An SDN-Based Architecture for Next-Generation Wireless Networks

Kun Wang, Yihui Wang, Deze Zeng, and Song Guo

Abstract

With the increase of new devices and applications, the past decade has witnessed exponential growth of traffic volume in communication networks. This triggers much effort for designing NWNs in both academia and industry. To gain natural evolution and meet emerging requirements, it is widely agreed that NWNs shall be multi-tier with overlay coverage and small cell deployment. However, dense deployment of small cells introduces numerous challenges, including inconsistent interfaces, frequent handovers, and extensive backhauling. By decomposing the control plane and data plane, SDN offers a new direction to address the above challenges. In this article, by introducing SDNC, we propose an intelligent wireless network architecture for NWNs. In our architecture, virtual RATs design using interface sets is brought up to support diverse services. Along with our earlier handover approach, low handover latency between heterogeneous networks is achieved. Furthermore, we present SH mechanisms targeted at different failure cases in backhaul connections. With programmability provided by SDN, the aforementioned functions can be deployed as modules in the SDNC. Experimental results validate the efficiency of our proposal.

Introduction

With constant involvement of new applications, such as device-to-device (D2D) communications and the Internet of Things (IoT), current 4G cellular systems have to confront challenges due to the exponential growth in mobile traffic volume. Consequently, significant effort has been devoted into designing next-generation wireless network (NWNs) from both academia and industry.

With the increasing traffic demands in wireless access networks, denser networks and heterogeneous deployments are required [1]. To gain natural evolution from existing cellular networks and satisfy emerging requirements, the infrastructure of NWNs will be of a multi-tier structure with overlay coverage and small cell deployment. Wide coverage and mobility support will be provided by the cellular networks operating at low frequencies. Meanwhile, many small cells operating at high frequency are deployed to guarantee high data communication rate. However, numerous challenges are brought up in parallel.

Increasing diverse services and applications require many different radio access technologies (RATs). It is a common idea to accommodate multiple RATs simultaneously in NWNs [2]. In other words, new RATs will be developed to meet emerging requirements. Subsequently, designing and managing different RATs efficiently can be crucial for access networks in NWNs. Moreover, due to reduced size and dense deployment, frequent handovers happen in cellular systems and small cells. Given the power constraints of small cells and the stringent latency requirement in NWNs, an efficient handover scheme should be developed to reduce latency and offer seamless handover across cells with different RATs.

Besides the access networks, the backhaul segment is also non-negligible. As the number of cells is continuously increased to support high throughput and efficient spectral reuse, failure in backhaul may cause huge data loss. To ensure high robustness, the backhaul networks shall be able to operate as normal even in the presence of failures. Moreover, a robust backhaul stands as strong support for RATs. Consequently, a self-healing (SH) approach in backhaul shall be brought up.

By separating the control plane from the data plane, software defined networking (SDN) is a newly emerging networking paradigm offering efficient control architecture for NWNs [3, 4]. Different from traditional vertically integrated networks, separation in SDN makes switches only perform instructions from a programmable logical centralized controller. By applying SDN, the user access behaviors, including the access point, RAT used, access time, and so on, can be obtained at an SDN controller (SDNC), located in a mobile operator or a server. In this way, the SDNC is able to allocate radio resources intelligently and efficiently.

Moreover, seamless handover and real-time failure detection are enabled. Various intelligent control functions can be implemented in SDNC to guide the behavior of the switches and routers in networks. With global control ability, an SDNC can monitor users' behaviors (e.g., mobility), potentially enabling seamless handover. The SDNC can also monitor the network behavior and activate SH mechanisms once a failure occurs at the backhaul so as to enable high quality of experience. By such means, global network management and smooth innovation for emerging requirements can be achieved.

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The main features of our proposed architecture are summarized as follows:

- Virtual RATs design using interface sets and controlled by an SDNC is proposed to deal with heterogeneous RATs and to optimize radio resources allocation. It also improves network flexibility and lowers maintenance cost.
- By introducing user-specific attributes as user contexts (UCs), the SDNC can predict a user's next cell and activate the relevant access points (APs) to make the handover in advance. Seamless handover is thus enabled, and handover latency is reduced.
- For SH of backhaul, elements involved in the NWNs are all connected to the SDNC with wired or wireless links. The SDNC keeps detecting any failure in the backhaul. Once a failure occurs, corresponding SH mechanisms will be activated immediately.

Preliminaries

Before introducing our architecture, let us first briefly review related background and motivation.

Radio Access Technologies

Driven by IoT, public safety, smart devices and social networks, the increasing mobile data service demands are introducing various challenges into the NWNs' radio access network design. For example, an access point shall support simultaneous access from a large number of IoT subscribers with low power consumption. Public safety, especially in natural disasters, requires communications even when the pubic communication infrastructure is destroyed.

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Multiple RATs (multi-RATs) are promising to meet such demands. Although third/fourth generation (3G/4G) and WiFi already provide data and voice services targeting different scenarios, there are still many challenges when multi-RATs are considered [5]. First, to cut down the cost and complexity, many diverse and rich services call for as few RATs as possible. Second, achieving high spectrum efficiency is based on the radio access resources' sharing and optimization between different RATs. Third, seamless handover between cells with different RATs should be supported given the fact that mobile users may leave one cell and join another one frequently.

All of the aforementioned challenges can hardly be addressed in the traditional multi-RATs way, with neither standalone RATs nor integrated RATs [6]. In standalone RATs, different services are provided through different RATs that work alone. No information exchange takes place since each RAT keeps its own protocol stack and runs in its own platform. Manual operation is needed to perform switches between different RATs. In integrated RATs, although some coordination can be done and automatic switching can be executed, high cost and high complexity are inevitable as different RATs are not combined at the hardware level. Therefore, a new multi-RATs method is urgently needed.

Handover Authentication

Although the heterogeneous network paradigm brings many benefits, it also raises some technical challenges, especially the handover issue, which requires efficiency. In existing wireless networks, admission control and cryptographic exchange are the common practice to guarantee safe handover. The components involved in the handover procedures are APs, users and an authentication server. Pairing of specific hashing output enables the handover between a new network and a user. When within the same network, the current associated AP will inform the next target AP about the possible handover. The target AP then retrieves the related authentication and key user context.

The aforementioned procedures are the basis of many handover schemes proposed in the literature. In the small cell scenario, numerous authentication servers are involved to enable handover across different wireless networks. Due to each network's relatively closed structure, trust relationship authentication and handover shall be executed frequently during mobility. Meanwhile, the specific key and handover message flows provided by the Third Generation Partnership Project (3GPP) exhibit high handover complexity. Unacceptable delay, up to hundreds of milliseconds, may be introduced due to frequent queries between a remote authentication server and APs for user verification [7]. Therefore, the authors in [8] proposed a simplified scheme where direct handover between APs and users was made on the basis of pubic cryptography. Although key agreements and mutual authentication are realized efficiently via a three-way handshake, delay and computation cost are increased due to vast message exchanges.

When the handover is within the same network, a context transfer mechanism can be utilized. In this case, the handover latency is mainly made up of the scanning time and the round-trip time spending on the target AP and the authentication server. A user-assisted handover scheme was proposed in [9], where a signed authentication certificate was transferred by the current AP as a security context via the user to the target AP. Latency is reduced due to the user's active participation. However, security is not guaranteed using just a combination of signature and identity as the security context.

Self-Healing

Like other systems, NWNs are prone to failure due to many reasons. Either software failures or hardware ones may happen at runtime. Software failures can be addressed automatically via reloading or restarting the failed software. However, a few hours may be needed to visit the failure site and repair the hardware failures manually. During this period, the networks must still ensure high reliability and availability as well as near normal conditions.

SH aims to minimize human interaction and obtain a high level of automated repair in the presence of failure. Most SH studies mainly focus on cell outage detection and compensation. Cell outage detection, fault detection, classification, and failure detection time minimization are the core targets of the work in [10]. Concerning cell outage compensation, neighbor cells can jointly compensate the failed one by increasing transmission power and changing antenna tilt [11].

When the failure comes to the backhaul, huge loss of data may be incurred due to the high data rate in backhaul networks [12]. A robust back-

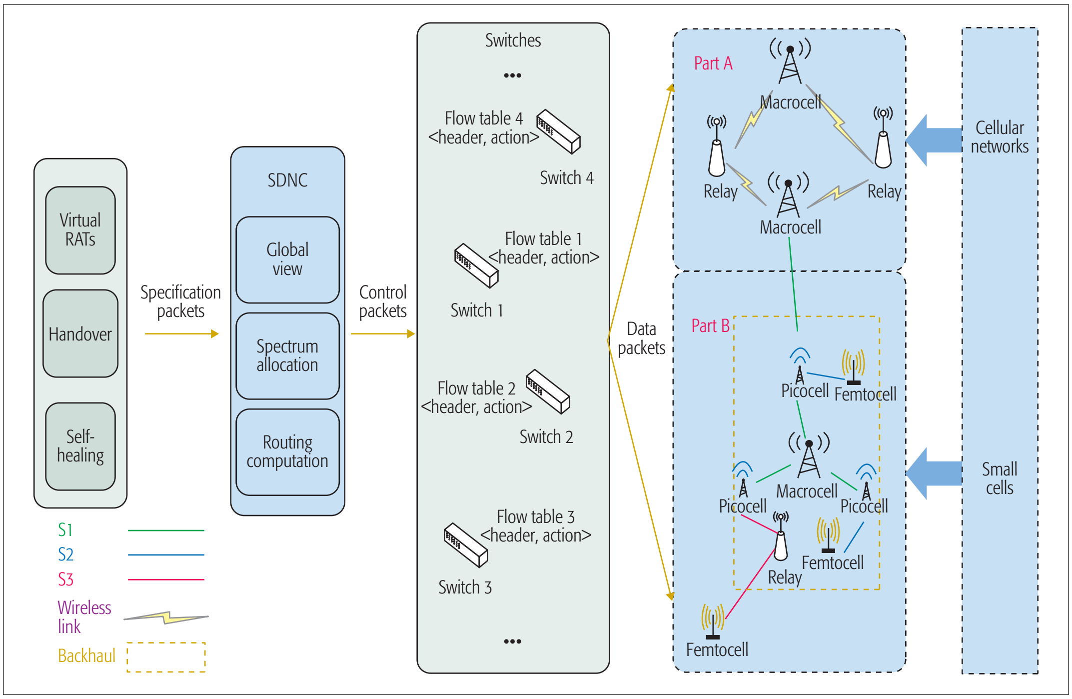

FIGURE 1. Overall architecture for NWNs.

Although low-power nodes like traditional microcells of a cellular network have been discussed a lot in 3GPP, they are not covered in the existing framework. This is because the legacy mobile system places emphasis mainly on the macro-coverage-based design, which requires that the air interface technologies be kept the same all the time.

haul is strong support for heterogeneous RATs in NWNs. Therefore, it is significant to consider SH in backhaul.

THE ARCHITECTURE WITH AN SNDC FOR NWNS

In this section, we present the detailed design of our SDN-based architecture. Figure 1 presents an overview of our architecture.

Although low-power nodes like traditional microcells of a cellular network have been discussed a lot in 3GPP, they are not covered in the existing framework. This is because the legacy mobile system places emphasis mainly on the macro-coverage-based design, which requires that the air interface technologies be kept the same all the time. Nevertheless, a traditional macro-coverage-based cellular network, marked as Part A in Fig. 1, still serves as a main part in our architecture. Complementary to Part A, to meet requirements in energy, cost, and frequency efficiency, small cells are introduced as Part B in our architecture. Thanks to the coexistence of the two network forms, our architecture can achieve wide coverage, mobility support, and high data rate. Both parts are controlled by a centralized SDNC.

By applying SDN, control logic and programmability are given to the SDNC. Thus, certain operations and functions can be executed in the control layer. The switches and routers in the data layer can then follow the instructions from the SDNC. Moreover, to meet emerging new requirements, innovations or modifications can be achieved smoothly by adding corresponding applications onto the SDNC.

The behaviors of the communication elements (e.g., APs, switches, as well as the communication resources) can be defined by an application specified by a network programming language. These specifications, acting as the network policies, are defined in the management plane, enforced in the control plane, and finally executed in the data plane accordingly. For wireless access, whenever a new RAT is needed, an application can define the RAT type and inform the SDNC via a northbound interface. Upon receiving such a request, the SDNC will forward flow-based decisions to the switches. These decisions are described as forwarding rules to be maintained in the forwarding table in SDN-enabled switches.

With the abstract and centralized view possessed by the SDNC, users' mobility can be predicted. Thus, handover can be made in advance, and a seamless experience with low handover latency can be obtained.

Since the aforementioned mechanisms are performed on the basis of a robust backhaul, SH is inevitably required for the consideration of robustness. With the surveillance of the global SDNC, once a failure at the backhaul is detected, corresponding SH mechanisms will be activated. Operations for SH on switches are instructed by the control packet from the SDNC and are initially defined by predefined management functions.

Comparisons between our proposal and existing wireless network architectures on different aspects are listed in Table 1.

ACCESS AND HANDOVER

As Parts A and B coexist, the access network is able to satisfy the need of multi-tier infrastructure in NWNs. However, the interface definition is crucial and difficult in the consideration of flexibility, interworking, and cost. To this end, we adopt the interface sets concept [8] targeted at the future radio access networks, where each interface can be programmed.

We define three interface sets. S_1 is an interface set of those between a small cell and an AP in traditional cellular networks. S_2 is an interface set of those among small cells, while S_3 comprises interfaces between relays and small cells. These sets are stored in the data center, and newly used interfaces are maintained within the switches' flow tables.

Based on existing interfaces, S_1 is just the one used in existing networks. By applying our SDNC, any modifications on the interface can be completed efficiently. For S_2 and S_3, they are initially the same as S_1 for the consideration of updating cost. But when being deployed in a specific scenario, one interface will be selected and then programmed by the instructions from the SDNC to perform corresponding operations. These modifications will be updated in both the flow tables of the switch and the data center.

Being programmable and selectable according to different scenarios, high flexibility can be achieved. For example, to support different backhaul methods, interfaces from corresponding sets are selected. To allow wired backhaul between an AP and a small cell, an interface should be selected from set S_1. Wireless backhaul within two small cells is supported by the interface selected from S_2. Direct backhaul between a relay and a small cell is also available by choosing an interface from S_3. More specific modifications are then done by the SNDC to suit different cases.

However, it is not feasible to have one RAT for one service as many new applications may coexist in NWNs. To support multiple services, a common protocol stack is more desirable. As shown in Fig. 2, the common protocol stack is revised from the traditional one used in the 3GPP network, consisting of radio resource control (RRC), radio link control (RLC), media access control (MAC) layer, and physical layer (PHY), from top to bottom. Being programmable, the common protocol stack is then converted to a software package according to a specific RAT. Different software packages, supporting different kinds of services for different RATs, can run on the same hardware platform.

In this way, integration complexity is significantly reduced. Besides, with a network-wide overview, the SDNC can assist in information exchanges between RATs. Thus, internetworking coordination and optimal radio resources allocation can be achieved, enabling strong support to seamless handover.

In Fig. 2, we illustrate a case in which two virtual RATs run on the same hardware under the control of an SDNC. Selected from our interface sets and tailored from the common protocol, there are RAT_1 and RAT_2 for two different scenarios running on a hardware platform. The SDNC is responsible for the RRC layer and enables efficient utilization of radio resources. The radio link situations are stored in the RLC layer and are then collected by the SDNC as the reference for radio resources allocation. Based on the common protocol stack, the two RATs are able to exchange information freely. Thus, RAT_1's RRC can gain the radio resource information of RAT_2 via communication with RAT_2's PHY and vice versa. The allocation information can also be shared through the SDNC.

As users may join and leave small cells frequently, in order to offer seamless user experience and meet stringent latency delay in NWNs, an efficient handover mechanism is needed. We introduce user-specific attributes [13] acting as UCs. Apart from identity and signature, the UCs include users' mobility information. With the overall view of the SDNC, the UCs can be collected to predict the movement path. Thus, it enables handover to be done in advance.

To illustrate the handover procedure in our architecture, let us take user U currently in cell X as an example. Suppose its future path along cell Y to cell Z is detected by the SDNC from U's UCs. Being in cell X means $State(X, U)$ is authenticated by X's AP. Our goal is to accelerate the

		Our proposal	Existing architectures	
RATs		Virtual RATs	Standalone RATs	Integrated RATs
	Hardware platform	Common	Different	Different
	Protocol	Common	Different	Different
	Coordination between RATs	Free	No	Constrained
	Maintenance cost	Low	High	Medium
	Flexibility	High	Low	Low
Handover scheme		Advanced	Direct	User-assisted
	Simplicity	Yes	No	Yes
	Latency	Low	High	Medium
	Computation cost	Low	High	Medium
	Interoperability	High	Low	Low
Backhaul SH		SDN-based	Automatic detection framework	
	Global control	Yes	No	
	Spectrum reuse	Yes	No	
	Network-wide detection	Yes	No	
	Scalability	High	Low	

TABLE 1. Comparisons between our proposal and existing studies.

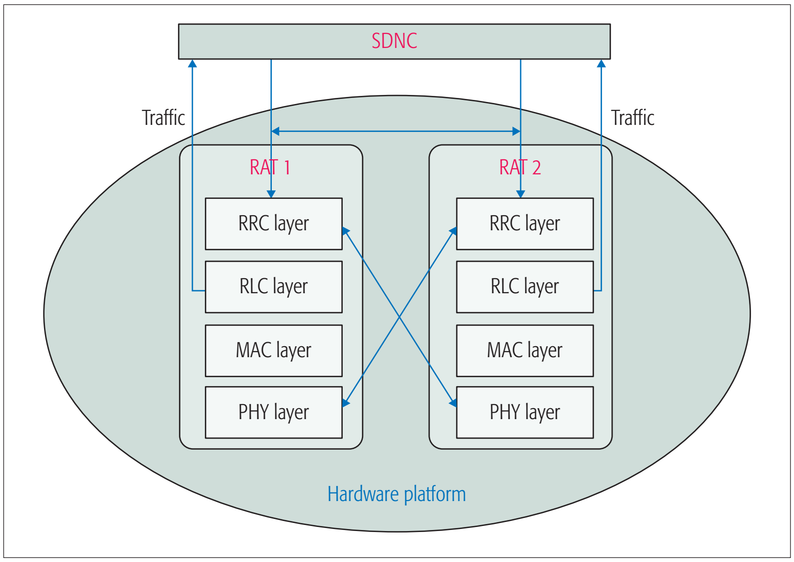

FIGURE 2. An example of implementing two RATs.

authentication of *State*(*Y*, *U*) and *State*(*Z*, *U*) within the corresponding AP. SDNC first collects *U*'s UCs that contain the moving direction of *U*. Cell *Y* is said to be visited in the near future. Before *U* arrives at AP of *Y*, SDNC sends notification packet to AP of *Y* about *U*'s coming. Specifically, the SDNC searches the optimal radio resources in advance and is ready to trigger the virtual RAT's choice reply according to the UCs' information. The AP of *Y* sends a handoff request to *X* until a reply is received. In this way, handover is made in advance, and when *U* is actually in *Y*, the *State*(*Y*, *U*) has already been authenticated. UCs are then updated to include the latest information. A similar procedure is applied before *U* moves from *Y* to *Z*. If the prediction is wrong and *U* actually moves from *Y* to *W*, the authentication of *State*(*W*, *U*) is then done in *W* as a normal procedure in traditional architecture, guaranteeing robustness.

The SDNC's overall view of the radio resources makes the optimal allocation achievable via simple data flow between controller and switches. Furthermore, when different failure cases happen in backhaul access or handover stage, SH mechanisms will be triggered so as to guarantee the performance of virtual RATs. The SDNC keeps detecting the network and sends instructions to switches once a failure occurs at backhaul, and activates the SH mechanisms.

Backhaul Self-Healing

Femtocells are deployed by the operator or network users and are backhauled by wired connections. They therefore are categorized into two different types, operator-deployed femtocells (OFs) and user-deployed femtocells (UFs). The difference between the two is the owner. OFs are under the control of the network operator and deployed in large enterprises, while UFs are in charge of network users and used in a small office or home.

Sharing the same spectrum as their operators, there are additional radios to provide alternative connections in the presence of backhaul failure. According to cognitive radio, a secondary user can detect channels in use and tune to vacant ones intelligently. It vacates a channel once the primary users become active [14]. In the backhaul layer, we let the same users act as both primary and secondary users. APs are in the primary role when recovering from backhaul failures using the channels allocated for recovery. Without backhaul failures, APs act as secondary users executing normal operation and using those primary channels. That is to say, role switching only happens when there is a failure, changing from secondary to primary users. Overall spectrum utilization can be obtained using the cognitive radio concept.

Let us present our SH strategy by the scenario [15] shown in Fig. 3, where there is a macrocell in the center of the architecture, serving outdoor users and providing picocells with backhaul connectivity. Three OFs are in the macrocell's additional radio range in three sectors. There is one OF within each picocell's additional radio range. All network elements except the users are connected to the SDNC logically, and connections between each other follow the virtual RATs way. OFs deployed by

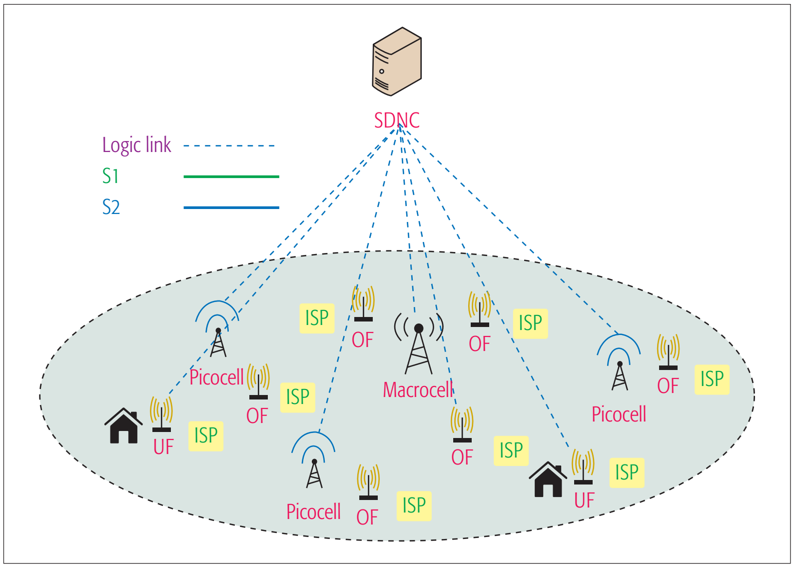

Figure 3. Underlying framework for backhaul SH.

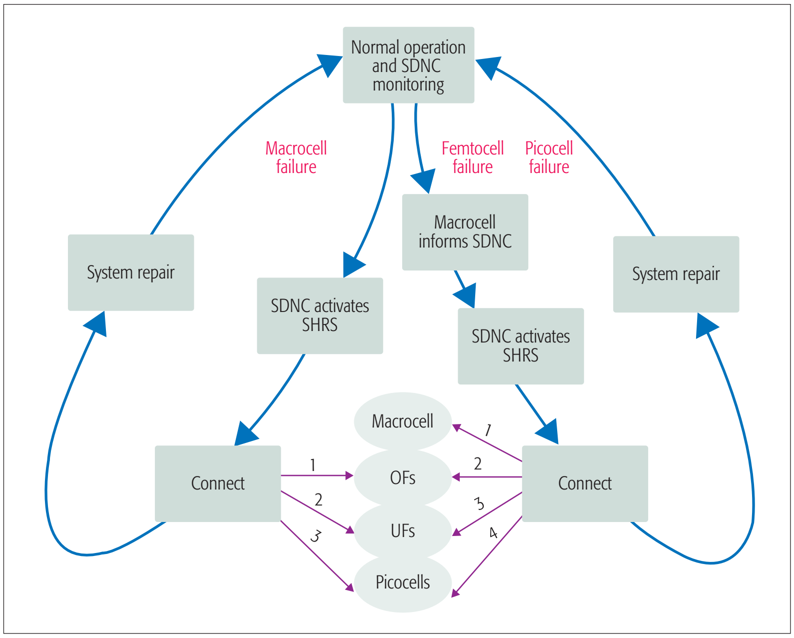

Figure 4. The SH mechanisms.

the operator offer service to users and SH connections to small cells in failures.

The SDNC keeps monitoring the whole network and performing normal operations such as executing the virtual RATs or handover mechanisms. But when a failure in backhaul of a certain type is detected, corresponding SH mechanisms in the SDNC will inform it to pass SH instructions onto switches. After matching within their flow table, switches obtain the optimal route to fix this position and run the SH. Only when the failure is fixed will the SDNC deactivate the SH operations and tune networks to normal mode.

The small cell backhaul failures can be categorized into three kinds, that is, macrocell failure, femtocell failure, and picocell failure, as shown in Fig. 4, according to the position where failure happens. From an SDN perspective, the SH mechanisms are installed on the SDNC and define the operations of the underlying forwarding devices.

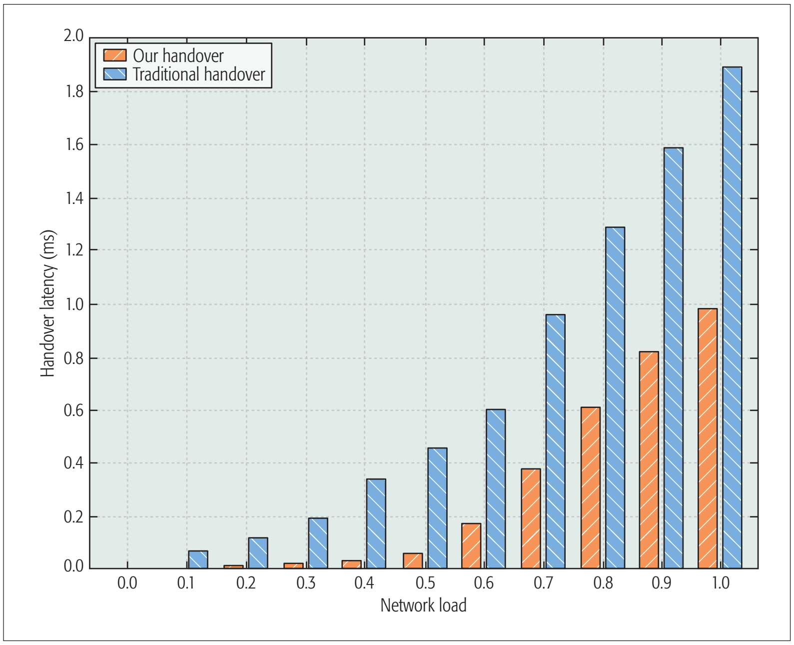

FIGURE 5. Comparison of authentication handover latency.

Macrocell Failure

Being the center of the aforementioned architecture and providing backhauling to other small cells, the macrocell is of the most importance. Therefore, macrocell failure shall be carefully addressed.

Once a macrocell failure is detected by the SDNC, it immediately activates all cells' additional radios within the failure region. Then all the picocells will look for alternative backhauling cells. They try to connect to different cells from OFs and UFs to picocells. The least priority is given to the picocells and this happens only when there are no OFs or UFs available. After that, the macrocell looks for backhaul connections from OFs and UFs using its additional radios and establishes connectivity through available radio from picocells directly backhauled from femtocells. The unused radios of femtocells are disabled, and the statuses of cells within the failed macrocell's range are collected by the SDNC.

Picocell Failure

Upon a picocell failure, the SDNC will be informed by the macrocell, and then the additional radios of cells within the failed picocell range will be activated. The failed picocell sequentially tires to connect to the macrocell, OFs, picocells, and UFs until one successful connectivity is established.

Femtocell Failure

Due to the similarities between the femtocell and picocell, the same SH process is followed as in the picocell backhaul failure.

Experiment and Simulation

In this section, we present our simulation results to evaluate the handover latency in our proposed architecture. We adopt the commonly used hexagonal grids to build up a MATLAB simulator. The total number of cells is 14, and the radius of each is 100 m. APs are located exactly in the center of each cell. Five hundred users are initially distributed around APs randomly. They also move randomly with a constant speed of 4 km/h. The arrivals of new users follow a Poisson process. We compare the handover latency in our architecture with the one in traditional architecture. Figure 5 gives the performance evaluation results.

With new users constantly joining, we define the network load as the ratio of arrival rate and the SDNC's processing rate. As can be seen from Fig. 5, different methods show no difference in handover latency in fairly low loads. The two curves deviate with the network load increasing. While traditional authentication handover grows faster in latency, our proposed method keeps under 1 ms most of the time. Therefore, our architecture is believed to provide more stable user experience in dense cells with frequent handover in NWNs.

Conclusion

Due to the exponential growth in traffic amount and increasing requirements on flexibility, scalability and interoperability, NWNs have been introduced for increasing data rates, coverage, connectivity, and broad bandwidth accompanied by reducing latency and energy consumption. In this article, we propose an SDN-based architecture with an SDNC for NWNs. Virtual RATs using an interface set and common protocol stack to deal with heterogeneous RATs is adopted. SDNC is introduced to aid the allocation of radio access resources and optimize internetworking coordination. Our SDNC is also able to predict a user's movement path such that the relevant AP is able to do handover in advance. The handover procedure is thus accelerated, and overall latency is reduced. Moreover, we present a novel SH approach to mitigate different failures occurring in backhaul to promote the robustness and reliability of NWNs. Finally, our proposal is validated to meet the stringent handover latency requirements in NWNs.

Acknowledgments

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