Software-Defined Wireless Mesh Networks: Architecture and Traffic Orchestration

Huawei Huang, Peng Li, Song Guo, and Weihua Zhuang

Abstract

SDN has been envisioned as the next generation network paradigm by decoupling control plane and data plane, such that network management and optimization can be conducted in a centralized manner using global network information. In this article, we study how to apply SDN concept to a wireless mesh network that has been widely adopted by various applications. We first propose a novel architecture of SD-WMNs, and identify several critical challenges. Since wireless spectrum is a scarce resource that is shared by both data and control traffic in SD-WMNs, we propose three spectrum allocation and scheduling algorithms, namely FB-NS, NFB-NS, and NFB-S that orchestrate both control and data traffic. Finally, performance is evaluated via extensive simulations.

Typically, the backbone of a wireless mesh network (WMN) is made up of dedicated wireless nodes called mesh routers (MRs), which are configured in an ad hoc mode and use omnidirectional antennas, with one or multiple wireless radio interfaces based on IEEE 802.11 technologies. These MRs can be freely organized into any network topology, and communicate with each other using protocols such as Optimized Link State Routing (OLSR) [1] and Better Approach to Mobile Ad Hoc Networking (BATMAN) [2]. However, traditional WMNs are difficult to manage and upgrade because configurations are made manually and are error-prone. It normally takes weeks or even months to provide new services for service activation, test, and assurance. Furthermore, mesh routers work in a self-organizing manner without a global view, leading to poor network resource allocation and low performance, especially in large-scale networks.

Software defined networking (SDN) is a promising network paradigm that significantly simplifies network management [3]. By decoupling control plane and data plane, SDN enables flexible control and dynamic resource configuration with a global view of the entire network. In this way, network policies (e.g., traffic load balancing, access control, and fault-tolerance) can be easily realized, and new services be rapidly and agilely deployed.

In this article, we propose a novel architecture of software-defined wireless mesh networks (SD-WMNs) providing Internet services. A logically centralized controller maintains all of the network information, and conducts global resource allocation. Software-defined MRs make data forwarding according to rules specified by the controller. In particular, we extend OpenFlow [3] to implement complicated interactions between the controller and software-defined MRs in wireless networks.

Huawei Huang, Peng Li, and Song Guo are with the University of Aizu.

Weihua Zhuang is with the University of Waterloo.

We then summarize several critical challenges in SD-WMNs, such as spectrum isolation of control and data planes, status monitoring and collection, and congestion control.

Although the SD-WMN approach is promising due to its global network knowledge and centralized management, frequent message exchange between controller and software-defined MRs can lead to a high traffic load that would aggravate transmission congestion in wireless networks. In order to improve resource utilization, we examine the traffic characteristics in SD-WMNs, and propose three novel spectrum allocation and traffic scheduling algorithms, that is, Fixed-Bands Non-Sharing (FB-NS), Non-Fixed-Bands Non-Sharing (NFB-NS), and Non-Fixed-Bands Sharing (NFB-S) algorithms, to exploit frequency and spatial multiplexing. Finally, the performance of the proposed three algorithms are evaluated by extensive simulation.

Preliminaries and the State of the Art

SDN and OpenFlow

SDN has been envisioned as the next generation network paradigm [3] that decouples the control plane and data plane such that complicated network logic is no longer installed in switches or routers, but at a logically centralized controller. Each switch at the data plane conducts data forwarding according to the rules installed by the centralized network operating system. Each rule can be expressed in the form of ⟨*Match*, *Action*⟩, where the *Match* field is used to match against the packet header of a traffic flow. If a rule is matched, the switch executes the specified actions in the *Action* field. For example, a rule ⟨Match:{*ip*, *nw_src* = 10.0.0.1, *nw_dst* = 10.0.0.2}, *Action* = *output*:3⟩ means that the packets from a host with IP address 10.0.0.1 to a destination with IP address 10.0.0.2 will be forwarded to *output* port 3 of the switch.

As an open source implementation of the SDN paradigm, OpenFlow has attracted much attention from both industry

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Literature and algorithms	Fashion	Approaches to building a control channel	Spectrum spatial reuse	Guaranteed control traffic	Multiple interfaces required
[7]	Out-of-band	Service set identifiers (SSIDs)	No	No	Yes
[8]	Out-of-band	A substitutive wired network	No	No	Yes
	In-band	Legacy mesh communication	No	No	Yes
[9]	In-band	OLSR routing protocol	No	No	Yes
[10]	In-band	Virtual private network (VPN) tunnel	No	No	Yes
FB-NS	Out-of-band	Spectrum division within a fixed band range	Medium	Yes	No
NFB-NS	Out-of-band	Spectrum division with no fixed band range restriction	Medium	Yes	No
NFB-S	In-band	Based on NFB-NS, control and data traffic can share each subband capacity	Strong	Yes	No

Table 1. Comparison of state-of-the-art work.

and academia. A group of large companies, including Google, Microsoft, Facebook, Cisco, and AT&T, have shown a great interest in OpenFlow and formed the Open Networking Foundation (ONF) [4] to standardize OpenFlow protocols. In an OpenFlow-enabled network, the controller periodically communicates with all dominated switches via secure channels to obtain network information. With a global view of the network, the controller dynamically adjusts forwarding rules at switches to implement management policies.

Wireless Mesh Networks

The next generation wireless community networks are envisioned to provide high-speed and high-throughput connectivity for end users by leveraging a number of technologies, such as fourth/fifth generation (4G/5G) mobile cellular systems, IEEE-802.11-based wireless networks, and IEEE 802.16 (WiMAX) broadband wireless networks. The WMN is one of the key components of such community networks, offering multihop connection between end users and Internet gateways. WMN has been successfully deployed in intelligent transportation systems [5] and public Internet access systems [6].

A typical WMN consists of a number of nodes that connect to each other in a multihop manner via wireless links. The network nodes can be static wireless routers or mobile devices, for example, laptops or smartphones, that can join or leave the network at any time. The great flexibility of WMNs is a double-edged sword. On one hand, one can easily be set up without a fixed infrastructure, and has been widely deployed in various applications. For example, a number of wireless routers can easily be deployed to provide Internet services to mobile users in a large coverage area without the support of dedicated cellular base stations.

On the other hand, WMNs are difficult to manage because of device diversity and dynamic network topology. The network may consist of different devices (e.g., wireless routers, laptops, and smartphones) with distinct processing and communication capabilities. Meanwhile, network topology changes due to user mobility, imposing a great challenge in optimizing network resource usage. Furthermore, due to its infrastructureless nature and lack of centralized monitoring points, WMNs are vulnerable to various attacks.

The State of the Art of Applying SDN to WMNs

When applying SDN to wireless networks, the recent work can be generally classified into two categories according to the communication styles between the controller and network nodes: (1) out-of-band, which builds a dedicated control network [7], and (2) in-band, which compels control and data traffic within the same network [8, 9].

Dely *et al.* [7] use the service set identifiers (SSIDs) in the IEEE 802.11 standard to separate the control and data networks within one physical network.

Detti *et al.* [8] have deployed an in-band-style by using OLSR for both control and data packets.

Yang *et al*. [9] have also adopted the in-band approach to build an OpenFlow-based WMN that balances the Internet traffic load.

Chung *et al.* [10] have shown both out-of-band and and in-band deployment experiences. In the out-of-band deployment, they deploy a substitutive wired network for control messages, which would be difficult to apply in practice because additional infrastructure is required. They also conducted a simple OpenFlow-based in-band control deployment, where the control traffic is forwarded through a cascade-connected topology between the controller and switches.

When control and data packets contend for the shared wireless medium, it would lead to low performance and resource utilization without a traffic contention mechanism.

In this article, we propose three traffic orchestration algorithms, that is, FB-NS, NFB-NS, and NFB-S, using spectrum division for traffic and data traffic. Compared to existing proposals, the advantages of our design are shown in Table 1.

Architecture

In this section, we present a novel architecture of SD-WMNs. We first provide an overview of our system, and then present the detailed design of the controller and software-defined MRs.

Overview

As shown in Fig. 1a, our proposed SD-WMN contains a centralized controller and several SDN-enabled mesh routers. A gateway (e.g., MR 5 in Fig. 1a) connects to the Internet. When a client (e.g., a smartphone) requests an Internet ser-

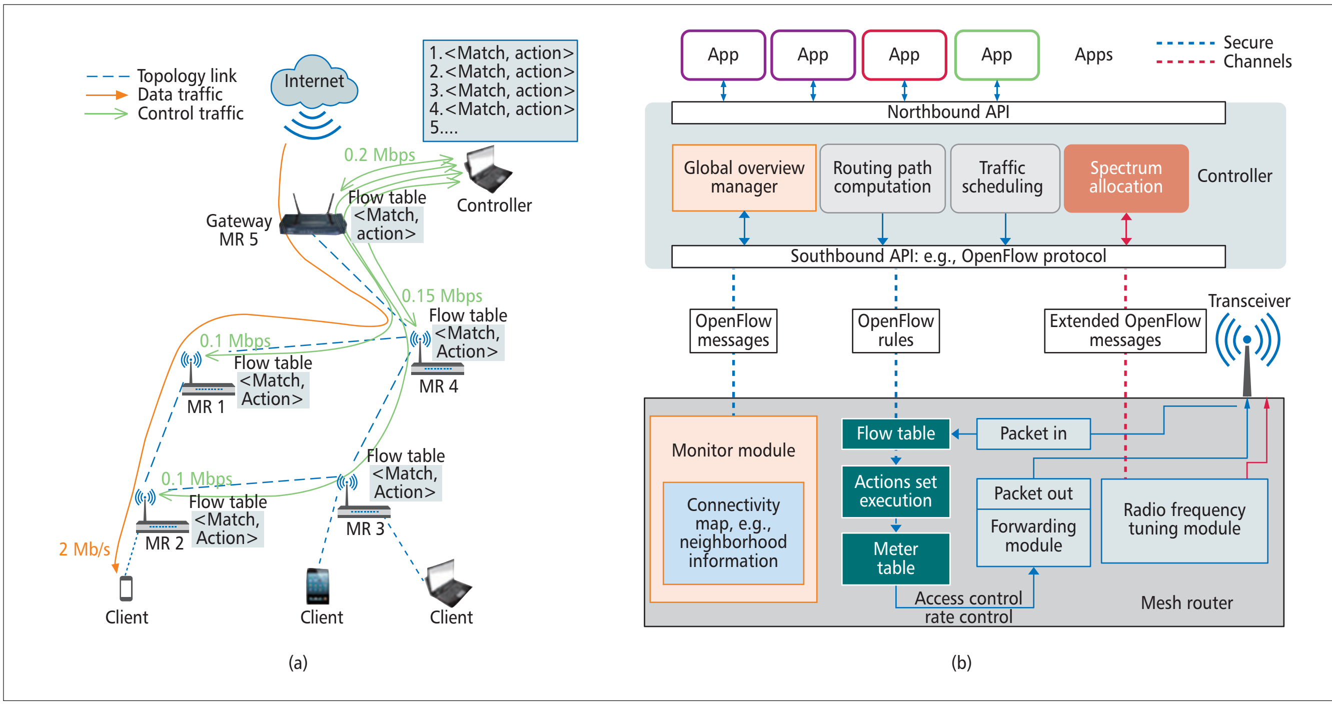

Figure 1. The proposed architecture of SD-WMN: a) SD-WMN topology; b) SD-WMN design.

vice, the request is first forwarded to the controller, which selects a path between the gateway and client. In addition, the controller allocates radio resources for the data transmission by jointly considering the existing data and control traffic in the network. Finally, a set of rules are installed at routers, for example, MRs 2, 1, 4, and 5, along the data path. The controller and software-defined MRs play critical roles in our proposed SD-WMN, as discussed in the following.

Controller

The logically centralized controller implements the intelligence of the SD-WMN with four main modules, as shown in Fig. 1b. The global overview manager is in charge of monitoring the whole network and maintains a network topology that can be used to perform global control. The module of routing path computation can be implemented by a path searching algorithm, such as Dijkstra's shortest path algorithm, aiming to find a routing path for traffic flows based on the global network overview. The traffic scheduling module schedules transmission of both control and data packets according to a specific control policy. The last module, spectrum allocation, is responsible for configuring spectrum resources in the SD-WMN.

In addition, the controller interacts with various applications in the upper layer through northbound application programming interfaces (APIs), while communicating with data plane hardware via southbound APIs (e.g., OpenFlow protocol).

Software-Defined MRs

Software-defined MRs conduct data forwarding according to the rules installed by the controller. The main modules in a software-defined MR are shown in Fig. 1b. The monitor module manages the connectivity with its neighbors, and sends this information to the global manager in the controller. The received forwarding rules are cached in flow tables. When a packet is received, the MR compares it with the rules in the flow tables. If there is a match, the corresponding action is executed, that is, to forward, modify, or drop the packet. After that, the packet is further processed by OpenFlow meter tables that collect network statistics information, such as the traffic rate and available transmitting bandwidth resources in the MR, and set quality of service (QoS) configurations (e.g., access control and rate control). Finally, the packet is delivered to the forwarding module, which sends out the queued packet when the network interface is ready.

In order to configure the radio frequency in each MR in real time while transmitting traffic from separated control and data networks, we use the extended OpenFlow messages to forward the information of radio frequency. Such configuration information is generated from a spectrum allocation algorithm residing in the control plane and sent to the radio frequency tuning module residing in the MR. The goal is to make the transceiver work in an appropriate newly assigned frequency band at each time.

To overcome the physical interface limitation in MRs, we adopt a software-defined radio (SDR) module [11] to build the control and data networks by allocating a given wide range of radio spectrum. The SDR is capable of reconfiguring radio frequency and tuning to the instantly selected frequency bands. Another advantage of SDR technology is that it does not require contiguous frequencies/channels. Packets can be sent over discrete frequency bands. By applying SDR to spectrum scheduling in SD-WMNs, radio transceivers can be tuned arbitrarily within the given radio spectrum. As a result, our proposed architecture is independent of the number of physical radio interfaces of MRs.

Challenges in SD-WMNs

Hardware Limitation in MRs

Unlike SDN-enabled wired networks, where control and data planes are implemented with two sets of dedicated hardware, wireless medium is shared by both control and data traffic. The sophisticated multi-channel multi-radio (MC-MR) technology [12] has been widely studied for channel assignment in WMNs. However, as MC-MR systems rely on hardware-based radio technologies, a radio interface in a mesh router can only work in a single channel at a time, and the number of concurrent channels a wireless router can use is limited by the number of radio interfaces in the device. The network throughput capacity is also constrained.

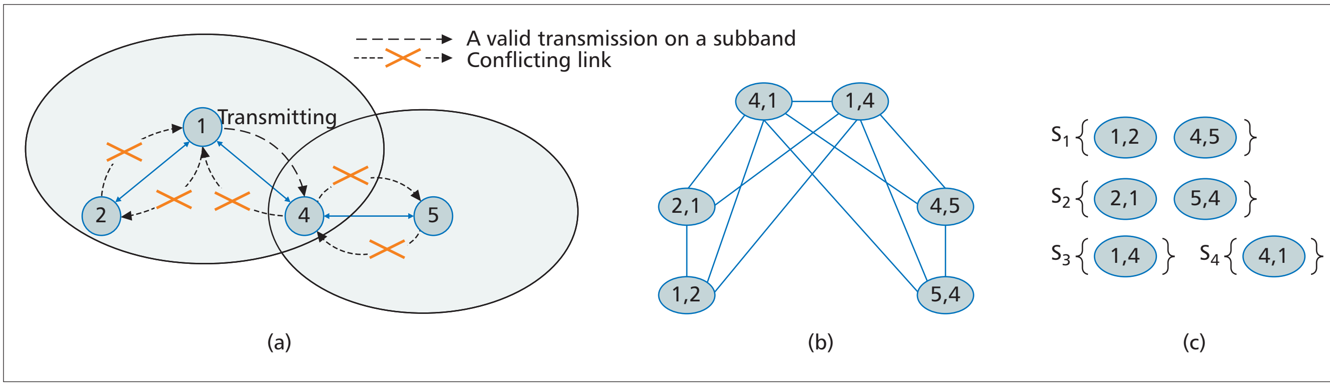

Figure 2. The partial topology of the WMN shown in Fig. 1a, the corresponding directional conflict graph, and a case of independent sets: a) the interference illustration of the protocol model under a half-duplex mechanism on a topology of four MRs.; b) directional conflict graph; c) obtained independent sets..

Spectrum Allocation for Control and Data Planes

Radio spectrum is a scarce resource that should be efficiently utilized. For example, the frequency range adopted by the IEEE 802.11b standard is between 2.4 and 2.483 GHz, which supports only three non-overlapping channels. An intuitive method is to use these three non-overlapping channels to build connections in WMNs. However, this approach brings high interference conflict in the links connecting to more than three neighbors of each MR, because the concurrent working channels are constrained to three. As a result, the network throughput is limited. Defining more slices of the given spectrum band is another approach, in which the interference conflict possibilities can be decreased in theory. However, it requires more sophisticated scheduling. Furthermore, the optimal scheduling requires global topology and link-related status over the network.

Status Monitoring and Collecting

The global network information is critical for policy programs to make decisions. Status information in the network shall be collected as much as possible, such as the traffic rate in each link, rule size in each forwarding hardware, and spectrum allocation in each radio link. The status information has to be reported to the controller via secure channels. The controller may respond with new instructions to each device. The bidirectional communications contribute to the control traffic by a non-negligible fraction. Furthermore, transmission quality is greatly affected by congestion and interference in wireless links. Since network status information and corresponding control messages share the wireless medium with data traffic, sophisticated scheduling algorithms are needed to orchestrate traffic in the SD-WMN.

Congestion within the Shared Medium

Besides the monitored information, the transmission of policy rules to guide the routing of data traffic is another major contribution of control traffic. As rules are generated to serve the data traffic, the data traffic can get transmitted only after the corresponding control traffic are transmitted successfully. That is, control traffic is more important than data traffic. An efficient SD-WMN system should provide higher priority to control traffic than to data traffic. It can be seen that, compared to the traditional WMN, more control traffic exists in the network, and it competes with data traffic for radio resource in an SD-WMN. Therefore, it is possible that the control traffic is congested with data traffic in busy connection links, which incurs a long latency of control traffic and results in inconsistent controlling logics in SDN-enabled networks. This problem is even worse in the links near gateways in a WMN. For example, in Fig. 1b, the aggregate traffic rate in link (4, 5) is 2.55 Mb/s, which is much higher than other links. Congestion is likely to occur in this link. As a result, control messages and rules will suffer high latency.

How to preferentially satisfy the control traffic flows in the shared medium becomes a big challenge.

Problem Description and Algorithms Design

Under the proposed architecture, a number of optimization problems can be studied on various objectives like network throughput, delay, link utilization, and congestion. In this section, we focus on a weighted throughput maximization problem by leveraging data and control traffic in SD-WMN. We first present the system model and problem description, and then propose three algorithms with different deployment costs and performance.

Problem Description

Consider an SD-WMN $\mathcal{G} = (N, E)$ consisting of a controller and N software-defined MRs all working under half-duplex mode. The global topology can be obtained by periodically collecting network information. Given a set of data traffic requirements from end users, the controller first calculates a routing path for each data traffic flow, and then estimates corresponding control traffic over each link. The available radio spectrum is divided into B subbands.

To characterize the interference in wireless networks, both a physical model and a protocol model [13] are widely adopted. Without loss of generality, we use the protocol model in this article to depict interference in a homogeneous network, where each node uses the same transmission power.

Under the protocol model, a valid transmission occurs when the intended receiver is located inside the transmission range of its transmitter and falls outside the interference range of other irrelevant transmitters. In other words, if a receiving node is located in the interference range of an unintended transmitting node, it is considered to be interfered. Consequently, the receiving node cannot receive correctly from its intended transmitter. For example, in Fig. 2a, suppose that band b_1 is allocated for data transmission over directed link (1, 4). Since MR 1 is the transmitting node and the receiving node MR 4 is also located in the transmission ranges of MR 5, the directed links (1, 2), (2, 1), (4, 1), (4, 5), and (5, 4) cannot use the same band b_1 simultaneously.

Based on the system model, we study a *weighted throughput maximization problem* (WTMP) with the objective of maximizing the sum of weighted throughput defined as follows:

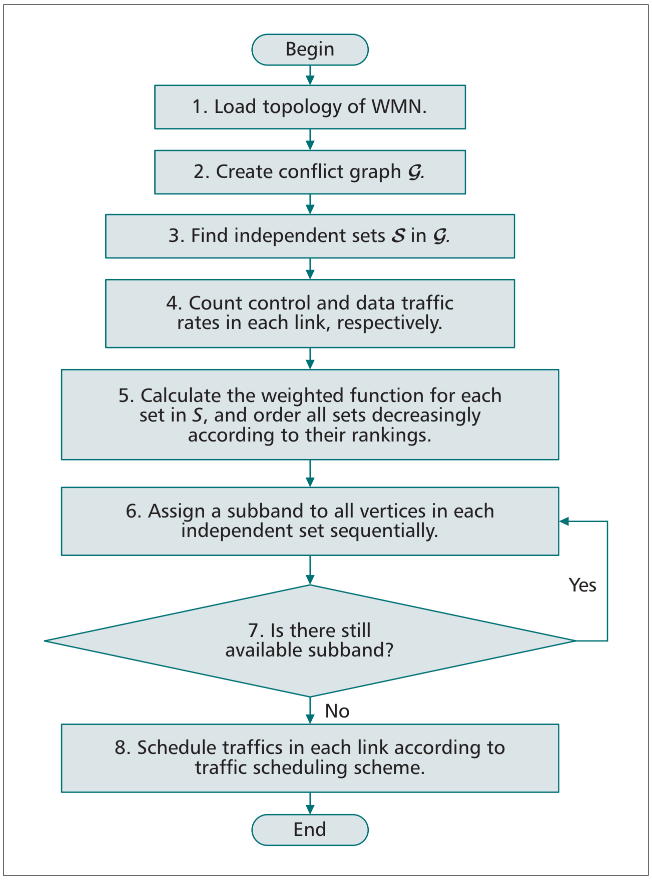

Figure 3. The framework of the FB-NS topology.

$$\textbf{WTMP}: \max \mathcal{F}_{\text{WMN}} = \sum_{(u,v)\in E} \delta \cdot T_{\texttt{control}}(u,v) + T_{\texttt{data}}(u,v), \quad (1)$$

where $\delta > 1$ denotes the weight of control traffic, $\mathbb{E}$ the edge set of topology, and $T_{\texttt{control}}(u, v)$ and $T_{\texttt{data}}(u, v)$ the aggregate traffic flow rates in directional link (u, v) belonging to control and data planes, respectively.

Fixed-Bands Non-Sharing Algorithm

First, we present the FB-NS algorithm as shown in Fig. 3. The basic idea is to allocate a fixed fraction (denoted by α) of subbands to control traffic. In other words, among all B subbands, $\alpha \cdot B$ subbands can be used to transfer control traffic, and the remaining $(1 - \alpha) \cdot B$ subbands can be used to transmit data traffic. As shown in Fig. 3, after learning the topology of WMN in step 1, a conflict graph $\mathbb{G}$ as well as a set of independent sets $\mathbb{S}$ are created in the second and third steps, respectively.

Conflict graphs have been used extensively to describe interference in radio networks [14]. We construct a conflict graph G for $\mathcal{G}$ by creating a vertex $v(a, b)$ for any directional link from a to b in $\mathcal{G}$, and connecting two vertices if they conflict, that is, they cannot be scheduled with the same subband simultaneously according to the adopted interference model. For example, in Fig. 2, vertices (1, 2), (2, 1), (1, 4), (4, 1), (4, 5), and (5, 4) shown in Fig. 2b indicate all the direction links in the topology shown in Fig. 2a.

Since the problem of finding the maximum independent set is NP-complete [15], we use a polynomial-time heuristic algorithm that works as follows. A new independent set is created by including as many vertices in G as possible such that all of them have no links between each other. These vertices and all relevant links are then removed from G. The above procedure repeats until G is empty. For example, the corresponding conflict graph and associated independent sets of topology in Fig. 2a are shown in Figs. 2b and 2c, respectively. Since links (1, 2) and (4, 5) are in the same independent set s_1, they can work simultaneously under the same subband.

Next, based on the rate requirement of each individual traffic flow, we determine the aggregate rates of both control and data traffic on each link, denoted as $T_{control}(V_{ij})$ and $T_{data}(V_{ij})$, respectively, where V_{ij} is the jth vertex in an independent set $S_i \in S$. Then, in step 5, all independent sets are sorted in descending order of their weighted throughput, defined as $\sum_{j=1}^{|Si|} \delta T_{control}(V_{ij}) + T_{data}(V_{ij})$, for each set S_i.

Step 6 sequentially checks each independent set and assigns a subband, if available, to all vertices in the set. Note that, as mentioned earlier, the FB-NS algorithm specifies $\alpha \cdot B$ subbands to transmit control traffic, and the remaining $(1 - \alpha) \cdot B$ subbands for forwarding data traffic. After each iteration of allocating frequency subbands, the current system status shall be checked in terms of whether or not all subbands have been used up. If not, we should go back to step 6 and begin the next iterations; otherwise, the flow diagram goes to step 8. Note that, after finishing all the iterations in steps 6 and 7,

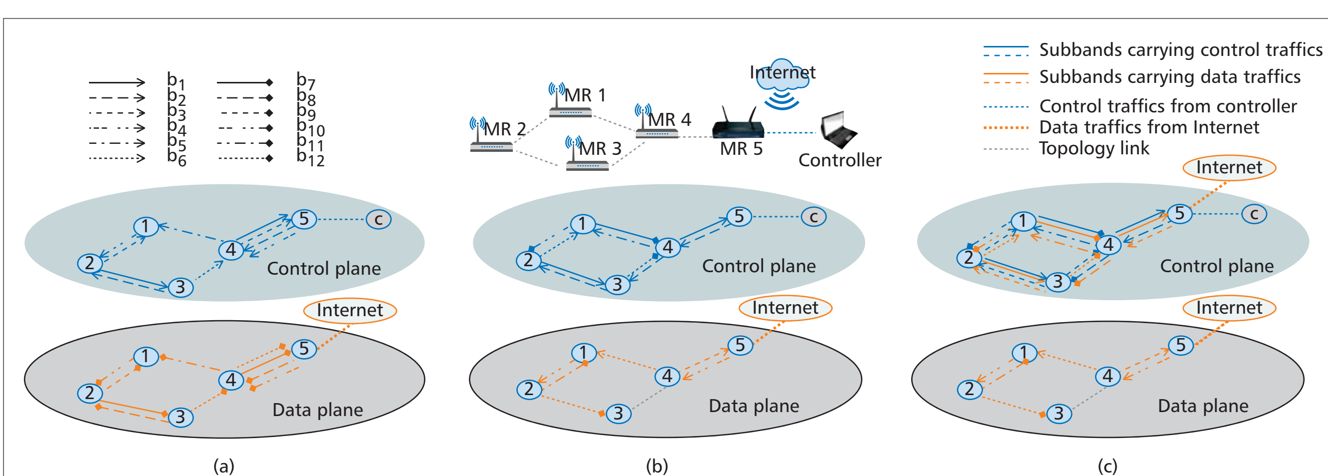

Figure 4. The illustration of three algorithms: a) traffic scheduling in the FB-NS algorithm; b) traffic scheduling in the NFB-NS algorithm; c) traffic scheduling in the NFB-S algorithm.

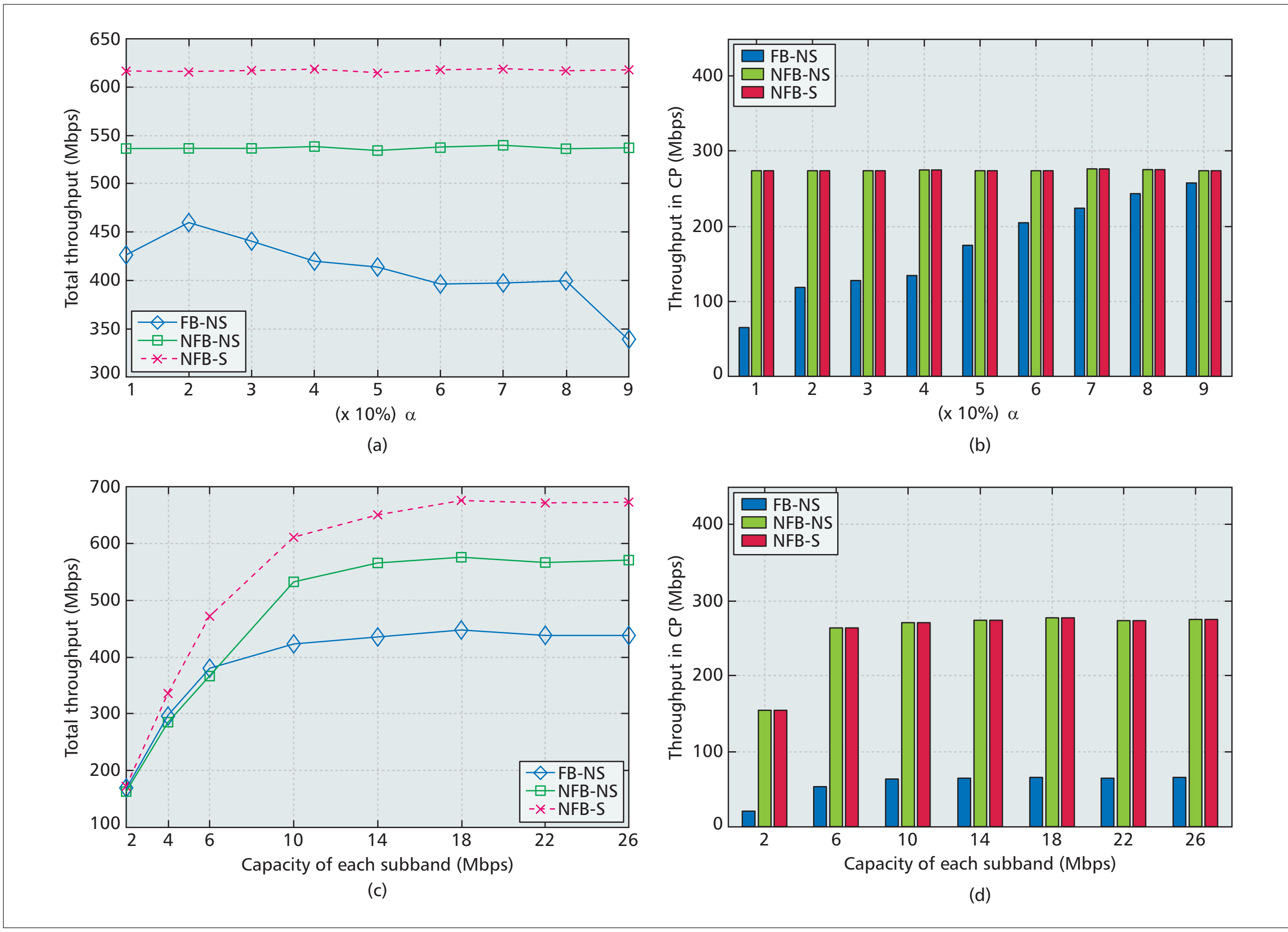

Figure 5. Throughput evaluation of three algorithms: a) total throughput vs. fixed band range; b) throughput in control plane vs. fixed band range; c) total throughput vs. capacity of subband; d) throughput in control plane vs. capacity of subband.

each link may be assigned with multiple subbands, which can work concurrently to increase the link capacity.

Finally, all the traffic rates from both the control and data planes shall be scheduled according to the following scheme. All of the spectrum subbands are partitioned to dedicate usage of control and data traffic. For instance, in Fig. 4a, subbands b_1 to b_6 are dedicated to carrying control traffic, and b_7 to b_{12} to data traffic. The performance of control traffic greatly depends on parameter α, whose effect is evaluated below.

Non-Fixed-Band Non-Sharing Algorithm

Although the FB-NS algorithm is simple and easy to deploy in practice, its fixed spectrum allocation would lead to low resource utilization because traffic in SD-WMN is uneven over the whole network. For example, control traffic is busy in the links near the controller, and data traffic is busy in the links close to the gateway. In order to avoid congestion occurring in these busy links, we propose the NFB-NS algorithm by relaxing the fixed spectrum allocation.

Compared to the FB-NS algorithm, the NFB-NS algorithm does not specify spectrum partitioning. Additionally, when the traffic flows are being scheduled in each link, the available subbands are selected freely for control traffic and data traffic with a higher priority given to control traffic. For example, in link (4, 1), subband set b_5 is scheduled first for the control plane; the other available subband set, b_6, is then selected to carry data traffic in the data plane. However, control and data traffic flows cannot share the same subband, that is, they are transmitted in separated networks. For example, in link (5, 4), b_2 can be exploited to transmit control traffic only but not data traffic even though it has remaining capacity.

Non-Fixed-Band Sharing Algorithm

Since a subband cannot be shared by control and data traffic once it is allocated in the previous NFB-NS algorithm, its forwarding capability may not be fully exploited when the traffic rate is less than subband capacity. This motivates us to develop a subband sharing algorithm to improve spectrum utilization.

Compared to the NFB-NS algorithm, the NFB-S algorithm has the same rationale of spectrum allocation. The only difference is that, after satisfying the control traffic flows, if there is still available bandwidth remaining in each subband, say b_2 in link (5, 4) of Fig. 4c, the remaining bandwidth of b_2 can be exploited to transmit data traffic.

Performance Evaluation

In this section, we present simulation results to evaluate the performance of our proposed algorithms. The topology adopted in our simulation includes 20 MRs and 27 bidirectional links. The control and data traffic rates are generated randomly within designated ranges. In the simulation, we divide the entire frequency band into 10 subbands, all of which have the same bandwidth capacity. All simulation results are averaged over 100 instances.

We first investigate the performance of the proposed algorithms by varying α from 10 to 90 percent. The bandwidth capacity of each subband is fixed to 10 Mb/s, and $\delta = 3$. The control and data traffic rates are generated randomly within the ranges of [1, 10] and [1, 15] Mb/s, respectively. Figure 5a shows the total throughput of the three algorithms. It is observed that the performance of NFB-NS and NFB-S are independent of α. Furthermore, the NFB-S algorithm has higher throughput than the other algorithms. This can be attributed to the fact that in-band transmission is allowed in NFB-S. Parts of the idle bandwidth resources in all subbands can be shared with data traffic, which increases the total throughput. On the other hand, when α is 10 percent, the total throughput of the FB-NS algorithm is low due to the low throughput in the control plane. When more radio resources are allocated to the control plane, the total throughput increases. However, after $\alpha = 80$ percent, the total throughput drops sharply. With excessive radio resources dedicated to control traffic, the throughput in the data plane and the total throughput are low.

As shown in Fig. 5b, the throughput in the control plane (CP) increases in the FB-NS algorithm when α grows from 10 to 90 percent. However, the performance of NFB-NS and NFB-S is not affected by α. This is because in both algorithms the control traffic is always guaranteed, while subbands in each link are separated to serve control and data traffic in the FB-NS algorithm. The latter is less flexible in scheduling transmissions.

Next, the capacity of each subband varies from 2 to 26 Mb/s with $\alpha = 10$ percent and the settings of other parameters unchange. It is observed from Fig. 5c that the total throughput of all three algorithms increases with the capacity until the bandwidth capacity reaches 14 Mb/s and then becomes saturated. The over-reservation of capacity of each subband does not always benefit the throughput. Figure 5d shows that the throughput in the control plane has similar behavior as shown in Fig. 5c.

In summary, we can observe that:

- The FB-NS algorithm can compete with the other two only under certain configurations, for example, when subband capacity at 2–4 Mb/s, as shown in Fig. 5c.
- The control traffic can always be guaranteed under NFB-S and NFB-NS algorithms.
- The NFB-S algorithm has the best performance when resource is limited, while the operating overhead would be higher to implement its sophisticated traffic orchestration.

Conclusion

In this article, a novel architecture is presented to establish the SD-WMN concept. We focus on how to address the challenges of building separated control and data networks via spectrum division and avoid the congestion that occurs in the shared medium. Three novel spectrum allocating and traffic scheduling algorithms, that is, Fixed-Bands Non-Sharing, Non-Fixed-Bands Non-Sharing, and Non-Fixed-Bands Sharing, are proposed and evaluated by extensive simulations.

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Biographies

HUAWEI HUANG received the Master degree in computer science from the China University of Geoscience (Wuhan) in 2013. He is currently a Ph.D. candidate at the School of Computer Science and Engineering, University of Aizu, Japan. His research interests are mainly in the area of software defined networking and wireless networks.

PENG LI received his B.S. degree from Huazhong University of Science and Technology, China, in 2007, and his M.S. and Ph.D. degrees from the University of Aizu, in 2009 and 2012, respectively. He is currently an associate professor at the University of Aizu. His research interests include networking modeling, cross-layer optimization, network coding, cooperative communications, cloud computing, smart grid, and performance evaluation of wireless and mobile networks.

SONG GUO [M'02, SM'11] received his Ph.D. degree in computer science from the University of Ottawa, Canada. He is a full professor at the School of Computer Science and Engineering, University of Aizu. His research interests are mainly in the areas of wireless communication and mobile computing, cloud computing and networking, and cyber-physical systems. He serves as Associate Editor of *IEEE TPDS* and *IEEE TETC*. He is a Senior Member of ACM.

WEIHUA ZHUANG [F'08] is a professor and a Tier I Canada Research Chair in wireless communication networks at the University of Waterloo, Canada. She is the VP-Mobile Radio and an elected member of the Board of Governors (BoG) of the IEEE Vehicular Technology Society. She was the Editor-in-Chief of *IEEE Transactions on Vehicular Technology* (2007–2013).