5G ULTRA-DENSE CELLULAR NETWORKS

XIAOHU GE, SONG TU, GUOQIANG MAO, CHENG-XIANG WANG, AND TAO HAN

Xiaohu Ge, Song Tu, and Tao Han are with Huazhong University of Science and Technology.

Guoqiang Mao is with the University of Technology Sydney.

Cheng-Xiang Wang is with Heriot-Watt University.

ABSTRACT

Traditional ultra-dense wireless networks are recommended as a complement for cellular networks and are deployed in partial areas, such as hotspot and indoor scenarios. Based on the massive multiple-input multi-output antennas and the millimeter wave communication technologies, the 5G ultra-dense cellular network is proposed to deploy in overall cellular scenarios. Moreover, a distribution network architecture is presented for 5G ultra-dense cellular networks. Furthermore, the backhaul network capacity and the backhaul energy efficiency of ultra-dense cellular networks are investigated to answer an important question, that is, *how much densification can be deployed for 5G ultra-dense cellular networks.* Simulation results reveal that there exist densification limits for 5G ultra-dense cellular networks with backhaul network capacity and backhaul energy efficiency constraints.

INTRODUCTION

To meet 1000× wireless traffic volume increment in the next decade, the fifth generation (5G) cellular network is becoming a hot research topic in telecommunication companies and academia. First, massive multiple-input multiple-output (MIMO) technology was proposed to improve the spectrum efficiency of 5G mobile communication systems [1]. Second, millimeter-wave communications was presented to extend the transmission bandwidth for 5G mobile communication systems [2]. Furthermore, the small cell concept has appeared to raise throughput and save energy consumption in cellular scenarios [3]. To satisfy seamless coverage, a larger number of small cells have to be densely deployed for 5G cellular networks. As a consequence, the ultra-dense cellular network is emerging as one of the core characteristics of 5G cellular networks. However, the study of ultra-dense cellular networks is still in an initial stage. Some basic studies, such as the network architecture and cellular densification limits, need to be further investigated for future 5G cellular networks.

In the third generation (3G) cellular networks, the densification of macrocell base stations (BSs) aimed to improve the transmission rate in partial areas, such as macrocell BSs deployed in urban areas. To avoid interference in adjacent macrocell BSs, the frequency reuse and sectorized BS technologies were developed for macrocell densification, where the density of macrocell BSs is about 4–5 BSs/km^2. In the fourth generation (4G) cellular networks, such as Long Term Evolution-Advanced (LTE-A) mobile communication systems, the microcell BSs (e.g., hotspot BSs and femtocell BSs) have been deployed to satisfy high-speed transmission in specified regions, where the density of microcell BSs is approximate 8–10 BSs/km^2. Moreover, all the above BSs are directly connected by gateways, and all backhaul traffic is forwarded by fiber links or broadband Internet. In 3G and 4G cellular networks, the aim of BS densification is to improve the wireless transmission rate in partial regions, and the greatest challenge of BS densification is interference coordination for cellular networks.

In 5G cellular networks, massive MIMO antennas will be integrated into BSs, where hundreds of antennas are utilized for transmitting gigabit-level wireless traffic. When the 5G BS transmission power is constrained to the same level of 4G BS transmission power, each antenna's transmission power at a 5G BS has to be decreased 10–20 times compared to each antenna's transmission power at a 4G BS. As a consequence, the radius of a 5G BS has to be decreased by one magnitude considering the decrease of transmission power at every antenna. Another potential key technology for 5G cellular networks is millimeter-wave communication technology, which is expected to provide hundreds of megahertz bandwidth for wireless transmissions. However, the transmission distance of millimeter-wave communications has to be restricted to 100 m considering the propagation degradation of millimeter-wave in the atmosphere. Motivated by the above two technologies, small cell networks have been presented for 5G cellular networks. To satisfy seamless coverage, the density of 5G BSs is highly anticipated to come up to 40–50 BSs/km^2. Therefore, the future 5G cellular network is an ultra-dense cellular network.

Some initial studies involving ultra-dense wireless networks were explored in [4–12]. Yunas *et al.* investigated the spectrum and energy efficiency of ultra-dense wireless networks under different deployment strategies, such as the densification of classic macrocell BSs, ultra-dense indoor femtocell BSs, and outdoor distributed antenna systems [4]. Soret *et al.* discussed the interference problem for dense scenarios of LTE-A cellular networks and proposed two algorithms to apply time domain and frequency domain small cell interference coordination

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for dense wireless networks [5]. Based on LTE and WiFi technologies, a joint coordinated intra-cell and inter-cell resource allocation mechanism was proposed to opportunistically exploit network density as a resource [6]. However, these solutions were mainly presented for 4G cellular networks, such as LTE networks. Bhushan *et al.* discussed advantages of network densification, which include spatial densification, for example, dense deployment of small cell and spectrum aggregation, that is, utilizing larger portions of radio spectrum in diverse bands for 5G networks [7]. Moreover, in this densified network architecture, the dense deployment of small cells is limited to indoor scenarios; users in outdoor scenarios are still covered by traditional macrocells. By absorbing the machine-type communication (MTC) traffic via home evolved NodeBs, a new architecture was proposed with the use of small cells to handle the massive and dense MTC rollout [8]. As concluded in [7, 8], these dense wireless networks are complementary to existing macrocell networks.

Considering the backhaul traffic challenge in 5G small cell networks, centralized and distributed wireless backhaul network architectures were compared in [9]. Simulation results suggested that the distributed wireless backhaul network architecture is more suitable for future 5G networks employing massive MIMO antennas and millimeter-wave communication technologies. It is noteworthy that the distributed wireless backhaul network architecture was also discussed for IEEE 802.16 mesh networks in [10]. Considering that the radius of IEEE 802.16 BSs is typically 1500 m, which is much larger than the 50–100 m radius of small cells, IEEE 802.16 mesh networks are not ultra-dense wireless networks. Therefore, the small cell density deployment bottleneck is not a problem for IEEE 802.16 mesh networks. With millimeter-wave communication emerging in 5G mobile communication systems, millimeter-wave communication has been considered the wireless backhaul solution for small cell networks. However, most studies on millimeter-wave backhaul technologies focused on the design of the antenna array and RF components of transceivers, such as beamforming and modulation schemes [11, 12]. An efficient beam alignment technique using adaptive subspace sampling and hierarchical beam codebooks was proposed for implementation in small cell networks [11]. The feasibility of short- and medium-distance links at millimeter-wave frequencies was evaluated for wireless backhauling, and the requirements for the transceiver architecture and technologies were analyzed in [12].

However, in all the aforementioned ultra-dense wireless network studies, only simple scenarios, such as indoor scenarios, were considered, and only basic features of 5G networks were discussed. Besides, system-level investigation of ultra-dense cellular networks with millimeter-wave backhaul is lacking in the open literature. Although the distributed network architecture is recommended for ultra-dense cellular networks, the constraints and performance limits of ultra-dense cellular networks employing distributed network architecture are not clear. Moreover, a key question, that is, how dense can small cells be deployed in 5G ultra-dense cellular networks before the performance benefits fade, has not been investigated.

In this article, we propose a distributed architecture for ultra-dense cellular networks with single and multiple gateways, which can be deployed in all 5G cellular scenarios. Furthermore, based on our early proposed network capacity relationship in wireless multihop networks, the impact of different numbers of small cell BSs on the backhaul network capacity and the backhaul energy efficiency of ultra-dense cellular networks is investigated. Simulation results demonstrate that there is a density threshold of small cells in ultra-dense cellular networks. When the density of ultra-dense cellular networks is larger than the density threshold, the backhaul network capacity and the backhaul energy efficiency of ultra-dense cellular networks will reduce with a further increase in small cell density. Finally, future challenges of 5G ultra-dense cellular networks are discussed, and conclusions are drawn.

With the development of massive MIMO antennas and millimeter-wave communication technologies in 5G mobile communication systems, a large number of small cells will be deployed to form 5G ultra-dense cellular networks. Therefore, the first challenge is how to design the architecture of 5G ultra-dense cellular networks.

ARCHITECTURE OF 5G ULTRA-DENSE CELLULAR NETWORKS

With the development of massive MIMO antenna and millimeter-wave communication technologies in 5G mobile communication systems, a large number of small cells will be deployed to form 5G ultra-dense cellular networks. Therefore, the first challenge is how to design the architecture of 5G ultra-dense cellular networks. In this section, the distributed architecture of ultra-dense cellular networks with single and multiple gateways is proposed for further evaluation in the following sections.

CONVENTIONAL CELLULAR NETWORK ARCHITECTURE

The conventional cellular network architecture is a type of tree network architecture, where every macrocell BS is controlled by the BS managers in the core network, and all backhaul traffic is forwarded to the core network by the given gateway. In order to support microcell deployment (e.g., femtocell, picocell, and hotspot deployment), a hybrid architecture is presented for conventional cellular networks with microcell deployment. In this hybrid network architecture, the microcell network is also configured as a type of tree network architecture, where every microcell BS is controlled by microcell BS managers in the core network, and the backhaul traffic of microcell BSs is forwarded to the core network by the broadband Internet or fiber links. The coverage of microcells is overlapped with the coverage of macrocells. Compared to macrocell BSs, microcell BSs can provide high-speed wireless transmission in indoor and hotspot scenarios. Both the macrocell BS and microcell BS can independently transmit user data and management data to associated users. Users can hand over in macrocells and microcells according to their requirements. Moreover, the handover process is controlled by macrocell and microcell managers in the core network. In this network architecture, the microcell network is complementary to the conventional macrocell network to satisfy high-

In 5G ultra-dense cellular scenarios, to solve the mobile user frequent handover problem in small cells, the macrocell BS is configured only to transmit the management data for controlling the user handover in small cells and the small cell BS takes charge of the user data transmission. Therefore, the small cell network is not a complement for the macrocell network.

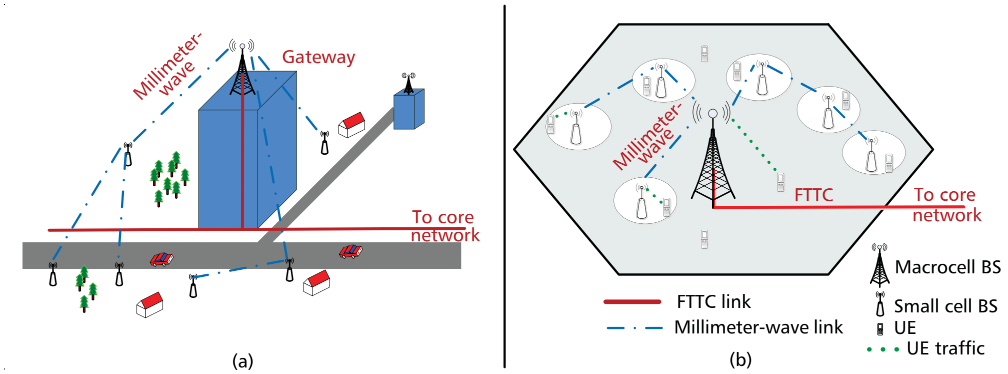

Figure 1. Distributed ultra-dense cellular networks with a single gateway: a) the deployment scenario with a single gateway; b) the logical architecture with a single gateway.

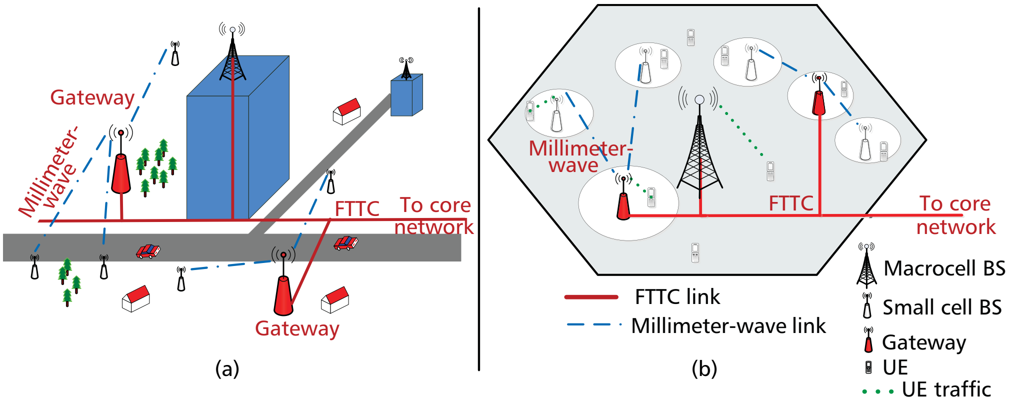

Figure 2. Distribution ultra-dense cellular network with multiple gateways: a) the deployment scenario with multiple gateways; b) the logical architecture with multiple gateways.

speed wireless transmission in partial regions (e.g., indoor and hotspot scenarios).

DISTRIBUTION ARCHITECTURE OF ULTRA-DENSE CELLULAR NETWORKS

Motivated by the massive MIMO antenna and millimeter-wave communication technologies, the densification deployment of small cells is emerging in 5G cellular networks. However, it is difficult to forward the backhaul traffic of every small cell BS by broadband Internet or fiber links considering the cost and geographic deployment challenges in urban environments. Moreover, the small cell BS usually cannot directly transmit wireless backhaul traffic to a given gateway since small cell BSs adopting millimeter-wave technology restrict the wireless transmission distance. In this case, the wireless backhaul traffic has to be relayed to the given gateway by multihop links. As a consequence, a distributed network architecture is a reasonable solution for 5G ultra-dense cellular networks. In 5G ultra-dense cellular scenarios, to solve the mobile user frequent handover problem in small cells, the macrocell BS is configured only to transmit the management data to control the user handover in small cells, and the small cell BS takes charge of the user data transmission. Therefore, the small cell network is not a complement for the macrocell network. 5G ultra-dense cellular networks are jointly composed of small cells and macrocells. Based on the backhaul gateway configuration, two distribution architectures of ultra-dense cellular networks are proposed as follows.

Ultra-Dense Cellular Networks with a Single Gateway: When only one gateway is deployed in the macrocell, the corresponding scenario and logical figures are illustrated in Fig. 1. Without loss of generality, the gateway is configured at the macrocell BS, which usually has enough space to install massive MIMO millimeter-wave antennas for receiving the wireless backhaul traffic from small cells in the macrocell. The backhaul traffic of a small cell BS is relayed to the adjacent small cell BS by millimeter-wave links. All backhaul traffic of small cells is finally forwarded to the macrocell BS by multihop millimeter-wave links. In the end, the backhaul traffic aggregated at the macrocell BS is forwarded to the core network by fiber to the cell (FTTC) links.

Ultra-Dense Cellular Networks with Multiple Gateways: In the distribution architecture of ultra-dense cellular networks, multiple gateways deployment is flexible for forwarding the backhaul traffic into the core network. In this case, gateways are deployed at multiple small cell BSs according to the requirement of backhaul

Network types	Conventional cellular networks	Ultra-dense cellular networks with a single gateway	Ultra-dense cellular networks with multiple gateways
Network architecture	Centralized architecture	Distributed architecture [9]	Distributed architecture
Densification deployment target	Macrocells [4]	Small cells	Small cells
Densification deployment reason	Satisfy crowded communication requirements in urban scenarios	Massive MIMO antennas and millimeter-wave communication technologies [7]	Massive MIMO antennas and millimeter-wave communication technologies
Coverage between macrocells and microcells	Overlap [7]	No overlap	No overlap
Functions of macrocell and microcell	Same [7]	Macrocells transmit management data, microcells transmit user data	Macrocells transmit management data, microcells transmit user data
Microcells/small cells deployment	Deployed in partial areas	Deployed in all cellular scenarios	Deployed in all cellular scenarios
Backhaul method	Backhaul traffic is directly forwarded into the core network by the gateway [9]	Backhaul traffic is relayed to the gateway by multihop wireless links	Backhaul traffic is relayed to the gateway by multihop wireless links
Number of backhaul gateways in a macrocell	One	One	Multiple
Merit	Flexible deployment and low cost [3]	Ubiquitous and high bit rate [4]	Ubiquitous and high bit rate
Demerit	Small cell partial deployment, low network capacity, uneven distribution of the achievable data [4]	Low mobility and the backhaul capacity bottleneck	Low mobility and high cost

Table 1. Comparison between conventional cellular networks and 5G ultra-dense cellular networks.

traffic and geography scenarios. In Fig. 2, the backhaul traffic of a small cell BS is relayed to the adjacent small cell BS by millimeter-wave links. Different from the single gateway configuration, the backhaul traffic of small cells will be distributed into multiple gateways in the macrocell. The backhaul traffic aggregated at the specified small cell BS, that is, the gateway, is finally forwarded into the core network by FTTC links. Detailed scenario and logical figures are illustrated in Figs. 2a and 2b.

Based on the comparison results shown in Table 1, the detailed differences between conventional cellular networks and 5G ultra-dense cellular networks with single/multiple gateways are explained as follows: the architecture of conventional cellular networks is a centralized network architecture, and some microcells are densely deployed in partial areas (e.g., urban areas) to satisfy crowded communication requirements. When 5G small cell BSs are equipped with massive MIMO antennas and millimeter-wave communication technologies, the coverage of a small cell is obviously reduced. To realize seamless coverage, 5G cellular networks must be densely deployed by a large number of small cells. In this case, 5G ultra-dense cellular networks can provide high bit rates in all cellular coverage regions. Moreover, the architecture of ultra-dense cellular networks is distributed, considering cost and geographic deployment requirements. Every BS in conventional cellular networks has the same function, and the coverage of macrocells and microcells overlaps. For 5G ultra-dense cellular networks, macrocell BSs transmit the management data, and small cell BSs take charge of the user data transmission. There is no overlap of the function and coverage between macrocell BSs and small cell BSs. Besides, 5G ultra-dense cellular networks with single gateways are cost efficient, but the backhaul capacity bottleneck may exist at the single gateway. 5G ultra-dense cellular networks with multiple gateways experience high cost of small cell deployment. Compared to conventional cellular networks, 5G ultra-dense cellular network performance will provide graceful degradation as the degree of mobility increases. To overcome this challenge, multi-cell cooperative communication is a potential solution for 5G ultra-dense cellular networks.

BACKHAUL NETWORK CAPACITY AND BACKHAUL ENERGY EFFICIENCY

Although the density of small cells can approach infinity in theory, it is unrealistic to deploy ultra-dense cellular networks with infinite density in practical engineering applications. The impact of the deployment density of ultra-dense cellular networks on the backhaul network capacity and energy efficiency is investigated in the following.

Parameters	Values
Number of backhaul gateways in a macrocell	3
Radius of small cell *r*	100 m, 150 m, 200 m
Radius of macrocell	1 km
Parameter *a*	7.85
Parameter *b*	71.5 W
Normalized BS backhaul transmission power P_{Norm}	1 W
Normalized BS backhaul throughput Th_0	1 Gb/s
Lifetime of small cell BS $T_{Lifetime}$	5 years
Embodied energy consumption E_{EM}	20 percent of total energy consumption

Table 2. Simulation parameters.

BACKHAUL NETWORK CAPACITY OF ULTRA-DENSE CELLULAR NETWORKS

How much densification can be deployed in ultra-dense cellular networks is a key question for future 5G network designs. Utilizing massive MIMO antenna and millimeter-wave communication technologies, the small cell is anticipated to provide more than 1 Gb/s throughput in 5G ultra-dense cellular networks. But all small cell throughput has to be forwarded into the core network by wireless backhaul networks. Therefore, the backhaul network capacity will be a bottleneck constraining the small cell densification in 5G ultra-dense cellular networks. The wireless multihop relay backhaul scheme of ultra-dense cellular networks is defined as follows:

- The closest gateway is selected by the small cell BS for receiving backhaul traffic.
- Two conditions should be satisfied for the small cell BS which is selected for the next hop candidate:
  ① The distance between the transmitter and the receiver is less than or equal to the radius of small cell *r*.
  ② The distance between the next hop small cell BS and the gateway is less than the distance between the transmitter and the gateway.
  ③ When multiple small cell BSs satisfy ① and ②, the small cell BS closing the gateway is selected as the next hop candidate.
- When the distance between the small cell BS and the gateway is less than *r*, the small cell BS directly transmits backhaul traffic to the gateway without relaying. To avoid interference from adjacent small cells, the distance of simultaneous transmission by small cell BSs is configured to be larger than $(1 + \Delta)r$, where $\Delta \times r$ is the interference protection distance in 5G ultra-dense cellular networks.

Based on our early results in [13], a simple relationship is proposed to estimate the backhaul network capacity of ultra-dense cellular networks as follows:

$$\text{Backhaul network capacity } = \frac{Y(n) \times W}{K(n)},$$

where n denotes the number of small cell BSs in a macrocell, $Y(n)$ is the average number of simultaneous transmissions in the macrocell, W is the transmission rate of a small cell BS, and $k(n)$ is the average hop number of wireless backhaul traffic in the macrocell. Without loss of generality, the 5G ultra-dense cellular network with multiple gateways shown in Fig. 2 is considered for the following simulation analysis. The macrocell is assumed to be a regular hexagon with 1 km radius. Small cell BSs are scattered following a Poisson point process in a macrocell. All small cells are assumed not to overlap each other in coverage. Moreover, three gateways are assumed to be symmetrically deployed at the top vertices of the hexagon macrocell. The interference safeguard distance is configured as $0.5 \times r$, and the transmission rate of a small cell BS is normalized as 1 Gb/s in the following simulations. The detailed simulation parameters are configured in Table 2.

Based on the Monte Carlo simulation method, the backhaul network capacity and energy efficiency of ultra-dense cellular networks are simulated in Figs. 3 and 4, respectively. When the radius of small cell *r* is fixed, the backhaul network capacity with respect to the number of small cell BSs is illustrated in Fig. 3a: the backhaul network capacity first increases with the increase in the number of small cell BSs; after the backhaul network capacity achieves the maximum threshold, the backhaul network capacity decreases with the increase of the number of small cell BSs; in the end, the backhaul network capacity achieves a stationary saturation value when the number of small cell BSs approaches infinity. When the radius of small cell *r* is fixed, the backhaul network capacity with respect to the average number of simultaneous transmissions is described in Fig. 3b: considering the interference protection distance $\Delta \times r$ configured by the wireless multihop relay backhaul scheme, the maximum average number of simultaneous transmissions decreases with the increase of small cell radius when the macrocell coverage is fixed. For example, the maximum average number of simultaneous transmissions is 29, 25, and 19 when the radius of small cell is configured as 100 m, 150 m, and 200 m, respectively. The backhaul network capacity increases with the increase of the average number of simultaneous transmissions in the macrocell. Moreover, the backhaul network capacity approaches a saturation limit when the average number of simultaneous transmissions is larger than 27, 23, and 15, which correspond to small cell radii 100 m, 150 m, and 200 m, respectively. When the number of small cell BSs or the average number of simultaneous transmissions is fixed, the backhaul network capacity decreases with increased radius of small cells. Based on simulation results in Fig. 3a, the backhaul network capacity will achieve a stationary saturation value when the average number of simultaneous transmissions or the densit of small cell BSs (i.e., the number of small cell BSs in a macrocell) is larger than a given threshold. This result provides a guideline for designing the densification of 5G ultra-dense cellular networks.

BACKHAUL ENERGY EFFICIENCY OF ULTRA-DENSE CELLULAR NETWORKS

In addition to the backhaul network capacity, the backhaul energy efficiency is another key constraint that restricts the densification of 5G ultra-dense cellular networks. The backhaul energy consumed at the small cell BS is decomposed by the embodied energy E_{EM} and the operation energy E_{OP} [14]. The embodied energy is the energy consumed by all processes associated with the BS production and accounts for 20 percent of the backhaul BS energy consumption in this article. The operation energy is the energy consumed for the backhaul operation in the lifetime T_{Lifetime} and is defined by $E_{\mathrm{OP}} = P_{\mathrm{OP}} \times T_{\mathrm{Lifetime}}$, where P_{OP} is the BS operating power. Without loss of generality, the small cell BS operating power is assumed as a linear function of the small cell BS backhaul transmission power P_{TX} and is expressed as $P_{\mathrm{OP}} = a \times P_{\mathrm{TX}} + b$, where $a = 7.84$ and $b = 71.5$ W [15]. In general, the BS backhaul transmission power depends on the BS backhaul throughput. To simplify the model derivation, the backhaul transmission power of a small cell BS is normalized as $P_{\mathrm{Norm}} = 1$ W when the normalization BS backhaul throughput Th_0 is assumed to be 1 Gb/s. Similarly, the small cell BS backhaul transmission power with the average BS backhaul throughput Th_{Avg} is denoted by $P_{\mathrm{TX}} = P_{\mathrm{Norm}} \times (Th_{\mathrm{Avg}}/Th_0)$, where the average small cell BS backhaul throughput is calculated by the backhaul network capacity [13]. Furthermore, the small cell BS operating power is calculated by $P_{\mathrm{OP}} = a \times P_{\mathrm{Norm}} \times (Th_{\mathrm{Avg}}/Th_0) + b$. In the end, the backhaul energy efficiency of ultra-dense cellular networks is derived by

$$\text{Backhaul energy efficiency} = \frac{\text{backhaul network capacity}}{n \times (\text{small cell BS backhaul energy consumption})}.$$

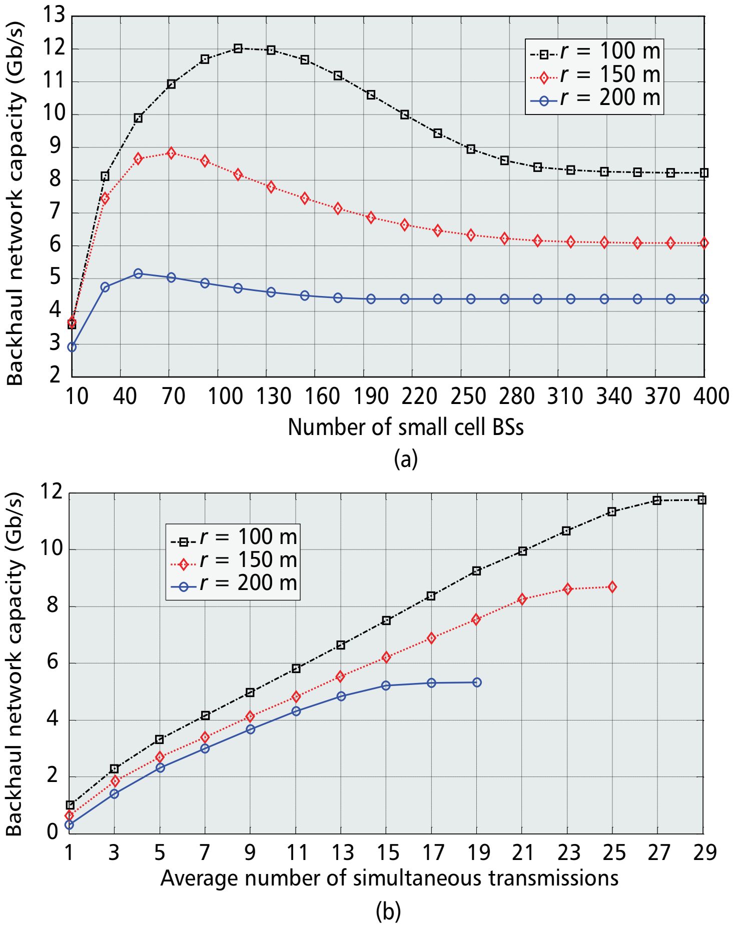

Figure 3. Backhaul network capacity of ultra-dense cellular networks: a) the backhaul network capacity vs. the number of small cell BSs; b) the backhaul network capacity vs. the average number of simultaneous transmissions.

Without loss of generality, the lifetime of a small cell BS is configured as $T_{\mathrm{Lifetime}} = 5$ years. When the radius of a small cell r is fixed, the backhaul energy efficiency of ultra-dense cellular networks with respect to the number of small cell BSs is analyzed in Fig. 4a: the backhaul energy efficiency first increases with the increase of the number of small cell BSs; then the backhaul energy efficiency decreases with the increase of the number of small cell BSs after the backhaul energy efficiency reaches the maximum threshold; in the end, the backhaul energy efficiency of ultra-dense cellular networks achieves a stationary saturation value when the number of small cell BSs approaches infinity. When the number of small cell BSs is fixed, the backhaul energy efficiency increases with the increase of the small cell radius when the number of small cell BSs is less than 10. When the number of small cell BSs is larger than or equal to 10, the backhaul energy efficiency decreases with the increase of the small cell radius. When the radius of small cell r is fixed, the backhaul energy efficiency with respect to the average small cell BS throughput is illustrated in Fig. 4b: the backhaul energy efficiency first increases with the increase of the average small cell BS throughput; then the backhaul energy efficiency decreases with the increase of the average small cell BS throughput after the backhaul energy efficiency achieves the maximum threshold; in the end, the backhaul energy efficiency of ultra-dense cellular networks achieves a stationary saturation value when the average small cell BS throughput is larger than 0.35, 0.45, and 0.5 Gb/s, which correspond to small cell radii 200, 150, and 100 m.

FUTURE CHALLENGES

As discussed in the above sections, the emergence of ultra-dense cellular networks is motived by massive MIMO antenna and millimeter-wave communication technologies. Moreover, the distribution network architecture is a reasonable solution for 5G ultra-dense cellular networks. From the results in Table 1, it is obvious that the ultra-dense cellular network would bring great changes in future 5G cellular networks. Therefore, the ultra-dense cellular network is one of the most important challenges for future 5G cellular networks. Some potential challenges are presented here.

The first challenge is the multihop relay opti-

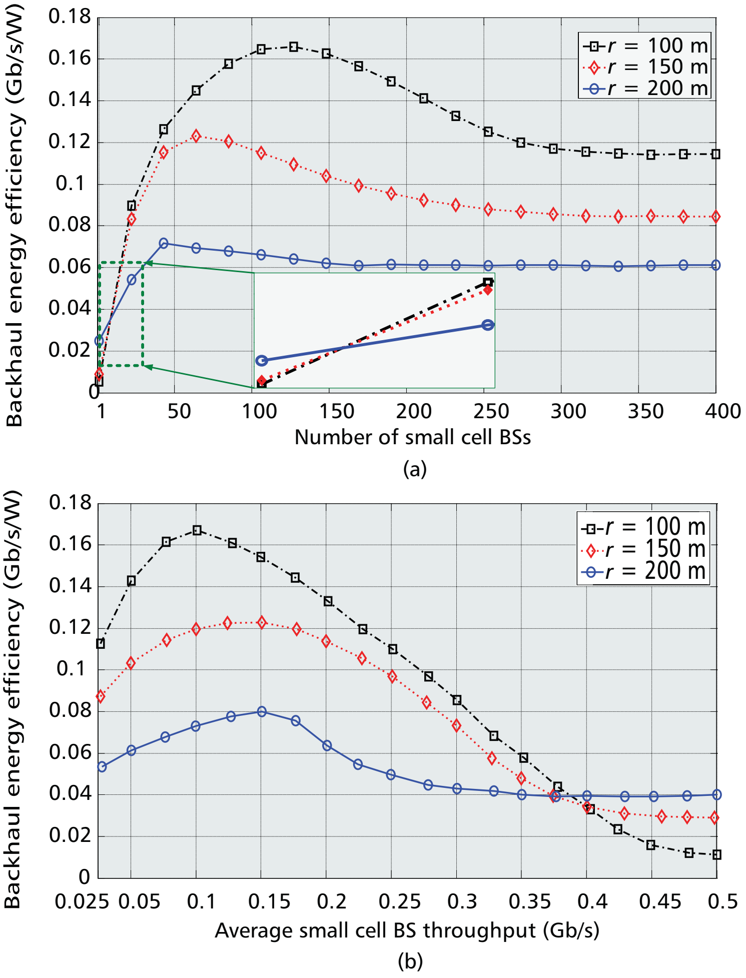

Figure 4. Energy efficiency of ultra-dense cellular networks: a) backhaul energy efficiency vs the number of small cell BSs; b) backhaul energy efficiency vs average small cell BS throughput.

mization in 5G ultra-dense cellular networks. In the distribution network architecture, not only backhaul traffic but also fronthaul traffic needs to be relayed to the destination. The selection of a relay small cell BS should be carefully considered in 5G ultra-dense cellular networks. Hence, the wireless multihop routing algorithm is a key challenge for 5G ultra-dense cellular networks. Although a small cell BS equipped with massive MIMO antennas has enough antennas to simultaneously transmit backhaul traffic and fronthaul traffic, another important challenge is how to reasonably allocate massive antennas for backhaul and fronthaul transmissions. The small cell coverage of ultra-dense cellular networks is obviously less than the macrocell coverage of conventional cellular networks. For a high-speed mobile user, the frequent user handover in small cells not only increases redundant overhead but also decreases the user experience. Moreover, the wireless transmission of small cell BSs equipped with millimeter-wave antennas and beamforming technologies has strong directivity, which has an advantage in high-speed transmission and a disadvantage in covering the high-speed mobile user. The cooperative transmission of small cells is a potential solution to this problem. How to organize adjacent small cells for cooperative transmission is the second challenge for 5G ultra-dense cellular networks. For example, how to dynamically group small cells for seamlessly covering the high-speed mobile user track is an open issue. With the emergence of millimeter-wave communication technology for 5G wireless transmission, the beamforming method will be widely used. When the beamforming method is performed by massive MIMO antennas, the computation scale of the beamforming method and the computation power of wireless transceivers will obviously be increased by the large scale of signal processing in BS baseband processing systems. Therefore, the proportion between the computation power and transmission power may be reversed at wireless transceivers adopting massive MIMO antenna and millimeter-wave communication technologies. In this case, the computation power cannot be ignored for the BS energy consumption. Considering the proportion change between computation power and transmission power, the new energy efficiency model needs to be investigated for ultra-dense cellular networks with massive MIMO antenna and millimeter-wave communication technologies. To face the above challenges in 5G ultra-dense cellular networks, some potential research directions are summarized to solve these issues:

- A new multihop relay scheme and distributed routing algorithm should be developed for 5G ultra-dense cellular networks.
- Massive MIMO antennas and millimeter-wave communications provide enough resource space for small cell BSs. How to utilize and optimize the resource allocation for BS relaying and self-transmission is a critical problem in 5G ultra-dense cellular networks;
- Cooperative and backhaul transmission will become important directions in future 5G ultra-dense cellular networks.
- Motived by massive MIMO antenna and millimeter-wave communication technologies, the computation power consumed for BS baseband processing systems need to be rethought for 5G ultra-dense cellular networks.

Conclusions

Until recently, ultra-dense wireless networks have mainly been deployed only in parts of networks, such as indoor and hotspot scenarios. Ultra-dense wireless networks are still considered as complementary to cellular networks with centralized network architecture. Nassive MIMO antenna and millimeter-wave communication technologies enable 5G ultra-dense cellular networks to be deployed in all cellular scenarios. In this article, a distributed network architecture with single and multiple gateways are presented for 5G ultra-dense cellular networks. Considering the millimeter-wave communication technology, the impact of small cell BS density on the backhaul network capacity and energy efficiency of ultra-dense cellular networks is investigated. Simulation results indicate that there is a density threshold of small cells in ultra-dense cellular networks. When the density of ultra-dense cellular networks is larger than the density threshold, the backhaul network capacity and energy efficiency of ultra-dense cellular networks will decrease with further increase in small cell density. These results provide some guidelines for the optimum deployment of 5G ultra-dense cellular networks.

In 2G and 3G mobile communication systems, the wireless communication system was considered as a noised-limited communication system. With MIMO antenna technology being adopted in 4G mobile communication systems, the wireless communication system has transitioned into an interference-limited communication system. In this article, it has been shown that there is a maximum backhaul network capacity corresponding to a given number of small cell BSs in a macrocell, referred to by us as the density threshold of an ultra-dense cellular network. When the density of ultra-dense cellular networks, measured by the number of small cells per macrocell, is larger than the density threshold, the backhaul network capacity will reduce with a further increase in the density. Moreover, a similar bottleneck is also observed in the backhaul energy efficiency of ultra-dense cellular networks. As a consequence, we conclude that the 5G ultra-dense cellular network is a density-limited communication system. How to analytically determine the optimum density of small cell BSs in 5G ultra-dense cellular networks is an open issue. If this is done, a difficult challenge would indeed emerge in the next round of the telecommunications revolution.

We conclude that the 5G ultra-dense cellular network is a density-limited communication system. How to analytically determine the optimum density of small cell BSs in 5G ultra-dense cellular networks is an open issue. If this is done, a difficult challenge would indeed emerge in the next round of the telecommunications revolution.

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BIOGRAPHIES

XIAOHU GE [M'09, SM'11] (xhge@hust.edu.cn) is currently a full professor with the School of Electronic Information and Communications at Huazhong University of Science and Technology (HUST), China, and an adjunct professor with the Faculty of Engineering and Information Technology at the University of Technology Sydney (UTS), Australia. He received his Ph.D. degree in communication and information engineering from HUST in 2003. He serves as an Associate Editor for *IEEE Access*, the *Wireless Communications and Mobile Computing Journal*, and other publications.

SONG TU (u201013039@hust.edu.cn) received his B.E. degrees from HUST in 2014. Now he is working toward a Master's degree in the School of Electronic Information and Communications at HUST. His research interests are in the area of green communications and distributed wireless networks.

GUOQIANG MAO [S'98, M'02, SM'08] (g.mao@ieee.org) is a professor of wireless networkingand director of the Center for Real-Time Information Networks at UTS. He has published more than 100 papers in international conferences and journals, which have been cited more than 3000 times.

CHENG-XIANG WANG [S'01, M'05, SM'08] (cheng-xiang.wang@hw.ac.uk) received his Ph.D. degree from Aalborg University, Denmark, in 2004. He has been with Heriot-Watt University since 2005 and became a professor in 2011. His research interests include wireless channel modeling and 5G wireless communication networks. He has served or is serving as an Editor or Guest Editor for 11 international journals, including *IEEE Transactions on Vehicular Technology* (2011–present), *IEEE Transactions on Wireless Communications* (2007–2009), and the *IEEE Journal on Selected Areas in Communications*. He has published one book and over 210 papers in journals and conferences.

TAO HAN [M'13] (hantao@hust.edu.cn) received his Ph.D. degree in communication and information engineering from HUST in December 2001. He is currently an associate professor with the School of Electronic Information and Communications, HUST. His research interests include wireless communications, multimedia communications, and computer networks.