these metrics can also be used to measure wireless network virtualization.

1) Costs: Costs are the total investment from wireless network operators for the infrastructure constructing and network operating, including CapEx and OpEx. For wireless networks, especially for cellular networks, the CapEx consists of the cost of building up base station equipments, backhaul transmission equipments, radio network controller equipments, core network equipments and site (equipment) installation. Unlike CapEx, OpEx includes energy charge, site and backhaul lease, and operation and maintenance costs [77]. Also, deployment

TABLE I
PERFORMANCE METRICS OF WIRELESS NETWORK VIRTUALIZATION.

Types	Metrics	Units	Description
Metrics of Traditional Wireless Networks	Costs	Currency units (e.g., US$)	Including CapEx and OpEx
	Revenue	Currency units (e.g., US$)	Earned revenue
	Coverage	m^3	A certain 3D area covered by wireless services
	Capacity (Throughput)	bps	Peak data rate for a certain area
	Deployment Efficiency	$m^3/\$$ $Mbps/\$$	Throughput (capacity) / Deployment Costs
	Spectrum Efficiency	bps/Hz	Throughput (capacity) / bandwidth, in a certain coverage area
	Energy Efficiency	$bps/Joul$	Throughput (capacity) / energy consumption
	QoS	various	Quality of service experienced by end users
	Service Latency & Signaling Delay	$second$	Packet delay and signaling delay
Wireless-Virtualization-Specific Metrics	Throughput between virtual entities	bps	Average data rate achieved between virtual entities
	Delay between virtual entities	$second$	The amount of time needed for a packet to go from one virtual node in the network to another virtual node
	Path length between virtual entities	number of nodes	The number of hops in the physical link to construct a virtual direct link
	Isolation level	unitless	The lowest virtualized physical resource level
	Utilization and stress	unitless	used resources / available resources available resources / total resources

costs include the cost of using licensed spectrum issued by the authorities when the MNO or InP is new to the market.

In wireless network virtualization, since additional equipments and maintenance are required, these parts of cost should be considered as CapEx and OpEx as well. As MVNOs and SPs are usually not responsible for network deployment, MNOs or InPs need to bear the majority of the deployment coasts. However, since MVNOs and SPs are given more flexibility, programmability and manageability in wireless network virtualization, the OpEx may be beard by both MNOs (InPs) and MVNOs (SPs).

2) Revenue: In addition to the reduced costs, the increased revenues compared to traditional networks is another purpose of wireless network virtualization. Profit, which is the difference between costs and revenues, can be used to evaluate wireless network virtualization. Moreover, revenue to cost ratio (RCR) can be used as another measure as well. The higher the profit (RCR) value, the more the motivations for MNOs and SPs to deploy wireless network virtualization mechanisms.

3) Coverage and capacity (throughput): Coverage refers to the whole geographical area where the wireless network services can cover. Capacity refers to the maximal aggregated peak rate (maximum theoretical throughput) for a certain area served by a BS (or access point). Throughput usually refers to the data rate delivered to end users in a certain time duration and area. Coverage and capacity (throughput) play the fundamental roles in wireless network design and optimization. For a certain access network technology (e.g., wide code division multiplexing access(WCDMA), LTE or 802.11 family), coverage and throughput are mainly related to bandwidth, transmit power, network planning, which are briefly presented as follows.

a) Bandwidth: Bandwidth is the total available radio spectrum in a certain area for serving end users. It should be noted that, with the development of cognitive radio and network sharing, the available radio spectrum may contain some free spectrum and other MNOs' licensed spectrum.

b) Transmit power: Transmit power is the power transmitted from BSs to end users as well as from end users to BSs.

c) Network planning: Network planning refers network topological design, network synthesis and network realization, with the aim at ensuring that a new network or service meets the needs of end users and operators. The deployment of small cells and relays will lead to higher throughput and larger coverage. Network sharing among MNOs and small cells also can bring novel network planning strategies, which are different from traditional network planning.

4) Deployment efficiency: Deployment efficiency (DE) metric measures the ratio between system throughput (or coverage) and deployment costs (including both CapEx and OpEx) [77]. DE is an important network performance indicator for wireless operators. Usually, wireless engineers need to estimate the deployment efficiency during network planning.

5) Spectrum efficiency: Spectrum efficiency (SE) metric can be defined as the ratio between system throughput (or coverage) and bandwidth. SE has been widely accepted as an important criterion for wireless network optimization [77], especially for cellular networks. To study the SE in a certain area, one can add the SE achieved by all the cells, including macro cells and small cells, which use the same spectrum in this area. In addition, more detailed spectrum efficiency metrics can be used to evaluate the performance, such as the cell edge spectrum efficiency and the worst %5 users spectrum efficiency.

6) Energy efficiency: Energy efficiency (EE) metric can be defined as the ratio between system throughput (or coverage) and energy consumption. It should be noted that the energy consumption is not limited to transmission energy consumption but should include the whole network energy consumption while operating the network, including network equipments energy and accessories (e.g., air conditions, lightning facilities, etc.) [78].

7) QoS: The metrics mentioned above are related to system performance and resource efficiency. Different from the above metrics, QoS is usually related to end users. Generally, a certain QoS requirement is represented by several variables that characterize the performance experienced by end users [79]. For instance, in 3GPP LTE [80], QoS is classified to 9 kinds of so called QoS class identifiers (QCIs) that associate to resource types (guaranteed bit rate or non-guaranteed bit rate), priority (9 levels), packet delay budget and packet loss rate.

8) Signaling latency: Signaling latency refers to the delay of control signals among entities that hold the functions of network management. Since wireless network virtualization enables the programmability for SPs and MVNOs, the number signaling exchanges will be increased in the network, which can cause higher delay of signaling.

B. Wireless Virtualization-Specific Metrics

In addition to the performance metrics of traditional wireless networks, there are some virtualization-specific metrics that can be used to measure the quality and performance of a virtualized wireless network.

1) Throughput between virtual entities: Different from traditional throughput, virtualization-specific throughput is the average data rate achieved between virtual entities. This throughput metrics can be used to measure the connection performance between virtual nodes, SPs to end users, and MNOs to end users. Using this measure, one can evaluate resource allocation algorithms and management efficiency in virtualized wireless networks.

2) Utilization and stress of substrate networks: Since the substrate physical resources are used to map virtual slices, virtual nodes and virtual links, utilization is defined as the ratio between the used substrate resources and the total amount of resources [10]. For example, to evaluate a substrate physical eNodeB, utilization can be derived with the used bandwidth, power, time-slots, signal processing resources divided by available bandwidth, power, time-slots, signal processing resources, respectively. In addition, stress evaluates the capability that the substrate physical resources can bear the maximal virtual entities. For example, stress measures how much virtual eNodeB can be mapped by a physical eNodeB. Utilization and stress can be used to evaluate the resource allocation algorithms and virtualization mechanisms.

3) Delay and jitter between virtual entities: Delay describes the amount of time needed for a packet to go from one node in the network to another node [10]. Here, this node can be a virtual node, SP and end user, depending on different architectures. The packet inter arrival times can be measured by jitter, which is inherent to substrate networks [10]. Jitter is not specific in virtualized networks, but has greater effects on the performance of virtualized wireless networks than traditional networks. Especially in the wireless environment, due to the unreliable and varied link quality, delay and jitter become more important. Delay and jitter can be used to to evaluate virtualization mechanisms and management efficiency, since different mapping strategies and controller methods may affect the network greatly.

4) Path length between virtual entities: Since some interconnected virtual nodes are connected by virtual links, which means that the direct physical link may not exist, the path length metric measures the number of links between two substrate nodes that are finally mapped one direct virtual link to connect the virtual nodes. The path length will affect the delay and jitter due to that longer path length needs more physical nodes to forward the packets. Therefore, path length can be used to evaluate the virtualization mechanisms and resource allocation algorithms.

5) Isolation level: Since wireless network virtualization may be done at different levels, such as network level, flow level, sub-channel or time-slot level, or even hardware level (such as antennas and signal processors) [12], isolation level can be used to measure the lowest virtualized physical resource level. For example, in wireless virtualization, if an MNO slices their resource to time-slot-based slices, the isolation level is time-slot.

VI. ENABLING TECHNOLOGIES FOR WIRELESS NETWORK VIRTUALIZATION

In this section, some enabling technologies for wireless network virtualization are summarized. We first present the classification methodologies, then these enabling technologies are presented according to different radio access technologies.

Before presenting the enabling technologies in wireless network virtualization, we first discuss the differences between resource partitioning and slicing, as well as resource virtualization and multiple accessing. Resource partitioning is the process of dividing the physical resources from some particular aspects and allocating them to different parties. It should be noted that the objects and results of partitioning are both physical. Slicing also does dividing and allocating, but may be on virtual resource or physical resource [13]. There is no virtualization or sharing in resource slicing and partitioning, but the ultimate purpose of slicing and partitioning is to provide resource virtualizing or sharing. According to [13], virtualization and multiple access both aim to sharing the physical resources among multiple parties but in different levels. Multiple access tries to share resources among individual users while virtualization provides resource sharing among different network slices or groups of users. Obviously, multiple access techniques are always the basis since any wireless network relies on particular multiple access techniques. All the users must deploy the same access technique in the same network. By contrast, in virtualization, the protocols, multiple access techniques, even network topologies running on multiple slices may totally different. To reduce possible confusion, an instance of air interface virtualization is described as follows.

Suppose there are two MVNOs requesting virtual networks from an InP. This InP has two air interfaces corresponding to two kinds of multiple access technologies, CDMA and LTE.

Based on the requests from the MVNOs, the InP virtualizes these two air interfaces into four virtual air interfaces comprising two CDMA-based and two LTE-based air interfaces. Considering the case of LTE, the InP can divide the total available physical radio resource blocks (PRBs) into two parts and allocate them to each MVNO separately. For CDMA, the air interface can be sliced in the domain of time or frequency for the purpose of isolation, which means that each MVNO is allocated part of the available spectra or time slots.

A. Classification

Since wireless networks include a variety of different technologies, it is difficult to present the enabling technologies for wireless network virtualization by a particular property. Therefore, we will describe the following categorizing methodologies and use them as a taxonomy to classify the enabling technologies for wireless network virtualization.

1) Radio access technologies: Unlike wired networks, the radio access technologies in wireless networks are different and often incompatible with each other. Most of current enabling technologies focus on 802.11-based networks, cellular networks (including LTE systems and WiMax systems), heterogeneous networks, and others. The term of “others” used here refers to technologies that do not specify the access technology used in their approaches.

2) Isolation level: The enabling technologies for wireless network virtualization can also be classified according to the isolation level. Isolation level refers to the minimum resource units, which isolate the SPs from each other. As we mentioned in the last section, wireless network virtualization may be done at different levels, such as network level, flow level, subchannel or time-slot level, or even hardware level (such as antennas and signal processors) [12].

3) Control method: Control methods can be used to classify enabling technologies as well. Centralized control, distributed control, or hybrid control are the possible control methods to enable wireless network virtualization. If a single entity in the MNO receives SPs’ requirements, then creates and operates wireless network virtualization, this kind of control method is a centralized approach. By contrast, if each element in a wireless physical network performs the virtualization independently in a distributed manner, this kind of control method is a distributed approach.

4) Purpose: Originally, network virtualization is proposed for experimental purposes where multiple protocols need to run simultaneously on the same infrastructure. Network virtualization in the commercial market can be considered as the extension to the successful experiment. Thus, from the purpose’s point of view, the enabling technologies can be classified to experimental and commercial.

In the following, we present the enabling technologies according to different radio access technologies. These enabling technologies are summarized in Table II.

B. IEEE 802.11-based Wireless Network Virtualization

In [81], a WLAN virtualization approach named *virtual WiFi* is proposed to extend the virtual network embedding from wired networks to wireless networks. Kernel-based virtual machine (KVM)) is used in virtual WiFi to virtualize WiFi devices to multiple virtual machines (VMs) so that VMs can be operated like a virtual wireless LAN device. Since each VM has to establish its own wireless connection, MAC layer is separated from multiple virtual MACs via time domain multiplexing. However, some VMs may want to migrate to other physical devices or some physical devices want to aggregate multiple VAPs for some reasons, e.g., saving power and spectrum resource. A framework is proposed in [82] to realize the migration of VMs after embedding virtual nodes and links. In this approach, the connection between VMs and end users is maintained by migrating VMs and enabling them on the other physical access points (PhyAPs). Similar to [81], the virtual WLAN network in [82] is embedded based on MAC layer by employing tunneling to pass the frame of L2 in the router. It should be noted that although [82] tries to aggregate WLAN APs together rather than slicing them, it utilizes virtualization technologies to manage the aggregated AP.

Frequency-division multiplexing (FDM) is used in [50], [83], [84] to enable wireless link virtualization embedding, which can isolate the virtual transmission medium in the frequency domain. Both [83] and [84] choose ORBIT testbed as the platform. In [83], to virtualize the hardware, an OS running on the hardware has to bear the user mode Linux (UML) operating system, which plays as the VMs, while [84] chooses OpenVZ to run multiple operating systems (VMs) on the physical device. Whatever OS used in physical devices, the OS has to be able to schedule the resources, e.g., CPU, memory and etc., for VMs. Extending their works, the authors of [50] propose a novel testbed VNEWS, which can move the emerging TaaS to the wireless cloud. Spectrum slicing used in [50] enables the co-existence of multiple virtual topologies and an appropriate heuristic determines the mapping between the requested and substrate resources. Moreover, this approach adopts and extends a resource specification language (ProtoGENI V2 format RSpec) for wireless experimentation.

Time-division multiplexing (TDM) is studied in [85], [86] for wireless link virtualization. By utilizing TDM, the physical network is partitioned in the time domain across different virtual networks, such that each experiment [85] or virtual operator [86] is isolated in the time domain. The authors of [85] implement their virtualization mechanism on a large-scale IEEE 802.11 wireless testbed facility, while [86] evaluates the TDM-based link virtualization from the aspects of delay, jitter and network utilization. A similar work is proposed in [87] but focuses on the fairness issue of uplink in WLANs. In [87], the physical access point is allowed to allocate different UL air-time quotas for individual virtual access points based on two proposed algorithms, called linear proportional feedback control (LPFC) and LPFC+, which control the air-time using traffic shaper (bandwidth control). Using these two algorithms, the infrastructure can enforce fairness across slices (referred to the resources allocated to a group of users belonging to a single SP.), thus allowing individual SPs to fairly share the underlying WLAN hardware and the corresponding channel. However, in [88], the authors argue that bandwidth schedule

TABLE II
ENABLING TECHNOLOGIES IN WIRELESS NETWORK VIRTUALIZATION.

Radio Access Technologies	Ref	Networking and Purposes	Isolation	Contributions
IEEE 802.11	[81], [82]	WLAN / Experimental	MAC layer / TDM	Enabling access point virtualization
	[50], [83], [84]	WLAN / Testbed	Spctrum / FDM	Moving the testbed-as-a-service to the wireless environment and enabling virtualization of network operating systems
	[85]	WLAN / Testbed	Time-slot / TDM	Implementing virtualization mechanisms on a large-scale 802.11 wireless testbed
	[86]–[88]	WLAN / Testbed	Time-slot / TDM	Enabling TDM-based link virtualization
	[51]	WLAN / Testbed	Spatial / SDM	A comparison between space-division and time-division is given
	[89], [90]	Multihop Network / Experimental		Experimental results are given
	[91]	WMN / Testbed	Time-slot / asynchronous time sharing	Proposing asynchronous time sharing between several slices on a node
	[92]	WMN / Testbed	TDM	Embedding the virtual networks under unreliable wireless links
	[93]	WMN / Testbed	FDM	Proposing a heuristic algorithm based channel allocation solution
3GPP LTE	[69], [94]–[96]	Cellular / Commercial	PRB	Enabling eNodeB virtualization
	[97]	Cellular / Commercial	PRB	Introducing the bankruptcy game into the resource allocation of LTE virtualizaiton
	[76]	Cellular / Commercial	Packet	Using FlowVisor to slice eNodeB to certain number of virtual eNodeBs
	[71], [98]	Cellular / Commercial	Packet	Enabling SDN in RAN
	[70]	Cellular / Commercial	Packet	Abstracting out base stations as a virtual big base station
IEEE 802.16 (WiMAX)	[99], [100]	Cellular / Commercial	Traffic types	Introducing the virtual network traffic shaper
	[12], [43], [101]	Cellular / Commercial	Flow	Enabling simultaneous reservations of two classes slices without modifying the MAC schedulers
	[102], [103]	Cellular / Commercial	Sub-carriers	Enabling partially slicing and combination of sub-carries and power allocation
Heterogeneous	[104]	Cellular / Commercial	Sub-carriers	Proposing cognitive virtualization platform
	[105]	Cellular / Commercial	Sub-carriers	Enabling dynamic resource reallocation
	[68]	Cellular / Commercial	Multilevel	Enabling virtualization by using the concept of OpenFlow
Others	[74], [106]		Sub-channel	Proposing a rate region, which is computed as the set of rate that can be achieved by any spectrum allocation
	[107]		Sub-channel	Handling the online requests of wireless virtualization
	[108]		TDM / SDM	Enabling maximal resources utilization
	[109], [110]	WMN	Context	Splitting networks into several virtual networks based on context demands

cannot achieve such high utilization when the static resource allocation ratio to each slice is preset. Thus, an MAC layer air-time control mechanism is proposed in [88]. Unlike [85] and [86], [51] proposes a space-division multiplexing (SDM) to embed virtual links in a 802.11-based experimental network called ORBIT. The comparison in this paper reveals that the isolation is comparable for both TDM and SDM, while SDM achieves better efficiency than TDM.

Although the above studies promote wireless network virtualization significantly, they may not provide complete solutions for wireless network virtualization due to the lack of fully virtualized access points (nodes), programmability of MAC layer and upper Layer, customizable mechanisms on flows scheduling, routing, resource allocation, etc. Although these works have been done around IEEE 802.11 family, cellular networks also can benefit from the achievements of them. Moreover, the purposes of these experimental networks are to test and evaluate the innovative protocols and mechanisms, which may directly applicable to cellular networks.

In [89], [90], the wireless network virtualization embedding problem has been extended to the case of wireless multi-hop networks based on IEEE 802.11. In these papers, the authors propose to use revenue, which is proportional to the requested resources including CPU resource and bandwidth resource. The substrate physical network performs the embedding based on the objective of maximizing the revenue.

In [91]–[93], wireless network virtualization is studied for wireless mesh networks (WMNs). An experimental testbed,

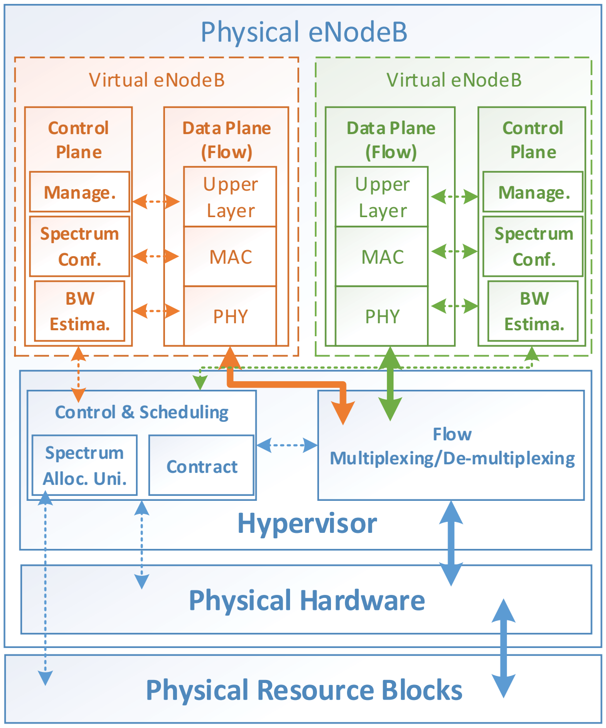


Fig. 8. An example of LTE virtualization.

called WISEMESH, is used in [91] with asynchronous time sharing between several slices on a node. [92] focuses on multicast service-oriented virtual networks and embeds the virtual networks in WMSs under the condition that wireless links are unreliable. A heuristic algorithm is proposed in [93] based on an enhanced genetic algorithm to obtain an approximate but effective solution, which allocates channels to virtual networks.

C. 3GPP LTE-based Wireless Network Virtualization

The concept of virtualization in cellular networks can be tracked back to [111] where the basic framework of virtual node and virtual radio has been proposed. In [111], the decoupling of data plane and control plane is clearly defined such that different protocols and management strategies are able to run at different virtual nodes and links. A *virtualization management* is used to manage the virtualized nodes and links by a centric method. However, practical implementations, especially resource allocation and isolation, are not mentioned in [111]. Nevertheless, this embryo gives initial ideas of introducing virtualization into the cellular area.

Currently, most approaches on wireless network virtualization discussed in cellular networks are based on 3GPP LTE systems. The authors of [69], [94], [112] investigate virtualizing eNodeB in 3GPP LTE and point out that virtualizing the eNodeB is similar to node virtualization that has a number of solutions. In this subsection, we take [112] as an example to illustrate the implementation of air interface virtualization in LTE-based cellular networks. As shown in Fig. 8, a *hypervisor* [113] is physically added to the LTE eNodeB and logically allocated between physical resource and virtual eNodeB. The LTE hypervisor takes the responsibility of virtualizing the eNodeB into a number of virtual eNodeBs, such as virtual machines (e.g., CPU, memory, I/O devices, etc.), and spectrum, which can be used by different SPs or MVNOs. Moreover, the LTE hypervisor is also responsible for scheduling the air interface (between eNodeBs and user equipments) resources (e.g., OFDMA sub-carriers). There are two proposed entities equipped in the hypervisor acting as the critical roles. The first one is *Spectrum Configuration and Bandwidth Estimation* (SCBE) that logically locates on each virtual eNodeB, and the other one is *Spectrum Allocation Unit* (SAU) that logically locates on hypervisor. To estimate the requirement of spectrum at virtual eNodeB is one of the main functions performed at SCBE. From each virtual operator at frequent time intervals, this spectrum bandwidth estimation is calculated by SCBE based on Exponential Moving Average and sent back to the SAU of hypervisor used for PRBs scheduling. Another main function of SCBE is to configure the spectrum at where each virtual eNodeB operates.

Since the PRB is the smallest unit that the LTE MAC scheduler can allocate to a user, scheduling PRBs among virtual eNodeBs means splitting the spectrum among different virtual eNodeBs. To split the spectrum for multiple virtual eNodeBs, the hypervisor has to schedule a number of PRBs based on some criteria (e.g., bandwidth, data rates, power, interference, pre-defined contracts, channel conditions, traffic load or a combination of them), virtual operators' requirements and isolation requirements. SAU is used to schedule air interface through a contract-based hypervisor algorithm to divide the spectrum among virtual eNodeBs based on pre-defined contracts. The following four types of pre-defined contracts can be considered: 1) Fixed guarantees where fixed spectrum bandwidth will be allocated; 2) Dynamic guarantees where PRBs are allocated according to the requirements of virtual eNodeB and upper bounded by a maximum value; 3) Best effort with minimum guarantees where a minimum guaranteed bandwidth will be allocated and additional bandwidth may be added in a best effort manner; 4) Best effort with no guarantees where bandwidth is allocated by a pure best effort manner. The approach presented in [112] is a practical and integrated mechanism to realize virtualization in LTE-based RANs. Nevertheless, there are still some aspects that need to be improved, including control signaling, isolation among virtual eNodeBs, and upper layers (e.g., routing) virtualization.

A mechanism that is similar to [69] is used in [95]–[97], with an extension to address multiple specific issues. The multiplexing gain by eNodeB virtualization is investigated in [95] from both analytical and simulation perspectives, and a generalized multi-party model is proposed to enable centralized spectrum sharing with a mechanism of spectrum budget estimation for real-time services. In [96], load balancing techniques are proposed and embedded to the framework proposed in [69]. Using the dynamic load balance mechanism, high loaded virtual eNBs can offload the excessive traffic to a low loaded virtual eNB, which brings a significant gain of the user performance. Also, this paper makes contributions on analyzing different applications, such as VoIP, real-time video, HTTP and FTP, in LTE virtualization. Unlike others approaches, [97] introduces a bankruptcy game into the resource allocation of LTE virtualization. Assuming that both "big" (higher traffic load and rate requirements) and "small" (lower traffic load and rate) MVNOs coexist, the PRBs owned by the InPs are limited and scarce such that the required PRBs are less than the available PRBs. Thus, the authors model the InPs, which own the PRBs, and MVNOs as the bankrupt company and players in the game, respectively. By solving the bankrupt game, the InPs guarantee relative fairness among VMOs when allocating the PRBs.

Since the concept of SDN was proposed, the idea of decoupling control plane and data plane has been applied in LTE virtualization [70]–[72], [98], [114]. Moreover, OpenFlow, as a technology to realize SDN, is also introduced in LTE virtualization [68], [76]. It should be noted that SDN or OpenFlow is not equal to network virtualization. According to the definition (mentioned in Section II) of SDN, SDN is a mechanism, which can be applied in network virtualization. In other words, it is possible to use SDN to realize a network virtualization but not necessary.

Both [98] and [76] provide architecture level solutions on LTE virtualization by using FlowVisor [73], while [76] focuses on the virtualizing of eNodeB, [98] studies packet-processing of the whole network. In [76], the eNodeB has been sliced to a number of virtual eNodeBs by FlowVisor policy, and the same number of controllers are created to assign to the corresponding SPs or MVNOs. When one SP sends information to their virtual eNodeB, FlowVisor stops the traffic and maps it to the allowed resource based on the policies at eNodeB. Similarly, the FlowVisor only forwards the traffic originating from eNodeB to the respective controller, which is operated by the SP whose flowspace matches this traffic. Thus, the SP does not realize that the eNodeB has been sliced to multiple virtual eNodeBs. Likewise, [98] also utilizes the FlowVisor but extends it to CellVisor, which can support flexible resource slicing for base stations and high level semantic space definition. Moreover, the mechanism in [98] gives a more wide range resource to slice in addition to eNodeB, including bandwidth, topology, traffic, device CPU, and forwarding tables.

The concept of SDN is applied in cloud-RAN (C-RAN) [71]. The proposed C-RAN is a software-defined RAN architecture containing three main parts: wireless spectrum resource pool (WSRP), cloud computing resource pool (CCRP) and SDN controller. In this architecture, WSRP, consisting of multiple physical remote radio units (pRRUs) distributed at various locations, virtualizes one pRRU into several virtual RRUs (vRRUs) with different wireless protocols (GSM, UMTS, or LTE) coexisting in one shared pRRU. CCRP is comprised of a large amount of physical processor constructing a high speed cloud computing network and virtualized to virtual BBUs and virtual BSCs. Obviously, the WSRP and CCRP create several complete virtual RANs. SDN controller takes the responsibility of the control plane of this heterogeneous RANs. [70] proposes a more general software defined radio access network by considering all the physical base stations (not only RRU) in a geographical area as radio elements and abstracts out them as a virtual base station.

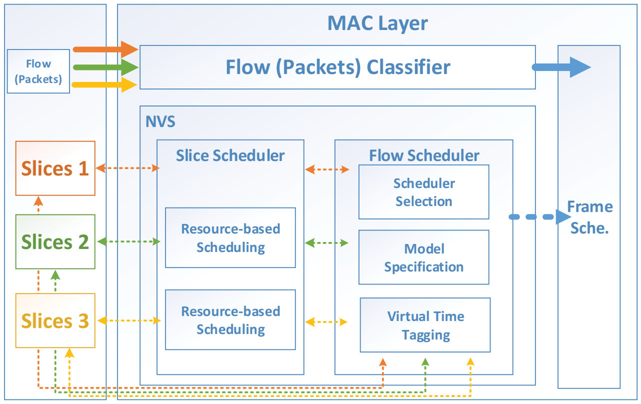


Fig. 9. An example of WiMax virtualization.

D. IEEE 802.16-based Wireless Network Virtualization

Several virtualization approaches focus on IEEE 802.16e&m. A virtual network traffic shaper is introduced in [99] for air time fairness, which is also considered in [87] for the downlink of WiMAX (802.16e) systems. The authors of [100] propose a virtual base station architecture, and a virtualization substrate is studied in [101] for WiMAX networks. A weighted fair sharing algorithm is proposed in [100] based on an airtime fairness metric to enhance the fairness for multiple slices (assigned to virtual basestations).

Here we take network virtualization substrate (NVS) [12], [101] as an example to show WiMax virtualization. NVS can be considered as a solution to virtualization of not only WiMax but also other cellular networks. NVS, composed of two main schedulers (*Slice Scheduler* and *Flow Scheduler*), runs at MAC layer of the network and operates at MAC-frame granularity. To enable isolation, the provably-optimal slice scheduler allows simultaneous reservations of two classes of slices, which are bandwidth-based (which means a certain data rate) and resource-based (which means a certain amount of spectrum or time-slots), respectively. For each frame, the slice scheduler chooses the slice based on the criterion that the utility of MNO is maximized. The utility is calculated by utility functions agreed between MNO and SPs such that it can maximize the base station revenue and meet the individual slice requirements at the same time.

After slice selection, the flow scheduler will choose a flow within the chosen slice and to ensure that each slice can employ custom flow scheduling policies. In other words, by building a generic flow scheduling framework, NVS allows each slice to determine the order, in which packets are to be sent in the downlink direction, and resource slots are allocated in the uplink direction. There are three modes in this framework: scheduler selection, model specification, and virtual time tagging. The customized flow scheduling is provided by either scheduler selection or model specification. In virtual time tagging, flow-level feedback is delivered to a slice by NVS, which allows each slice to deploy its own flow scheduler. Each packet arriving into the per-flow queues will be tagged by NVS through monotonically increasing virtual time. NVS can select packets based on this virtual time from the heads of flow queues of the slices.

Although NVS can provide an efficient mechanism for WiMax virtualization, further research needs to be done for WiMax virtualization. Firstly, NVS needs significant modification on the MAC layer of current WiMax systems. Secondly, virtualization at network layer is not considered in NVS. Thirdly, full virtualization (e.g., full flexibility, customization, and programmability) is still not available in NVS.

The authors of [43] continue the NVS research by proposing a novel system named CellSlice based on NVS. Firstly, CellSlice overcomes the deployment barrier, which modifies the MAC schedulers within the base station in NVS by moving slice scheduling to the gateway. Moreover, because CellSlice dynamically adapts parameters of flow shaping, it enables the following benefits: 1) Isolation and the slice requirements can be satisfied simultaneously; 2) Flows (arriving and departing dynamically) within a slice can experience a fair allocation of resource; 3) Maximization of resource can be achieved.

Rather than scheduling slices on a per OFDM frame basis in [12], [101], the authors of [102] propose to schedule slices on a per sub-carrier basis, which goes one step further into an OFDM frame. Furthermore, one interesting feature of this scheme is that MNO does not slice all of wireless networks and allocate to MVNOs, but only slices part of them and rent to MVNOs. Thus, the authors propose a slice assignment scheme to separate the frame from/to local MNO's users and foreign virtual networks (MVNOs)' users. This paper formulates a typical binary integer programming problem, where the optimization objective is to assign sub-carriers to meet the requirements of all flows in the slices while occupying as few sub-carriers as possible. In addition to the sub-carriers allocation problem in [102], power allocation is studied in [103]. To solve this more complicated problem, a multi-step dynamic optimization approach is proposed to achieve sub-carrier allocation using binary integer programming and power allocation using nonlinear programming.

E. Wireless Network Virtualization in Heterogeneous Wireless Networks

There are several studies on virtualization for heterogeneous wireless networks, such as [68], [104], [105]. A cognitive virtualization platform, called AMPHIBIA, is proposed in [104]. AMPHIBIA supports cooperative resource management over wired and heterogeneous wireless networks, where end-to-end slicing over wired and wireless networks is enabled. Moreover, AMPHIBIA can virtualize a cognitive base station with full cognitive radio functionalities. [105] proposes an adaptive virtual network radio resource allocation (VRRA) mechanism. The VRRA algorithm conducts adaptive radio resource allocation after an initial allocation and takes the responsibility of dynamically reallocating resource to satisfy the minimum capacity requested by heterogeneous virtual base stations. The VRRA algorithm is based on the requirements of virtual networks in terms of data rate, delay, and error rates. Using the concept of OpenFlow, [68] enables the virtualization in an integrated cellular network, including heterogeneous access technologies.

F. Others

In this subsection, some approaches that do not specify a certain radio access technology are introduced. [74], [106], [115] use game theory to allocate resource for virtual networks or slices. In [115], a bandwidth (capacity) allocation scheme based on the non-cooperative game model is established and an iterative algorithm is proposed to solve the bandwidth allocation problem by finding the Nash equilibrium. However, since bandwidth is directly used to represent the radio resource in [115], the relationship between capacity and radio resource is not considered in [115]. In [74], [106], the authors virtualize the wireless network and abstract the wireless network resource as the rate region, which is computed as the set of rate that can be achieved by any spectrum allocation. Then, a mechanism is proposed that the network resources are sequentially bidden by the SPs. Since the dynamic environment and requirements are considered in this mechanism, the sequential auction is modeled as a stochastic game. By solving the Nash equilibrium of the stochastic game model, efficient rate allocation is obtained.

To handle the online requests of wireless virtualization and embed the virtual networks dynamically, [107] uses an interesting method, called Karnaugh-map like online embedding algorithm. In [108], a time-space combined resource allocation algorithm is proposed to ensure isolation and improve resources utilization for wireless experimental networks. In this algorithm, maximal resources utilization is achieved by minimizing the scheduled time-slot. A novel architecture is proposed in [109], [110] where a network is split into several personalized accessible adaptable virtual networks for users based on user context demands (context can be security, mobility or service requirements). Similar users are grouped and associated to virtual networks according to their contexts.

VII. CHALLENGES AND BROADER PERSPECTIVES

Despite the potential vision of wireless network virtualization, many significant research challenges remain to be addressed before widespread deployment of wireless network virtualization. In this section, we present some of these challenges. Broader perspectives are presented in this section as well.

A. Challenges of Wireless Network Virtualization

1) Isolation: Isolation is the basic issue in virtualization that enables abstraction and sharing of resources among different parties. Any configuration, customization, topology change of any virtual networks should not affect and interfere other coexisting parties. While isolation is relatively easier in wired networks, isolation in wireless networks is challenging. Unlike wired networks, where bandwidth resource abstraction and isolation can be done on a hardware (e.g., port and link) basis, radio resource abstraction and isolation is not straight-forward, due to the inherent broadcast nature of wireless communications and stochastic fluctuation of wireless channel quality. For example, in wireless networks, especially cellular networks, any change in one cell may introduce high interference to neighbor cells [53]. Moreover, in wireless networks with different cell sizes, there are two sources of inter-cell interference. The first interference source arises when a macro base station coverage area is overlapping with small base station coverage areas causing cross-layer interference [116]. The second interference source emerges when the small base station’ coverage areas are partially overlapping with each other causing co-layer interference [116]. Also, isolation should be realized at different levels, such as at flow level, at subchannel or time-slot level, or hardware level (antennas and signal processors) [12]. In addition, the mobility of end users may create instability of a specific area. Therefore, isolation become more difficult and complicated in wireless networks compared to the wired counterparts.

2) Control signaling: Connectivity needs to be established between SPs and InPs before a virtual network can be created. With this connectivity, SPs can express their requirements of resources to serve end users. In addition, since virtualization can happen among InPs, a standard language to express explicit sharing information among InPs becomes necessary. Moreover, the communication between SPs and end-users is also needed. This introduces a circularity where networks connectivity is a prerequisite to itself [37]. Thus, proper control signaling and interface considering delays and reliability need to be designed carefully to enable the communication among different parties involved in wireless network virtualization. Due to the particular properties of wireless networks, SPs or end user may require different QoS attributes. In contrast to functional service features, there is less agreement regarding the specification of QoS attributes. Therefore, the control signaling and interface should be compatible with different kinds of requirements. Furthermore, as various radio access technologies (e.g., IEEE 802.11, cellular, and IEEE 802.16) may be used, the control signaling and interface should be adapted among different radio access technologies. Also, a bootstrapping capability is needed because of the customization of the virtualized resources allocated to SPs. It should develop the programmability of the network elements available to the SPs by standard methods [117]. Standardized control signaling and interface are the key for successful wireless network virtualization.

To provide control signaling that can handle these issues, an out-of-band mechanism or another network is needed. In wireless networks, if an out-of-band mechanism does not exist, at least one part of the resource (e.g., spectrum) has to be dedicated to realize control signaling. However, unlike wired signaling networks, due to the instability of radio channels and scarcity of spectrum, the overload and delay of signaling have to be considered carefully. Also, the tradeoff of flexibility and complexity is another important issue in the design of control signaling.

3) Resource discovery and allocation: In order to realize wireless network virtualization, InPs or MVNOs should discover the available active and passive resources in the underlaying physical wireless networks. InPs need to decide the physical resources used to virtualized, which means InPs may reserve some resource for their own usage. Since resource may be shared among multiple InPs, an efficient coordination mechanism should be designed appropriately. Also some communication protocols have to be included in the coordination mechanism. Moreover, to discover the available resource in MVNOs, another well-designed communication protocol has to be used between InPs and MVNOs. Naming and addressing are important issues in resource discovery as well, since they initialize processes that VMNOs recognize the physical nodes and links. An MVNO may combine the resources from multiple InPs, and end users may also connect to multiple virtual networks simultaneously [6]. Therefore, a global naming and addressing mechanism is necessary for the sake of identities of physical elements and virtual elements.

Resource allocation is another significant challenge of wireless network virtualization. Resource allocation schemes need to decide how to embed a virtual wireless network on physical networks (e.g., Which nodes, links and resources should be picked and what should be optimized [13]). As defined in [5], resource allocation in a network virtualization environment refers to static or dynamic allocation of virtual nodes and links on physical nodes and paths, respectively. It is pointed out in [118] that embedding virtual networks, with constraints on resources or requirements, can be reduced to an NP-hard optimization problem. In [10], a survey on virtual network embedding can be found. Moreover, unlike wired networks, resource allocation becomes much more complicated in wireless network virtualization due to the variability of radio channels, user mobility, frequency reuse, power control, interference, coverage, roaming, etc. Also, since the properties of uplink and downlink may not be the same in the wireless environment and the traffic is not symmetric in both directions, resource allocation should be considered for both uplink and downlink cases.

Resource scheduling is also important for both InPs and VMNOs. As the range of services from SPs can be wide from best-effort to delay-sensitive, the QoS of these different services must be dynamically mapped to physical wireless links. InPs and VMNOs have to implement proper scheduling algorithms that can run on all elements of both virtual and physical elements. Other resources, such as CPU, memory, disk and cache (both physical and virtual), also need to be scheduled efficiently in wireless network virtualization. Again, due to the unpredictable properties in the wireless environment, resource scheduling is a complicated problem.

Another issue in resource allocation is admission control. The objective of admission control is to maximize the utilization (revenue) while guaranteeing the QoS of existing users by controlling the admission of incoming users. With wireless network virtualization, there are two kinds of admission controls: traditional wireless admission control for end users and admission for SPs. In the admission control for SPs, VMNOs need to conduct accurate estimation and ensure that the virtual resources allocated to SPs do not exceed the capacity of underlaying physical networks. This is complicated in wireless environment because the number of end users and their traffic change dynamically in a particular geographic area, which causes unpredictable aggregated throughput in this area.

In resource discovery and allocation, the time granularity (i.e., how often should resource discovery and allocation be performed?) needs to be carefully designed [13]. If the time interval is too small, the cost of overload and signaling may increase significantly. However, long time interval would lead degradation to static architecture of traditional networks.

4) Mobility management: Mobility management is an important issue in wireless networks that ensures successful delivery of new communications to users and maintains ongoing communication with minimal disruptions, while users move freely and independently [119]. There are two components in mobility management: location management and handoff (also referred to as handover in the literature) management. Location management enables the network to deliver communications to users by tracking their locations. Handoff management maintains service continuity by keeping a user connected when its point of connection to the network moves from one access point (or base station) to another. With wireless network virtualization, tracking a user's location is challenging, since it may perform location update with different VMNOs or InPs. A centralized location management can solve the problem. However, latency will be introduced in centralized management, thus some distributed mechanisms merits further research. In addition, since a user with ongoing communications may switch among multiple VMNOs or InPs, the handoff management problem becomes more complicated than that in traditional wireless networks. To maintain service continuity when a user switches among multiple VMNOs or InPs, proper synchronization mechanisms among different networks are necessary.

5) Network management: Network management is always a big challenge for the carriers. Management of wireless network virtualization is crucial to guarantee the proper operation of the physical infrastructure, the host virtual wireless networks and the wireless services supported by the virtual networks. As a (virtual) network may span over multiple underlying physical networks, network management and operation face new challenges. In addition, an SP may change resource requests dynamically to accommodate user changes. Consequently, network management systems need to provide elasticity in order to adapt to changes of SPs' requests. Moreover, information from multiple devices, diverse management mechanisms from participating parties requires to be aggregated to allow to avoid conflicting. Since underlying physical networks can be formed by heterogeneous networks (e.g. WLAN, macrocell, smallcell, relay, and even M2M networks) and each of them has unique and particular properties, some specific solutions and mechanisms are required for provisioning, operation, and maintenance of virtualized wireless networks.

6) Security: A widely used assumption in wireless network virtualization is that different parties are always trusted. However, this assumption may not be valid, since there are a large number of intelligent devices/nodes with self adaptation/context awareness capabilities in wireless network virtualization. Particularly, a compromised party can take advantage of the virtualization mechanisms to misbehave in a malicious manner. Therefore, in addition to the vulnerabilities and threats of traditional wireless networks, the involvement of intelligence in wireless network virtualization present new security challenges. For many security issues, authentication is an important requirement, which is crucial for integrity, confidentiality, and non-repudiation [120]. In addition, the experience in security of traditional wired and wireless networks indicates the importance of multi-level protections because there are always some weak points in the system, no matter what is used for prevention-based approaches (e.g., authentication). This is especially true for wireless network virtualization, given the low physical security autonomous functions of mobile devices. To solve this problem, detection-based approaches (e.g., intrusion detection systems (IDSs)), serving as the second wall of protection, can effectively help identify malicious activities. Both prevention-based approaches and detection-based approaches need to be carefully studied for wireless network virtualization.

B. Broader Perspectives

Since wireless network virtualization is in its infancy, many other technologies may affect the development of wireless network virtualization. Meanwhile, wireless network virtualization may have impacts on them as well. Here, we briefly discuss these technologies.

Cognitive radio [54] is an enabling technology to allow cognitive users (i.e., unlicensed users or secondary users) to operate on the vacant parts of the spectrum allocated to licensed users (i.e., primary users). Cognitive radio is widely considered as a promising technology to deal with the spectrum shortage problem caused by the current inflexible spectrum allocation policy. It is capable of sensing its radio environment, and adaptively choosing transmission parameters according to sensing outcomes, which improves cognitive radio system performance and avoid interfering with primary users [121]. Recent extensive research on cognitive radio has developed a wide set of techniques to allow spectrum sharing between different wireless systems in different situations [122]–[129]. Cognitive radio technologies have been considered in cellular networks, including expanding LTE spectrum [130], resource management [131], tiered heterogeneous network [132]–[134] and next generation cellular network [135], [136]. Since the use of cognitive radio with dynamic spectrum sharing can be viewed as a type of radio spectrum virtualization, it is natural to use cognitive radio techniques in wireless network virtualization. However, as we described above, wireless network virtualization is a much more broader concept than cognitive radio.

Another promising approach to improve network performance in terms of capacity and energy efficiency is to use a multi-tier or hierarchical structure with small cells [121], [137], [138]. This architecture represents a novel wireless networking paradigm based on the idea of deploying short-range, low-power, and low-cost base stations, which operate in conjunction with macro-cells. In this paradigm, there are heterogeneous cell types, such as macro, micro, pico, femto cells, as well as wireless relays, and distributed antennas. In a heterogeneous wireless cellular network, large cells provide ubiquitous coverage and mobility support, while smaller network elements take connectivity closer to the users thereby increasing data rate with less energy consumption. One of the major challenges to successful deployment of heterogeneous networks is resource management among cells. Particularly, since all the cells operate on the same frequency band (i.e., the frequency reuse factor is one), inter-cell interference becomes a critical issue as the number of small cells increases. Therefore, it is essential to develop efficient and effective network resource management schemes. Such schemes should require low coordination among cells, since coordination introduces signaling overhead, complexity, and scalability issues. In addition, since backhaul networks are constrained in capacity, the system dynamics information (e.g., channel state information) used for centralized schemes can be lost or outdated. Therefore, distributed network resource management schemes are desirable. On one hand, in this multi-tier environment, wireless network virtualization becomes complicated. On the other hand, some mechanisms in wireless network virtualization (e.g., spectrum and infrastructure sharing) can facilitate the deployment of heterogeneous wireless cellular networks. In addition, heterogeneous wireless networks need a convergent and powerful network management mechanism, which can be provided by wireless network virtualization.

Cloud computing, as a new information technology paradigm, has become one of the hottest topics in both academia and industry. Cloud computing is a model for enabling on-demand access to a shared pool of configurable resources (e.g., servers, storage, applications, services, etc.). The essential characteristics of cloud computing include on-demand self-service, broad network access, resource pooling, rapid elasticity and measured service [139]. Cloud computing would have profound impacts on the design and operation of wireless network virtualization. On one hand, with recent advances of wireless mobile communication technologies and devices, more and more end users access cloud computing systems via mobile devices, such as smart phones and tablets. The integration of cloud computing into the mobile environment enables mobile cloud computing (MCC), which is widely considered as a promising mobile computing paradigm with huge market [140]–[143]. On the other hand, the powerful computing platforms in the cloud can be beneficial to radio access networks (RAN) as well (in addition to mobile end users), which leads to a novel concept of C-RAN [144]–[146]. Unlike the existing cellular networks, where computing resources for baseband processing are located at each cell site, in C-RAN, the computing resources are located in a central wireless network cloud with powerful computing platforms. This transition from distributed to centralized infrastructure for baseband processing can have significant benefits: saving the operating expenses due to centralized maintenance; improving network performance due to advanced coordinated signal processing techniques; reducing energy expenditure by exploiting the load variations [144], [145]. Wireless network virtualization in the cloud computing environment can be a promising research direction.

VIII. CONCLUSION

This paper addresses wireless network virtualization, which is becoming an important concept that enables abstraction and sharing of infrastructure and radio spectrum resources, reduced expenses of wireless network deployment and operation, easier migration to newer services and products and flexible managements. We began our discussion with an overview of network virtualization. Here, we presented a brief history and current projects of network virtualization with emphasis on SDN and OpenFlow. We then discussed the motivations of wireless virtualization. In particular, we presented the business models with different roles and the functions of these roles in the wireless network market. Next, we discussed the framework of wireless network virtualization with four main components, radio spectrum resource, wireless network infrastructure, wireless virtual resource, and wireless virtualization controller. We then discussed some performance metrics that are can be used to compare different architectures, virtualization mechanisms, resource allocation algorithms, management systems, customization flexibility, energy saving, interfaces, etc. Next, some enabling technologies for wireless network virtualization were discussed according to different radio access technologies. We also discussed some significant research challenges in wireless network virtualization, including isolation, control signaling, resource discovery and allocation, mobility management, network management, and security. Finally, we explored some broader perspectives, such as cognitive radios and networks, hierarchical cellular networks, and cloud computing.

In summary, research on wireless network virtualization is quite broad and a number of research issues and challenges lay ahead. Nevertheless, it is in favor of the wireless community to swiftly address these challenges to adopt these technologies. This article attempts to briefly explore the current technologies related to wireless network virtualization and we discuss future research that may be beneficial in pursing this vision.

ACKNOWLEDGMENT

We thank the reviewers for their detailed reviews and constructive comments, which have helped to improve the quality of this paper. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada and Huawei Technologies Canada CO., LTD.

REFERENCES

[1] C. Morin and I. Puaut, "A survey of recoverable distributed shared virtual memory systems," *IEEE Trans. Parallel & Distributed Systems*, vol. 8, no. 9, pp. 959–969, Sep. 1997.

[2] J. E. Smith and R. Nair, "The architecture of virtual machines," *IEEE Computer*, vol. 38, no. 5, pp. 32–38, May 2005.

[3] A. G. Dimakis, K. Ramchandran, Y. Wu, and C. Suh, "A survey on network codes for distributed storage," *Proc. The IEEE*, vol. 99, no. 3, pp. 476–489, Mar. 2011.

[4] G. Schulz, *The green and virtual data center*. U.S.: CRC Press, 2010.

[5] N. Chowdhury and R. Boutaba, "Network virtualization: state of the art and research challenges," *IEEE Commun. Mag.*, vol. 47, no. 7, pp. 20–26, Jul. 2009.

[6] N. M. K. Chowdhury and R. Boutaba, "A survey of network virtualization," *Computer Net.*, vol. 54, no. 5, pp. 862–876, Apr. 2010.

[7] G-lab. [Online]. Available: http://www.german-lab.de/

[8] M. Achemlal, T. Almeida, and etc., "D-3.2.0 virtualisation approach: Concept," The FP7 4WARD Project, Tech. Rep., 2009.

[9] Q. Duan, Y. Yan, and A. Vasilakos, "A survey on service-oriented network virtualization toward convergence of networking and cloud computing," *IEEE Trans. Network and Service Management*, vol. 9, no. 4, pp. 373–392, 2012.

[10] A. Fischer, J. Botero, M. Beck, H. De Meer, and X. Hesselbach, "Virtual network embedding: A survey," *IEEE Commun. Surveys & Tutorials*, vol. to be published, 2013.

[11] H. Wen, P. K. Tiwary, and T. Le-Ngoc, *Wireless Virtualization*. Springer, 2013.

[12] R. Kokku, R. Mahindra, H. Zhang, and S. Rangarajan, "Nvs: a substrate for virtualizing wireless resources in cellular networks," *IEEE/ACM Trans. Netw.*, vol. 20, no. 5, pp. 1333–1346, Oct. 2012.

[13] X. Wang, P. Krishnamurthy, and D. Tipper, "Wireless network virtualization," in *Proc. Int'l Conf. on Computing, Networking and Commun. (ICNC)*, San Diego, CA, Jan. 2013.

[14] H. Wen, P. K. Tiwary, and L.-N. Tho, "Current trends and perspectives in wireless virtualization," in *Proc. Int'l Conference on Selected Topics in Mobile & Wireless Networking (MoWNeT)*, Montreal, Canada, Aug. 2013.

[15] V. Rajaravivarma, "Virtual local area network technology and applications," in *Proc. the 29th Southeastern Symp. on System Theory*, Cookeville, TN, Mar. 1997, pp. 49–52.

[16] P. Ferguson and G. Huston. (1998) What is a VPN? [Online]. Available: http://www.123seminarsonly.com/Seminar-Reports/006/48862380-Virtual-Private-Network.pdf

[17] E. C. Rosen and Y. Rekhter. (1999) Bgp/mpls vpns. [Online]. Available: http://tools.ietf.org/html/rfc2547.html

[18] ——. (2006) Bgp/mpls ip virtual private networks (VPNs). [Online]. Available: http://xml2rfc.tools.ietf.org/html/rfc4364

[19] T. Takeda, I. Inoue, R. Aubin, and M. Carugi, "Layer 1 virtual private networks: service concepts, architecture requirements, and related advances in standardization," *IEEE Commun. Mag.*, vol. 42, no. 6, pp. 132–138, Jun. 2004.

[20] L. Andersson and E. Rosen, "Framework for layer 2 virtual private networks (L2VPNs)," RFC 4664, Tech. Rep., Sep. 2006.

[21] R. Callon and M. Suzuki, "A framework for layer 3 provider-provisioned virtual private networks (PPVPNs)," RFC 4110, Tech. Rep., Jul. 2005.

[22] G. Held, *Higher Layer VPNs*. England: John Wiley & Sons, Ltd, Jan. 2005, pp. 133–201.

[23] D. H. S. Denazis and L. L. G. J. Minden, *Active and Programmable Networks*. Germany: Springer, 2009.

[24] J. Touch, "Dynamic internet overlay deployment and management using the X-Bone," *Computer Net.*, vol. 36, no. 2, pp. 117–135, Jul. 2001.

[25] J. E. van der Merwe, S. Rooney, L. Leslie, and S. Crosby, "The tempest-a practical framework for network programmability," *IEEE Network Mag.*, vol. 12, no. 3, pp. 20–28, May 1998.

[26] B. Nandy, D. Bennett, I. Ahmad, S. Majumdar, and B. S. Arnaud. (2006) User controlled lightpath management system based on a service oriented architecture. [Online]. Available: http://www.solananetworks.com/UCLP/files/UCLPv2-SOA.pdf

[27] A. I. Sundararaj and P. A. Dinda, "Towards virtual networks for virtual machine grid computing," in *Proc. Virtual Machine Research and Tech. Symp.*, San Jose, CA, May 2004, pp. 177–190.

[28] M. Boucadair, B. Decraene, M. Garcia-Osma, A. Elizondo, J. R. Sanchez, B. Lemoine, E. Mykoniati, P. Georgatsos, D. Griffin, J. Spencer *et al.*, "Parallel internets framework," AGAVE Consortium, Tech. Rep., Sep. 2006.

[29] D. Grossman, "New terminology and clarifications for DiffServ," Internet RFC 3260, Tech. Rep., Apr. 2002.

[30] A.-S. Jun and A. Leon-Garcia, "Virtual network resources management: a divide-and-conquer approach for the control of future networks," in *Proc. IEEE Globecom*, Sydney, NSW, Nov. 1998.

[31] S. da Silva, Y. Yemini, and D. Florissi, "The NetScript active network system," *IEEE J. Sel. Areas Commun.*, vol. 19, no. 3, pp. 538–551, Mar. 2001.

[32] M. E. Kounavis, A. T. Campbell, S. Chou, F. Modoux, J. Vicente, and H. Zhuang, "The genesis kernel: A programming system for spawning network architectures," *IEEE J. Sel. Areas Commun.*, vol. 19, no. 3, pp. 511–526, Mar. 2001.

[33] P. Szegedi, S. Figuerola, M. Campanella, V. Maglaris, and C. Cervelló-Pastor, "With evolution for revolution: Managing FEDERICA for future internet research," *IEEE Commun. Mag.*, vol. 47, no. 7, pp. 34–39, Jul. 2009.

[34] N. Spring, L. Peterson, A. Bavier, and V. Pai, "Using PlanetLab for network research: myths, realities, and best practices," *ACM SIGOPS Operating Systems Review*, vol. 40, no. 1, pp. 17–24, Jan. 2006.

[35] L. Peterson, T. Anderson, D. Blumenthal, D. Casey, D. Clark, D. Estrin, J. Evans, D. Raychaudhuri, M. Reiter, J. Rexford *et al.*, "Geni design principles," *IEEE Computer*, vol. 39, no. 9, pp. 102–105, Sep. 2006.

[36] A. Bavier, N. Feamster, M. Huang, L. Peterson, and J. Rexford, "In vini veritas: realistic and controlled network experimentation," *ACM SIGCOMM Comp. Commun. Reivew (CCR)*, vol. 36, no. 4, pp. 3–14, Oct. 2006.

[37] N. Feamster, L. Gao, and J. Rexford, "How to lease the internet in your spare time," *ACM SIGCOMM Comp. Commun. Reivew (CCR)*, vol. 37, no. 1, pp. 61–64, Jan. 2007.

[38] N. M. K. Chowdhury, M. R. Rahman, and R. Boutaba, "Virtual network embedding with coordinated node and link mapping," in *Proc. IEEE INFOCOM*, Rio de Janeiro, Apr. 2009.

[39] L. Sarakis, T. Zahariadis, H.-C. Leligou, and M. Dohler, "A framework for service provisioning in virtual sensor networks," *EURASIP J. on Wireless Commun. & Netw.*, vol. 2012, no. 1, pp. 1–19, 2012.

[40] ONF, "Onf white paper: Software-defined networking: The new norm for networks," ONF, Tech. Rep., 2012.

[41] S. Sezer, S. Scott-Hayward, P. K. Chouhan, B. Fraser, D. Lake, J. Finnegan, N. Viljoen, M. Miller, and N. Rao, "Are we ready for SDN? implementation challenges for software-defined networks," *IEEE Commun. Mag.*, vol. 51, no. 7, Jul. 2013.

[42] N. McKeown, T. Anderson, H. Balakrishnan, G. Parulkar, L. Peterson, J. Rexford, S. Shenker, and J. Turner, "Openflow: Enabling innovation in campus networks," *SIGCOMM Comput. Commun. Rev.*, vol. 38, no. 2, pp. 69–74, 2008.

[43] R. Kokku, R. Mahindra, Z. Honghai, and S. Rangarajan, "Cellslice: Cellular wireless resource slicing for active RAN sharing," in *Proc. Int'l Conf. on Commun. Systems & Net. (COMSNETS)*, Bangalore, Jan. 2013.

[44] G. Schaffrath, C. Werle, P. Papadimitriou, A. Feldmann, R. Bless, A. Greenhalgh, A. Wundsam, M. Kind, O. Maennel, and L. Mathy, "Network virtualization architecture: proposal and initial prototype," in *Proc. ACM workshop on Virtualized Infrastructure Systems & Architectures*, New York, NY, 2009.

[45] R. Bless and C. Werle, "Network virtualization from a signaling perspective," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Dresden, Jun. 2009.

[46] A. Belbekkouche, M. M. Hasan, and A. Karmouch, "Resource discovery and allocation in network virtualization," *IEEE Commun. Surveys & Tutorials*, vol. 14, no. 4, pp. 1114–1128, Feb. 2012.

[47] T. K. Forde, I. Macaluso, and L. E. Doyle, "Exclusive sharing & virtualization of the cellular network," in *Proc. IEEE Symp. on New Frontiers in Dynamic Spectrum Access Net. (DySPAN)*, Aachen, May 2011.

[48] X. Xu, "From cloud computing to cloud manufacturing," *Robotics and Computer-Integrated Manufacturing*, vol. 28, no. 1, pp. 75–86, Feb. 2012.

[49] X. Costa-Perez, J. Swetina, G. Tao, R. Mahindra, and S. Rangarajan, "Radio access network virtualization for future mobile carrier networks," *IEEE Commun. Mag.*, vol. 51, no. 7, Jul. 2013.

[50] A. Leivadeas, C. Papagianni, E. Paraskevas, G. Androulidakis, and S. Papavassiliou, "An architecture for virtual network embedding in wireless systems," in *Proc. 1st Int'l Symp. Net. Cloud Computing and Applications (NCCA)*, Toulouse, Nov. 2011.

[51] R. Mahindra, G. D. Bhanage, G. Hadjichristofi, I. Seskar, D. Raychaudhuri, and Y. Y. Zhang, "Space versus time separation for wireless virtualization on an indoor grid," in *Proc. Next Generation Internet Networks (NGI)*, Krakow, Apr. 2008.

[52] D.-E. Meddour, T. Rasheed, and Y. Gourhant, "On the role of infrastructure sharing for mobile network operators in emerging markets," *Computer Net.*, vol. 55, no. 7, pp. 1576–1591, May 2011.

[53] D. Gesbert, S. Hanly, H. Huang, S. Shamai Shitz, O. Simeone, and W. Yu, "Multi-cell MIMO cooperative networks: A new look at interference," *IEEE J. Sel. Areas Commun.*, vol. 28, no. 9, pp. 1380–1408, 2010.

[54] J. Mitola and G. Maguire, "Cognitive radio: making software radios more personal," *IEEE Personal Comm.*, vol. 6, no. 4, pp. 13–18, 1999.

[55] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201–220, Feb. 2005.

[56] D. Knisely, T. Yoshizawa, and F. Favichia, "Standardization of femtocells in 3GPP," *IEEE Commun. Mag.*, vol. 47, no. 9, pp. 68–75, Sep. 2009.

[57] G. Middleton, K. Hooli, A. Tolli, and J. Lilleberg, “Inter-operator spectrum sharing in a broadband cellular network,” in *Proc. IEEE 9th Int’l Symp. Spread Spectrum Techniques & Applications*, Aug. 2006, pp. 376–380.

[58] H. Kamal, M. Coupechoux, and P. Godlewski, “Inter-operator spectrum sharing for cellular networks using game theory,” in *Proc. IEEE Symp. Personal, Indoor & Mobile Radio Commun. (PIMRC)*, Sep. 2009, pp. 425–429.

[59] M. Hoffmann and M. Staufer, “Network virtualization for future mobile networks: General architecture and applications,” in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kyoto, Jun. 2011.

[60] 3GPP, “Technical Specification Group Services and System Aspects; Network Sharing;Architecture and functional description,” 3rd Generation Partnership Project (3GPP), TS 23.251 V11.5.0, Mar. 2013. [Online]. Available: http://www.3gpp.org/ftp/Specs/html-info/23251.htm

[61] NEC Corporation, “RAN sharing - NEC’s approach towards active radio access network sharing,” NEC Corporation, Tech. Rep., 2013.

[62] N. S. Networks, “Nsn nw sharing moran and mocn for 3G,” Report, 2013.

[63] C. Mobile, “C-RAN: the road towards green RAN,” Report, 2011.

[64] V. UK. (2012) Better coverage. fewer masts. your complete guide to our network joint venture! [Online]. Available: http://blog.vodafone.co.uk/2012/11/20/better-coverage-fewer-masts-your-complete-guide-to-our-network-joint-venture/

[65] A. Kearney. (2012) The rise of the tower business. [Online]. Available: http://www.atkearney.com

[66] 3GPP, “Technical Specification Group Services and System Aspects; Service aspects and requirements for network sharing,” 3rd Generation Partnership Project (3GPP), TR 22.951 V11.0.0, Sep. 2013. [Online]. Available: http://www.3gpp.org/ftp/specs/html-INFO/22951.htm

[67] J. Panchal, R. Yates, and M. Buddhikot, “Mobile network resource sharing options: Performance comparisons,” *IEEE Trans. Wireless Commun.*, vol. to be published, pp. 1–13, 2013.

[68] K. Pentikousis, W. Yan, and H. Weihua, “Mobileflow: Toward software-defined mobile networks,” *IEEE Commun. Mag.*, vol. 51, no. 7, Jul. 2013.

[69] Y. Zaki, Z. Liang, C. Goerg, and A. Timm-Giel, “LTE wireless virtualization and spectrum management,” in *Proc. 3rd Joint IFIP Wireless & Mobile Net. Conf. (WMNC)*, Budapest, Oct. 2010.

[70] A. Gudipati, D. Perry, L. E. Li, and S. Katti, “Softran: software defined radio access network,” in *Proc. ACM SIGCOMM WS. Hot Topics in Software Defined Networking (HotSDN)*, Jun. 2013, pp. 25–30.

[71] M. Yang, Y. Li, D. Jin, L. Su, S. Ma, and L. Zeng, “OpenRAN: a software-defined RAN architecture via virtualization,” in *Proc. ACM SIGCOMM*, Hong Kong, China, 2013.

[72] J. Kempf, B. Johansson, S. Pettersson, H. Luning, and T. Nilsson, “Moving the mobile evolved packet core to the cloud,” in *Proc. IEEE Int’l Conf. Wireless & Mobile Computing, Networking and Commun. (WiMob)*, Barcelona, Oct. 2012.

[73] R. Sherwood, G. Gibb, K.-K. Yap, G. Appenzeller, M. Casado, N. McKeown, and G. Parulkar, “Flowvisor: A network virtualization layer,” *OpenFlow Switch Consortium, Tech. Rep*, 2009.

[74] F. Fangwen and U. C. Kozat, “Stochastic game for wireless network virtualization,” *ACM/IEEE Trans. Networking*, vol. 21, no. 1, pp. 84–97, Apr. 2013.

[75] R. P. Esteves, L. Z. Granville, and R. Boutaba, “On the management of virtual networks,” *IEEE Commun. Mag.*, vol. 51, no. 7, Jul. 2013.

[76] V. Philip, Y. Gourhant, and D. Zeghlache, *OpenFlow as an Architecture for e-Node B Virtualization*, ser. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering. Springer Berlin Heidelberg, 2012, vol. 92, ch. 5, pp. 49–63.

[77] Y. Chen, S. Zhang, S. Xu, and G. Y. Li, “Fundamental trade-offs on green wireless networks,” *IEEE Comm. Mag.*, vol. 49, no. 6, pp. 30–37, June 2011.

[78] S. Bu, F. R. Yu, Y. Cai, and P. Liu, “When the smart grid meets energy-efficient communications: Green wireless cellular networks powered by the smart grid,” *IEEE Trans. Wireless Commun.*, vol. 11, pp. 3014–3024, Aug. 2012.

[79] F. Capozzi, G. Piro, L. A. Grieco, G. Boggia, and P. Camarda, “Downlink packet scheduling in LTE cellular networks: Key design issues and a survey,” *IEEE Commun. Surveys & Tutorials*, vol. 15, no. 2, pp. 678–700, June 2013.

[80] 3GPP, “Technical Specification Group Services and System Aspects; Policy and charging control architecture,” 3rd Generation Partnership Project (3GPP), TS 23.203 V12.2.0, Sep. 2013. [Online]. Available: http://www.3gpp.org/ftp/specs/html-INFO/23203.htm

[81] L. Xia, S. Kumar, X. Yang, P. Gopalakrishnan, Y. Liu, S. Schoenberg, and X. Guo, “Virtual wifi: bring virtualization from wired to wireless,” *ACM SIGPLAN Not.*, vol. 46, no. 7, pp. 181–192, Mar. 2011.

[82] T. Nagai and H. Shigeno, “A framework of ap aggregation using virtualization for high density WLANs,” in *Proc. 3rd Int’l Conf. Intelligent Networking & Collaborative Systems (INCoS)*, Fukuoka, Dec. 2011, pp. 350–355.

[83] G. Bhanage, I. Seskar, Y. Zhang, and D. Raychaudhuri, “Evaluation of openvz based wireless testbed virtualization,” Tech. rep. WINLAB-TR-331, Rutgers University, Report, 2008.

[84] S. Singhal, G. Hadjichristofi, I. Seskar, and D. Raychaudhri, “Evaluation of UML based wireless network virtualization,” in *Proc. Next Generation Internet Networks (NGI)*, Krakow, Apr. 2008.

[85] G. Smith, A. Chaturvedi, A. Mishra, and S. Banerjee, “Wireless virtualization on commodity 802.11 hardware,” in *Proc. 2nd ACM Int’l Workshop on Wireless Net. Testbeds, Experimental Evaluation & Characterization*, Montreal, QC, Sep. 2007.

[86] S. Perez, J. M. Cabero, and E. Miguel, “Virtualization of the wireless medium: A simulation-based study,” in *Proc. IEEE Veh. Tech. Conf. (VTC) - Spring*, Barcelona, Apr. 2009.

[87] G. Bhanage, D. Vete, I. Seskar, and D. Raychaudhuri, “Splitap: Leveraging wireless network virtualization for flexible sharing of WLANs,” in *Proc. IEEE Globecom*, Miami, FL, Dec. 2010.

[88] K. Nakauchi, Y. Shoji, and N. Nishinaga, “Airtime-based resource control in wireless lans for wireless network virtualization,” in *Proc. Int’l Conf. Ubiquitous & Future Net. (ICUFN)*, Phuket, Jul. 2012.

[89] D. Yun and Y. Yi, “Virtual network embedding in wireless multihop networks,” in *Proc. Int’l Conf. Future Internet Technologies*, Seoul, Jun. 2011.

[90] D. Yun, J. Ok, B. Shin, S. Park, and Y. Yi, “Embedding of virtual network requests over static wireless multihop networks,” *Computer Net.*, vol. 57, no. 5, pp. 1139–1152, Apr. 2013.

[91] S. L. Shrestha, J. Lee, and S. Chong, “Virtualization and slicing of wireless mesh network,” in *Proc. Int’l Conf. Future Internet Technologies*, Seoul, Jun. 2008.

[92] L. Pin, C. Zhiping, X. Jia, and X. Ming, “Multicast service-oriented virtual network embedding in wireless mesh networks,” *IEEE Commun. Let.*, vol. 16, no. 3, pp. 375–377, Mar. 2012.

[93] P. Lv, X. Wang, and M. Xu, “Virtual access network embedding in wireless mesh networks,” *Ad Hoc Networks*, vol. 10, no. 7, pp. 1362–1378, Sep. 2012.

[94] Y. Zaki, L. Zhao, C. Goerg, and A. Timm-Giel, “LTE mobile network virtualization,” *Mobile Net. & Applications*, vol. 16, no. 4, pp. 424–432, Aug. 2011.

[95] L. Zhao, M. Li, Y. Zaki, A. Timm-Giel, and C. G, “LTE virtualization: from theoretical gain to practical solution,” in *Proc. 23rd Int’l Teletraffic Congress*, Shanghai, Sep. 2011.

[96] L. Ming, Z. Liang, L. Xi, L. Xiaona, Y. Zaki, A. Timm-Giel, and C. Gorg, “Investigation of network virtualization and load balancing techniques in LTE networks,” in *Proc. IEEE Veh. Tech. Conf. (VTC) - Spring*, Yokohama, May 2012.

[97] L. Bin and T. Hui, “A bankruptcy game-based resource allocation approach among virtual mobile operators,” *IEEE Commun. Let.*, vol. 17, no. 7, pp. 1420–1423, Jul. 2013.

[98] L. E. Li, Z. M. Mao, and J. Rexford, “Cellsdn: Software-defined cellular networks,” Princeton University Computer Science, Technical report, 2012.

[99] G. Bhanage, R. Daya, I. Seskar, and D. Raychaudhuri, “VNTS: A virtual network traffic shaper for air time fairness in 802.16e systems,” in *Proc. IEEE Int. Conf. Commun. (ICC)*, Cape Town, South Africa, May 2010.

[100] G. Bhanage, I. Seskar, R. Mahindra, and D. Raychaudhuri, “Virtual basestation: architecture for an open shared WiMAX framework,” in *Proc. 2nd ACM SIGCOMM Workshop on Virtualized Infrastructure Systems & architectures*, New Delhi, India, Sep. 2010.

[101] R. Kokku, R. Mahindra, H. Zhang, and S. Rangarajan, “NVS: a virtualization substrate for WiMAX networks,” in *Proc. Annual ACM/IEEE Int. Conf. Mobile Computing & Net. (MobiCom)*, Chicago, Illinois, Sep. 2010.

[102] X. Lu, K. Yang, Y. Liu, D. Zhou, and S. Liu, “An elastic resource allocation algorithm enabling wireless network virtualization,” *Wiley Wireless Commun. & Mobile Computing*, Dec. 2012.

[103] X. Lu, K. Yang, and H. Zhang, “An elastic sub-carrier and power allocation algorithm enabling wireless network virtualization,” *Wireless Pers. Commun.*, pp. 1–23, Oct. 2013.

[104] K. Nakauchi, K. Ishizu, H. Murakami, A. Nakao, and H. Harada, “Amphibia: A cognitive virtualization platform for end-to-end slicing,” in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kyoto, Jun. 2011.

[105] L. Caeiro, F. D. Cardoso, and L. M. Correia, “Adaptive allocation of virtual radio resources over heterogeneous wireless networks,” in *Proc. 18th European Wireless Conf.*, Poznan, Poland, Apr. 2012.

[106] F. Fangwen and U. C. Kozat, “Wireless network virtualization as a sequential auction game,” in *Proc. IEEE INFOCOM*, San Diego, CA, Mar. 2010, pp. 1–9.

[107] Y. Mao, L. Yong, Z. Lieguang, J. Depeng, and S. Li, “Karnaugh-map like online embedding algorithm of wireless virtualization,” in *Proc. 15th Int’l Symp. Wireless Personal Multimedia Commun. (WPMC)*, Taipei, Sep. 2012, pp. 594–598.

[108] Z. Xu, L. Yong, J. Depeng, S. Li, Z. Lieguang, and H. Pan, “Efficient resource allocation for wireless virtualization using time-space division,” in *Proc. 8th Int’l Wireless Commun. & Mobile Computing Conf. (IWCMC)*, Limassol, Aug. 2012.

[109] R. Matos, C. Marques, and S. Sargento, “Distributed approach to control and manage context-based multi-virtual networks,” *Mobile Net. & Applications*, vol. 17, no. 4, pp. 447–462, Aug. 2012.

[110] R. Matos, S. Sargento, K. A. Hummel, A. Hess, K. Tutschku, and H. de Meer, “Context-based wireless mesh networks: a case for network virtualization,” *Telecom. Systems*, vol. 51, no. 4, pp. 259–272, Dec. 2012.

[111] J. Sachs and S. Baucke, “Virtual radio: a framework for configurable radio networks,” in *Proc. Annual Int. Wireless Internet Conf. (WICON)*, Maui, HI, Nov. 2008.

[112] Y. Zaki, *LTE Optimization and Mobile Network Virtualization*. Springer, 2012.

[113] T. X. Project”. (2013) The xen project, the powerful open source industry standard for virtualization. [Online]. Available: http://www.xenproject.org/

[114] X. Jin, L. E. Li, L. Vanbever, and J. Rexford, “Softcell: Taking control of cellular core networks,” *arXiv preprint arXiv:1305.3568*, May 2013.

[115] Z. Ye, L. Yong, S. Guang, J. Depeng, S. Li, and Z. Lieguang, “Game theory based bandwidth allocation scheme for network virtualization,” in *Proc. IEEE Globecom*, Miami, FL, Dec. 2010.

[116] D. Lopez-Perez, A. Valcarce, G. de la Roche, and J. Zhang, “OFDMA femtocells: A roadmap on interference avoidance,” *IEEE Comm. Mag.*, vol. 47, pp. 41–48, April 2009.

[117] J. C. Mogul, P. Yalagandula, J. Tourrilhes, R. McGeer, S. Banerjee, T. Connors, and P. Sharma, “Api design challenges for open router platforms on proprietary hardware,” in *Proc. ACM SIGCOMM WS. Hot Topics in Networks (HotNets)*, Calgary, AB, Oct. 2008.

[118] D. G. Andersen, “Theoretical approaches to node assignment,” *Computer Science Department*, pp. 1–13, 2002.

[119] F. R. Yu, V. W. S. Wong, J.-H. Song, V. C. M. Leung, and H. C. B. Chan, “Next generation mobility management: an introduction,” *Wireless Communications and Mobile Computing*, vol. 11, no. 4, pp. 446–458, 2011. [Online]. Available: http://dx.doi.org/10.1002/wcm.904

[120] S. Bu, F. R. Yu, X. Liu, and H. Tang, “Structural results for combined continuous user authentication and intrusion detection in high security mobile ad-hoc networks,” *IEEE Trans. Wireless Commun.*, vol. 10, no. 9, pp. 3064–3073, Sept. 2011.

[121] R. Xie, F. R. Yu, H. Ji, and Y. Li, “Energy-efficient resource allocation for heterogeneous cognitive radio networks with femtocells,” *IEEE Trans. Wireless Commun.*, vol. 11, no. 11, pp. 3910 –3920, Nov. 2012.

[122] P. Ahokangas, M. Matinmikko, S. Yrjola, H. Okkonen, and T. Casey, ““simple rules” for mobile network operators’ strategic choices in future cognitive spectrum sharing networks,” *IEEE Wireless Comm.*, vol. 20, no. 2, pp. 20–26, Apr. 2013.

[123] C. Luo, G. Min, F. R. Yu, M. Chen, L. Yang, and V. Leung, “Energy-efficient distributed relay and power control in cognitive radio cooperative communications,” *IEEE J. Sel. Areas Commun.*, vol. 31, no. 11, pp. 2442–2452, Nov. 2013.

[124] R. Xie, F. R. Yu, and H. Ji, “Dynamic resource allocation for heterogeneous services in cognitive radio networks with imperfect channel sensing,” *IEEE Trans. Veh. Tech.*, vol. 61, pp. 770–780, Feb. 2012.

[125] A. Attar, H. Tang, A. Vasilakos, F. R. Yu, and V. Leung, “A survey of security challenges in cognitive radio networks: Solutions and future research directions,” *Proceedings of the IEEE*, vol. 100, no. 12, pp. 3172–3186, 2012.

[126] F. R. Yu, M. Huang, and H. Tang, “Biologically inspired consensus-based spectrum sensing in mobile ad hoc networks with cognitive radios,” *IEEE Network*, vol. 24, no. 3, pp. 26 –30, May 2010.

[127] F. R. Yu, *Cognitive Radio Mobile Ad Hoc Networks*. New York: Springer, 2011.

[128] Z. Li, F. R. Yu, and M. Huang, “A distributed consensus-based cooperative spectrum sensing in cognitive radios,” *IEEE Trans. Veh. Tech.*, vol. 59, no. 1, pp. 383–393, Jan. 2010.

[129] Q. Guan, F. R. Yu, S. Jiang, and G. Wei, “Prediction-based topology control and routing in cognitive radio mobile ad hoc networks,” *IEEE Trans. Veh. Tech.*, vol. 59, no. 9, pp. 4443 –4452, Nov. 2010.

[130] J. Xiao, R. Hu, Y. Qian, L. Gong, and B. Wang, “Expanding LTE network spectrum with cognitive radios: From concept to implementation,” *IEEE Wireless Comm.*, vol. 20, no. 2, pp. 12–19, Apr. 2013.

[131] S.-Y. Lien, K.-C. Chen, Y.-C. Liang, and Y. Lin, “Cognitive radio resource management for future cellular networks,” *IEEE Wireless Comm.*, vol. 21, no. 1, pp. 70–79, 2014.

[132] H. ElSawy, E. Hossain, and D. I. Kim, “Hetnets with cognitive small cells: user offloading and distributed channel access techniques,” *IEEE Comm. Mag.*, vol. 51, no. 6, pp. 28–36, 2013.

[133] Y. Liu, L. Cai, X. Shen, and H. Luo, “Deploying cognitive cellular networks under dynamic resource management,” *IEEE Wireless Comm.*, vol. 20, no. 2, pp. 82–88, Apr. 2013.

[134] R. Xie, F. R. Yu, and H. Ji, “Interference management and power allocation for energy-efficient cognitive femtocell networks,” *Mobile Networks and Applications*, vol. 18, no. 4, pp. 578–590, 2013.

[135] C.-X. Wang, F. Haider, X. Gao, X.-H. You, Y. Yang, D. Yuan, H. Aggoune, H. Haas, S. Fletcher, and E. Hepsaydir, “Cellular architecture and key technologies for 5G wireless communication networks,” *IEEE Comm. Mag.*, vol. 52, no. 2, pp. 122–130, Feb. 2014.

[136] K. Arshad, R. Mackenzie, U. Celentano, A. Drozdy, S. Leveil, G. Mange, J. Rico, A. Medela, and C. Rosik, “Resource management for QoS support in cognitive radio networks,” *IEEE Comm. Mag.*, vol. 52, no. 3, pp. 114–120, Mar. 2014.

[137] J. Hoadley and P. Maveddat, “Enabling small cell deployment with HetNet,” vol. 19, no. 2, pp. 4–5, Apr. 2012.

[138] S. Bu and F. R. Yu, “Green cognitive mobile networks with small cells for multimedia communications in the smart grid environment,” *IEEE Trans. Veh. Tech.*, vol. 63, no. 5, pp. 2115–2126, June 2014.

[139] G. Pallis, “Cloud computing: the new frontier of internet computing,” *IEEE Internet Computing*, vol. 14, no. 5, pp. 70–73, 2010.

[140] H. T. Dinh, C. Lee, D. Niyato, and P. Wang, “A survey of mobile cloud computing: architecture, applications, and approaches,” *Wireless Communications and Mobile Computing*, vol. 13, no. 18, pp. 1587–1611, 2013. [Online]. Available: http://dx.doi.org/10.1002/wcm.1203

[141] S. Wang and S. Dey, “Adaptive mobile cloud computing to enable rich mobile multimedia applications,” *IEEE Trans. Multimedia*, vol. 15, no. 4, pp. 870–883, 2013.

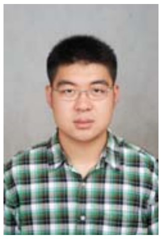
[142] Z. Yin, F. R. Yu, and S. Bu, “Joint dynamic cloud and wireless networks operations in the mobile cloud computing environment,” in *Proc. IEEE Globecom’14*, 2014.

[143] Y. Cai, F. R. Yu, and S. Bu, “Cloud computing meets mobile wireless communications in next generation cellular networks,” *IEEE Network*, to appear, 2014.

[144] O. S.-H. Park, and Simeone, O. Sahin, and S. Shamai, “Robust and efficient distributed compression for cloud radio access networks,” *IEEE Trans. Veh. Tech.*, vol. 62, no. 2, pp. 692–703, Feb. 2013.

[145] S. Bhaumik, S. P. Chandrabose, M. K. Jataprolu, G. Kumar, A. Muralidhar, P. Polakos, V. Srinivasan, and T. Woo, “CloudIQ: A framework for processing base stations in a data center,” in *Proc. ACM Mobicom’12*, Istanbul, Turkey, 2012.

[146] Y. Cai, F. R. Yu, and S. Bu, “Joint dynamic cloud and wireless networks operations in the mobile cloud computing environment,” in *Proc. IEEE Infocom’14 Workshop on Mobile Cloud Computing*, Toronto, ON, Apr. 2014.



Chengchao Liang received the B.Eng. in Communication Engineering and M.Eng. in Communication and Information Systems, both from Chongqing University of Posts and Telecommunications, China, in 2010 and 2013, respectively. From 2011 to 2012, he was a visiting student in the Mobile Telecommunications Research Lab, Inha University, South Korea.

He is currently pursuing his Ph.D. degree in the Department of Systems and Computer Engineering at Carleton University, Ottawa, Canada. His research interests include wireless network virtualization, radio resource allocation, interference management for cellular systems as well as applications of convex optimization in wireless networks.

F. Richard Yu (S'00-M'04-SM'08) received the PhD degree in electrical engineering from the University of British Columbia (UBC) in 2003. From 2002 to 2004, he was with Ericsson (in Lund, Sweden), where he worked on the research and development of wireless mobile systems. From 2005 to 2006, he was with a start-up in California, USA, where he worked on the research and development in the areas of advanced wireless communication technologies and new standards. He joined Carleton School of Information Technology and the Department of Systems and Computer Engineering at Carleton University in 2007, where he is currently an Associate Professor. He received the IEEE Outstanding Leadership Award in 2013, Carleton Research Achievement Award in 2012, the Ontario Early Researcher Award (formerly Premier's Research Excellence Award) in 2011, the Excellent Contribution Award at IEEE/IFIP TrustCom 2010, the Leadership Opportunity Fund Award from Canada Foundation of Innovation in 2009 and the Best Paper Awards at IEEE ICC 2014, Globecom 2012, IEEE/IFIP TrustCom 2009 and Int'l Conference on Networking 2005. His research interests include cross-layer/cross-system design, security, green IT and QoS provisioning in wireless-based systems.

Dr. Yu is a senior member of the IEEE. He serves on the editorial boards of several journals, including IEEE Transactions on Vehicular Technology, IEEE Communications Surveys and Tutorials, ACM/Springer Wireless Networks, EURASIP Journal on Wireless Communications Networking, Ad Hoc and Sensor Wireless Networks, Wiley Journal on Security and Communication Networks, and International Journal of Wireless Communications and Networking, and a Guest Editor for IEEE Transactions on Emerging Topics in Computing for the special issue on Advances in Mobile Cloud Computing and IEEE Systems Journal for the special issue on Smart Grid Communications Systems. He has served on the Technical Program Committee (TPC) of numerous conferences, as the TPC Co-Chair of IEEE Globecom'14, WiVEC'14, INFOCOM-MCC'14, Globecom'13, GreenCom'13, CCNC'13, INFOCOM-CCSES'12, ICC-GCN'12, VTC'12S, Globecom'11, INFOCOM-GCN'11, INFOCOM-CWCN'10, IEEE IWCMC'09, VTC'08F and WiN-ITS'07, as the Publication Chair of ICST QShine'10, and the Co-Chair of ICUMT-CWCN'09.