Resource Allocation in Software Defined Wireless Networks

Bin Cao, Yun Li, Chonggang Wang, Gang Feng, Shuang Qin, and Yafeng Zhou

Abstract

Recently, various wireless networks have been deployed, and thus people can access the Internet conveniently. However, traditional architectures are closed and ossified, which causes wireless networks to become complicated, inflexible, and expensive. As a result, there are several challenges for management and QoS guarantees that should be addressed. In order to solve these challenges, a new architecture should be designed. To this end, SDN techniques have been a hot topic due to the advantages of flexibility and cost efficiency. In this article, we first introduce the basic idea of SDN and discuss the reason why using software defined wireless networking (SDWN) is necessary. Second, we review some typical SDWN-based architectures, and show a hierarchical mobile cloud computing based software defined wireless network (MCC-SDWN) for fifth generation wireless networks. Next, the state-of-the-art work on resource allocation for MCC-SDWN is reviewed. For performance evaluation and simulation, some mainstream implemental tools and simulation platforms are introduced. We also discuss potential problems and solutions.

Introduction

Wireless networks play a key role in daily life, and the number of users is increasing due to the development of machine-to-machine (M2M) communications. A variety of mobile applications are used; hence, multiple quality of service (QoS) and resource requirements should be satisfied. Therefore, higher capacity becomes the first goal of wireless networks. To this end, dense cellular cells have been widely deployed, because the quality of the transmission channel is improved with shorter transmission distance. On the other hand, the average number of users per base station (BS) would decline. However, due to dense deployment, interference among neighbor cells would also increase. Meanwhile, more handover requests would be triggered easily because of the unbalanced load conditions, and thus resource allocation would be frequent.

Therefore, self-organizing networks become a promising solution to solve these problems with distribution coordination. Nevertheless, each cell is individual nowadays, and frequent iterations and periodical adjustments are necessary in dense deployment scenarios, thus causing unacceptable overhead. Usually, multiple wireless networks are overlaid in the same area with various standards and protocols, for example, time-division duplex (TDD), frequency-division duplex (FDD), 802.11, and 802.15.4. In the meantime, the architecture and management in wireless networks have become increasingly closed and ossified. As a result, the cost of infrastructure is high and resource utilization is low. Therefore, how to design a simple and feasible architecture for the fifth generation (5G) to effectively allocate resource is a hot but unsolved issue. Considering the challenge caused by individual control in dense cells, a new architecture should be designed to manage from a global viewpoint.

Consequently, software defined networking (SDN) [1] has been a natural option, which aims to separate the control plane and the data plane. In this way, devices are only in charge of data forwarding according to the flow table, and all the management functions are centralized in a central controller. The flow table is defined by the central controller, and sent to devices through the southbound interface. Thus, devices only transmit data without standard and protocol understanding, reducing the cost and complexity of the infrastructure. For flexibility, the administrator can define various management functions using the northbound interface through a controller. To this end, the administrator or application is able to monitor the state of the whole system for timely and efficient resource allocation. Considering its benefits when managing heterogeneous wireless networks and dense deployment scenarios, SDN is seen as one of the most promising techniques for 5G. As a compatible technique for SDN, network functions virtualization (NFV) has also been widely discussed recently. Both require separation of the control plane and the data plane, and programmability, with SDN focusing on innovation and openness for networks, and NFV focusing on cost reduction and improved resource utilization.

Because traditional networks are closed and ossified, management and QoS guarantees have become a big challenge, attracting an increasing amount of attention. In response, a hierarchical framework using SDN and virtualization is becoming a common vision. As is well known, resource management and allocation are very important since they can significantly affect QoS and resource utilization. However, due to the new hierarchical framework designed for SDN, cross-layer resource allocation, the relationship between user satisfaction and resource limitation, and the interaction among various types of resources have not yet been fully studied.

To obtain the envisioned benefits of SDN in wireless scenarios, software defined wireless networking (SDWN) [1] has been proposed to provide powerful management for resource

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allocation and QoS. In the wireless scenario, a standard framework for resource management function module design, message exchange, and cross-layer cooperation should be further addressed. Moreover, traditional SDN has not considered the characteristics of wireless transmission, which does not do a good job of distinguishing between public resources that can be shared (e.g., spectrum) and private resources that cannot be shared (e.g., transmission power). Meanwhile, for joint optimization of resource allocation, alternatives among various resources should also be fully investigated to dynamically allocate and adjust to satisfy different requirements.

To this end, much work has been done with SDWN, and we review the state-of-the-art research on the architecture and resource allocation of SDWN. However, there still remain challenges that should be addressed, and thus we also discuss potential issues for future work. We also illustrate the mainstream protocols to support SDWN, and introduce realization approaches and experimental platforms for simulation and evaluation.

The rest of this article is organized as follows. First, the new SDWN architectures are introduced, and an initial concept of three-layer mobile-cloud-computing-based software defined wireless network (MCC-SDWN) architecture is proposed according to the existing research work. Then protocols, algorithms, and schemes in resource allocation are reviewed, and the relationship between public resources (e.g., spectrum) and private resources (e.g., power), and joint optimization between wireless and cloud resources are illustrated. Next, the main implemental and experimental tools are shown for the realization and evaluation of SDWN. Then some remaining issues and potential solutions are discussed as areas of future research. Finally, conclusions are drawn.

Architecture

In order to provide low-cost, high-resource-utilization, and energy-efficient wireless networks for 5G, various new architectures are proposed.

The cloud (or centralized) radio access network (C-RAN) has been proposed by China Mobile [2], which is a cooperative and open cloud-based infrastructure that includes baseband units (BBUs), remote radio units (RRUs), and antennas. The centralized BBUs can obviously reduce the number of base stations in the same area; the cooperative RRUs and antennas can effectively improve system spectrum effectiveness; and the open cloud-based infrastructure with virtualization techniques can share resources according to the requirement of different cells to reduce cost and power consumption.

Based on C-RAN, IBM has proposed a wireless network cloud (WNC) [3]. The basic idea is to use cloud computing and a general computing resource pool to provide baseband processing in future RANs. Recently, SDWN with cloud-computing-based architectures to improve management and system performance has been proposed. SDWN can allocate resources with a global view, and configure settings to realize smart and open management flexibly and dynamically. For example, OpenRAN is a typical SDWN-based architecture designed by Mao *et al.* in [4].

Although existing work focuses on the remote cloud data center, the local cloudlet, and the access cloud, joint optimization and cross-layer scheduling among these clouds has not been thoroughly investigated. In fact, the resource type and characteristics of the remote cloud data center are very similar to those on local cloudlets, called wireless resources (e.g., power, spectrum), but those on access clouds are totally different, called cloud resources (e.g., computation, video streaming service). Therefore, to successfully and effectively satisfy the various requirements of users, wireless and cloud resources should be well matched. Moreover, an acceptable implemental approach should be provided. In order to thoroughly understand the relationships and operation among the remote cloud data center, the local cloudlet, and the access cloud in SDN-based wireless networks, we adopt SDWN to design a hierarchical three-layer MCC-SDWN for effective resource allocation, according to the proposed architectures and mobile-cloud-computing-based framework.

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Considering the characteristics and functions on different layers, the authors in [5] address the remaining issues in 5G wireless systems. In order to adopt SDWN for mobile cloud computing networks, we design a hierarchical three-layer MCC-SDWN for effective resource allocation according to the proposed architectures in [2–5], which can provide a feasible network framework and model for deployment and cooperation of wireless access clouds, local cloudlets, and remote data clouds. Compared to the existing architectures, the hierarchical three-layer MCC-SDWN is designed to use SDN-based virtualization for cloud computing in wireless scenarios, where resource allocation and scheduling can be effectively and simply managed by the central controller with a global view.

In 5G wireless systems, access clouds can improve transmission capability through distributed radio frequency access, centralized signal processing, and resource allocation, which is similar to traditional access networks. Therefore, access clouds should be deployed between mobile users and the remote cloud data center. On one hand, access clouds can directly provide access service for mobile users; on the other hand, they can send the data to cloudlets or remote cloud data centers according to the service requirements. In contrast, remote data centers provide computing and storage services. According to the well-known concept of C-RAN, access clouds can be viewed as consisting of multiple RRHs and a BBU, where radio frequency signals are connected to the network by RRHs, and signal processing and wireless resource allocation are operated by BBUs. Meanwhile, according to the service demand and business type for transmission and processing, BBUs also play the role of external interface to the local cloudlet and mobile core network, respectively.

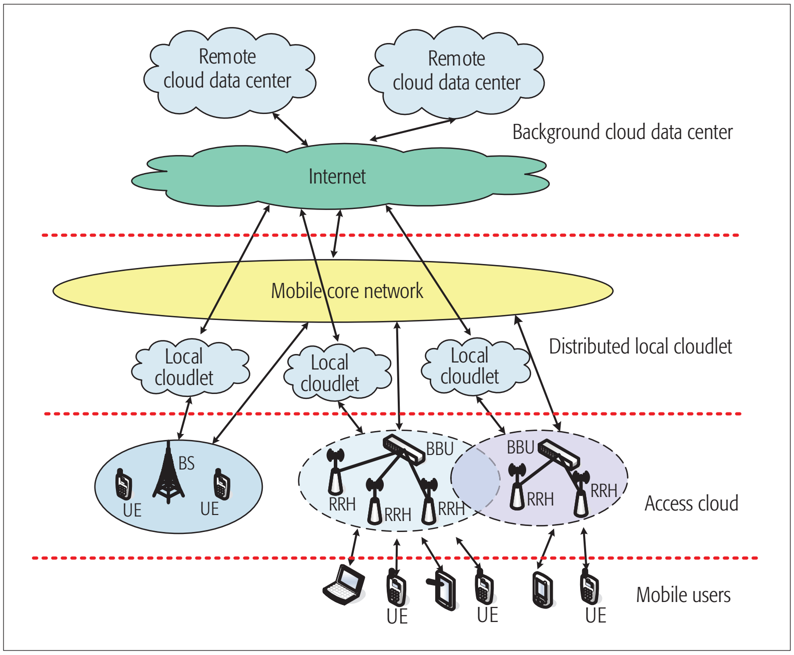

FIGURE 1. Architecture of MCC-SDWN.

Compared to remote cloud data centers, local cloudlets are deployed in geographic proximity to users, which can provide local transmission and processing for mobile Internet applications. Local cloudlets can forward mobile Internet application data to powerful remote cloud data centers, or cooperatively offload a large number of data to process locally. From a structural perspective, local cloudlets should be deployed on the same layer as mobile core networks, connecting to BBUs of access clouds, or traditional base stations on the lower layer through optical fiber high-speed physical transmission technology. Meanwhile, local cloudlets can deliver complex applications to remote cloud data centers when they cannot provide a service.

In a hierarchical mobile cloud computing network, a remote cloud data center connects to a mobile core network through the Internet, and communicates with multiple local clouds to provide support for mobile Internet applications. The corresponding function and structure of the remote cloud data center is similar to that in a traditional cloud computing network, but most of the data business transmission and processing service should be allocated to the distributed cloudlets system; thus, the workload in remote cloud data center would be effectively reduced.

The initial architecture of MCC-SDWN is shown in Fig. 1, including the access cloud layer, local cloudlet layer, and remote cloud data center. Based on the concept of C-RAN, an access cloud layer (L_1) includes a BBU and several RRUs. An RRU connects to users, and the BBU is in charge of baseband processing and wireless resource allocation, operating as an interface to access other layers. Generally, a local cloudlet (L_2) is closed to users to provide local data forwarding and processing instead of the remote cloud data center. Naturally, the remote cloud data center (L_3) is deployed on the Internet with a global view, which is similar to the traditional cloud computing idea except that the traffic flows could be shared by local cloudlets. For implementation and management, we use SDWN to realize the proposed architecture.

In L_1, we can deploy SDWN-based switches and controllers to separate the data plane and the control plane. Furthermore, we can use a controller to gather information and allocate wireless resource slices with virtualization. For details, please refer to the software defined virtual wireless network (SDVWN) framework in our previous work [6]. Similarly, an SDWN-based cloud can be introduced to the MCC-SDWN architecture for local cloudlets in L_2 and a remote cloud data center in L_3, respectively. Jain *et al.* [7] propose the idea of using SDN for cloud computing to improve the management and reduce the scheduling overhead.

Resource Allocation and Joint Optimization

There is consensus that resource allocation has a significant effect on system performance. In order to understand the relationship among various types of resources for effective allocation (in MCC-SDWN, wireless resources for transmission on L_1, and cloud resources for processing on L_2 and L_3), we review the existing work on resource allocation, show the differences and interactions among various types of resource, discuss the cross-layer matching problem of wireless resources and cloud resources, and open potential issues that could be addressed in the future.

Wireless Resource Allocation in L_1

As is known, suitable wireless resources such as power and spectrum should be allocated to a user according to its requirement. In fact, L_1 in the MCC-SDWN architecture acts as the RAN, and thus wireless resource allocation for transmission would be performed in L_1. On one hand, the more wireless resources that are allocated, the higher the satisfaction. On the other hand, corresponding cost would be incurred, and wireless resources are limited. Therefore, wireless resources should be traded off considering the balance between performance improvement and cost. Meanwhile, virtualization is usually adopted to collect various wireless resources for centralized management and allocation in SDWN scenarios, and thus the data plane requires that a flexible scheme be provided by the centralized control plane.

To this end, game theory is introduced for wireless resource allocation by Lv *et al.* in [8]. This work considers multiple heterogeneous architectures on a shared infrastructure with virtualization, and proposes a bandwidth allocation scheme based on Vickrey-Clarke-Groves (VCG) to maximize the total revenue of service providers in the virtualization environment. Moreover, in order to obtain optimal bidding strategies for auction, a Q-learning algorithm is designed.

Furthermore, as an essential feature in SDWN, virtualization yields physical and virtual networks. Yang *et al.* in [9] introduce an opportunistic spectrum sharing method into wireless virtualization for resource allocation, model the problem as NP-hard, and then propose a genetic algorithm, a dynamic programming algorithm, and a heuristic algorithm. The genetic algorithm can balance the performance and space complexity to obtain the second optimal revenue with low overhead.

Considering the characteristic of SDN, Feng *et al.* in [10] analyze the differences in the definition of network resources between SDN and traditional IP networking, taking flow table capacity into account. Accordingly, in order to achieve a proportional fair allocation of link bandwidth and the minimal global delay, a price-based joint allocation model of network resources in SDN is formulated, and a popular flow scheduling policy is proposed.

Understanding the Relationship among Various Wireless Resources for Allocation

In order to provide effective resource allocation to improve utilization, various research studies have been done under a specific architecture of SDWN, and most of them refer to some valuable work for SDN in wired scenarios that do not fully consider the feature of wireless networks. As a result, the corresponding resource allocation cannot effectively allocate various wireless resources as well as expected. Usually, the existing work only focuses on a single or a few wireless resources to satisfy the requirements, and do not distinguish the differences among various wireless resources. In fact, wireless resources can be divided into public resources and private resources. Public resources include spectrum, which can be freely shared by different physical infrastructures. In contrast, private resources include power, which only belongs to the owner, and cannot be scheduled and allocated to others as a public resource. For instance, there are two flows, from nodes A to B and from nodes C to D, respectively. For transmission, the spectrum or channel (f_1 and f_2) should be allocated, and the power of nodes A (P_a) and C (P_c) would be consumed. As a public resource, f_1 could be allocated to A2B or C2D, but the private resource of P_a at node A cannot be shared by other nodes even though the power resource is not enough at node C.

Therefore, public and private resources should be clearly defined and distinguished for accurate resource allocation. Meanwhile, the difference, complementarity, and substitutability between public and private resources have not been well understood. Moreover, a different resource allocation would have a different cost and overhead, and the improvement and negative effects should both be considered in resource allocation design. Furthermore, load balancing should be thoroughly investigated considering various wireless resource joint allocations, because some wireless resources might be overloaded, while others might be underloaded. Therefore, for efficient and balanced resource utilization, the issues of dynamic wireless resource joint optimization and trade-off allocation will be valuable topics in the future.

Cloud Resource Allocation in L_2 and L_3

In the proposed MCC-SDWN architecture, various resources such as computation for processing and video content for content are centralized on L_2 and L_3. In other words, these resources, called cloud resources, are stored on local cloudlets or in a remote cloud data center. In order to schedule and allocate cloud resources according to requirements and QoS guarantees, an effective

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cloud resources allocation method is necessary. To this end, a SDN-based architecture for cloud computing [7] is designed, which is similar to L_2 and L_3 in the MCC-SDWN architecture.

As shown in Fig. 1, we can see a cloud computing environment with multiple cloudlets over a wide area on L_2, and each local cloudlet would provide different network delay to users at different locations. Therefore, joint multiple resource allocation methods have been proposed for this scenario. However, the most frequent QoS requirement and total processing time in data centers have not been taken into account, and thus resource allocation cannot be optimal. To enhance the performance of the existing resource allocation, Feng *et al.* in [11] propose two functions:

- Preventing the degradation in service quality when the highest QoS requirement is frequent.
- Taking account of the total time, including network delay and computation time.

Bandwidth is another key resource in cloud networks. On one hand, each tenant wants to obtain the assigned bandwidth with proportional price. On the other hand, the cloud vender wants to improve link bandwidth utilization for more clients. Sun *et al.* in [12] first show that the network proportionality fairness cannot be provided by the traditional Proportional Sharing at Network level (PS-N) bandwidth allocation algorithm when the network is over-subscribed. Next, to solve the unfairness and bandwidth utilization issues, persistence proportional sharing at the network level (PPSN) and bandwidth efficiency persistence proportional sharing at the network level (BEPPS-N) are proposed, respectively.

In cloud computing, various resources are required, and thus multiple resource scheduling is one of the most important problems. However, resource scheduling algorithm design and implementation are big challenges due to the high overhead as NP-complete. To jointly consider task resource requirements for storage, bandwidth, and CPU, Feng *et al.* [13] design an efficient and practical algorithm to maximize resource utilization. Taking into account the constraints of storage, bandwidth, and CPU cycles, maximizing system-wide resource utilization is formulated as a centralized optimization problem. Since the optimization problem is NP-hard, the authors introduce a Nash bargaining game and prove that the optimal solution of maximizing resource utilization is equivalent to that of a Nash bargaining game.

Nowadays, some works only focus on how to allocate wireless or whether resources cannot maximize the performance of the whole system, since the service request usually includes transmission capacity and computing capacity simultaneously. Therefore, Sardellitti *et al.* [14] work on joint radio and computation resource allocation for offloading in a multiple-input multiple-output

	SDN protocol	System-level simulation	Running environment	Programming language	Charge	Feature in SDN-based simulation
MININET	OpenFlow, NetFlow, sFlow, etc.	Yes	Linux	Python	Open source and free	Specific widely used SDN-based simulation platform that fully supports various SDN protocols.
NS3	OpenFlow	Yes	Linux/UNIX/ MAC OS	C++/Python	Open source and free	NS3 can use OpenFlow switches, relies on building an external OpenFlow switch library.
NS2	Can be defined	Yes	UNIX/Linux	C++/Otcl	Open source and free	NS2 is a discrete event simulator targeted at networking research for simulation of TCP, routing, and multicast protocols over wired and wireless networks. The basic idea of SDN can be realized through reprogramming and redefinition.
OPNET	Can be defined	Yes	Windows/ HP/SUN	Proto-C	Commercial software	OPNET is a useful engineering and research tool for streamlining the design and performance analysis of communication systems and protocols. The basic idea of SDN can be realized through reprogramming and redefinition.
MATLAB	Not supported	No	Windows/ Linux	Matlab	Commercial software	MATLAB is a high-level technical computing language and interactive environment, which is very useful to evaluate the performance of various SDN-based algorithms, protocols, and systems.

TABLE 1. SDN simulation platforms.

(MIMO) multicell system. However, joint and cross-layer optimization still faces many challenges that should be addressed, and are further illustrated later.

Experimental Platform Implementation

As mentioned, SDN cannot fully satisfy the needs of 5G wireless networks, since SDWN should provide higher flexibility, but existing rules supported by SDN only consider the traditional TCP (or UDP)/IP. In SDWN, rules definition should consider any byte in the packet for matching, for instance, to route packets based on the specific carried information. Meanwhile, rules definition should also mean that matching could be conditioned by relational operators other than equality, for example, configuring an alternative route for packets according to the carried threshold value information. However, there is still little outcome for SDWN, and thus we introduce the existing SDN-based implemental approaches, which can be extended for SDWN and open minds for future design.

SDN-Based Protocols

OpenFlow: In order to realize the idea of SDN, various implemental protocols, including OpenFlow, OpenFlow Management and Configuration Protocol (OF-CONFIG), NetFlow, and so on, have been proposed. OpenFlow is one of the most famous SDN protocols, which is widely adopted and added as a feature to SDN-based commercial Ethernet switches (e.g., the Cisco Nexus 7000 switch series, the HP 3800 switch series, and the NEC PF 5240/5280 switch series). OpenFlow is an open source project that can define the switch and controller to realize the separate data plane and control plane. Through the northbound and southbound interfaces, the management functions and flow table can be programmed and defined by the controller and switch, respectively.

OF-CONFIG: OF-CONFIG is a protocol to manage physical and virtual switches in an OpenFlow environment. The purpose of OF-CONFIG is to provide an open interface to configure and manage switching without affecting the flow table and data forwarding. For example, OpenFlow defines the flow table and data forwarding, and OF-CONFIG operates an IP address and enables/disables ports. In fact, OF-CONFIG can be seen as a southbound interface.

NetFlow: Cisco NetFlow and IPFIX (the Internet Engineering Task Force [IETF] standard based on NetFlow) define a protocol for exporting flow records, which is an early SDWN-based protocol to collect network traffic information such as source IP, destination IP, ports, protocols, bandwidth utilization, applications, and more. IP flow data would be collected by a NetFlow-capable router or switch based on the flow collector, and NetFlow packets could be deciphered and interpreted by the collector in a user-friendly manner for further traffic analysis.

SDN-Based Switch

As widely used, OpenFlow is supported by most SDN-based switches, in which the significant metrics are maximum flow table number, matching capability, flow table issuance, message, flow action, and others. For practical realization, SDN-based switches can be divided as hardware and software implementations, respectively. The ideal hardware SDN-based switch for the Open Network Foundation (ONF) is that using an application-specific integrated circuit (ASIC) to support OpenFlow. Pat *et al.* [15] propose a new RISC-inspired pipelined architecture for switching chips for OpenFlow implementation. Also, OpenvSwitch (OVS) is a software open source SDN-based switch that can be installed on the traditional switch to provide standard management interfaces and protocols including OpenFlow, NetFlow, sFlow, and so on.

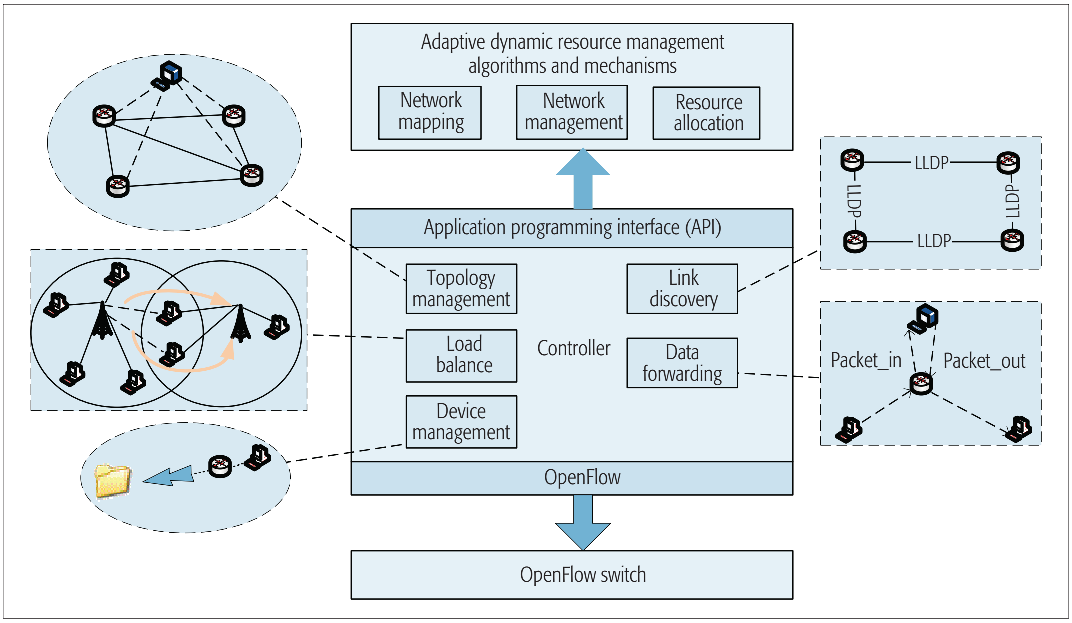

FIGURE 2. SDWN research development.

Simulation Platforms for SDN

For computational experiments, various simulation platforms have been designed. NS2, OPNET, and MATLAB are the most widely used traditional simulation platforms, which can simulate various environments to evaluate performance. For SDN, a specific simulation platform is MININET. Meanwhile, NS3 also added an external OpenFlow switch library (OFSID) to provide OpenFlow. The summaries and comparisons are listed in Table 1.

As mentioned, the existing SDN protocols and tools cannot fully support the requirements of SDWN. Therefore, further development should be studied, considering the limitations of SDN protocols such as OpenFlow for resource allocation in 5G. To this end, according to the proposed MCC-SDWN architecture with various resource allocation schemes in wireless scenarios, a basic design idea for extended SDWN research development is shown in Fig. 2. Using the northbound interface, a series of an adaptive dynamic resources management algorithm and mechanisms could be fully defined by a user. Through an application programming interface, the central controller could flexibly operate topology management, link discovery, load balancing, data forwarding, device management, and so on. Via a southbound interface, the function of hardware such as SDN-based switches would be redefined and simplified with lower overhead.

Furthermore, in order to show the differences between software and hardware SDWN simulation platforms, we use a simple experiment for illustration. In this experiment, we conduct a repeatable experiment in the same network topology with the software and hardware SDWN simulation platforms in Fig. 3.

In the experiment, we use MININET as the software SDWN simulation platform with a Floodlight controller. On a hardware SDWN simulation platform, we use TP-Link TL-WR1043ND with OVS as the SDWN switch with a Floodlight controller. We use 100 packets with 32 B/packets sent from the switch to the host to evaluate performance metrics in terms of minimal transmission delay, maximal transmission delay, and average transmission delay. The experimental results are listed in Table 2.

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On one hand, we can see that the experimental results gap between software and hardware SDWN simulation platforms are obvious, because:

- The environment in the former is more ideal than that in the latter.
- The processing capability limitation of the former has not been considered, but that of the latter has a significant effect.

On the other hand, the performance of the proactive flow table strategy is also different from that of the reactive flow table strategy. The proactive strategy can effectively reduce the overhead of addressing and flow table definition, but the reactive strategy is more flexible.

Future Research Directions

Nowadays, most work focuses on how to allocate a single wireless or cloud resource, and some improvements have been obtained. However, single-type resource allocation is not suitable for practical systems, so some studies propose various multiple resource allocation methods with significantly improved performance. Nevertheless, these research studies only work on either wireless or cloud resources; joint allocation considering both wireless and cloud resources has not been well investigated. First, we propose that resource allocation should consider the interactions and mapping between wireless and cloud resources. Next, we show that joint optimization should consider the effects of varying time, different locations, and various requirements. Finally, we also propose some requirements and challenges to design a widely used SDN platform for experiments and evaluations.

	Minimal transmission delay (ms)	Maximal transmission delay (ms)	Average transmission delay (ms)
Hardware SDWN simulation platform with proactive flow table strategy	16	194	74
Hardware SDWN simulation platform with reactive flow table strategy	6	699	340
Software SDWN simulation platform with proactive flow table strategy	0.077	0.319	0.138
Software SDWN simulation platform with reactive flow table strategy	0.071	11.983	0.401

TABLE 2. Experimental results.

Interactions between Wireless and Cloud Resources

From the viewpoint of MCC-SDWN architecture, cross-layer resource allocation among L_1, L_2, and L_3 should be designed. To this end, the interactions between wireless and cloud resources should first be fully understood. In 5G networks, such as the architecture of MCC-SDWN, allocated wireless resources in RAN on L_1 should match the allocated cloud resources on L_2 and L_3. On one hand, wireless resource allocation should satisfy the transmission requirements. On the other hand, cloud resource allocation should meet processing capability and content demand. Therefore, wireless and cloud resources should be allocated jointly, and the specific resource should be accurately configured to practical applications.

Joint Optimization among Multiple Dimension Resources

For resource allocation, three dimensions (time, space, and service) should be considered. In the dimension of time, the resource requirement of an application would be changed. There could be multiple scenarios over time. First, the highest demand is storage; second, it becomes bandwidth; finally, transmission power is the priority. In the space dimension, the load conditions of various cells are different, resources are limited when the cell is overloaded, and resource utilization is low when the cell is underloaded. Therefore, resource allocation with load balancing and a dynamic scheduling scheme should be considered. In the service dimension, various QoS guarantees also lead to different resource allocations. In practical situations, cross-layer wireless and cloud resource joint allocation and matching is necessary, because wireless and cloud resources could affect a user's satisfaction and system performance simultaneously, but they belong to different layers.

Simulation Platform Design

For future research study and development, a powerful and easily extended simulation platform should be designed. First, the simulation platform should construct a network flexibly and quickly according to the various requirements. To this end, a fine-grained resource allocation method should be provided to allocate and release resources. Meanwhile, since various virtual networks might run on the same simulation platform, isolation while running in parallel is also an important issue that should be addressed. Furthermore, in practical systems, the requirements and situations are changeable. As a result, dynamic adjustment and reliable control, such as a handover scheme and a load balancing algorithm, would further improve the system performance and exploit the benefit of SDWN.

Conclusions

In this article, we briefly introduced the concept of SDN and its limitation in the wireless scenario, as well as the challenges for SDWN. We discussed the typical SDN-based architectures and illustrated an MCC-SDWN architecture for 5G. Under this architecture, we reviewed the state-of-the-art research work on resource allocation, and investigated the relationship between public and private wireless resources. In order to develop well and evaluate accurately SDWN-based protocols and systems, we summarized and compared

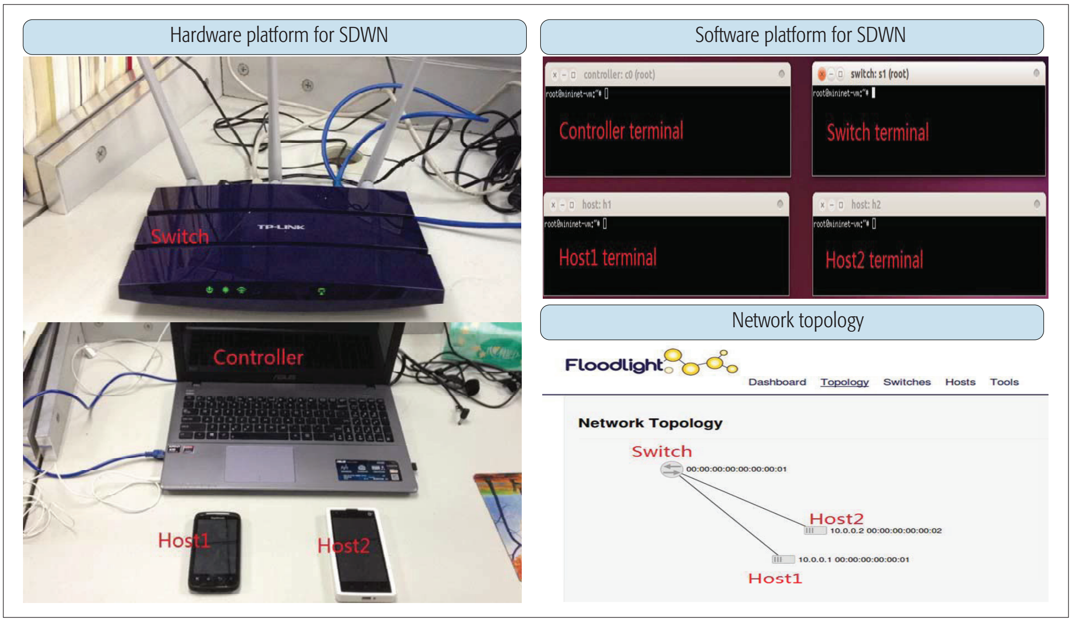

FIGURE 3. SDWN simulation platform.

mainstream platform tools. We also showed a basic idea for SDWN design and gave interesting experimental results. Finally, we discussed valuable future research directions.

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On one hand, wireless resource allocation should satisfy the transmission requirements. On the other hand, cloud resource allocation should meet processing capability and content demand. Therefore, wireless and cloud resources should be allocated jointly, and the specific resource should be accurately configured to practical applications.