An Intelligent SDN Framework for 5G Heterogeneous Networks

Songlin Sun, Liang Gong, Bo Rong, and Kejie Lu

ABSTRACT

In fifth-generation (5G) mobile networks, a major challenge is to effectively improve system capacity and meet dynamic service demands. One promising technology to solve this problem is heterogeneous networks (HetNets), which involve a large number of densified low power nodes (LPNs). This article proposes a software defined network (SDN) based intelligent model that can efficiently manage the heterogeneous infrastructure and resources. In particular, we first review the latest SDN standards and discuss the possible extensions. We then discuss the advantages of SDN in meeting the dynamic nature of services and requirements in 5G HetNets. Finally, we develop a variety of schemes to improve traffic control, subscriber management, and resource allocation. Performance analysis shows that our proposed system is reliable, scalable, and implementable.

INTRODUCTION

In the past few years, the fourth-generation (4G) mobile communication system has been rapidly deployed and successfully operated in many countries. To provide enhanced connectivity for more diversified devices with higher mobility, the entire industry is focusing on the fifth-generation (5G) mobile system, and related technologies in 5G have become popular research topics.

A major challenge in the 5G era is to efficiently meet the increasing demand for network capacity while spectrum resource remains scarce. For instance, it is expected that future networks should be capable of handling the complex context of operations characterized by a tenfold increase in traffic [1] with guaranteed quality of service (QoS). In addition, energy efficiency has also been recognized as an urgent issue, since service providers are inceasingly concerned about operating expenses (OPEX) as well as the impact on global climate change and air pollution [2].

To address these challenges, one of the most promising technologies is the heterogeneous network (HetNet) architecture, which consists of a large number of densified low power nodes (LPNs). In HetNets, LPNs can provide high data rates to nearby mobile stations and can improve system capacity with frequency reuse. Moreover, LPNs can transmit signals with low power, leading to a significant reduction in energy consumption.

Despite the promising features of HetNets, with the drastic increase in the ultra-dense deployment of small cells in 5G networks, total energy consumption may easily exceed acceptable levels [3]. Moreover, fluctuating volumes of traffic also bring a considerable increase in energy consumption, which will also cause extra OPEX to service providers. In short, wireless network operators are now facing an unprecedent expansion in the number of users and the size of network.

In recent years various attempts have been made to address the issues of spectrum scarcity and energy consumption. For example, cognitive radio (CR) technology combined with software defined radio (SDR) is an effective solution to the problem of insufficient spectrum resources [5]. Adaptive resource allocation techniques, such as bit and power allocation, can become an efficient method to save energy [6]. Methods of subscriber churn prediction provide a viable method for service providers to balance their service load and provide network evolution insight [7]. Although the aforementioned solutions are feasible, they are mainly targeting a single part of the entire problem.

In this article we consider an intelligent management framework based on the concept of software defined networks (SDN), which features the decoupling of the control plane from the data plane [8]. In essence, SDN recognizes the network as an operating system and abstracts the applications from the hardware [8]. It enables the management-related functions to be implemented in a centralized manner, and thus network intelligence can be realized logically in a centralized SDN controller that maintains the entire system globally. More specifically, an SDN controller is programmed to learn about the physical topology of the network and the status of individual network elements through certain discovery mechanisms or appropriate databases, so as to orchestrate the entire network in a cost-efficient and energy-efficient manner.

In this article we propose the intelligent schemes of HetNet SDN to handle the dynamic environment of 5G. Specifically, our intelligent SDN framework will provide a viable approach to face the existing challenges in a unified manner. The rest of the work is organized as follows. We first review the existing SDN standards and pro-

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pose possible extensions. We then present our system model and develop a variety of adaptive schemes to make SDN work smartly with environmental change. We finally conclude the article.

SDN Standards and Possible Extensions

Current Standardization Progress

The concept of SDN was first introduced in the 1990s and became popular in the 21st century. The architecture of SDN was formally defined by the open networking forum (ONF) [9]. The ONF is also responsible for the maintenance of OpenFlow standards, technical specifications of the OpenFlow Swich, and the conformance testing of SDN enabled devices. The architecture of SDN consists of three layers: the application layer, the control layer, and the infrastructure layer. The function of the two lower layers are called OpenFlow controller and OpenFlow Switch, corresponding to the control and data planes of traditional IP/MPLS network switches and routers. With the OpenFlow standard, the OpenFlow controller instructs the OpenFlow Switch to define the standard functional messages such as packet-received, send-packet-out, modify-forwarding-table, get-stats, etc.

In addition to the ONF, the Internet Engineering Task Force (IETF), the International Telecommunications Union Telecommunication Standardization Sector (ITU-T), the European Telecommunications Standards Institute (ETSI), and the China Communications Standards Association (CCSA) have also started standardization work on SDN. IETF issued an RFC concerning the requirements and application issues relating to SDN from an operator's perspective [10], while ITU-T has not published a formal recommendation since the project began in 2012. Table 1 summarizes the formally published SDN standards.

Currently, SDN has found its best practices in campus networks and data centers, and has drawn increasing attention recently. SDN is regarded as a promising technology to solve current and emerging problems. However, necessary extensions are still required for future 5G HetNets.

Standardization organization	Main related standards and activities	Functionality
ONF	Software-Defined Networking: The New Norm for Networks (white paper) Interoperability Event Technical Paper v0.4/v1.0	Definition and interoperability
ITU	ITU-T Resolution 77	Standardization for SDN
IETF	IETF RFC 7149	Perspective
ETSI	NFV ISG	Use cases and framework and requirements
CCSA	TC6 WG1	Application scenarios and framework protocol

Table 1. Current main standards for SDN.

Extension for 4G/5G	Challenge
Mobility management	Seamless handoff between service providers.
Heterogeneous network support	Indiscriminate service regardless of location or type of network access.
Security	SDN control and privacy issues.

Table 2. Standard extensions for SDN.

Necessary Standard Extensions for Future 5G Networks

As mentioned previously, future 5G networks are characterized by their heterogeneity. At the same time, more effective technologies need to be employed for spectrum management, traffic control, resource allocation, density management, security, etc., in order to support the interconnection of more diversified user equipment and devices. The exploitation of SDN technology will largely reduce the complexity of 5G networks, lower the cost of network construction, facilitate future network evolution, and empower the network with intellectualization. However, current standardization work has not taken 5G networks into consideration. Thus, we aim to present the necessary extensions to current standards.

Table 2 summarizes and lists the suggested extensions to the standards of SDN. For instance, inter-ISP handoff and control plane security will be the key points for the development of SDN. Since the control plane is decoupled from the data plane, the switching of multi-homing user equipment between HetNets can be easily managed without sudden loss of connectivity or service interruption. The existing standardized solutions include the IEEE 802.11f, 802.11k, 802.11r for the homogeneous handover situations, and the IETF mobile IP (MIP) for handoff between the networks of different service providers. The implementation of SDN is straightforward, as OpenFlow controllers can communicate with one another to update and maintain a roaming IP-address table globally. Also, security is an important issue that must be emphasized in future SDN standards. Specifically, we must pay attention to some key aspects, such as the protection of subscribers' privacy, and robust defenses against cyber and malware attacks in different roaming scenarios.

System Model of Intelligent SDN

This section presents the system model that integrates intelligent SDN into the infrastructure of 5G network.

The 5G network will inherit the system architecture evolution (SAE) of 4G LTE, which is an evolved network framework that consists of a core network and a radio access network, as illustrated in Fig. 1. The core network (CN) of the system, known as the evolved packet core (EPC), is comprised of the serving gateway (S-GW), the

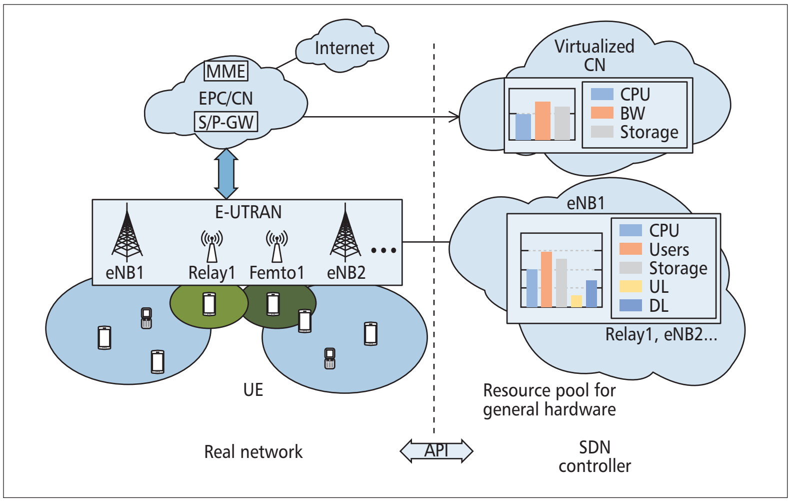

Figure 1. The proposed system model of intelligent SDN.

mobility management entity (MME), and the packet data network (PDN) gateway (P-GW). The radio access network (RAN), known as the evolved-universal terrestrial radio access network (E-UTRAN), is made up of macrocell BSs (also known as evolved NodeBs (eNBs)), pico, and femto (or home) relay nodes. For 5G core networks, SDN allows a high-level abstract, to which a set of underlying network resources are automatically and dynamically mapped. As for E-UTRAN, the eNBs and relay nodes can be implemented in a virtualized manner on general hardware coordinated and managed centrally by SDN controllers. The SDN controller, which is physically deployed on centralized servers, abstracts current resource usage and operates the network elements with intelligent strategy through standard APIs. In that case, different QoS requirements could be satisfied at the same time, and different kinds of service could be fulfilled with the most suitable resources.

Scenarios and Schemes for Network Intelligence

Resource Virtualization Vector

The architecture of intelligent SDN integrated with a 5G network consists of two layers: the SDN controller layer and the underlying physical network layer. The SDN controller instantiates the virtualized functional model CNs and the virtual base stations (VBSs) so that the signaling information can be exchanged locally. In this manner, we can achieve more adaptive and efficient management of the entire network. Specifically, the resources of the network can actually be categorized by computation (CPU utility), storage, bandwidth, etc. There are two vectors of a CN and a VBS representing the resource information respectively for convenience of the processing and modeling.

The CN supports two types of operation: the request for network association from a UE and the network's response. Thus, the resources in the CN mainly include three parameters, including the utility of the CPU, the size of the storage, the and data bandwidth. We can further define $\vec{V}_1 = (c_1, b, s_1)$, where c_1 and s_1 represent the percentage of CPU and random-access memory usage respectively, and b represents the available bandwidth. Similarly, $\vec{V}_2 = (c_2, f_{up}, f_{dn}, s_2, n_u, p)$ denotes the vector representing the resource parameters of a virtual VBS with four extra elements, f_{up}, f_{dn}, n_u and p, respectively, describing the uplink and downlink data flows, the number of users attached to the nodes, and the transmitted power.

Application Scenarios

In this section we introduce and discuss specific scenarios that demand dynamic and intelligent resource coordination over the entire network.

Scenario 1–Multimedia Services: Figure 2 shows the resource consumption of three types of multimedia services: live video conferencing, live TV streaming, and OTT with HTTP adaptive streaming (HAS). For video conferencing service, the network should provide a multi-point to multi-point connection among the attendees with low latency and delay variation to ensure a sufficient quality of experience (QoE). It indicates fast data forwarding and stable bandwidth, although data storage and processing may not be required as much. In other words, the demand for uplink and downlink data transmission should be much more urgent than for the CPU and storage. As for live TV streaming, which is a one-point to multi-point service, downlink bandwidth consumption is the dominant issue, while uplink only transmits the signaling data. Similar to video conferencing, live TV streaming only requires limited CPU and storage resources. However, it will become quite different with over-the-top (OTT) services. As the transcoder is involved in generating video slices of dynamic bit rates tailored for various screen sizes, all four aspects of resource requirement should be relatively more intense than the foregoing cases. The scenario of multimedia services presents an explicit example of how service deployment impacts the resource allocation requirement.

Scenario 2–Network Load Variation: Network load usually varies dynamically over time. The variation is usually regular, but sometimes sudden fluctuations may be observed.

Figure 3a illustrates the curves of daily network load fluctuation for business and residential areas. This partially reflects the resource utilization differences in time and locations. For a business area, the network load becomes relatively high in the daytime but low at night, while the situation for residential areas shows the opposite. The explanation is simply that most residents go to work in the daytime and come home in the evening. This scenario indicates the network must be aware of and adaptive to traffic fluctuations in both time and geographic dimensions.

When an emergency or a hotspot event happens, a sudden burst in network load will occur, as shown in Fig. 3b. Thus, the network should be intelligent enough to handle this situation. A viable method is to automatically allocate dedicated resources and to switch to distribute the hotspot contents by eMBMS technology. Thus, we can largely suppress the burst in resource consumption.

Moreover, the network load can vary from area to area. Figure 4a shows the radial traffic demand under random traffic distribution around a certain LPN. With traffic-aware schemes, we can divide the cell into two or more layers and assign each layer different power according to their traffic demands, so the system achieves lower power consumption as more layers become involved in the algorithm. Figure 4b presents the radial traffic demand under exponential traffic distribution, which leads to a similar result as that shown in Fig. 4a. We can conclude that traffic-aware schemes can better fit the network load variation and make full use of resources.

Different Intelligent Schemes

In this section we analyze in detail strategies of intelligent SDN concerning four aspects of 5G networks: traffic prediction, load balancing, user density prediction, and radio resource allocation.

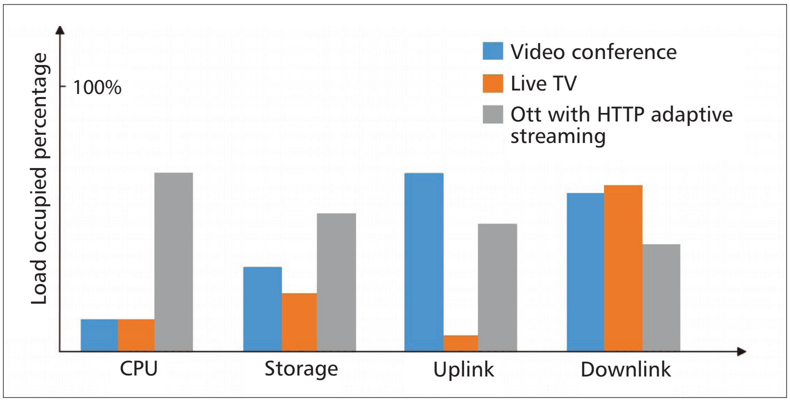

Figure 2. Scenario 1: different multimedia services.

Traffic Behavior Prediction: With the increasing traffic demand of users in the larger and more complex network, network management and monitoring seems to be a vital step of solving the problems. It can be carried out by traffic control, also known as traffic prediction, which predicts network traffic over a certain period of time. Accurate prediction of traffic requires the building of practical network traffic models according to different kinds of networks based on tracking fluctuations of data flows. Different from the conventional network models, the 5G network with intelligent SDN technology shows significant irregularity over time due to many non-linear factors in the network. Therefore, we can no longer describe the system only by combination and linear recursion techniques.

Considering the architecture proposed in this article, many methods [11] can be applied such as the real-time method, time series analysis, machine learning methods, etc. For the real-time method, the basic idea is that the system takes the latest obtained data profile as the one that will hold into the future. Under this circumstance, only in the case of slight variation from time to time can we achieve good performance. For the time series analysis, it takes the advantage of the fact that consecutive measurements can be represented by successive values in the data file. Nevertheless, the model becomes unreliable when trying to forecast further than the observation. Compared with the two approaches above, the methods referring to machine learning seem to be better solutions, and we next discuss two featured schemes: back-propagation (BP) and support vector machine (SVM).

BP is a neural network technology based on a multi-layer hierarchy, in which the upper neurons are full associated with lower neurons [12]. For traffic prediction, a hierarchy of three layers is sufficient, including an input layer, a middle layer, and an output layer. The learning samples are supplied from the input layer to the output layer through the middle layer neurons. The BP algorithm is implemented on the hidden middle layer by identifying the non-linear pattern, through which the traffic characteristics can be characterized and further predicted for the output layer. Applying this model could shorten the time of the training process with better accuracy of prediction.

SVM is in the category of learning algorithms, exploring better prediction techniques even under the traffic condition if intensive variability. The non-linear factor of the network will make most of the models useless, but as a relatively new machine learning technique, SVM can overcome the non-linear issue. The main idea of SVM for traffic prediction is to optimize the support vector that reflects the error of training data. This model applies three parameters, stream speed, volume, and density, to compose the training data and characterize the traffic stream. With training data, we can employ the support vector regression by using a ε-insensitivity loss function with linear kernel to approximately predict the traffic.

Load Balancing: For a cellular network, it is necessary to allocate time and frequency resources efficiently due to insufficient spectrum consumption. Normally, each macro cell is provisioned to possess an equal amount of resources. However, users in motion may spread in a dynamic and non-uniform manner, which often causes competition for resources in user populated cells while leaving a large amount of residual resources wasted in other cells. As a result, a homogeneous quality of service cannot be ensured over the entire network. Therefore, an efficient load balancing algorithm that makes full use of resources globally is vital for a cellular network. For 5G networks with intelligent SDN technology, the load balancing between macrocells and femtocells is a particularly crucial issue to deal with.

Hopefully, the classic single server processor sharing queue [13] can provide a feasible and dynamic solution to intercell load balancing. First, the optimal probabilistic dispatching policy is able to minimize the mean sojourn time; second, the dynamic load balancing polices are considered to acquire and adapt to the time-varying traffic. This two-stage approach determines whether to serve the flow locally in the microcell or to dispatch it to anther macrocell.

User Density Prediction: The density distribution of users in a cellular network provides valuable information that influences location based services and applications. With accurate user density, the network is able to allocate resources more wisely and purposefully. User density can be predicted with power allocation distribution, i.e. a high power sensed in one area usually indicates high user density in that area. Application of the mapping vector between the power in one

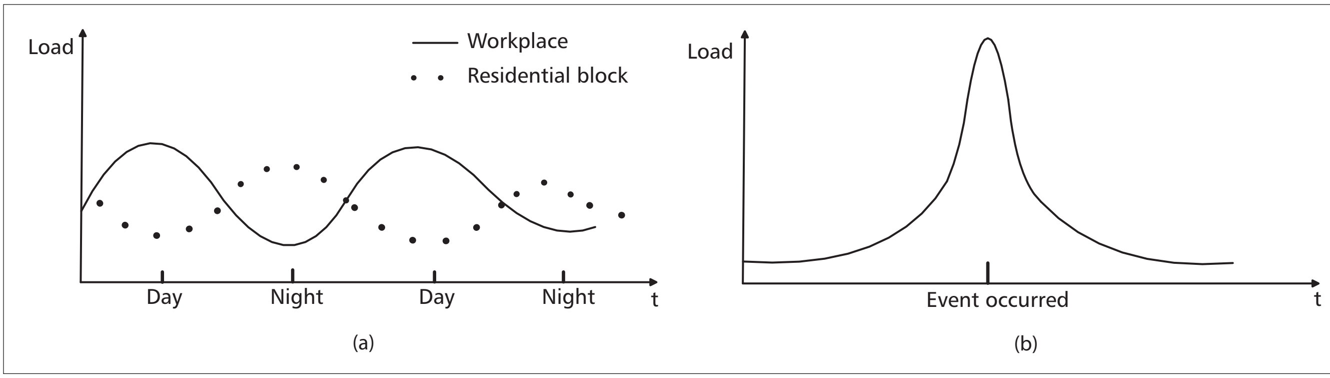

Figure 3. Scenario 2: Network load variation: a) daily network load variation; b) emergent and hotspot events.

area and the user density in that area can realize the density measurement without any other complex algorithm, but cannot ensure accuracy.

In practice, user density prediction usually works together with an enhanced version of the SFR scheme, also called SFFR, which is a traffic demand oriented scheme. This scheme not only pursues the overall throughput but also takes traffic demands in different area in consideration. The basic idea is to perform the power allocation constrained by the traffic demand. According to all the constrained conditions in the network, it can be further modeled as an optimized problem. Thus, we can realize the power allocation scheme with a power upper bound imposed in case of overlarge traffic demand. It is necessary to note that the scheme could lead to a serious interference with the adjacent cells when the distribution of the traffic demand becomes overwhelming.

Radio Resource Allocation: In HetNets, radio resource management (RRM) is a key to jointly managing resources from multiple access networks. The SDN controller works as a global optimizer to jointly manage resources among the networks to maximize network utility, and the UEs with multiple interfaces have the flexibility to select the cell to attach to so as to improve local capacity. Moreover, traffic that is tidal in nature, which means the traffic regularly varies with a large time-scale (i.e. hours), makes RRM and performance analysis more complex and difficult. The following two intelligent schemes are proposed to improve the efficiency of resource allocation.

Genetic Algorithm Based Joint Resource Allocation: The joint resource allocation of bandwidth and power transmission aims at maximizing the overall system capacity of HetNets. In effect, it is a multidimensional nonlinear constrained optimization problem with high complexity. The genetic algorithm (GA) provides an effective means to solve this nonlinear optimization problem. Actually, the GA features significant global search capacity and robustness in problem solving [14]. Aided by the GA, the joint resource allocation problem targeting the maximization of the system capacity can be achieved efficiently and intelligently.

•**Inter-Tier Spectrum Sharing Using Game Theory**: In 5G HetNets, the interference between macro-eNodeBs (MeNBs) and pico-eNodeB (PeNBs) needs to be coordinated to maximize the overall macro-cell throughput. This problem can be solved in the architecture of game theory. In paricular, by applying the Stackelberg game, the MeNB is the leader of the game and PeNBs the followers. The MeNB shall impose a price on the PeNBs for shared frequency bandwidth. The more bandwidth the PeNB demands, the higher expenditure PeNB has to pay. However, the PeNBs could serve some victim macro-users during ABS subframes in their expanded CRE range to reduce the PeNB expenditure. Both MeNBs and PeNBs intend to maximize their utilities. Through the interaction of the two kinds of nodes, frequency resources are allocated dynamically and efficiently with ICI well contained.

Performance Improvements

This subsection addresses the performance improvement achieved from our proposed intelligent SDN in 5G mobile network. These advantages result from four factors: reliability, scalability, complexity, and availability.

For reliability, the basic architecture illustrated in this article is based on models resulting from highly authoritative studies. Moreover, the maturity of SDN standardization also ensures reliability. The proposed architecture is also scalable, as an inherent characteristic of SDN. Specifically, the hardware involves general-purpose devices with functions and features defined by software, facilitating changes in configuration without replacing underlying physical devices.

The algorithms proposed in this article are studied in depth to guarantee both optimality and efficiency. Even for non-linear problems with unpredicted factors, we suggest low complexity solutions such as neural network technology and the GA. For availability, the proposed strategy is in general flexible and intelligent. Several smart schemes are involved to manage different categories of resources to enhance system performance in terms of traffic control, subscriber management, and resource allocation. In addition, the proposed schemes aim at distinct application scenarios.

Conclusions

This article presents an intelligent system that equips SDN with awareness and adaptiveness for dynamic networking in 5G HetNets. In our design, the SDN controller takes the responsibility of managing the infrastructure and optimizing resources. We first identify the key problems in 5G HetNets

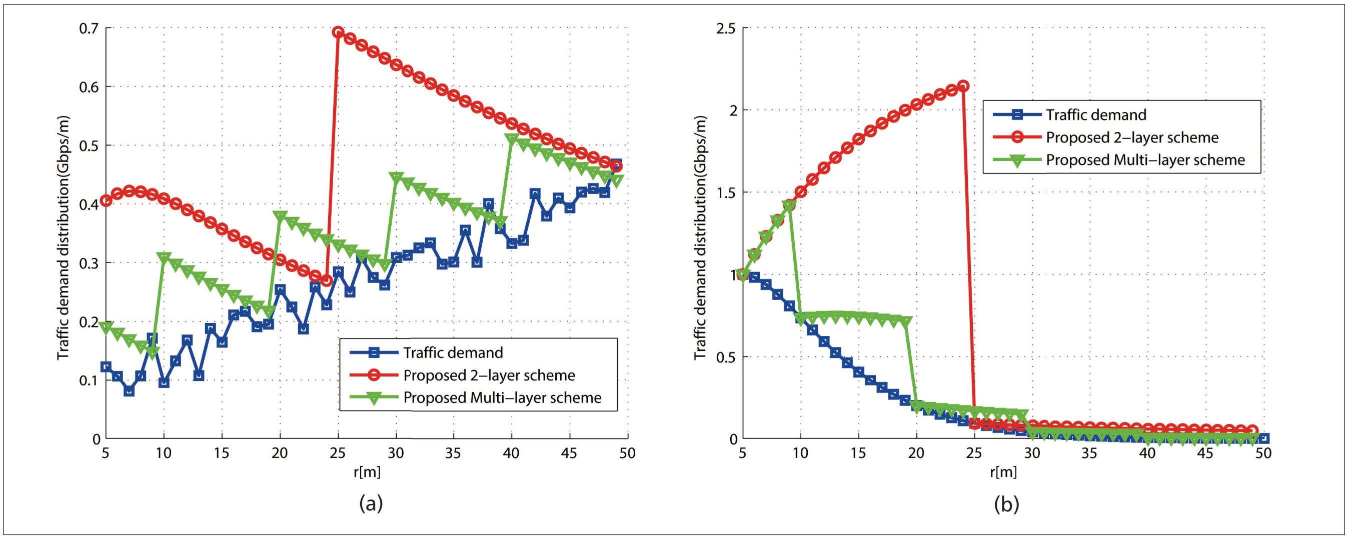

Figure 4. Actual traffic demand and the resulting available traffic from different power allocation schemes: a) random distribution; and b) exponential distribution.

as traffic control, load balancing, density prediction, and resource allocation. We then develop a number of smart schemes to overcome these challenges. Finally, we conduct performance analysis based on practical scenarios and demostrate that our schemes can deal with 5G network dynamics with low complexity and high flexibility.

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BIOGRAPHIES

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