A Software-Defined Wireless Networking Enabled Spectrum Management Architecture

Wei Wang, Yingjie Chen, Qian Zhang, and Tao Jiang

The authors systematically investigate 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.

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 fail to be efficient 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. However, manufacturers hesitate to make hardware investments without comprehensive understanding of these designs. To break this stalemate, software-defined wireless networking (SDWN) has been pushed to 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 the IEEE 802.11 protocol stack and commodity 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.

INTRODUCTION

Recent years have witnessed a boom in 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 understanding is 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 understanding of 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 on a new paradigm, software-defined wireless networking (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

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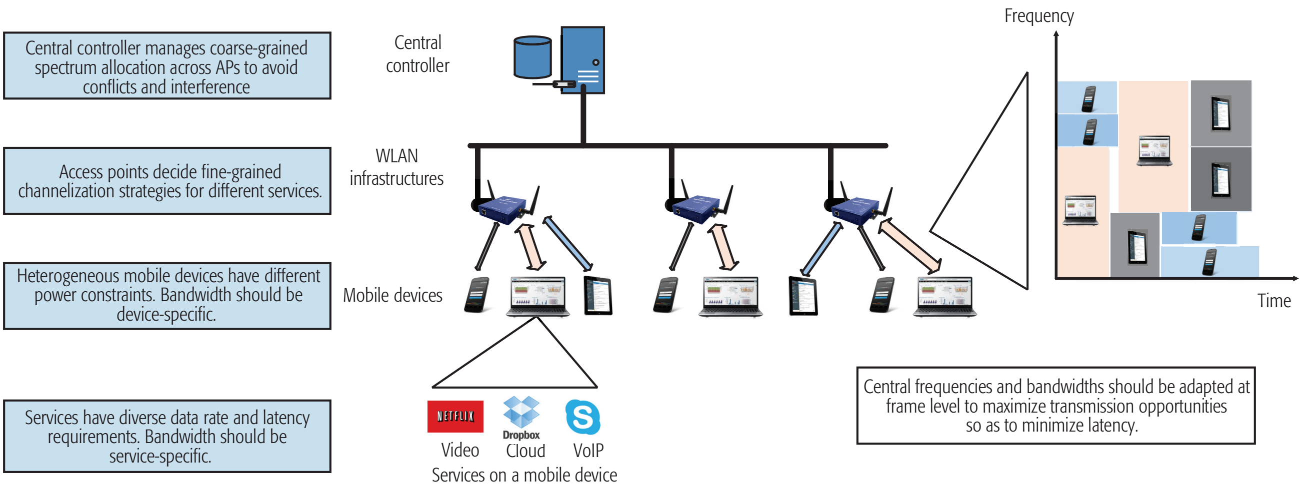

Figure 1. Illustration of fine-grained spectrum management.

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 coordination 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 into 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.

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.

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 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, the essential concepts of which are introduced in the following section.

SDWN Paradigm

SDWN is an emerging paradigm that has pioneered the introduction of programmability to network management. Architecturally, it contains three pillars, which are 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 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; 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 networks.

Achieving SDWN-Enabled Spectrum Management: Designs and Challenges

The SDWN paradigm has promise 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 side, meanwhile retaining simple management at the operator 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 the RF front-end.
- It is **efficient**, in that it enables existing hardware to perform fine-grained channelization with merely lightweight 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 consideration 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] and 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 the PHY and RF front-end. As such, the protocol stack and the RF front-end are agnostic to 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 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 investigation into how to precisely translate the upper-layer requirements into spectrum configurations at the 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:

- Out-of-band signal detection.
- 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.

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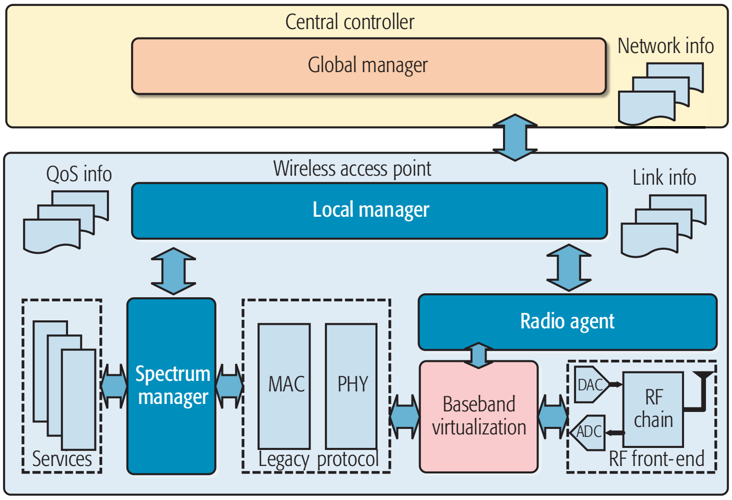

Figure 2. SDWN-enabled system architecture for spectrum management.

Spectrum Management Architecture

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

Overview

Figure 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 the global manager, residing in the central controller, and a mid-level manager, referred to as the 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 few 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 the 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 RF 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 part of the control plane. Note that we can also add a management plane to implement management functions and specify the management interface to configure the control plane.

Interface

At a 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 one hand, the spectrum manager extracts the quality of service (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 RF front-end to tune the bandwidth and central frequency of each transmission.

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, which specifies the interference relations among APs, and a demand vector, which specifies the traffic load of each AP. The channelization attributes specify the bandwidth and central frequency of each AP.

Local Manager

The goal of the local manager is to dynamically schedule which flow to transmit and its spectrum configurations (i.e., the central frequency and bandwidth). The local manager takes the QoS

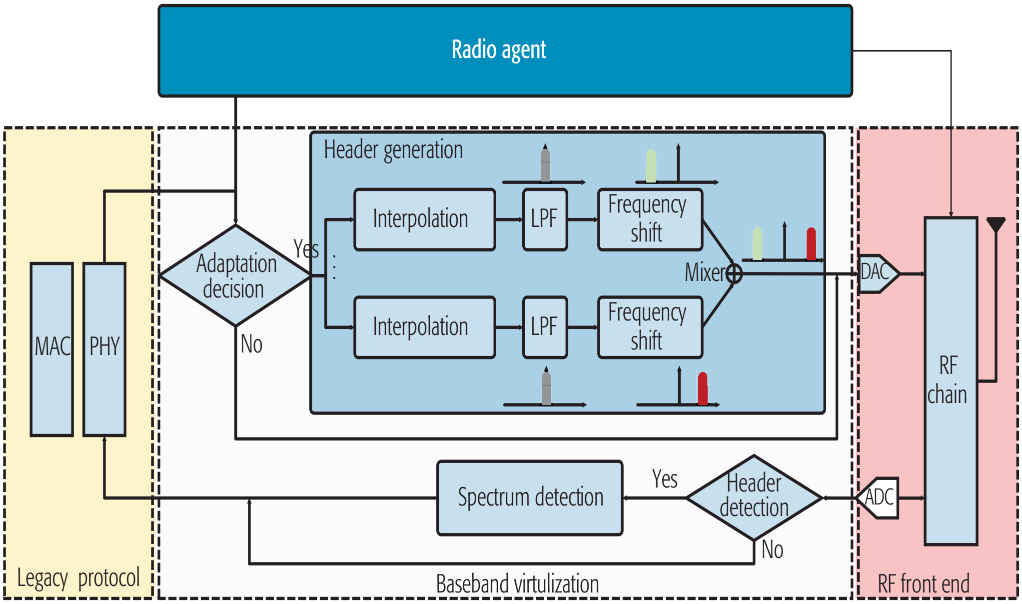

Figure 3. Architecture of baseband virtualization.

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.

requirements and 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 fine-grained channelization can be realized via baseband virtualization, which is 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 flow's packets toward 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 spectrum manager compile these commands, and enforce corresponding configurations to the devices.

Basically, the local manager makes scheduling and allocation decisions based on service types. The service type is categorized based on required data rate and latency. The local manager tags each flow with a class identifier, with standardized values associated with corresponding characteristics, such as scheduling priority, packet delay budget, and packet error loss rate as defined in the Third Generation Partnership Project (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.

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 RF front-end. This layer 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 are shown in Fig. 3. On one hand, the radio agent gathers link and channel statistics from lower layers and exports 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 prompt 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 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 to the user terminal, the user terminal should be spectrum agile so that prompt spectrum adaptation can be performed.

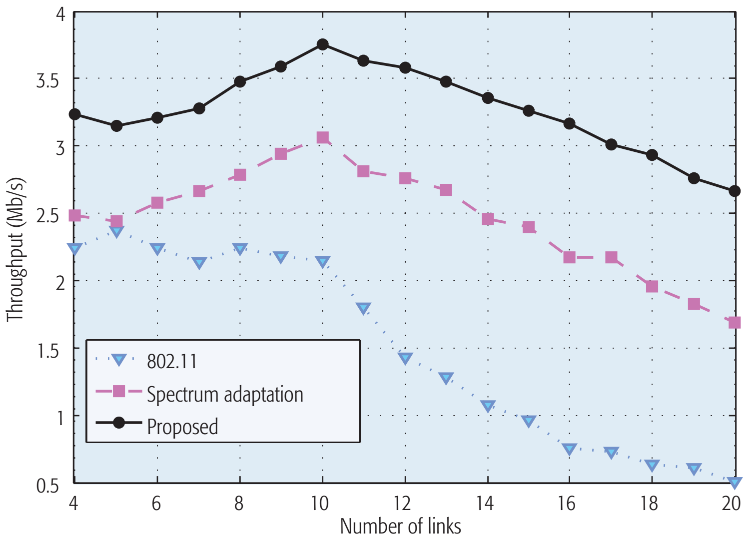

Figure 4. Throughput under various numbers of links.

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 Universal Software Radio Peripheral (USRP) hardware drive (UHD). Nodes in our experiments are USRP N210 devices equipped with RFX2450 daughterboards as the RF front-end, which operate in the 5.1–5.2 GHz range. Due to large processing delay of USRP hardware and limited power of general-purpose processors, 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 operating under IEEE 802.11n. In particular, we use Intel 5300 network interface cards (NICs) to send back-to-back frames and log the CSI and signal-to-noise ratio (SNR) traces at receivers. We vary the sender's and receiver's locations to measure 20 different links, with SNRs varying from –3 dB to 28 dB. Each link transmits 500 frames for every 20 MHz channel across an entire 80 MHz 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 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 does the global manager reassign 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 with legacy Wi-Fi nodes, all nodes conform to the legacy data communication function (DCF) MAC (e.g., IEEE 802.11a/g/n/ac) to contend for channels. In particular, all nodes sense channel, backoff, and transmit as legacy nodes.

Baselines. In Fig. 4, we compare the proposed architecture (*proposed*) with two baseline approaches: 802.11 standard channelization (802.11) and the state-of-the-art spectrum adaptation approach [9] (*spectrum adaptation*). It is worthwhile noting that we take into account the spectrum adaptation overhead.

Figure 4 varies the number of links accessing the 80 MHz spectrum, which consists of four 20 MHz channels. The results show that on average, the proposed architecture outperforms 802.11 and spectrum adaptation approaches by 102 and 37 percent, respectively. When the number of links goes larger than 10, the throughput of all approaches decreases due to larger contention overhead. Figure 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 demonstrate 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 multiple-input multiple-output signal processing blocks, to high layers.

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 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 resulting from our investigation, we have presented a spectrum management architecture that reaps the merits of the SDWN paradigm and fine-grained spectrum adaptation. To efficiently support high-level SDWN-enabled architecture, we also devise a new virtual baseband that removes the need for extra spectrum coordination. The virtualized baseband is a clean-slate design that integrates with existing commodity radios without any hardware modification. We provide 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 to future wireless networks by better supporting heterogeneous devices and versatile services.

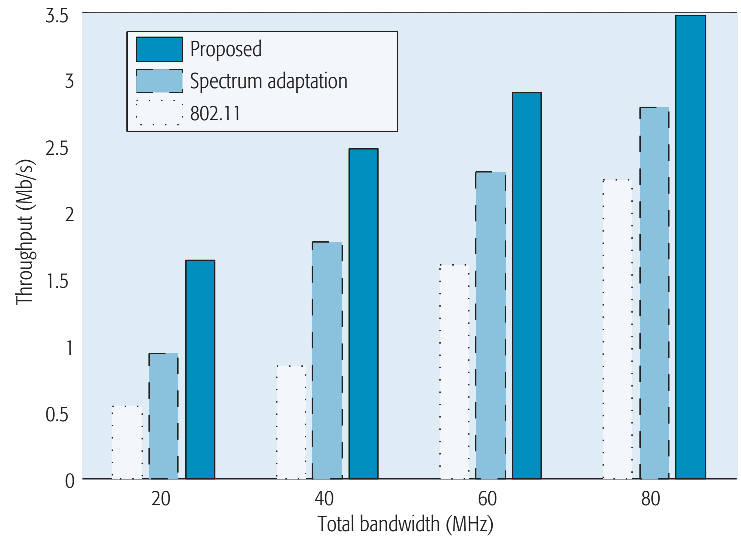

Figure 5. Throughput under various total bandwidths.

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