Information-Centric Network Function Virtualization over 5G Mobile Wireless Networks

Chengchao Liang, F. Richard Yu, and Xi Zhang

Abstract

Wireless network virtualization and information-centric networking (ICN) are two promising techniques in software-defined 5G mobile wireless networks. Traditionally, these two technologies have been addressed separately. In this paper we show that integrating wireless network virtualization with ICN techniques can significantly improve the end-to-end network performance. In particular, we propose an information-centric wireless network virtualization architecture for integrating wireless network virtualization with ICN. We develop the key components of this architecture: radio spectrum resource, wireless network infrastructure, virtual resources (including content-level slicing, network-level slicing, and flow-level slicing), and information-centric wireless virtualization controller. Then we formulate the virtual resource allocation and in-network caching strategy as an optimization problem, considering the gain of not only virtualization but also in-network caching in our proposed information-centric wireless network virtualization architecture. The obtained simulation results show that our proposed information-centric wireless network virtualization architecture and the related schemes significantly outperform the other existing schemes.

To accommodate the significant growth in wireless traffic and services over the fifth-generation (5G) mobile wireless networks, it is beneficial to extend *virtualization*, which has been successfully used in wired networks (e.g. virtual private networks (VPNs)), to wireless networks [1]. Using the network function virtualization (NFV) technique, wireless network infrastructure can be decoupled from the services that it provides, so that differentiated services can share the same infrastructure, maximizing their utilization [1]. As a result, NFV provides the momentum for new emerging design principles toward software-defined 5G wireless networks, which is the architecture extension of software-defined networks (SDN) with the network functions programmable-capabilities for 5G mobile wireless networks. In addition, wireless network virtualization enables easier migration to newer technologies while supporting legacy technologies by isolating part of the network. Several research projects have been undertaking around the world in the area of wireless network virtualization, such as Virtualized dIstributed plaTfoRms of smart Objects (VITRO) [2]. The authors of [3] propose a wireless local area network (WLAN) virtualization approach to extend the virtual network embedding from wired networks to wireless networks. Virtualizing eNodeB in 3rd Generation Partnership Project (3GPP) Long term evolution (LTE) is investigated in [4] in terms of node virtualization and software defined networks (SDNs).

Another new technology, called *information-centric networking* (ICN), has attracted great interests from both academia and industry [5]. The basic principle behind ICN is to promote the content to a first-class citizen in the network. A significant advantage of ICN is to provide native support for scalable and highly efficient content retrieval while enabling the enhanced capability for mobility and security. ICN can realize in-network *caching* to reduce the duplicate content transmission in networks. The ICN-based air caching technique has been recognized as one of the promising-candidate techniques to efficiently implement the SDN-based 5G wireless networks [6]. A number of research efforts have been dedicated to ICN, including the EU funded project Publish-Subscribe Internet Technology (PURSUIT) and the US funded project Named Data Networking (NDN).

Although some excellent works have been done on wireless network *virtualization* and *ICN*, these two important areas have traditionally been addressed separately in the literature. However, as shown in the following, it is necessary to jointly consider these two advanced technologies together to provide better services in 5G mobile wireless networks. Therefore, in this article we propose to integrate wireless network virtualization with the ICN technique in order to improve the end-

---

Chengchao Liang and F. Richard Yu are with Carleton University.

Xi Zhang is with Texas A&M University (corresponding author, e-mail address: xizhang@ece.tamu.edu).

The research work of Chengchao Liang and F. Richard Yu reported in this paper was supported in part by the Natural Sciences and Engineering Research Council of Canada and in part by Huawei Technologies Canada CO., LTD. The research work of Xi Zhang reported in this paper was supported in part by the U.S. National Science Foundation under Grants ECCS-1408601 and CNS-1205726.

0890-8044/15/$25.00 © 2015 IEEE

to-end network performance. The motivations behind our work are based on the following observations:

- On one hand, wireless network virtualization enables the sharing of not only the infrastructure, but also the content, among different service providers. Consequently, the capital expenses (CapEx) and operation expenses (OpEx) of content delivery, wireless access networks, as well as core networks, can be significantly reduced.
- On the other hand, virtual resource allocation (e.g. which nodes, links, and resources should be selected and optimized) is a significant challenge of wireless network virtualization. As content retrieval (instead of other traditional parameters, such as spectrum efficiency) is given a high priority in ICN, the processes in wireless network virtualization (e.g. virtual resource abstracting, slicing, sharing, and control) will be significantly affected by ICN.
- Therefore, integrating wireless network virtualization with the ICN technique can significantly improve the end-to-end network performance and maximize the utility function and efficiency of virtual mobile wireless network operations.

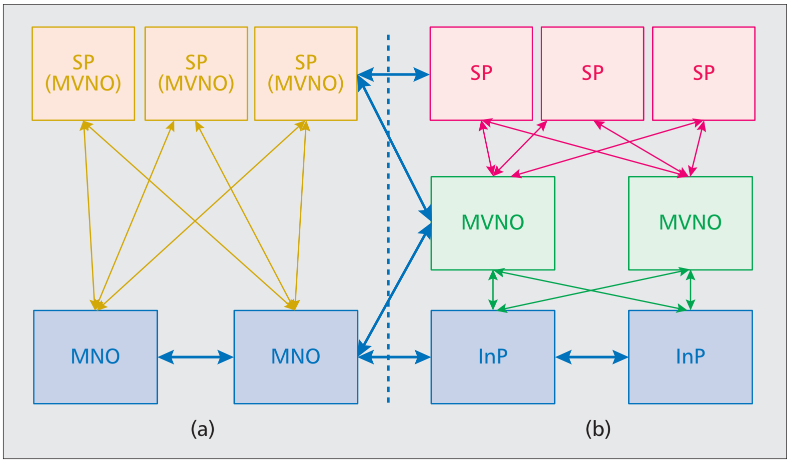

Figure 1. Business models of wireless network virtualization: a) A two-level model; b) A three-level model, where SP — service provider; MNO — mobile network operator; MVNO — mobile virtual network operator; InP — infrastructure provider.

The major contributions of this article are as follows:

- We propose an information-centric wireless network virtualization architecture that can enable both wireless network virtualization and ICN in 5G mobile wireless networks.
- We define and develop the key components of this architecture: radio spectrum resource, wireless network infrastructure, virtual resources (including content-level slicing, network-level slicing, and flow-level slicing), and an information-centric wireless virtualization controller.
- We formulate the virtual resource allocation and in-network caching strategies as a joint optimization problem, taking into account the gains of not only virtualization but also in-network caching in the proposed information-centric wireless network virtualization architecture. Simulation results are presented to validate and evaluate the performance of our proposed architecture and schemes.

The rest of this article is organized as follows. The following section introduces wireless network virtualization and information-centric networking. Then we propose the architecture of information-centric wireless network virtualization. Following that we formulate the virtual resource allocation and in-network caching strategy. Then we evaluate our proposed scheme through simulations. The final section concludes this article and briefly discusses the future work.

Wireless Network Virtualization and Information-Centric Networking

In this section we present the business models and logical roles in wireless network virtualization, followed by the introduction of the ICN technique.

Wireless Network Virtualization

With virtualization, physical cellular network infrastructure resources and physical radio resources can be abstracted and sliced into virtual cellular network resources holding certain corresponding functionalities, and shared by multiple parties through isolating each other. In other words, virtualizing mobile cellular networks is to realize the process of abstracting, slicing, isolating, and sharing mobile cellular networks. Generally speaking, the physical resources in cellular networks consist of licensed spectrum resource and infrastructure resources, including radio access networks (RANs), core networks (CNs), and transport networks.

As shown in Fig. 1a, two logical roles can be identified after virtualization: *mobile network operator* (MNO) and *service provider* (SP). MNOs own and operate infrastructures and radio resources of physical substrate wireless networks, including licensed spectrum, RANs, backhaul, transmission networks, and CNs. MNOs implement the virtualization, and slice the physical mobile network resources into virtual mobile network resources. For brevity, we use virtual resources to indicate the virtual mobile network resources. SPs lease, operate, and program these virtual resources to offer end-to-end services to mobile users.

The roles in the business model can be further decoupled into more specialized roles, including SP, infrastructure provider (InP), and mobile virtual network operator (MVNO) [7], as shown in Fig. 1b. Their functions in this model are detailed as follows.

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

InP: Owns the physical cellular network infrastructure resources and physical radio resources. In some special cases, the physical radio resources may not be owned by InPs. Specifically, some wired network InPs who have no RAN and licensed spectrum can provide backhaul network service. Moreover, some companies (e.g. tower companies) who only build BSs without providing services also do not have licensed spectrum.

MVNO: Leases the network resources from InPs, creates virtual resources based on the requests from SPs, operates the virtual resources, and assigns them to SPs. The emergence of MVNOs breaks the value chain dominated by the traditional MNOs [8]. Compared to MNOs, MVNOs do not own spectrum and radio access networks [1]. Compared to the existing MVNOs in Fig. 1a, MVNOs in Fig. 1b have more opportunities to access cellular networks including RANs through leasing and operating mobile network resources from InPs, and they can deploy and create more flexible virtual networks.

The above business models can be summarized using the emerging concept of X-as-a-service (XaaS) in cloud computing. Infrastructure-as-a-service (IaaS) is provided by InPs; network-as-a-service (NaaS) is operated by MVNOs. Moreover, SPs can provide software-as-a-service (SaaS) (or cloud-as-a-service (CaaS)).

In commercial markets, CapEx and OpEx can be signifi-

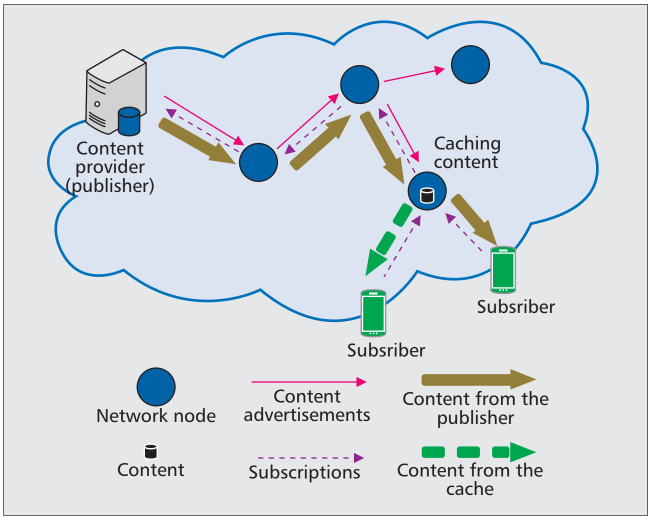

Figure 2. The information-centric networking model.

cantly reduced due to the sharing enabled by wireless network virtualization. The authors of [9] estimate that up to 40 percent of $60 billion used for OpEx and CapEx can be saved by operators worldwide over a five-year period. Over the past years, MVNOs and over-the-top (OTT) SPs have become strong players in mobile network markets, and have brought their featured services to impact the ecotope of the traditional market dominated by MNOs. The OTT SPs refer to those who provide audio, video, and other media applications over networks without the involvement of network operators in the control or distribution of the content. Fortunately, wireless network virtualization brings a win-win situation for both MVNOs and MNOs [10]. MVNOs or other types of SPs can lease virtual networks from MNOs, and MNOs can attract a 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 the customized and more flexible services can be provided more easily, and quality of service (QoS) can be enhanced as well. This also brings revenues to MNOs, because SPs need to pay MNOs for the leased virtual networks.

Information-Centric Networking

Figure 2 shows the ICN model. As shown in Fig. 2, the communication paradigm within ICN is different from what it is with the Internet Protocol (IP). Current IP architectures revolve around a host-based conversation model (i.e. a connection of communication is established between two hosts before any content is transferred), and the delivery of data in the network follows a source-driven approach (i.e. the path is set up from the sender to the receiver). In contrast, the main concern of ICN is to disseminate, find, and deliver information rather than the reachability of end hosts and the maintenance of conversations between them. In ICN, the user requests content without knowledge of the host that can provide it, and the communication follows a receiver-driven principle (i.e. the path is set up by the receiver to the provider), and the data follows the reverse path. The network is then in charge of doing the mapping between the requested content and where it can be found (see Fig. 2). The match of requested content rather than the findability of the endpoint that provides it thus dictates the connection establishment in ICN.

To be efficient, one key aspect of ICN is *naming*. Content should be named in such a way as to be independent of the location of the node where the content can be found, which is the main objective of ICN (to separate naming and location). As shown in Fig. 2, ICN also includes a native caching function in the network, in such a way that nodes can cache the contents passing through it for a while (depending on the cache size and replacement algorithm) and deliver them to the requesting users. Via this in-network caching mechanism, the content is replicated, and the delivery probability of this content to the end user is increased.

Decoupling naming from location also allows native support of mobility or multicast in ICN. Indeed, when users move, they are connected to another node in the ICN network, but since no IP address is used for the routing, it is transparent, as opposed to IP, where the address should be changed. For multicast, as soon as one user has requested a given content, one node can cache it and then deliver it for subsequent requests for the same content. It then naturally creates a multicast-like content delivery.

Another similar technique, which is called *content delivery networking* (CDN), tries to put the content near the customers. CDN is deployed as overlays at the application layer, while ICN applies the techniques at the lower layers (e.g. networking layer). Another difference is that CDN typically employs network-unaware mechanisms. By contrast, efficient information retrieval can benefit from ICN that provides Internet-wide infrastructure supporting in-network mechanisms.

Information-Centric Wireless Network Virtualization

In this section we propose an architecture for enabling both wireless network virtualization and ICN, which is called information-centric wireless network virtualization. We present the motivations, radio spectrum resource, mobile network infrastructure, virtual resources, and information-centric virtualization controller in this novel architecture.

Motivations Behind Information-Centric Wireless Network Virtualization

Traditionally, dedicated physical resources from specific operators are used for content delivery. As these physical resources cannot be shared by different operators, content delivery increase the complexity of the network, as well as the CapEx and OpEx [11]. Moreover, content delivery is a very volatile market with new protocols, content formats, device types, and so on. With dedicated physical resources, operators do not have the flexibility to react to these rapid changes. Fortunately, wireless network virtualization enables the sharing of not only the infrastructure, but also the content, among different service providers. By introducing network virtualization into ICN, new networking technologies that are designed for ICN can be deployed and implemented quickly without effecting traditional networks. Furthermore, through the combination of virtualization and ICN, not only the physical resources but also the content can be shared. Since duplicative content transmissions consume physical resources (especially backhaul networks), sharing content among virtual networks can reduce the unnecessary duplicative transmissions. Consequently, the CapEx and OpEx of wireless access networks, content delivery, as well as core networks, can be significantly reduced.

On the other hand, virtual resource allocation is a significant challenge of wireless network virtualization. Virtual resource allocation schemes need to decide how to embed a virtual wireless network in physical networks (e.g. which nodes, links, and resources should be selected and optimized).

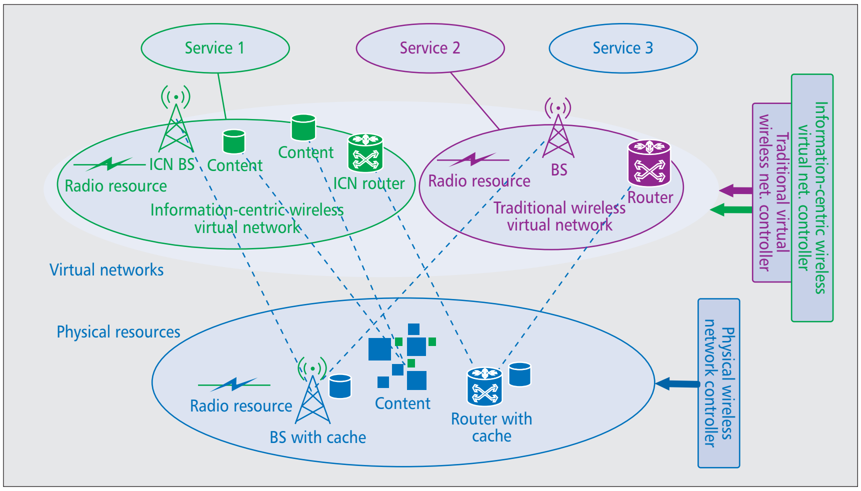

Figure 3. The architecture of our proposed information-centric wireless network virtualization. Here, the substrate physical wireless networks are virtualized into two virtual networks. One is running ICN, while the other is based on traditional networks.

As content retrieval (instead of other traditional parameters, such as spectrum efficiency) is given a high priority in ICN, the processes in wireless network virtualization (e.g. virtual resource abstracting, slicing, sharing, and control) will be significantly affected by ICN. ICN will introduce new challenges to network virtualization in terms of virtual content naming, caching, distributing, and so on.

Therefore, integrating wireless network virtualization with the ICN technique can significantly improve the end-to-end network performance. We propose an architecture of information-centric wireless network virtualization, as shown in Fig. 3. In this example, the substrate physical wireless networks are virtualized into two virtual networks. One is running ICN, while the other is based on traditional networks. Different services are provided by these virtual networks. End users logically connect to the virtual network from where they subscribe to the service, while they physically connect to the physical network. A virtual wireless network controller needs to be deployed at the network to realize the virtualization process.

Radio Spectrum Resource

Radio spectrum resource is one of the most important resources in wireless communications and networks. Usually, radio spectrum resource refers to the licensed spectrum or some dedicated free spectrum. As cognitive radio emerges, radio spectrum extends its range from dedicated spectrum to white spectrum, which implies the idle spectrum licensed but unused by its owner can be used by the unlicensed mobile users.

With spectrum sharing, all or part of the licensed spectra owned by operators can be utilized by multiple operators 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, which can improve the spectrum efficiency and network capacity. Actually, inter-operator spectrum sharing has been proposed for many years. However, due to reasons related to policies and markets instead of technologies, spectrum sharing is not popular in current cellular networks. Fortunately, spectrum sharing will play an important role in wireless network virtualization to promote full virtualization, in which all the available radio spectra can be shared by multiple operators.

Wireless Network Infrastructure

The infrastructure components are the “foundation” of cellular networks and occupy the majority of the investment of MNOs. In modern cellular networks, the entire cellular network may be possessed by one MNO, or some parties may only own part of the entire network, for example, some parties own CNs while others only have the transport networks. In some cases, MNOs may be the competitors at a certain geographical area, and no sharing or limited sharing (e.g. roaming) exists among them. In this case, virtualization can be realized within a single MNO.

The term ‘network sharing’ refers to the scenario where multiple MNOs share the infrastructure of the same 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 then share with each other. Network sharing can also be considered as an important step to enable IaaS.

Virtual Resources

Virtual resources are created by slicing physical resources 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 complete slice is a universal wireless virtual network. For example, an SP requesting a slice from an MNO implies that this SP wants to have a virtual network from CN to air interface, and is able to customize all the virtual elements in this slice. However, in reality this ideal slice may not always be necessary. Specifically, some MVNOs, who have their own CN but do not have radio coverage, only need RAN slices [12], while some SPs only need the slices at a specific area or time. In another scenario, emerging OTT SPs may want to pay more to MNOs to ensure a guaranteed QoS to their end users. The MNOs need to allocate a certain number of resource slices to these OTT SPs, and these resource slices can be customized by OTT SPs according to their own requirements [10]. Thus, based on different requirements, wireless virtual resources imply different levels of virtualization. Here we present the main three levels of wireless virtual resources, which are content-level slicing, network-level slicing, and flow-level slicing.

Content-Level Slicing: Content-level slicing can be considered as an extension of dynamic content access and sharing. In this paradigm, through time multiplexing, space multiplexing, and so on, physical content (cache) is sliced and assigned to MVNOs or SPs [11]. The framework of the content-level slicing is shown in Fig. 4. There are three physical contents, and three services share the these physical contents. In this example, each physical content is sliced into several virtual contents. One service can use one or several slices without knowing the existence of other slices, while the other slices of this physical content may be used for other virtual resources. The request rate of some contents can be much higher than the others, and thus these contents may be virtualized into more virtual contents. Conceptually speaking, we can say that content-level slicing is an application of content sharing and dynamic access in the virtualization environment.

Network-Level Slicing: Network-level slicing is the ideal case for wireless network virtualization. Particularly, in LTE-based next generation cellular networks, the network-level

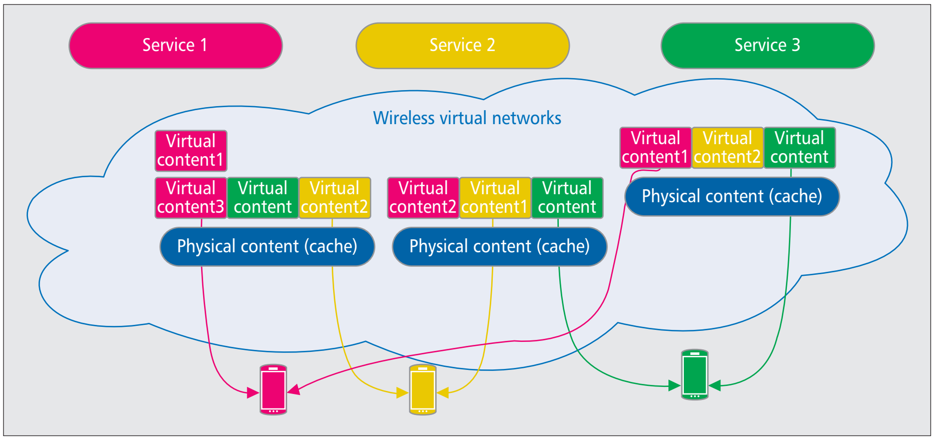

Figure 4. The framework of our proposed content-level slicing. Here, the physical content (cache) is sliced into virtual contents, which can be shared by different services dynamically. The slicing can be time multiplexing (different time slots) or space multiplexing (different locations).

slicing has attracted much research attention [13]. For example, MVNO 1 that has its own CN but without a RAN in this area requests a virtual RAN from the MNO. Based on this request, the MNO virtualizes a specific virtual RAN (V_RAN 1) to MVNO 1. Assume that MVNO 1 wants to have more control on the network. A virtual eNB (V_eNB), a virtual relay (V_Relay), and a virtual femtocell (V_Femto) are created, and assigned to MVNO 1. MVNO 1 may operate this virtual RAN on virtual spectrum and connect it to its own CN. In another example, MVNO 2 wants a virtual cellular network including spectrum, RAN, and CN. Therefore, the MNO creates another virtual RAN (V_RAN 2) and a virtual CN (V_CN), and assigns the created virtual RAN and created virtual CN to MVNO 2. Unlike MVNO 1, MVNO 2 may only need a virtual BS (V_BS) instead of a full RAN. In other words, the MNO can virtualize one or some of the access points (e.g. eNB, relay, or femto) in this area to be 'one' virtual BS based on the location and channel state of UEs.

Flow-Level Slicing: The main idea of flow-level slicing virtualization was first proposed in FlowVisor [14]. 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 [10]. Some works have been done toward this architecture (e.g. [9, 10]). 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 [10]. A typical example is an MVNO that 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 a certain data rate from the MNO who actually operates the physical networks. Unlike the network-level slicing case, the SP cares more about the link between the SP and its end-users, and the capability of bearing and customizing flows on these virtual slices, instead of detailed networks. The topologies and components of cellular networks are totally transparent to the SP in this scenario.

Information-Centric Wireless Virtualization Controller

An information-centric wireless virtualization controller is used for realizing customizability, manageability, and programmability of virtual resources available to SPs. Through the controller, the control plane is decoupled from the data plane, and SPs can customize the virtual resources within their own virtual slices. Usually, there are two parts in the controller: a *substrate controller* and a *virtual controller*. The substrate controller is used for MNOs or InPs to virtualize and manage the substrate physical network. The virtual controller is used for MVNOs and SPs to manage the virtual slices or networks. Specifically, MNOs use the wireless virtualization controller to create virtual slices and embed the virtual slices onto wireless physical substrate networks. This process includes physical resource allocation, abstraction, virtualization, slicing, isolation, and assignment. Through the virtual controller, an SP can customize their own end-to-end protocols and services, such as scheduling and forwarding. Since SDN and OpenFlow have been considered as the most promising and effective technologies in the network management domain, applying SDN in wireless networks has attracted significant research attention [4].

Virtual Resource Allocation and In-Network Caching Under Our Proposed Architecture

The two important components in our proposed information-centric wireless network virtualization architecture are the *efficient virtual resource allocation* scheme and the *in-network caching strategy*, which are elaborated on, respectively, in more detail in the following. The virtualization procedure done by MVNOs can be considered as the mapping process between virtual resources and physical resources. Thus, MVNOs need to allocate appropriate physical resources so that the requirements demanded by virtual resources are satisfied. At the same time, the aggregate utility of MVNOs needs to be maximized. Specifically, it is MVNOs' duty to first select appropriate infrastructure (e.g. BSs, routers, computing resource, and cache) and radio resources from all leased infrastructure, and then map these physical resources to the various virtual resources, including virtual spectrum, virtual slicing, virtual networks, and so on. The virtual resource allocation can be characterized by binary control variable $x_{ki} \in \{0, 1\}$ where if infrastructure i with $i \in \mathcal{I} \triangleq \{1, 2, \ldots, I\}$ is selected for mobile user k with $k \in \mathcal{K} \triangleq \{1, 2, \ldots, K\}$, then $x_{ki} = 1$; otherwise $x_{ki} = 0$. Moreover, the proportion of resources allocated to mobile user k at infrastructure i is measured by the control variable y_{ki} with $y_{ki} \in [0, 1]$. Then, the average gain achieved by the resource virtualization is given by

$$\mathbb{E}\left[Gain_{virtualization}\right] = \sum_{k\in\mathcal{K},\, i\in\mathcal{I}} r_{ki} x_{ki} y_{ki} \tag{1}$$

where r_{ki} is the gain obtained through the resource virtualization, which takes into account the cost of leasing infrastructure from InPs and the revenue of providing virtual resource to SPs and $\mathbb{E}[\cdot]$ is expectation operation.

The caching strategy can be characterized by a binary control variable $z_{kj} \in \{0, 1\}$ where if network element (BS or router) j with $j \in \mathcal{J} \triangleq \{1, 2, \ldots, J\}$ caches the content requested by mobile user k with $k \in \mathcal{K}$, then $z_{kj} = 1$; otherwise $z_{kj} = 0$. Therefore, the expected reward (gain) of this caching strategy is given by

$$\mathbb{E}\left[Gain_{caching}\right] = \sum_{k\in\mathcal{K},\, j\in\mathcal{J}} q_k o_{kj} z_{kj} \tag{2}$$

where q_k is the request rate of the content requested by mobile user k and o_{kj} is the gain obtained through caching. In [6] the authors pointed out that three objectives can be achieved by carefully considering content popularity, freshness, diversity, and replica locations over the network topology. These three objectives are to minimize the inter-ISP traffic (outbound traffic), intra-ISP traffic (traffic within the RAN), and content access delay of all users. Therefore, o_{kj} can be defined as the reduction of traffic (backhaul bandwidth) $\overline{R}$ or access delay $\overline{\tau}$.

Therefore, we can formulate the virtual resource allocation and in-network caching strategy as the following joint optimization problem:

$$\max_{x_{ki}, y_{ki}, z_{kj}} \sum_{k\in\mathcal{K}, j\in\mathcal{I}} U_\upsilon\left(\mathbb{E}\ Gain_{virtualization}\right) + \sum_{k\in\mathcal{K}, j\in\mathcal{J}} U_c\left(\mathbb{E}\ Gain_{caching}\ \right)$$

$$\begin{aligned} s.t.\ C1 &: All\ the\ control\ variables\ (x_{ki}, y_{ki},\ and\ z_{kj})\ are\ feasible \\ C2 &: All\ users\ satisfy\ the\ requirements\ demanded\ by\ virtual\ resources \end{aligned} \quad (3)$$

where $U_v(\cdot)$ and $U_c(\cdot)$ are two utility functions defined with respect to $\mathbb{E}[Gain_{virtualization}]$ given by Eq. 1 and $\mathbb{E}[Gain_{caching}]$ given by Eq. 2, respectively. There are several methods (e.g. the interior point method) which can be employed to solve the above optimization problem. For lack of space, we omit these details here.

Simulation Results and Discussions

To evaluate the performance of our proposed virtual resource allocation and in-network caching schemes, we conducted simulations based on a heterogeneous network (including a macro cell and 12 small cells) with the in-network caching capability. In the simulations, we considered two RAN InPs, two backhaul InPs, one MVNO, and three SPs. RAN InP 1 owns a two-tier cellular network with one macro BS and six small BSs. RAN InP 2 owns six small BSs. In our simulations, the location of the macro BS is fixed in the center and the locations of 12 small BSs are uniformly distributed.

We compare the proposed scheme with a traditional max-SINR association scheme [15], where a user associates with the BS who provides the largest received SINR, and each BS performs proportional fairness resource allocation. No wireless network virtualization and in-network caching is considered in this traditional scheme. In addition, we also show the performance of the proposed scheme without in-network caching.

Figure 5 shows the average backhaul bandwidth used by all users. From Fig. 5 we can observe that the proposed scheme with in-network caching significantly reduces the total backhaul usage as compared with the traditional scheme and the proposed scheme without in-network caching. This is because our proposed architecture of information-centric wireless network virtualization enables in-network caching, which reduces the duplicate content transmission in networks. In addition, due to the sharing of not only the infrastructure but also the content among different service providers, the CapEx and OpEx can be significantly reduced.

Next we compare the number of users who are satisfied with the minimum data rate requirements requested by SPs, as shown in Fig. 6. We can see that by deploying our proposed virtual resource allocation and in-network caching scheme, network function virtualization can be realized without violating data rate requirements, which is because we put virtualization as constraints in our optimization problem. By contrast, in the traditional scheme, the isolation of virtualization may not be satisfied. Some users are affected by others, and may not receive the requested data rate. Therefore, the number of satisfied users is less than the total number of users in the traditional scheme.

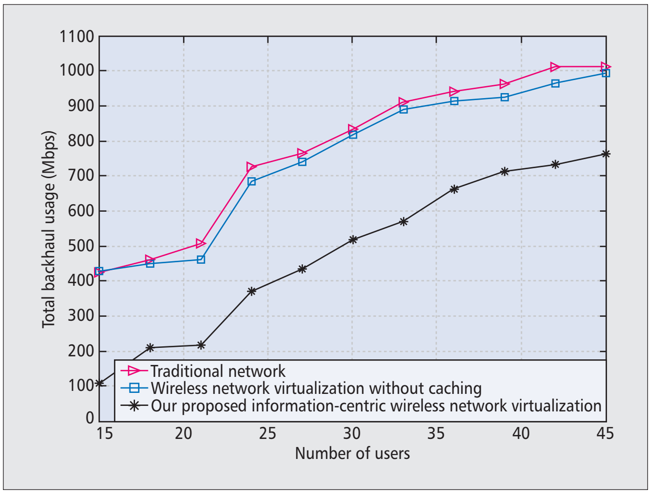

Figure 5. The backhaul usage in different schemes.

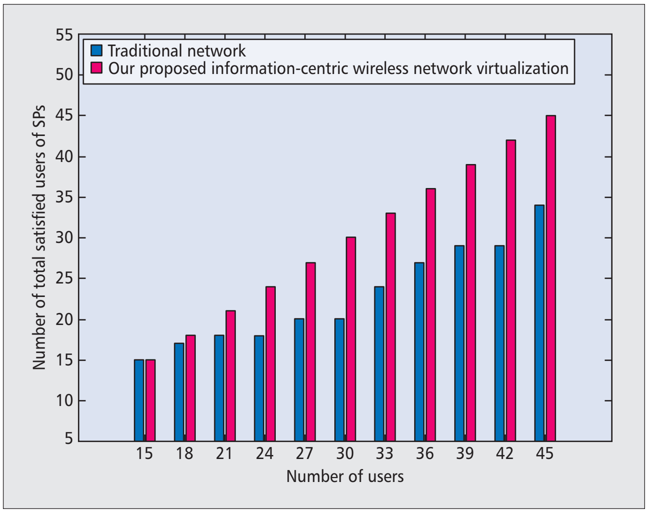

Figure 6. The number of total satisfied users of SPs.

Conclusions and Future Work

We proposed to integrate wireless network virtualization with the information-centric networking technique over 5G mobile wireless networks. We developed an information-centric wireless network virtualization architecture for enabling both wireless network virtualization and information-centric networking. We detailed designs for the key components in this architecture. Then we formulated the virtual resource allocation and in-network caching strategy as an optimization problem, which maximizes the utility function of mobile virtual network operations. The obtained simulation results show that the performance of backhaul alleviation can be substantially improved in our proposed architecture and schemes. Future work is in progress to consider admission control in the proposed architecture. In addition, since wireless network virtualization should have open interfaces to service applications, the interfaces between in-network caching and virtualization controllers will be studied in our future work.

References

[1] C. Liang and F. R. Yu, "Wireless Network Virtualization: A Survey, Some Research Issues and Challenges," *IEEE Comm. Surveys and Tutorials*, vol. 17, no. 1, pp. 358-380, First Quarter 2015.

[2] L. Sarakis *et al.*, "A Framework for Service Provisioning in Virtual Sensor Networks," *EURASIP J. Wireless Commun. & Netw.*, vol. 2012, no. 1, 2012, pp. 1–19.

[3] L. Xia *et al.*, "Virtual WiFi: Bring Virtualization from Wired to Wireless," *ACM SIGPLAN Not.*, vol. 46, no. 7, Mar. 2011, pp. 181–92.

[4] K. Pentikousis, W. Yan, and H. Weihua, "Mobileflow: Toward Software-Defined Mobile Networks," *IEEE Commun. Mag.*, vol. 51, no. 7, Jul. 2013, pp. 44–53.

[5] B. Ahlgren *et al.*, "A Survey of Information-Centric Networking," *IEEE Commun. Mag.*, vol. 50, no. 7, Jul. 2012, pp. 26–36.

[6] X. Wang *et al.*, "Cache in the Air: Exploiting Content Caching and Delivery Techniques for 5G Systems," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 131–39, Feb. 2014.

[7] A. Belbekkouche, M. M. Hasan, and A. Karmouch, "Resource Discovery and Allocation in Network Virtualization," *IEEE Commun. Surveys & Tutorials*, vol. 14, no. 4, Feb. 2012, pp. 1114–28.

[8] T. K. Forde, I. Macaluso, and L. E. Doyle, "Exclusive Sharing & Virtualization of the Cellular Network," *Proc. IEEE Symp. on New Frontiers in Dynamic Spectrum Access Net. (DySPAN)*, May 2011.

[9] X. Costa-Perez *et al.*, "Radio Access Network Virtualization for Future Mobile Carrier Networks," *IEEE Commun. Mag.*, vol. 51, no. 7, Jul. 2013.

[10] R. Kokku *et al.*, "NVS: A Substrate for Virtualizing Wireless Resources in Cellular Networks," *IEEE/ACM Trans. Netw.*, vol. 20, no. 5, Oct. 2012, pp. 1333–46.

[11] ETSI, "Network Functions Virtualisation (NFV): Use Cases," Tech. Rep. 2013001, Mar. 2013.

[12] 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; available: http://www.3gpp.org/ftp/Specs/html-info/23251.htm

[13] Y. Zaki *et al.*, "LTE Mobile Network Virtualization," *Mobile Net. & Applications*, vol. 16, no. 4, Aug. 2011, pp. 424–32.

[14] R. Sherwood *et al.*, "Flowvisor: A Network Virtualization Layer," *OpenFlow Switch Consortium*, Tech. Rep., 2009.

[15] D. Bethanabhotla *et al.*, "User Association and Load Balancing for Cellular Massive MIMO," *Proc. Information Theory and Applications Workshop (ITA) 2014*, Feb. 2014, pp. 1–10.

Biographies

CHENGCHAO LIANG received the B.Eng. in communication engineering and a 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, and interference management for cellular systems, as well as applications of optimization in wireless networks.

F. RICHARD YU [SM] is an associate professor at Carleton University, Canada. He received the IEEE Outstanding Leadership Award in 2013, the Carleton Research Achievement Award in 2012, the Ontario Early Researcher Award (formerly the Premier's Research Excellence Award) in 2011, the Excellent Contribution Award at IEEE/IFIP TrustCom 2010, the Leadership Opportunity Fund Award from the Canada Foundation of Innovation in 2009, and the Best Paper Awards at IEEE ICC 2014, Globecom 2012, IEEE/IFIP TrustCom 2009, and the Int'l Conference on Networking 2005. His research interests include cross-layer design, security, green IT, and QoS provisioning in wireless networks. He serves on the editorial boards of several journals, including co-editor-in-chief for *Ad Hoc & Sensor Wireless Networks*, lead series editor for *IEEE Transactions on Vehicular Technology*, and editor for *IEEE Communications Surveys & Tutorials*. He has served on the Technical Program Committee (TPC) of numerous conferences, as the TPC Co-Chair of IEEE GreenCom'15, INFOCOM-MCV'15, Globecom'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.

XI ZHANG [S'89, SM'98] received the B.S. and M.S. degrees from Xidian University, Xi'an, China, the M.S. degree from Lehigh University, Bethlehem, PA, USA, all in electrical engineering and computer science, and the Ph.D. degree in electrical engineering and computer science (electrical engineering systems) from The University of Michigan, Ann Arbor, MI, USA. He is currently a professor and the founding director of the Networking and Information Systems Laboratory, Department of Electrical and Computer Engineering, Texas A&M University, College Station. He was a research fellow with the School of Electrical Engineering, University of Technology, Sydney, Australia, and the Department of Electrical and Computer Engineering, James Cook University, Australia. He was with the Networks and Distributed Systems Research Department, AT&T Bell Laboratories, Murray Hill, New Jersey, and AT&T Laboratories Research, Florham Park, New Jersey, in 1997. He has published more than 300 research papers on wireless networks and communications systems, network protocol design and modeling, statistical communications, random signal processing, information theory, and control theory and systems. He received the U.S. National Science Foundation CAREER Award in 2004 for his research in the areas of mobile wireless and multicast networking and systems. He is an IEEE Distinguished Lecturer for both the IEEE Communications Society and IEEE Vehicular Technology Society. He received Best Paper Awards at IEEE GLOBECOM 2014, IEEE GLOBECOM 2009, IEEE GLOBECOM 2007, and IEEE WCNC 2010, respectively. One of his *IEEE J-SAC* papers has been listed as the IEEE ComSoc Best Readings (receiving the top citation rate) Paper on Wireless Cognitive Radio Networks. He also received a TEES Select Young Faculty Award for Excellence in Research Performance from the Dwight Look College of Engineering at Texas A&M University, College Station, in 2006. Prof. Zhang is serving or has served as an editor for *IEEE Transactions on Communications*, *IEEE Transactions on Wireless Communications*, and *IEEE Transactions on Vehicular Technology*, twice as a guest editor for *IEEE Journal on Selected Areas in Communications* for two special issues on "Broadband Wireless Communications for High Speed Vehicles" and "Wireless Video Transmissions," an associate editor for *IEEE Communications Letters*, twice as the lead guest editor for *IEEE Communications Magazine* for two special issues on "Advances in Cooperative Wireless Networking" and "Underwater Wireless Communications and Networks: Theory and Applications," and a guest editor for *IEEE Wireless Communications Magazine* for a special issue on "Next Generation CDMA vs. OFDMA for 4G Wireless Applications," an editor for Wiley's *Journal on Wireless Communications and Mobile Computing*, *Journal of Computer Systems, Networking, and Communications*, and Wiley's *Journal on Security and Communications Networks*, and an area editor for Elsevier's *Journal on Computer Communications*, among many others. He is serving or has served as the TPC Chair for IEEE GLOBECOM 2011, TPC Vice-Chair IEEE INFOCOM 2010, TPC Area Chair for IEEE INFOCOM 2012, Panel/Demo/Poster Chair for ACM MobiCom 2011, General Vice-Chair for IEEE WCNC 2013, Panel/Demo/Poster Chair for ACM MobiCom 2011, and TPC/General Chair for numerous other IEEE/ACM conferences, symposia, and workshops.