A Software-Defined Wireless Network Enabled Spectrum Management Architecture

Wei Wang, *Student Member, IEEE*, Yingjie Chen, Qian Zhang, *Fellow, IEEE*, Tao Jiang, *Senior Member, IEEE*

Abstract

Recent years have seen the proliferation in versatile mobile devices and application services that demand different data rates and latencies. Fixed channelization configuration in today's wireless devices fall inefficient in the presence of such dynamic demands. In this regard, fine-grained spectrum management **designs** have been advocated by the research community to embrace the heterogeneity in devices and services. Yet, manufacturers hesitate to make hardware investments without comprehensive understandings of these designs. To break this stalemate, software-defined wireless network (SDWN) has been pushed to the market as a cost-effective paradigm. Motivated by recent innovations in SDWN, this article systematically investigates the spectrum management architecture design that reaps the benefits of SDWN while maintaining the features of fine-grained channelization. We shed light on design principles and key challenges in realizing the SDWN-enabled spectrum management architecture. With these principles and challenges in mind, we develop a general architecture with a new baseband virtualization design. We build a prototype that seamlessly integrates with IEEE 802.11 protocol stack and commodity radio frequency (RF) front-end. We demonstrate that the proposed architecture improves spectrum efficiency by emulating the upper layer behaviors using the traces captured in a campus WLAN.

W. Wang is with the School of Electronic Information and Communications, Huazhong University of Science and Technology and the Fok Ying Tung Research Institute, Hong Kong University of Science and Technology. E-mail: gswwang@cse.ust.hk.

Y. Chen and Q. Zhang are with the Department of Computer Science and Engineering, Hong Kong University of Science and Technology. E-mail: {ocgcyj,qianzh}@cse.ust.hk.

T. Jiang is with the School of Electronic Information and Communications, Huazhong University of Science and Technology. E-mail: taojiang@hust.edu.cn.

I. INTRODUCTION

Recent years have witnessed the boom of versatile applications and heterogeneous wireless devices. A wireless device, such as a smartphone or laptop, may simultaneously run different types of applications, including video streaming services (Youtube, Netflix), cloud computing applications (Google photo auto backup, Dropbox, iCloud) and so on. These applications differ in required data rates and delay sensitivities. Moreover, the emerging of a new generation mobile internet devices, such as tablets, smartphones and wearable devices, have augmented the heterogeneity in traffic demands.

The ever-increasing heterogeneity in traffic demands has raised the stakes on developing new spectrum management architecture to utilize the limited spectrum resource in a cost-effective manner. The research community has realized that flexible channelization should be advocated to embrace the heterogeneous traffic demands. This vision is illustrated in Fig. 1, where mobile devices adopt different bandwidths according to their power constraints and service types. Wi-Fi access points (APs) communicate with smartphones on narrower channels to conserve power by using lower sampling rates, with tablets on medium-width channels to balance power and data rate requirements, and with laptops on wider channels to support traffic-intensive desktop services. Moreover, each mobile device runs versatile services with different latency and data rate requirements, which calls for finer-grained channelization.

To embrace the above vision in today's wireless LANs (WLANs), comprehensive understandings are required to properly manage the spectrum allocated to each AP [1]. Network operators need to configure each AP separately and even set service-specific preferences using vendor-specific commands. The configurations should be upgraded together with wireless protocols, which evolve continuously (once every few months) [2]. In addition to complex configurations, the operators should also have deep understandings about the impact of link dynamics and load changes. Ultimately, this situation has made the capital and operational expenses in spectrum management prohibitively high.

To fend off this ossification, both the telecommunication industry and the research community have placed considerable attention to a new paradigm, software-defined wireless network (SDWN) [3], which creates a bundle of opportunities for managing current wireless networks in a cost-effective manner. Notably, SDWN simplifies network management by decoupling the control plane logic from the data forwarding plane. The control plane is logically centralized, while it can be implemented using a centralized controller or multiple controllers distributed in the network. As such, the logic of traditional networks is abstracted from within the hardware implementation and raised to a higher software level that can easily be manipulated by network operators.

Despite growing attempts and extensive efforts on SDWN-enabled management architectures [2], [4], [5], few have systematically investigated the spectrum management architecture to facilitate fine-grained channelization. The architecture should be carefully designed to ensure that the whole network stack operates reliably while performing fine-grained channelization at the lower layers, that is, it has to account for the mutual impact of the application requirements and the spectrum dynamics at the physical (PHY) and media access control (MAC) layers. Another challenge stems from the overhead incurred by spectrum adaptation, which mainly manifests itself in handling the spectrum agreement between transmission pairs and the coordinations among multiple links.

In this article, we explore how the SDWN paradigm can be leveraged to efficiently overcome the limitations in current spectrum management architectures, and call attention to a clean-slate redesign of the fine-grained channelization mechanism. Specifically, we start at a deep dive at the features of the SDWN paradigm, and then review the challenges in realizing the SDWN-based architectures for spectrum management. We propose a spectrum management architecture that harvests the benefits of flexibility and programmability through the SDWN paradigm, while maintaining high efficiency in fine-grained channelization via a new baseband virtualization design. The benefits of our architecture are verified through experimental evaluation, and implications about future lines of research in architecture designs and applications are provided.

II. SDWN-Enabled Spectrum Management: Design Principles and Challenges

This section first presents an introduction to fine-grained spectrum management and the SDWN concepts. In particular, we highlight how the SDWN paradigm can be exploited to benefit spectrum management. We also investigate key SDWN-related technologies and review the state of the art. Then, we discuss the challenges of realizing the SDWN-enabled spectrum management.

A. Fine-Grained Spectrum Management

This work considers a typical WLAN scenario as envisioned in Fig. 1, where a central controller interacts with APs in the WLAN through Ethernet backhaul. Each AP is associated with multiple clients, including different types of devices. Each client device may run a bundle of applications and services with different latency and data rate requirements.

In our vision, the bandwidth for each transmission is specified according to device and service types. On the one hand, the channel bandwidth affects transmissions in many aspects. Wider bandwidth can provide higher throughput but require higher sampling rates for encoding and decoding, thereby consuming more power. Additionally, the transmission opportunities for links with wider bandwidth are lower as these links require larger amounts of vacant spectrum. On the other hand, today's wireless devices range from energy-constrained personal devices such as smartphones and wearable devices, to powerful but data-hungry devices such as laptops and personal computers. For each device, services have heterogeneous requirements on data rates and latency. Therefore, the transmission bandwidth of each AP should be dynamically adjusted to fit the requirements of devices and services.

Traditionally, such fine-grained spectrum management schemes are prohibitively complicated for network operators to realize on WLAN infrastructures, which may consist of devices from different manufacturers and are incrementally upgraded to support new protocols. To overcome this predicament, we borrow the SDWN architecture, whose essential concepts are introduced in the following section.

B. SDWN Paradigm

SDWN is an emerging paradigm that have pioneered the way to introduce programmability to network management. Architecturally, it contains three pillars, which is borrowed from the general SDN architecture [6]:

- **Decoupled control and forwarding planes.** Control logic is completely removed from network devices, which become simple data forwarding elements.
- **Network logic abstraction.** The logic of traditional networks is abstracted from within the hardware implementation into a higher level defined by software.
- **The presence of a programmable network controller entity.** The controller interacts with the underlying forwarding plane devices and coordinates their forwarding decisions.

By the clear separation of control and forwarding planes, SDWN exposes functions that have traditionally been deeply hidden in the network stack to higher levels [7]. The control plane interacts with higher layers via the *northbound* interfaces to understand operational tasks and network policies. The forwarding plane is controlled by the *southbound* interfaces, which refer to the interface and protocol between the controller and the SDWN-capable devices. These interfaces are generic, in that they are not tied to any particular system design or hardware platform architecture.

The control plane encodes the decision logic using a set of *rules* that compile higher-level policies and translate them into lower-level device configurations, which is referred to as *actions* [6], [7]. Rules and actions are concrete representations of the separation of control and forwarding planes. In particular, rules determine the logic content, including scheduling and resource allocation, without dictating implementation details; while actions, on the contrary, only specify functional behaviors such as signal processing operations, without knowing the logic content. Note that the SDWN paradigm follows on the heels of the SDN design principle to separate the control and forwarding planes, while SDWN differs from SDN in that wireless networks have distinct functions and lower-layer protocols, which should be carefully considered when implementing the SDWN architecture for distinct use cases in wireless network.

C. Achieving SDWN-Enabled Spectrum Management: Designs and Challenges

The SDWN paradigm gives hope to facilitate the spectrum management that can achieve the best of both worlds: we can maximize the spectrum efficiency and service quality through fine-grained channelization at the device's side, meanwhile retaining simple management at the operator's side. Architecturally, the SDWN-enabled spectrum management should provide the following capabilities:

- It is **self-configuring**, in that network operators do not need to understand the detailed signal processing procedures and when/how to apply lower-layer configurations.
- It **automatically translates** higher-level decisions into signal processing procedures and dynamically enforces the right configurations at MAC, PHY and radio frequency (RF) front-end.
- It is **efficient**, in that it enables existing hardware to perform fine-grained channelization with merely light-weight overhead in both the time and frequency domains.

- It is **fully compatible**, in that it is integrated into existing infrastructures without modifying the existing protocol stack.

Realizing the above design goals requires systematic considerations from the high-level management architecture to the low-level baseband techniques. To make network management self-configuring and automatic, we need to properly design high-level management architecture. The SDWN paradigm has recently been applied to wireless network management in different aspects, from generic network architecture [3], programmable forwarding plane [2], to specific use cases such as mobility management [4] and interference management [5]. These architectures follow the notion of separated data and control planes as envisioned by the SDWN framework, and introduce programmability and automation into wireless infrastructures to support a wide range of management techniques.

To make network management efficient and fully compatible, virtualization techniques at lower layers are the cornerstones to management architectures seamlessly integrating with the network protocol stack and devices based on software. To support spectrum adaptation for generic MAC/PHY protocols and RF front-ends, baseband virtualization techniques can be exploited to separate spectrum programmability from the general PHY modulation design [8]. Architecturally, spectrum adaptation functions are abstracted away from PHY and RF front-end. As such, the protocol stack and the RF front-end are agnostic of the fine-grained spectrum dynamics as well as the underlying signal processing procedures, thereby adopting conventional configurations, such as modulation, pilot placements and channel contention, without any modification [9].

Although the above innovations demonstrate their significant benefits, in the case of fine-grained spectrum management, we still face several design challenges that have not yet been fully explored.

- **Systematic integration.** Both high-level management architecture and low-level baseband techniques should be seamlessly integrated with the conventional network protocol stack and hardware. It requires systematic investigations in how to precisely translate the upper-layer requirements into spectrum configurations at PHY and RF front-end. Furthermore, spectrum management functions and interfaces to the network stack and RF front-end should be carefully defined.
- **Spectrum adaptation overhead.** To achieve efficient channelization and spectrum adaptation, there are two practical hurdles: i) out-of-band signal detection, and ii) spectrum

agreement. As envisioned in Fig. 1, the spectrum band of one link is promptly adapted to maximize transmission opportunity. However, most existing approaches detect spectrum using spectrum virtualization techniques that are limited to signal detection within one channel (in-band signal detection). What prevents these techniques from out-of-band signal detection is that it results in frequency aliasing at the receiver. Additionally, before channel switching, senders and receivers need to agree on the transmission band, which is achieved by central coordination or separate control channels. Unfortunately, these approaches incur substantial overhead and are not prompt enough to respond to frame-level channel variance.

III. Spectrum Management Architecture

In this section, we develop an efficient spectrum management architecture that seamlessly integrates with the conventional network protocol stack and infrastructures.

A. Overview

Fig. 2 outlines the architecture building blocks and their interfaces. Basically, the proposed architecture conforms to the SDWN framework in that it separates the control and forwarding planes. In particular, the key design components are described as follows.

- The control plane is realized using a two-tiered architecture: a top-level manager, referred to as global manager, residing in the central controller and a mid-level manager, referred to as local manager at or near each AP. Note that the local manager can be either a dedicated controller locating near the AP, or a remotely programmable component within the AP. As such, the local manager can handle time-critical events with little latency and load-intensive events, while the global manager can handle events that require global coordination [10]. The design rationale is that the central controller manages spectrum allocation across APs to avoid conflicts and interference, while delegating the traffic scheduling of applications and services to the local manager at each AP, that is, the local manager dynamically schedules which flow to transmit and its spectrum configurations.
- The control plane interacts with the network protocol stack and the RF front-end through a spectrum manager and a radio agent, which expose functions and information deeply hidden in the network protocol stack to higher-level control plane.

- To support efficient and fine-grained spectrum adaptation, a decoupled baseband processing layer that employs baseband virtualization techniques, is added between the legacy PHY/MAC layer and the FR front-end. By decoupling spectrum tuning and detection from packet decoding and scheduling, the legacy PHY/MAC protocols work independently and the spectrum adaptation functionality can be integrated into existing devices without modifying the radio.

Our architecture focuses on the interaction and interfaces between the control and forwarding planes, while the management functions are simply implemented as a part of the control plane. Note that we can also add a management plane to implement management functions and specify management interface to configure the control plane.

B. Interface

At high level, our architecture conforms to the SDN architecture [6] to define the southbound and northbound interfaces. In particular, the local and global managers interact with higher-layer applications through the northbound interface, and interact with lower layers and RF front-end through the southbound interface. We define interfaces based on their functionalities: we define the spectrum management interfaces to interact with the network protocol stack, and the radio agent interfaces to interact with the RF front-end.

Spectrum manager interfaces. The spectrum manager acts as a central hub, coordinating the information flow between the control managers and the network protocol stack. On the one hand, the spectrum manager extracts the QoS requirements of different types of service from the upper layers, while it retrieves the spectrum availability information from the MAC layer. All the collected information is forwarded to the local and global managers, in order to assist them in traffic scheduling and spectrum adaptation. On the other hand, the control managers enforce the necessary configurations, including channel contention and traffic scheduling, into the network protocol stack through the interfaces of the spectrum manager.

Radio agent interfaces. As the spectrum adaptation and traffic scheduling decisions also rely on the link quality information, our architecture employs the radio agent to periodically pass the fine-grained link information such as channel state information (CSI) and clear channel assessment (CCA) to the control managers. Additionally, the radio agent controls the baseband and the RF front-end to tune the bandwidth and central frequency of each transmission.

C. Global Manager

The global manager is the top-level manager residing in the central controller. Essentially the global manager only handles global tasks that require coordination across APs, and offloads all AP-standalone functions to local managers. The global manager takes as input the network state from the spectrum manager interfaces and controls the channelization attributes of each AP through the local manager. The network state is described by an interference vector that specifies the interference relations among APs, and a demand vector that specifies the traffic load of each AP. The channelization attributes specify the bandwidth and central frequency of each AP.

D. Local Manager

The goal of the local manager is to dynamically schedule which flow to transmit and its spectrum configurations, that is, the central frequency and bandwidth. The local manager takes the QoS requirements and the link information as input, and allocates the spectrum band assigned by the global manager to different flows. Note that as the local manager is programmable, the QoS policy can be updated by the network administrator. In particular, the local manager can allocate the whole spectrum band to a single flow with high throughput requirement, or split the band into multiple orthogonal sub-bands, each of which acts as an independent channel to transmit a flow. Such a fine-grained channelization can be realized via baseband virtualization, which will be elaborated in the following section. To fulfill the throughput and latency requirements of each flow, the local manager prioritizes the traffic queue, and steers a flows packets towards a particular sub-band for transmission. After arbitration, the sub-band allocation command is directed to the radio agent, while the channel contention and traffic scheduling commands are forwarded to the spectrum manager. Then, the radio agent and the spectrum manager compile these commands, and enforce corresponding configurations to the devices.

Basically, the local manager makes scheduling and allocation decisions based on the service types. The service type is categorized based on required data rate and latency. The local manager tags each flow with a class identifier, whose values are standardized and associated with corresponding characteristics, such as scheduling priority, packet delay budget and packet error loss rate as defined in the 3GPP QoS Class Identifier (QCI) mechanism [11]. To enforce QoS requirements of different flows, the local manager controls the transmission properties, such as bandwidth, central frequency, data rate and power, of a flow.

E. Baseband Virtualization

The global and local managers frequently change PHY configurations and need different basebands to support flows for multiple clients. To support such flexibility on commodity hardware, we need to build a software abstraction layer that decouples the tight connection between the PHY and the RF front-end. This layer allows provides a virtual baseband that can be programmed by the control plane using the radio agent interfaces. The virtual baseband abstracts out the underly baseband dynamics and modifies the RF front-end for a given channelization configuration specified by the control plane. The baseband virtualization and its interactions with the radio agent is shown in Fig. 3. On the one hand, the radio agent gathers link and channel statistics from lower layers and export the statistics to the local and global managers. On the other hand, the radio agent exposes the functions of the virtual baseband to the local manager. The local manager controls the transmission attributes including bandwidth, central frequency, data rate, and power through the radio agent interfaces, and the virtual baseband takes the transmission attributes as input to reshape the baseband signals before feeding the signals to the RF front-end. The PHY/MAC exposes an interface to the virtual baseband to allow streams of complex digital baseband samples flowing between the layers. The virtual baseband receives spectrum adaptation decisions from the radio agent, and adds or removes extra preambles to those baseband samples for spectrum agreement and out-of-band detection. The prepended preamble exempts extra control frames for spectrum agreement and thus makes frame-level adaptation more promptly and efficient. As such, the functions of spectrum agreement and out-of-band detection are decoupled from packet encoding/decoding and channel contention, allowing the legacy PHY/MAC and the RF-front-end to work independently without any modification. It is worth noting that although the management architecture is built on top of WLAN infrastructure and does not involve changes on the user terminal, the user terminal should be spectrum agile so that prompt spectrum adaptation can be performed.

IV. Evaluation in a Campus WLAN Scenario

A primary motivation behind our spectrum management architecture is that the spectrum can be managed more efficiently when the fine-grained PHY functions are exposed to the upper-layer managers. The objective of this section is to demonstrate the efficacy of our architecture in promptly adapting spectrum according to link quality and upper-layer information.

Experimental setup. We realize the basic spectrum management blocks in existing OFDM PHY using commodity radios. We implement the entire baseband design directly in the USRP Hardware Drive (UHD). Nodes in our experiments are USRP N210 devices equipped with RFX2450 daughterboards as the RF front-end, which operates in the 5.1-5.2GHz range. Due to large processing delay of USRP hardware and limited power of general purpose processor, the spectrum adaptation strategy cannot be performed in real-time on USRP. To demonstrate the overall performance of the spectrum management architecture, we emulate the upper layer behaviors using the traces captured in a campus WLAN that operates under IEEE 802.11n. In particular, we use Intel 5300 NICs to send back-to-back frames and log the CSI and SNR traces at receivers. We vary the sender and receiver's locations to measure 20 different links, whose SNR vary from -3dB to 28dB. Each link transmits 500 frames for every 20MHz channels across an entire 80MHz band.

To minimize unnecessary coordination overhead, the control plane triggers spectrum adaptation only when the channel availability or quality is unable to support reliable transmission. We adopt two metrics – *transmission opportunity* and signal-to-noise ratio (SNR) – to estimate the channel conditions. The transmission opportunity is defined to be the ratio of successful transmissions to the total number of transmission attempts. Only when the transmission opportunity or the SNR falls below the predefined threshold, the global manager reassigns the central frequencies and bandwidths of APs. The central controller uses the following greedy spectrum adaptation strategy to assign channels. When an AP suffers from low transmission opportunity or low SNR, the local manager sends a spectrum adaptation request to the global manager via backhaul. The global manager goes through all possible channels, and selects the solution that maximizes the overall throughput in the WLAN. The global manager computes the overall throughput by measuring the SNR of each channel and mapping the SNR to corresponding data rate. Then, it selects the spectrum adaptation solution that maximizes the overall throughput. The global manager calls off the adaptation if reassignment cannot improve the overall throughput. The global manager coordinates multiple APs and may simultaneously change the channel configurations of multiple APs. To be compatible to legacy Wi-Fi nodes, all nodes conform to the legacy DCF MAC (e.g., IEEE 802.11a/g/n/ac) to contend channels. In particular, all nodes sense channel, backoff, and transmit as the legacy nodes.

Baselines. We compare the proposed architecture (named as *proposed*) with two baseline approaches: 802.11 standard channelization (named as *802.11*) and the state-of-the-art spectrum adaptation approach [9] (named as *spectrum adaptation*). It is worthwhile noting that we take into account the spectrum adaptation overhead.

Fig. 4 varies the number of links accessing the 80MHz spectrum, which consists of four 20MHz channels. The results show that on average, the proposed architecture outperforms 802.11 and spectrum adaptation approaches by 102% and 37%, respectively. When the number of links goes larger than 10, the throughput of all approaches decreases due to larger contention overhead. Fig. 5 further compares the performance of all approaches when varying the total bandwidth. The number of links is set to eight. By leveraging the frequency diversity of multiple channels, the proposed architecture achieves higher throughput than the other two approaches when there is more than one channel.

The results demonstrates the merits of our architecture in making decisions by jointly considering the global interference relations as well as fine-grained PHY attributes. We show that it is feasible to harvest the benefits of flexibility and programmability using the SDWN paradigm, while still achieving high efficiency in fine-grained channelization. However, the preliminary implementation considers the bandwidth and central frequency of each flow, future spectrum management schemes can expose PHY functions, such as MIMO signal processing blocks, to high layers.

V. Concluding Remarks

This article has envisioned the crucial roles of the SDWN paradigm and baseband virtualization in achieving efficient fine-grained spectrum management in WLANs. Instead of modifying existing wireless devices or protocols, the SDWN-enabled architecture realizes the abstraction of the fine-grained spectrum adaptation by employing decoupled components that seamlessly integrate with the network protocol stack or RF front-end. Through careful investigation of the pros and cons of existing approaches, we observe that the main hurdles in realizing the above vision lie in the systematic integration and spectrum adaptation overhead.

Under the design principles concluded from our investigation, we have presented a spectrum management architecture that reaps the merits of the SDWN paradigm and the fine-grained spectrum adaptation. To efficiently support high-level SDWN-enabled architecture, we also devise a new virtual baseband that exempts the need of extra spectrum coordination. The virtualized baseband is a clean-slate design that integrates with existing commodity radios without any hardware modification. We take a case study on a campus scenario to demonstrate the benefits of the proposed architecture. We believe that the SDWN-enabled spectrum management architecture can contribute the future wireless networks to better support heterogeneous devices and versatile services.

ACKNOWLEDGEMENT

The research was supported in part by grants from 973 project 2013CB329006, the National Science Foundation of China with Grants 61502114, 61173156, 61428104, and 61401169, RGC under the contracts CERG 622613, 16212714, HKUST6/CRF/12R, and M-HKUST609/13, Joint Specialized Research Fund for the Doctoral Program of Higher Education (SRFDP) and Research Grants Council Earmarked Research Grants (RGC ERG) with Grant 20130142140002, as well as the grant from Huawei-HKUST joint lab.

REFERENCES

[1] S. Rayanchu, V. Shrivastava, S. Banerjee, and R. Chandra, "FLUID: improving throughputs in enterprise wireless LANs through flexible channelization," *IEEE Trans. Mobile Compt.*, vol. 11, no. 9, pp. 1455–1469, 2012.

[2] M. Bansal, J. Mehlman, S. Katti, and P. Levis, "OpenRadio: A programmable wireless dataplane," in *Proc. ACM HotSDN*, 2012, pp. 109–114.

[3] C. Bernardos, A. De La Oliva, P. Serrano, A. Banchs, L. Contreras, H. Jin, and J. Zuniga, "An architecture for software defined wireless networking," *IEEE Wireless Commun.*, vol. 21, no. 3, pp. 52–61, 2014.

[4] L. Suresh, J. Schulz-Zander, R. Merz, A. Feldmann, and T. Vazao, "Towards programmable enterprise WLANs with Odin," in *Proc. ACM HotSDN*, 2012, pp. 115–120.

[5] S. Kumar, D. Cifuentes, S. Gollakota, and D. Katabi, "Bringing cross-layer MIMO to today's wireless LANs," *ACM SIGCOMM Computer Communication Review*, vol. 43, no. 4, pp. 387–398, 2013.

[6] J. A. Wickboldt, W. P. De Jesus, P. H. Isolani, C. Bonato Both, J. Rochol, and L. Zambenedetti Granville, "Software-defined networking: management requirements and challenges," *IEEE Comm. Mag.*, vol. 53, no. 1, pp. 278–285, 2015.

[7] H. Kim and N. Feamster, "Improving network management with software defined networking," *IEEE Comm. Mag.*, vol. 51, no. 2, pp. 114–119, 2013.

[8] K. Tan, H. Shen, J. Zhang, and Y. Zhang, "Enable flexible spectrum access with spectrum virtualization," in *Proc. IEEE DySPAN*, 2012, pp. 47–58.

[9] S. Yun, D. Kim, and L. Qiu, "Fine-grained spectrum adaptation in wifi networks," in *Proc. ACM MobiCom*, 2013, pp. 327–338.

[10] J. Schulz-Zander, N. Sarrar, and S. Schmid, "Aeroflux: A near-sighted controller architecture for software-defined wireless networks," *Proc. Open Networking Summit (ONS)*, 2014.

[11] "3GPP TS 23.203 policy and charging control architecture," 2015.

PLACE PHOTO HERE

Wei Wang (S'10) is currently a Research Assistant Professor in Fok Ying Tung Research Institute, Hong Kong University of Science and Technology (HKUST). He received his Ph.D. degree in Department of Computer Science and Engineering from HKUST, where his Ph.D. advisor is Prof. Qian Zhang. Before he joined HKUST, he received his bachelor degree in Electronics and Information Engineering from Huazhong University of Science and Technology, Hubei, China, in June 2010. His research interests include PHY/MAC in Wi-Fi networks, privacy and fault management in wireless networks.

PLACE PHOTO HERE

Yingjie Chen received his M.Phil. degree of computer science department from Hong Kong University of Science and Technology in 2012. He is currently a reseach assistant in Hong Kong University of Science and Technology. His research interests include PHY and MAC layer design in Wi-Fi network, and mobile computing.

PLACE PHOTO HERE

Qian Zhang (M'00-SM'04-F'12) joined Hong Kong University of Science and Technology in Sept. 2005 where she is a full Professor in the Department of Computer Science and Engineering. Before that, she was in Microsoft Research Asia, Beijing, from July 1999, where she was the research manager of the Wireless and Networking Group. Dr. Zhang has published about 300 refereed papers in international leading journals and key conferences in the areas of wireless/Internet multimedia networking, wireless communications and networking, wireless sensor networks, and overlay networking. She is a Fellow of IEEE for "contribution to the mobility and spectrum management of wireless networks and mobile communications". Dr. Zhang has received MIT TR100 (MIT Technology Review) worlds top young innovator award. She also received the Best Asia Pacific (AP) Young Researcher Award elected by IEEE Communication Society in year 2004. Her current research is on cognitive and cooperative networks, dynamic spectrum access and management, as well as wireless sensor networks. Dr. Zhang received the B.S., M.S., and Ph.D. degrees from Wuhan University, China, in 1994, 1996, and 1999, respectively, all in computer science.

PLACE
PHOTO
HERE

Tao Jiang (M'06-SM'10) is currently a Chair Professor in the School of Electronics Information and Communications, Huazhong University of Science and Technology, Wuhan, P. R. China. He received the B.S. and M.S. degrees in applied geophysics from China University of Geosciences, Wuhan, P. R. China, in 1997 and 2000, respectively, and the Ph.D. degree in information and communication engineering from Huazhong University of Science and Technology, Wuhan, P. R. China, in April 2004. From Aug. 2004 to Dec. 2007, he worked in some universities, such as Brunel University and University of Michigan-Dearborn, respectively. He has authored or co-authored over 200 technical papers in major journals and conferences and eight books/chapters in the areas of communications and networks. He served or is serving as symposium technical program committee membership of some major IEEE conferences, including INFOCOM, GLOBECOM, and ICC, etc.. He is invited to serve as TPC Symposium Chair for the IEEE GLOBECOM 2013, IEEEE WCNC 2013 and ICCC 2013. He is served or serving as associate editor of some technical journals in communications, including in IEEE Transactions on Signal Processing, IEEE Communications Surveys and Tutorials, IEEE Transactions on Vehicular Technology, and IEEE Internet of Things Journal, etc.. He is a recipient of the NSFC for Distinguished Young Scholars Award in P. R. China. He is a senior member of IEEE.

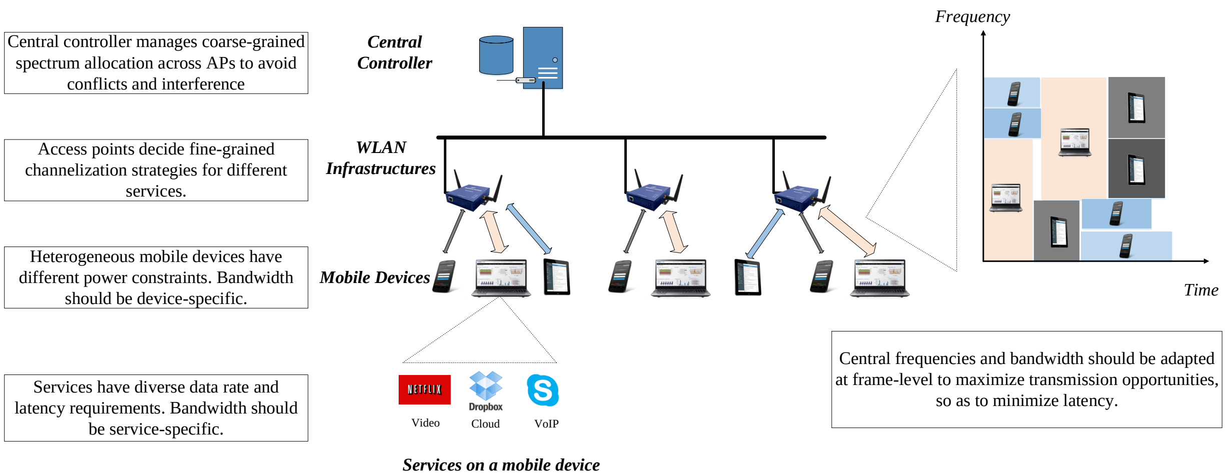

Fig. 1. Illustration of fine-grained spectrum management.

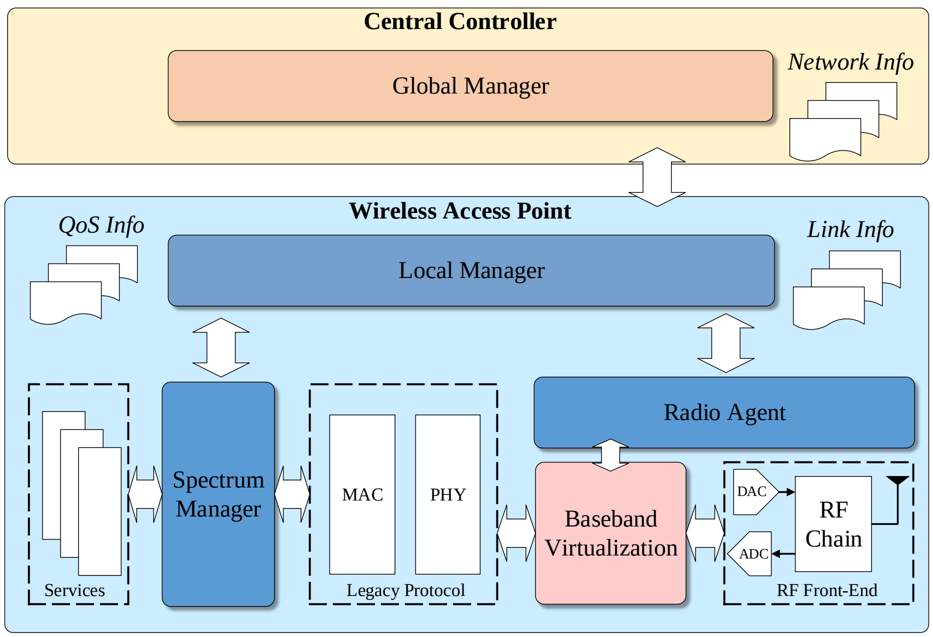

Fig. 2. SDWN-enabled system architecture for spectrum management.

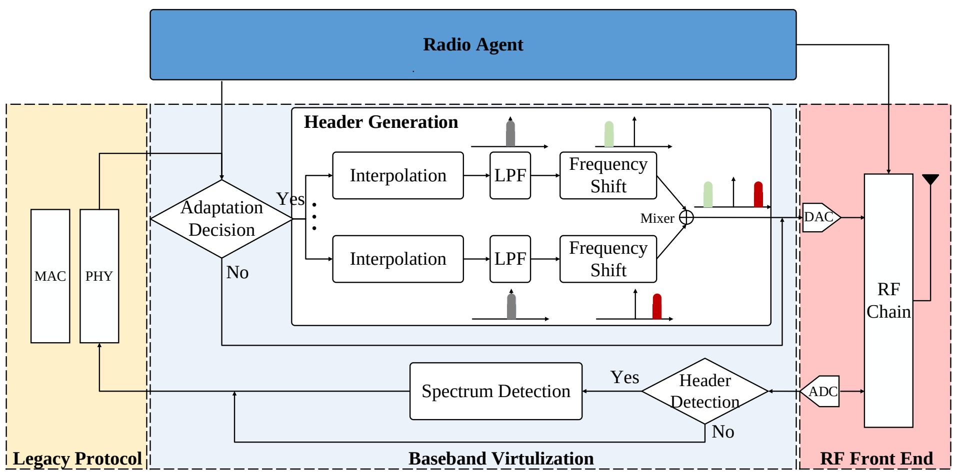

Fig. 3. Architecture of baseband virtualization.

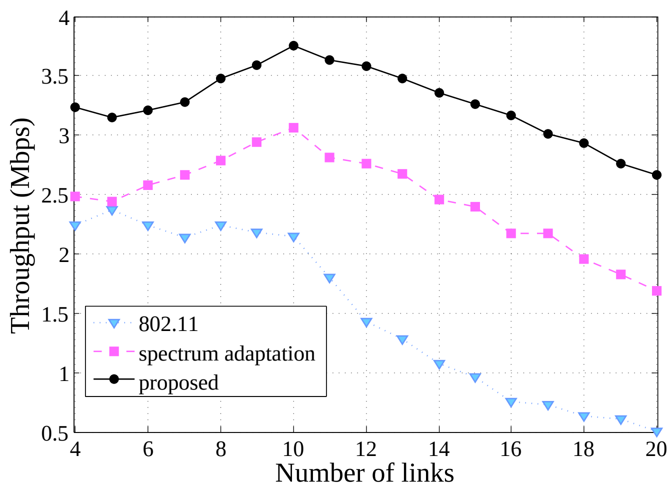

Fig. 4. Throughput under various numbers of links.

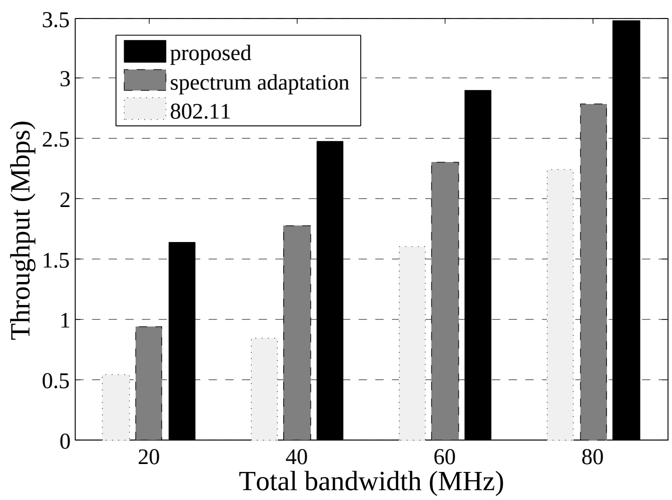

Fig. 5. Throughput under various total bandwidths.