Traffic Matching in 5G Ultra-Dense Networks

Yi Zhong, Xiaohu Ge, Howard H. Yang, Tao Han, and Qiang Li

The authors summarize and classify the spatiotemporal arrival properties of different traffic in ultra-dense networks, and optimize several promising technologies, such as dynamic time-division duplexing and full duplex radio, to adapt the network service to match the traffic. A new approach based on combining stochastic geometry and queueing theory is proposed to provide useful guidance for the design of ultra-dense networks when the traffic is spatiotemporally fluctuating.

ABSTRACT

Driven by enormous traffic demand, traditional cellular networks are evolving into an ultra-dense architecture. To take full advantage of such an ultra-dense architecture and efficiently serve the traffic with spatiotemporal fluctuation, the transmission mechanisms should be redesigned under the constraints of backhaul and energy consumption. In this article, we summarize and classify the spatiotemporal arrival properties of different traffic in ultra-dense networks, and optimize several promising technologies, such as dynamic time-division duplexing and full duplex radio, to adapt the network service to match the traffic. A new approach based on combining stochastic geometry and queueing theory is proposed to provide a useful guidance for the design of ultra-dense networks when the traffic is spatiotemporally fluctuating. Successive efforts, such as the analysis of different QoS requirements and more complicated but practical scenarios, still require attention along this line of research.

INTRODUCTION

Evolution of high data rate wireless applications, like high definition video, augmented/virtual reality, wearable devices, and the Internet of Things, leads to exponential growth of data demand in next generation wireless cellular networks. According to the forecast report, the requirement for wireless network capacity in the fifth generation (5G) era may exceed 25 Gb/s/km^2, which is about 100-fold over the current capacity [1]. In order to meet the huge traffic demand, various approaches, such as massive multiple-input multiple-output (MIMO) and mmWave communications, have been proposed. However, in mmWave communications, the communication distances should be limited to be less than 100 m due to the propagation attenuation property of mmWave in the air. In view of this, the size of cells should be further decreased, and the density of base stations (BSs) is envisioned to reach 10^3 BSs/km^2 to reduce power consumption while guaranteeing high data rate and seamless coverage. Thus, the wireless cellular networks will evolve to a structure of ultra-dense BSs.

The main traffic in wireless cellular networks is transforming from mobile voice to multimedia mobile data [2], which varies both spatially and temporally. In particular, hotspots such as office buildings, stadiums, and theaters might experience tremendous data traffic in working or activity times, while less crowded areas like suburban regions have smaller amounts of data demand. The amount of traffic also changes over time, for example, the data demand in daytime is much larger than that at midnight. The spatial and temporal variations of the traffic greatly affect the performance of wireless cellular networks, which in turn influences the service process of the traffic. To be specific, the traffic affects the statuses (idle or busy) of BSs, thus determining the activity pattern of interfering BSs. The coupling between the traffic and the service becomes even more noticeable as the traffic becomes more diversified and fluctuant.

In ultra-dense networks (UDNs), the network architecture is brand new due to the densification of BSs. With the new challenges introduced by the ultra-dense deployment of BSs, such as the limitations of power consumption and backhaul, configuring the network to match the varying traffic in UDNs is different from that in traditional cellular networks. For example, the spatial density of the traffic in a UDN may be much smaller than the density of BSs, and some of the BSs do not need to be active. Thus, the appropriate manner for UDNs to serve traffic with both high data rate and large energy efficiency needs to be explored [3].

In this article, we first propose to classify the traffic according to the arrival property and elaborate the necessity for configuring the UDN to match the traffic. Then we summarize several promising approaches for matching the varying traffic. Finally, a new analytical framework based on the combination of stochastic geometry and queueing theory is proposed, which serves for useful guidance in the design of UDNs to match the spatiotemporal traffic.

NEED FOR MATCHING THE TRAFFIC IN UDNS

Various kinds of traffic exist in next generation wireless cellular networks, such as voice, high definition video, virtual reality, wearable devices, cloud computing, real-time gaming, FTP data, and signaling. The statistical characteristics of the blended traffic is extremely difficult to describe. The spatial and temporal fluctuation of traffic in UDNs is much more drastic than that in traditional cellular networks since the architecture and the deployment of UDNs are more flexible and diversified. For example, the number of BSs may be much larger than that of users in UDNs, in which case the existing mechanisms and protocols will no longer be applicable. Generally, the blended traffic in UDNs can be classified into four types according to

Digital Object Identifier:
10.1109/MCOM.2018.1700956

*Yi Zhong, Xiaohu Ge, Tao Han, and Qiang Li are with Huazhong University of Science and Technology;
Howard H. Yang is with the Singapore University of Technology and Design. The corresponding author is Xiaohu Ge.*

the property of the spatial and temporal arrival. The four types are dense users with small arrival rates, sparse users with small arrival rates, dense users with large arrival rates, and sparse users with large arrival rates. In the following, we enumerate the potential scenarios of these four types of traffic as well as the challenges to match each type of traffic in UDNs.

Dense Users with Small Arrival Rate: The main composition of this type of traffic is generated by the applications used by a large number of users; meanwhile, the data amount required by these users is not much. Typically, the signaling for control information falls into this category. All users need to exchange control information with the BSs through the signaling, which produces only a small amount of data. In this sense, the UDN needs to support the access of large numbers of users, while the established links do not need to have high quality. To serve this type of traffic, frequency-division multiplexing among BSs can be used since only a small amount of bandwidth is required by each link; however, the backhaul becomes a bottleneck since it needs to support large numbers of independent data flows.

Sparse Users with Small Arrival Rate: The main composition of this type of traffic is generated by the applications used by a small number of users and requiring a small amount of data. Both voice and HTTP data belong to this type since only a few users simultaneously request a call or browse a web page. The main challenge to serve this type of traffic is to guarantee the performance of the users while reducing the power consumption of the network at the same time, which can be achieved by selectively turning off some BSs in a UDN [4].

Dense Users with Large Arrival Rate: This type of traffic corresponds to the case of heavy traffic, where both the number of users and the required amount of data are large. Augmented reality, wearable devices, and cloud computing belong to this type since these applications will become ubiquitous and require large amounts of data exchange. When serving this type of traffic, the advantages of UDNs are prominent compared to traditional wireless cellular networks since the ultra-dense deployment of BSs greatly improves the peak throughput by spatial reuse. The limitation of power consumption and backhaul also needs to be seriously considered to serve this type of heavy traffic.

Sparse Users with Large Arrival Rate: The main composition of this type of traffic is generated by the applications initiated by infrequent users requesting enormous data exchange. Applications such as real-time gaming, high-definition video, and virtual reality belong to this type. This type of application may become the typical deployment scenario for UDNs since the increasing density of BSs is expected to exceed the density of users. The UDN can concentrate the available time-frequency resources to serve infrequent users with large data demands. In particular, the densely deployed BSs can cooperatively serve such users.

Table 1 lists the potential classification of traffic generated by some usual applications.

Applications	Density of users	Arrival rate
Signaling for control information	Dense	Small
Voice and HTTP data	Sparse	Small
Augmented reality, wearable devices, and cloud computing	Dense	Large
Real-time gaming, high definition video, and virtual reality	Sparse	Large

Table 1. Potential classification of traffic for some applications.

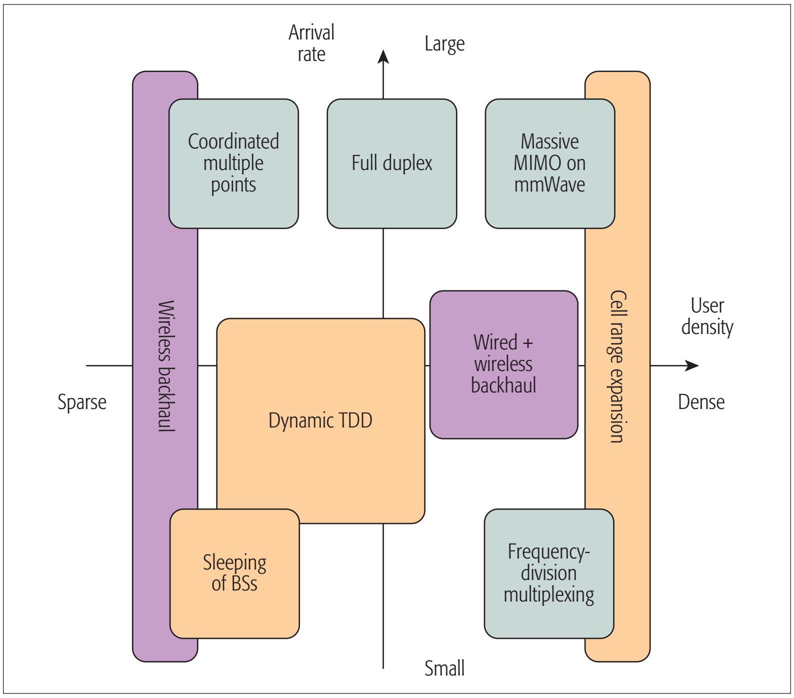

Figure 1. Illustration of different technologies in ultra-dense networks to match the spatiotemporal arrival property of traffic.

PROMISING APPROACHES TO MATCH THE TRAFFIC

In this section, we describe several promising approaches to match the various arrival properties of traffic in UDNs. In particular, Fig. 1 summarizes the choice of technologies corresponding to different scenarios of spatiotemporal arrival properties. Note that since the traffic may change dynamically in time, a UDN may switch between different technologies to match the real-time traffic. The switch between different technologies could be implemented by software defined networking, which is out of the scope of this article.

CELL RANGE EXPANSION

Cell range expansion is a technology that could be used in the heterogeneous UDN consisting of multiple tiers of BSs to offload the traffic. In cell range expansion, a bias factor is set for each tier of BSs based on the transmit powers [5]. By introducing different bias factors for different tiers of BSs, the cells with small coverage regions are extended to serve more users, while the number of users served by the BSs with large transmit power is decreased, thus reducing the interference in the overall network. The cell range expansion is especially useful when the users are densely distributed where the offloading is urgently needed.

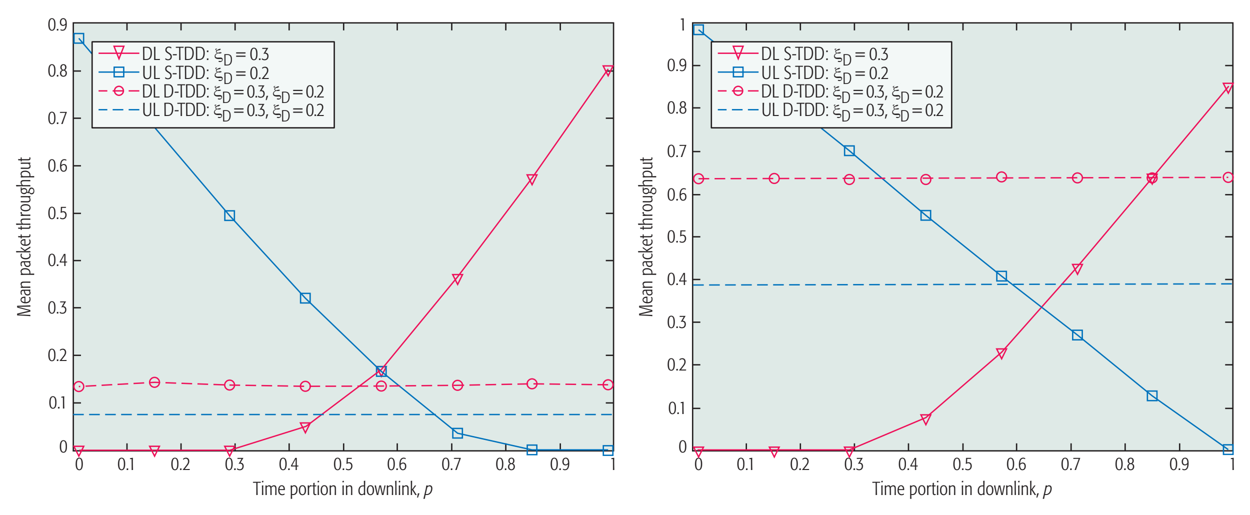

Figure 2. Comparison of mean packet throughput between S-TDD and D-TDD for different UL and DL packet arrival rates ξ_D and ξ_U. The density of users and that of small BSs is the same.

TDD TRANSMISSIONS

Time-division duplexing (TDD) means that the uplink (UL) and downlink (DL) transmissions share the same frequency but are separated in time. With the ultra-dense deployment of BSs, TDD becomes a more desirable choice for radio access than frequency-division duplexing (FDD), since the temporal resource allocation provides higher flexibility for the UDN to adapt the configuration according to the traffic and makes it particularly suitable to meet the drastic fluctuation of traffic in both UL and DL transmissions. On the other hand, as centralized scheduling becomes difficult in UDNs, the BSs are expected to self-organize and select their optimal DL/UL configurations. Therefore, dynamic TDD (D-TDD) is proposed, which configures the UL and DL subframes dynamically and adapts the network service to the drastic fluctuation of traffic [6]. By allowing the scheduling of traffic individually within each cell, D-TDD has the advantages of high efficiency for the spectrum utilization, reduced delay, and enhanced packet throughput, demonstrating itself as a more suitable candidate for future design of the UDN.

While very promising, the presence of out-of-cell interference, generated by both UL and DL transmitting interferers, can significantly limit the performance of D-TDD. Hence, dealing with cross-link interference is a key challenge for developing a D-TDD system. In the following, we list three approaches for the interference mitigation in UDN.

Almost Blank Subframe: The idea of the almost blank subframe (ABS) is straightforward, where certain subframes at the interferers are banned from transmitting packets. Thus, the cross-tier interference at some vulnerable users can be reduced in certain subframes. Although having the disadvantage of inefficient resource utilization, the ABS mechanism is simple to implement and effective in reducing inter-cell interference.

Coordinated Transmissions: In this scheme, the small BSs in UDNs can be organized into several clusters based on the distance or the path loss. The D-TDD can be used on the scale of clusters, that is, the UL and DL directions are consistent in each cluster but differ between clusters. Therefore, the exchange of information for the D-TDD configurations between clusters are required through the backhaul or the air interface [7].

mmWave Communication: Due to the large path losses at high frequency bands, mmWave is never appealing for BSs with large coverage regions but is well suited to the short-range transmissions in UDNs. With the distance between transmitter and receiver significantly reduced, the received signal strength can be boosted, whereas the large path losses are no longer a disadvantage but rather an opportunity to mitigate interference from neighboring cells. Moreover, mmWave allows the use of small antennas and packing many of them per unit of area, which results in very concentrated beams that bring not only improved received power but also reduced interference.

The comparison between static TDD (S-TDD) and D-TDD is shown in Fig. 2 with different traffic properties. The figure reveals that S-TDD is suitable for the scenarios with high packet arrival rates, while D-TDD is more beneficial with light or moderate amounts of traffic. Thus, we anticipate that the BSs in UDNs may form individual clusters, and when the arrival rate of traffic is large, the BSs within each cluster may coordinate the DL/UL transmissions and perform S-TDD; otherwise, each BS can independently configure its individual DL/UL transmission and operate in the more efficient D-TDD mode.

FULL DUPLEX RADIO

Full-duplex (FD) radio is a technology that allows a device to transmit its signal concurrently with reception on the same frequency. FD radio has recently been introduced as one of the key candidate technologies for 5G wireless systems [8]. This technology, if possible, will have tremendous implications for network design, including nearly doubled spectrum efficiency, significantly improved packet throughput, and greatly reduced delay. With almost instantaneous retransmission, FD radio enables the network to quickly react to any changes of traffic properties, thus providing very flexible choices for configuring the UDN to match the traffic. Nevertheless, several issues have to be addressed in order to achieve the full potential of FD radio.

Self-Interference Cancellation: The main challenge in implementing FD radio is the presence of self-interference, which is the interference generated by its own transmission [8]. Although the signal is already known at the digital band, the transmitted one that has gone through the entire system to the front-end is unknown to the radio receiver, making it very challenging to implement. Although significant work has been demonstrated, showing successfully implemented interference cancelling, lots of effort is still required to bring FD into practical implementation.

Inter-Cell Interference Management: Similar to that in D-TDD, devices with FD radio also suffer from the additional interference induced by the simultaneous UL and DL transmissions of the interfering cells. Research has been done to deal with this issue, including coordinated multipoint transmission, successive interference cancellation, power controls, and so on.

The FD radio is especially useful when the arrival rates of both the UL and DL transmissions are large.

BACKHAUL

Backhaul in a cellular system denotes the connections between the access points and the core network. With the densification of BSs in UDNs, the backhaul becomes a bottleneck in the network deployment. The performance gain of network densification may be counterbalanced by the limitation of backhaul. Backhaul solutions with different capabilities are proposed to cater for diverse network traffic. Basically, the backhaul solutions can be classified into two categories: wired backhaul and wireless backhaul. Wired backhaul networks are built with fiber/copper-based links, ensuring reliability and capacity. Nevertheless, the wired backhaul solutions are not cost-effective, because the cost of wired backhaul links depends on the capacity requirement and the backhaul link distance. Moreover, it is unnecessary to provide highly reliable wired backhaul links for the BSs in UDNs, since the traffic at each cell in a UDN is light compared to that in traditional cells. Different from the wired backhaul, the wireless backhaul has the advantages of feasibility and cost saving, thus becoming a viable alternative. In the following, we describe the backhaul design for different types of network traffic.

Wireless Backhaul: Wireless backhaul, which is flexible, can be implemented on varied frequency bands including mmWave, microwave, sub-6 GHz, and so on [9]. Nevertheless, the backhaul delay is a limiting factor of the wireless backhaul. Besides, the interference incurred by in-band wireless backhaul further degrades the system performance. Hence, the wireless backhaul is a viable solution for backhauling the traffic, especially when the users are sparsely distributed. On the other hand, with the densification of BSs in UDNs, the number of users in each cell is greatly reduced, leading to non-uniform distribution of traffic. Moreover, user mobility exacerbates the temporal fluctuation of the traffic in each cell. Since the resource allocation in wireless backhaul should match the traffic, the fluctuation of the traffic in UDNs will play a crucial role in the design of wireless backhaul.

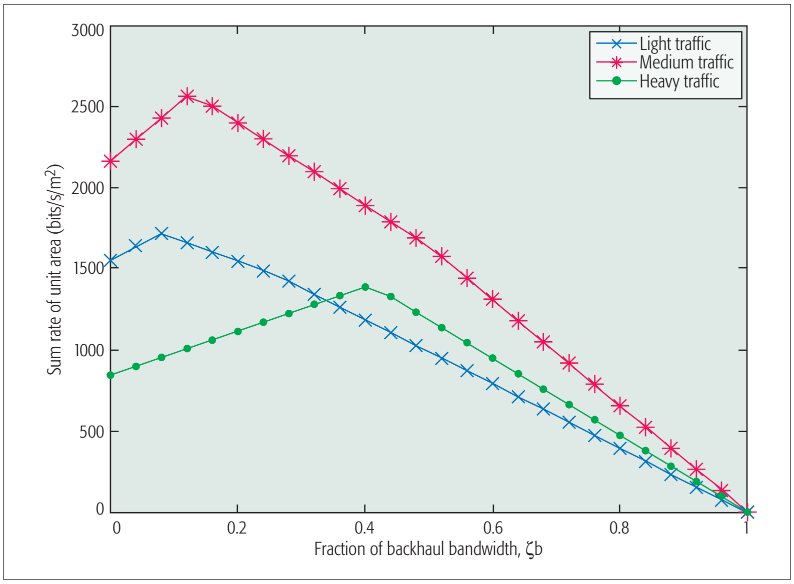

Figure 3. Sum rate of unit area as functions of the fraction of backhaul bandwidth b. The light, medium, or heavy traffic indicates the case where the number of users equals to 25 percent, 50 percent, or 100 percent of the maximum number of supported users.

Wired Backhaul: Due to high capacity and low latency, wired backhaul is likely to be a good choice for dense urban scenarios with large traffic demands [10]. However, the cost and flexibility of wired backhaul are major concerns. In order to strike a better balance between deployment cost and complexity, a combination of wired and wireless backhaul is preferred [11]. In this architecture, BSs backhaul wirelessly to anchored access points, which have wired backhaul links to the core network aggregator. Since backhaul connections have a significant impact on the quality of service (QoS) experienced by users, the fraction of anchored access points should be increased with the network densification in order to accommodate heavy traffic.

Figure 3 shows the sum rate of unit area as functions of the fraction of bandwidth for backhaul ζ_b ($0 < \zeta_b < 1$)under different intensities of traffic (density of users) [12]. The figure reveals that the optimal fraction of bandwidth for backhaul is different for different intensities of traffic. Generally, the optimal value for ζ_b increases as the traffic varies from light to heavy, indicating that more resource should be allocated to backhaul when increasing the traffic in order to achieve the maximum sum rate.

The wireless backhaul is especially useful when the density of users is much smaller than that of the small BSs, which is a typical scenario in UDNs.

NEW ANALYTICAL TOOLS TO HANDLE SPATIOTEMPORAL TRAFFIC IN UDN

To model and analyze the UDN with spatially and temporally random arrival of traffic is challenging, and the main difficulties lie in the following three aspects.

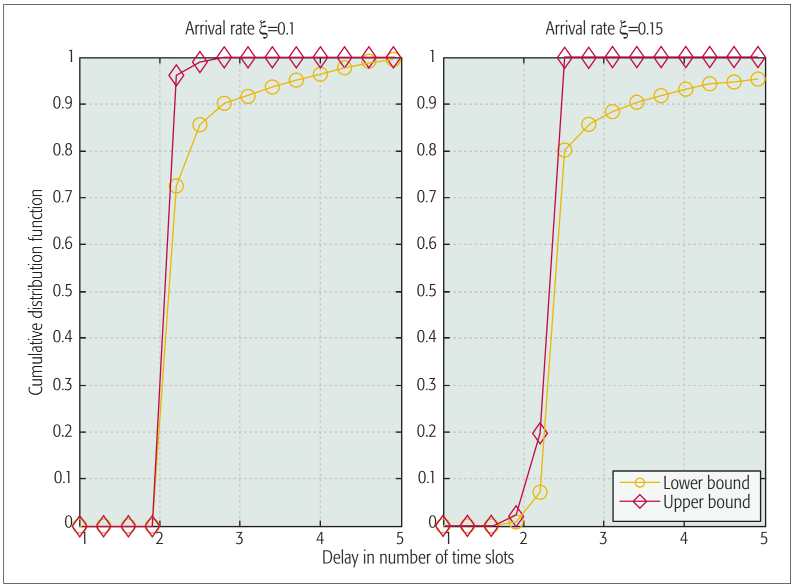

Figure 4. Comparison of lower and upper bounds for the statistical cdf of delay with different arrival rates ξ packets per time slot. The density of users and that of small BSs is the same.

- The spatial distribution of numerous small BSs in UDNs is by no means regular since the randomness (caused by site restriction or irregular traffic) inevitably exists in the deployment. Modeling the irregular topology of UDN, which determines the path losses of all links, is necessary and challenging.
- Although the temporal arrival of packets at different transmitters can be modeled as independent stochastic processes, the service rate of any queue is correlated with the statuses (either idle or busy) of all queues in the network. Thus, the queueing and service of packets in UDNs require sophisticated approaches for analysis.
- The channel gains as well as the medium access mechanisms randomly fluctuate, which greatly influences the interference and the outcomes of transmissions.

The commonly used stochastic geometry tool [13] has the limitation that it can only establish and analyze the spatial models of nodes in UDNs. Meanwhile, only the performance metrics obtained by analyzing a snapshot of the whole network (e.g., the coverage probability or the mean rate) can be tractably obtained through analytical approaches. In order to characterize the effect of temporal traffic variation and analyze the long-term metrics like delay, queueing theory should also be incorporated with a stochastic geometry tool to construct a more accurate model.

The model for the spatiotemporal traffic in UDNs consists of two parts: the spatial distribution of user locations and the temporal arrival of packets at each node. The spatial distribution of users can be modeled by a spatial point process, such as the Poisson point process for uniformly distributed users and the Poisson cluster process for clustered users. As for the temporal arrival of the traffic, the packet arrival processes for different users could be modeled as independent stochastic processes, such as Poisson arrivals.

The main difficulties in the analysis of combining stochastic geometry and queueing theory are the static nature of the topology and the interaction among different queues [14]. The static nature is due to the fact that the locations of nodes remain unchanged during a relatively long time once they are deployed, while the interacting queues problem comes from the coupling between the service rates and the statuses of queues.

Several promising methods can be introduced to make the analysis of UDNs with spatiotemporal traffic tractable. In particular, a dominant system and a modified system can be introduced to bound the interference and the performance metrics [15]. In the dominant system, the desired link under consideration remains unchanged, while idle links keeps transmitting "dummy" packets and continuously imposing interference. Thus, the queue sizes in the dominant system will not be less than those in the original network if the initial conditions for the two systems are the same. This way, the interference level in the dominant system will be an upper bound for the interference in the original network. In the modified system, the desired link also remains unchanged; however, for other links, a packet is dropped rather than retransmitted if it is not scheduled or fails in delivery. Then the interference in the modified system is a lower bound for that in the original network. By introducing these systems, the interacting queues in the networks are decoupled, and the analysis of UDNs with spatiotemporal traffic becomes tractable. Figure 4 shows a comparison of the bounds for the statistical cumulative distribution function (cdf) of the delay for different arrival rates. These methods provide useful guidance for the analysis and design of UDNs to match the spatiotemporal fluctuation of the traffic.

CONCLUSION AND FUTURE RESEARCH

The architecture of UDNs is different from that of the traditional network due to the excessive BS density, leading to new challenges to serve the traffic with spatiotemporal fluctuation under the constraints of backhaul and power consumption. This article summarizes the traffic property in UDNs and discusses several promising approaches to configure the network service to match the traffic. A new analytical method based on the combination of stochastic geometry and queueing theory to evaluate the performance of UDNs with spatiotemporally fluctuated traffic is introduced to provide accessible guidance for the design of UDNs.

Successive efforts are still required along this line of research. Some interesting and meaningful topics that can be further investigated are:

- Different QoS requirements, such as the reliability and the delay, can be considered together with the arrival property when configuring the UDN to match the traffic.
- With the emergence of new types of wireless applications, more advanced distributions that are able to capture the time domain correlation can be considered, leading to more perplexing spatiotemporal arrival processes of traffic.
- The proposed analytical approach of spatiotemporal traffic in UDNs can be further improved to obtain more accurate results.

Meanwhile, more complicated but practical scenarios that mix various types of traffic also need to be explored.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of the National Key R&D Program of China (2016YFE0133000): EU-China study on IoT and 5G (EXICITING-723227).

REFERENCES

[1] X. Ge *et al.*, "5G Ultra-Dense Cellular Networks," *IEEE Wireless Commun.*, vol. 23, no. 1, Mar. 2016, pp. 72–79.

[2] Z. Niu, "TANGO: Traffic-Aware Network Planning and Green Operation," *IEEE Wireless Commun.*, vol. 18, no. 5, Oct. 2011, pp. 25–29.

[3] C. Yang *et al.*, "Interference-Aware Energy Efficiency Maximization in 5G Ultra-Dense Networks," *IEEE Trans. Commun.*, vol. 65, no. 2, Feb. 2017, pp. 728–39.

[4] E. Oh *et al.*, "Toward Dynamic Energy-efficient Operation of Cellular Network Infrastructure," *IEEE Commun. Mag.*, vol. 49, no. 6, June 2011, pp. 56–61.

[5] A. Damnjanovic *et al.*, "A Survey on 3GPP Heterogeneous Networks," *IEEE Wireless Commun.*, vol. 18, no. 3, June 2011, pp. 10–21.

[6] Z. Shen *et al.*, "Dynamic Uplink-Downlink Configuration and Interference Management in TD-LTE," *IEEE Commun. Mag.*, vol. 50, no. 11, Nov. 2012, pp. 51–59.

[7] M. Ding *et al.*, "Dynamic TDD Transmissions in Homogeneous Small Cell Networks," *Proc. IEEE ICC*, June 2014, pp. 616–21.

[8] S. Hong *et al.*, "Applications of Self-Interference Cancellation in 5G and Beyond," *IEEE Commun. Mag.*, vol. 52, no. 2, Feb. 2014, pp. 114–21.

[9] U. Siddique *et al.*, "Wireless Backhauling of 5G Small Cells: Challenges and Solution Approaches," *IEEE Wireless Commun.*, vol. 22, no. 5, Oct. 2015, pp. 22–31.

[10] D. López-Pérez *et al.*, "Towards 1 Gbps/UE in Cellular Systems: Understanding Ultra-Dense Small Cell Deployments," *IEEE Commun. Surveys & Tutorials*, vol. 17, no. 4, June 2015, pp. 2078–2101.

[11] X. Ge *et al.*, "5G Wireless Backhaul Networks: Challenges and Research Advances," *IEEE Network*, vol. 28, no. 6, Nov. 2014, pp. 6–11.

[12] H. H. Yang, G. Geraci, and T. Q. Quek, "Rate Analysis of Spatial Multiplexing in MIMO Heterogeneous Networks with Wireless Backhaul," *Proc. IEEE ICASSP*, Mar. 2016, pp. 3586–90.

[13] M. Haenggi *et al.*, "Stochastic Geometry and Random Graphs for the Analysis and Design of Wireless Networks," *IEEE JSAC*, vol. 27, no. 7, Sept. 2009, pp. 1029–46.

[14] Y. Zhong *et al.*, "On the Stability of Static Poisson Networks Under Random Access," *IEEE Trans. Commun.*, vol. 64, no. 7, July 2016, pp. 2985–98.

[15] Y. Zhong, T. Q. S. Quek, and X. Ge, "Heterogeneous Cellular Networks with Spatio-Temporal Traffic: Delay Analysis and Scheduling," *IEEE JSAC*, vol. 35, no. 6, June 2017, pp. 1373–86.

BIOGRAPHIES

YI ZHONG [S'12, M'15] (yzhong@hust.edu.cn) is an assistant professor with the School of Electronic Information and Communications, Huazhong University of Science and Technology (HUST), Wuhan, China. He received his B.S. and Ph.D. degrees from the University of Science and Technology of China in 2010 and 2015, respectively. After that, he was a postdoctoral research fellow with the Singapore University of Technology and Design.

XIAOHU GE [M'09, SM'11] (xhge@hust.edu.cn) is currently a full professor with the School of Electronic Information and Communications, HUST, and an adjunct professor with the Faculty of Engineering and Information Technology at the University of Technology Sydney, Australia. He is the director of the China International Joint Research Center of Green Communications and Networking. He has served as an Editor for *IEEE Transactions on Vehicular Technology*.

HOWARD H. YANG [S'13, M'17] (hao_yang@mymail.sutd.edu.sg) received his B.Eng. degree in communication engineering from the Harbin Institute of Technology, China, in 2012, his M.Sc. degree in electronic engineering from the Hong Kong University of Technology and Science in 2013, and his Ph.D. degree from the Singapore University of Technology and Design. He received the IEEE WCSP Best Paper Award in 2014.

TAO HAN [M'13] (hantao@hust.edu.cn) received his Ph.D. degree in information and communication engineering from HUST in 2001. He is currently an associate professor with the School of Electronic Information and Communications, HUST. From 2010 to 2011, he was a visiting scholar with the University of Florida, Gainesville, as a courtesy associate professor. His research interests include wireless communications, multimedia communications, and computer networks.

QIANG LI [M'16] (qli_patrick@hust.edu.cn) received his B.Eng. degree from the University of Electronic Science and Technology of China in 2007 and his Ph.D. degree from Nanyang Technological University (NTU), Singapore, in 2011. From 2011 to 2013, he was a research fellow at NTU. Since 2013 he has been an associate professor at HUST. His research interests include next generation mobile communications, software-defined networking, full-duplex techniques, and wireless cooperative communications.

The architecture of UDN is different from the traditional network due to the excessive BS density, leading to new challenges to serve the traffic with spatio-temporal fluctuation under the constraints of backhaul and power consumption.