Wireless Backhaul Capacity of 5G Ultra-Dense Cellular Networks

(Invited paper)

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***Abstract*—With the growth of wireless transmission rate on user terminals, the backhaul network capacity becomes a bottleneck for improving the performance of future 5G ultra-dense cellular networks. Based on the wireless multi-hop relay technology, the backhaul network capacity of 5G ultra-dense cellular networks with multi-gateways is analyzed in this paper. Moreover, a minimum average hop number (MAN) algorithm is developed to improve the backhaul network capacity and energy efficiency of wireless backhaul networks for 5G ultra-dense cellular networks. Simulation results indicate there exist a stationary backhaul network capacity and a maximum energy efficiency of wireless backhaul networks when the density of small cell BSs is larger than the specified threshold.**

I. INTRODUCTION

With the development of massive multiple input multiple output (MIMO) and millimeter wave transmission technologies in the fifth generation (5G) mobile communication systems, the cell size is obviously reduced since the wireless propagation fading is serious in millimeter wave frequency bands [1]. Therefore, small cells are emerging into 5G cellular networks. To realize the seamless coverage in 5G cellular networks, a large number of small cells are deployed in urbans and form 5G ultra-dense cellular networks [2]. However, it is difficult for every small cell base station (BS) to be connected with the fiber to the cell (FTTC) in urban scenarios. It is a great challenge to forward the backhaul traffic of small cell BSs into core networks. The wireless backhaul network is an inevitable solution for 5G ultra-dense cellular networks [3].

5G ultra-dense wireless networks have become a hot point in academics and industries [4]–[7]. Considering the resource requirement of small cells clustering, a two-step joint clustering and scheduling (TS-JCS) scheme was proposed to improve the performance of ultra-dense cellular networks [4]. A distributed scheduling with interference aware power control was proposed for an uplink of the ultra-dense networks operating with time-division duplex (TDD), which would outperform the existing distributed user scheduling schemes when the threshold of the proposed scheduling was carefully chosen [5]. A framework was introduced for indoor planning of dense cellular networks based on millimeter wave communications, which would provide extremely high data rates to indoor users according to the traffic expectations of 5G mobile communication systems [6]. Although network densification increases the spatial frequency reuse efficiency, control signaling in such dense networks consumes considerable bandwidth and limits the densification gain. A tractable analytical model was presented for control plane and user plane splitting downlink cellular networks and the performance gain obtained via control and data splitting was quantified [7].

When the wireless transmission rate is greatly improved to satisfy the massive traffic from user requirements in 5G communication systems, how to solve the backhaul traffic is an important problem for future 5G cellular networks. Compared with the half-duplex backhauling, the full-duplex backhauling technologies were proved to improve the capacity of wireless backhauling for small cell networks [8]. A digitally controlled phase shifter network (DPSN)-based hybrid precoding/combining scheme and the associated compressive sensing (CS)-based channel estimation scheme were proposed to realize the desired point-to-multipoint (P2MP) backhaul topology and beam-division multiplexing (BDM)-based scheduling which can be facilitated for in-band backhaul over millimeter waves [9]. On the other hand, the energy efficiency of backhaul networks is an important issue and some potential solutions are explored in [10], [11]. Two low-complexity resource allocation algorithms were developed to solve the problem of energy efficiency maximization in the uplink of a cluster of multiple-antenna coordinated access points for future 5G networks [10]. Pervaiz *et al.* proposed two algorithms to jointly optimize energy efficiency and spectrum efficiency such that the network providers could dynamically tune the trade-off parameter for different design requirements in 5G small cell networks [11].

However, in all the aforementioned backhaul network studies, only conventional transmission technologies, such as FTTC technologies, were considered and wireless backhaul transmissions were limited in one hop wireless transmissions. Besides, the wireless backhaul network capacity of 5G ultra-dense cellular networks has not been investigated. Motivated

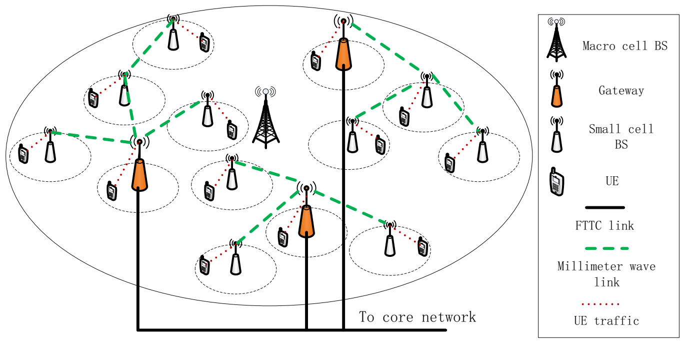


Fig. 1. 5G ultra-dense cellular networks.

by above gaps, in this paper we develop a minimum average hop number (MAN) algorithm to evaluate the backhaul network capacity and energy efficiency of wireless backhaul networks. The contributions and novelties of this paper are summarized as fellows.

1) The backhaul network capacity is analyzed for 5G ultra-dense cellular networks based on multi-hop relay technologies and multi-gateways configurations.
2) A MAN algorithm is developed for wireless backhaul networks. Simulation analysis is illustrated to evaluate the backhaul network capacity and energy efficiency of wireless backhaul networks.

The rest of this paper is organized as follows. Section II describes the system model of wireless backhaul networks. Considering the multi-hop relay technology and multi-gateway configurations, the backhaul network capacity of 5G ultra-dense cellular networks is derived in Section III. Furthermore, a MAN algorithm is developed to transmit wireless backhaul traffic with the minimum hop number in Section IV. Simulation analysis is illustrated in Section V. Finally, Section VI concludes this paper.

II. System Model

A. Distributed Architecture of Wireless Backhaul Networks

To realize the wireless backhaul traffic in 5G ultra-dense cellular networks, a distributed architecture of wireless backhaul network is illustrated in Fig. 1. Without loss of generality, a macro cell with the radius R is configured by a BS which is located at the center of macro cell and controls all wirless backhaul routing at small cells. $n = M + N$ small cell BSs are randomly densely deployed in the macro cell. M small cell BSs connecting with FTTC are configured as gateways for forwarding the backhaul traffic into the core network. The other N small cell BSs forward their backhaul traffic into M gateways in the macro cell. Assuming that the wireless backhaul traffic is transmitted by the millimeter wave transmission technology, every small cell BS has enough bandwidth for wireless backhaul transmissions. In this paper, the backhaul traffic of small cell BSs is forwarded into gateways by wireless multi-hop relay scheme in 5G ultra-dense cellular networks.

B. Backhaul Network Capacity

Considering the serious path loss fading in millimeter wave transmissions, the one hop distance of wireless backhaul transmission is less than or equal to D_0 meters in wireless backhaul networks. A small cell BS only connects with other small cell BSs which are located in the range of D_0 for wireless backhaul transmissions.

Without loss of generality, N small cell BSs are assumed to transmit the backhaul traffic to M gateways in the macro cell. The number of bits successfully transmitted from the small cell BS $1 \le i \le N$, to the gateway $1 \le j \le M$, in the time interval $[0, T]$ is denoted as $N_{i,j,T}^{\chi}$, where $\chi \in \Omega$ is a resource allocation scheme in wireless cellular networks, Ω is the set of all resource allocation schemes in temporal and spatial domains. When the same bit is transmitted to different destinations, such as wireless broadcasting, this bit is calculated once in the value of $N_{i,j,T}^{\chi}$. Moreover, the wireless backhaul network is assumed to be stationary for $\forall \chi \in \Omega$, i.e., the traffic coming into the wireless backhaul network is equal to the traffic coming out the wireless backhaul network. Assuming that a resource allocation scheme χ is adopted for wireless backhaul transmission in n small cell BSs, the backhaul transmission capacity is expressed as

$$C^{\chi}(M,N) \triangleq \lim_{T \to \infty} \frac{\sum_{i=1}^{N} \sum_{j=1}^{M} N_{i,j,T}^{\chi}}{T}. \quad (1)$$

Furthermore, the backhaul network capacity is defined by

$$C(M,N) \triangleq \max_{\chi \in \Omega} C^{\chi}(M,N). \quad (2)$$

As a consequence, the energy efficiency of wireless backhaul networks is calculated by

$$e(M,N) \triangleq \frac{C(M,N)}{E_{EM} + E_{OP} + M \cdot E}. \quad (3)$$

where E_{EM} is the total embodied energy of n small cell BSs in wireless backhaul networks, E_{OP} is the total operation energy of n small cell BSs in wireless backhaul networks, E is the additional energy consumption for the gateway after the specified small cell BS is configured as the gateway.

III. Backhaul Network Capacity of 5G Ultra-dense Cellular Network

Assume that all small cell BSs have the same transmission rate and all gateways have the same receive rate in wireless backhaul networks. Considering constraints of transmitters and receivers in wireless backhaul networks, the theorem 1 on the backhaul network capacity is proposed as follows.

Theorem 1: When a wireless backhaul network includes N small cell BSs and M gateways, the backhaul network capacity is calculated by

$$C^{\chi}(M,N) = \frac{\min(N \cdot W_S, M \cdot (W_G - W_S))}{Y^{\chi}(M,N)} + M \cdot W_S,$$

where $Y^{\chi}(M,N)$ is the average wireless transmission number for successfully transmitting a bit data into a gateway, W_G

is the maximum wireless backhaul receive rate at gateways which is configured as the fiber capacity connected with the gateway, W_S is the maximum wireless backhaul transmission rate at small cell BSs which corresponds to the maximum processing rate for the wireless traffic at small cell BSs.

Proof:

The kth bit data transmitted from the BS BS_i to the gateway GT_j is denoted as $b_{i,j,k}$. $h_{i,j,k}^{\chi}$ is the wireless transmission number, i.e., the hop number from the BS BS_i to the gateway GT_j when the resource allocation scheme $\chi \in \Omega$ is adopted in wireless backhaul networks. Therefore, the average wireless transmission number for a bit data successfully transmitted from the BS BS_i to the gateway GT_j is given by [12]

$$Y^{\chi}(M,N) = \lim_{T\to\infty} \frac{\sum\limits_{i=1}^{N}\sum\limits_{j=1}^{M}\sum\limits_{k=1}^{N_{i,j,T}^{\chi}} h_{i,j,k}^{\chi}}{\sum\limits_{i=1}^{N}\sum\limits_{j=1}^{M} N_{i,j,T}^{\chi}}. \tag{4}$$

The total maximum wireless backhaul transmission rate at small cell BSs is $N \cdot W_S$. Considering the gateway needs to forward its own backhaul traffic W_S into the core network, the maximum wireless backhaul receive rate at the gateway used for other small cell BSs is $W_G - W_S$. The total maximum wireless backhaul receive rate at gateways is $M \cdot (W_G - W_S)$. Based on the assumption of the stationary of wireless backhaul networks, the maximum simultaneous transmission rate of wireless backhaul networks is $min\{N \cdot W_S, M \cdot (W_G - W_S)\}$ in any time slots. As a consequence, the maximum average transmission rate at a small cell BS is $min\left\{W_S, \frac{M\cdot(W_G-W_S)}{N}\right\}$ in one time slot.

$\tau_{i,j,k,l}^{\chi}$, $1 \le l \le h_{i,j,k}^{\chi}$ is the average time of the lth hop in the transmission process $b_{i,j,k}$. When the total maximum wireless backhaul transmission rate at small cell BSs satisfies $N \cdot W_S \le M \cdot (W_G - W_S)$, the average time of the lth hop in the process of transmitting $b_{i,j,k}$ is equal to $\tau_{i,j,k,l}^{\chi} = \frac{1}{W_S}$; when the total maximum wireless backhaul transmission rate at small cell BSs satisfies $N \cdot W_S \ge M \cdot (W_G - W_S)$, the average time of the lth hop in the process of transmitting $b_{i,j,k}$ is equal to $\tau_{i,j,k,l}^{\chi} = \frac{N}{M\cdot(W_G-W_S)}$. Therefore, the average time of the lth hop in the process of transmitting $b_{i,j,k}$ is given by $\tau_{i,j,k,l}^{\chi} = \frac{1}{min\left\{W_S, \frac{M\cdot(W_G-W_S)}{N}\right\}}$.

In the time slot $[0,T]$, the total transmission time T_{total} between small cell BSs and gateways is assumed to be equal to the total transmission time at all small cell BSs, i.e., $N{\cdot}T$ in the wireless backhaul network. At time T, the total transmission time during $[0,T]$ is divided by $T_{total} = T_{gate} + T_{norm}$, where T_{gate} is the data arrived time accounting for the transmission time for backhaul traffic that has reached gateways, T_{norm} is the data transmitting time accounting for the transmission time for backhaul traffic still in transit at time T. The data arrived time T_{gate} is calculated by

$$\begin{aligned} T_{gate} &= \sum_{i=1}^{N}\sum_{j=1}^{M}\sum_{k=1}^{N_{i,j,T}^{\chi}}\sum_{l=1}^{h_{i,j,k}^{\chi}} \tau_{i,j,k,l}^{\chi} \\ &= \frac{1}{\min\{W_S, \frac{M\cdot(W_G-W_S)}{N}\}} \cdot \sum_{i=1}^{N}\sum_{j=1}^{M}\sum_{k=1}^{N_{i,j,T}^{\chi}} h_{i,j,k}^{\chi}. \end{aligned} \tag{5}$$

y_{max}^{χ} is the maximum hop number of routing lines in wireless backhaul networks considering the resource allocation scheme χ. It is obviously $y_{max}^{\chi} \le N$ since there does not exist a ring in the routing lines of wireless backhaul networks. When y_{max}^{χ} is equal to N, it indicates that there exists a routing line passing through all small cell BSs in wireless backhaul networks. Considering the stationary of wireless backhaul networks, there exists a positive constant α and the transmitting data at small cell BSs is less than or equal to αN. Therefore, the data transmitting time is calculated by

$$\begin{aligned} T_{norm} &\le y_{\max}^{\chi} \alpha N \tau_{i,j,k,l}^{\chi} \\ &\le \alpha N^2 \tau_{i,j,k,l}^{\chi} \\ &= \frac{\alpha N^2}{\min\{W_S, \frac{M\cdot(W_G-W_S)}{N}\}}. \end{aligned} \tag{6}$$

Based on results in (5) and (6), the following results are derived as

1) when $N \cdot W_S \le M \cdot (W_G - W_S)$, $T_{total} = N \cdot T$ and then $\frac{1}{W_S} \cdot \sum\limits_{i=1}^{N}\sum\limits_{j=1}^{M}\sum\limits_{k=1}^{N_{i,j,T}^{\chi}} h_{i,j,k}^{\chi} + T_{norm} = N \cdot T$;
2) when $N \cdot W_S > M \cdot (W_G - W_S)$, $T_{total} = N \cdot T$ and then $\frac{N}{M\cdot(W_G-W_S)} \cdot \sum\limits_{i=1}^{N}\sum\limits_{j=1}^{M}\sum\limits_{k=1}^{N_{i,j,T}^{\chi}} h_{i,j,k}^{\chi} + T_{norm} = N \cdot T$.

When the time interval $[0,T]$ is large enough, the data transmitting time T_{norm} can be ignored since the data arrived at gateways is much more than the data still transmitting at small cell BSs in wireless backhaul networks. As a consequence, we have the following results

$$\begin{cases} \lim\limits_{T\to\infty} \frac{\sum\limits_{i=1}^{N}\sum\limits_{j=1}^{M}\sum\limits_{k=1}^{N_{i,j,T}^{\chi}} h_{i,j,k}^{\chi}}{N\cdot W_S \cdot T} = 1, N \cdot W_S \le M \cdot (W_G - W_S) \\ \lim\limits_{T\to\infty} \frac{\sum\limits_{i=1}^{N}\sum\limits_{j=1}^{M}\sum\limits_{k=1}^{N_{i,j,T}^{\chi}} h_{i,j,k}^{\chi}}{M\cdot(W_G-W_S)\cdot T} = 1, N \cdot W_S > M \cdot (W_G - W_S) \end{cases} \tag{7}$$

Accounting for (1) and (4), the backhaul network capacity is expressed by

$$C^{\chi}(M,N) = \begin{cases} \frac{N\cdot W_S}{Y^{\chi}(M,N)}, N \cdot W_S \le M \cdot (W_G - W_S) \\ \frac{M\cdot(W_G-W_S)}{Y^{\chi}(M,N)}, N \cdot W_S > M \cdot (W_G - W_S) \end{cases} \tag{8}$$

When the maximum wireless backhaul transmission rate W_S

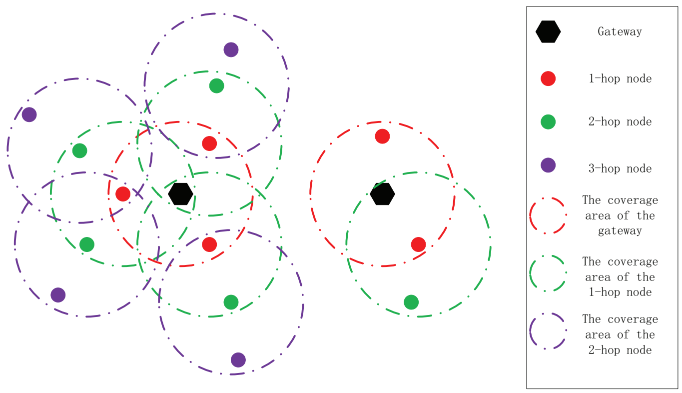


Fig. 2. Minimum average hop number of wireless backhaul traffic in the macro cell.

at gateways is included, (8) is extended as

$$C^{\chi}(M,N) = \begin{cases} \frac{N\cdot W_S}{Y^{\chi}(M,N)} + M\cdot W_S, N\cdot W_S \le M\cdot(W_G - W_S) \\ \frac{M\cdot(W_G - W_S)}{Y^{\chi}(M,N)} + M\cdot W_S, N\cdot W_S > M\cdot(W_G - W_S) \end{cases}. \quad (9)$$

i.e.,

$$C^{\chi}(M,N) = \frac{\min(N\cdot W_S, M\cdot(W_G - W_S))}{Y^{\chi}(M,N)} + M\cdot W_S. \quad (10)$$

Based on results of (3) and (10), the energy efficiency of wireless backhaul networks is given by

$$e(M,N) = \frac{\min(N\cdot W_S, M\cdot(W_G - W_S))}{(E_{EM} + E_{OP} + M\cdot E)\cdot Y^{\chi}(M,N)} + \frac{M\cdot W_S}{E_{EM} + E_{OP} + M\cdot E}. \quad (11)$$

IV. Minimum Average Hop Number Algorithm

In the Fig. 1, the wireless backhaul traffic is forwarded to the gateways by multi-hop relay scheme in 5G ultra-dense cellular networks. In this case, the average hop number $Y^{\chi}(M,N)$ of wireless backhaul traffic depends on the number and positions of small cell BSs and gateways in 5G ultra-dense cellular networks. To maximize the backhaul network capacity, the minimizing average hop number of wireless backhaul traffic $\min_{\chi\in\Omega} Y^{\chi}(M,N)$ is an effective approach, i.e.,

$$C(M,N) = \frac{\min(N\cdot W_S, M\cdot(W_G - W_S))}{\min\limits_{\chi\in\Omega} Y^{\chi}(M,N)} + M\cdot W_S. \quad (12)$$

Based on 5G ultra-dense cellular network scenarios, a solution of the minimum average hop number of wireless backhaul traffic is illustrated in Fig. 2. The detail description of MAN algorithm is presented in Algorithm MAN.

V. Simulation Results and Discussion

Based on the proposed backhaul network capacity and MAN algorithm, Monte Carlo simulation results are analyzed in detail in this section. The default parameters used for simulations are as fellows: the radius of macro cell is configured as R=500 meters, the one hop distance used for wireless backhaul transmission is D_0=200 meters, the maximum wireless backhaul transmission rate at small cell BSs is W_S=1 Gbps, the maximum wireless backhaul receive rate at gateways is W_G=100 Gbps. The operation energy of wireless backhaul networks in the total production lifetime is calculated by

$$E_{OP} = P_{OP}\cdot T_{Lifetime} = (P_{OP1} + P_{OP2})\cdot T_{Lifetime}, \quad (13a)$$

$$P_{OP1} = M\cdot(a\cdot P_{TX1} + b) = M\cdot(a\cdot P_{Norm}\cdot W_G/W_0 + b), \quad (13b)$$

$$P_{OP2} = N\cdot(a\cdot P_{TX2} + b) = N\cdot(a\cdot P_{Norm}\cdot W_S/W_0 + b), \quad (13c)$$

where the lifetime of small cell BSs is assumed to be $T_{Lifetime} = 5$ years, P_{OP1} is the operating power consumed by M gateways in wireless backhaul networks, P_{OP2} is the operating power consumed by N small cell BSs in wireless backhaul networks, two parameters in (13b) and (13c) are configured as a=7.84, b=71.5 Watt [13]. The normalized transmission power at small cell BSs is configured as $P_{Norm} = 1$ Watt when the transmission rate of small cell BSs is $W_0 = 1$Gbps. The embodied energy of wireless backhaul networks E_{EM} is configured as 20% of the sum power consumption of E_{EM} and E_{OP}. The additional energy consumption for the gateway is configured as $E = 1$GJ. To compare the impact of the distribution of small cell BSs on wireless backhaul networks, the distributions of small cell BSs are configured as the uniform distribution and the Poisson distribution for simulation analysis, respectively. In fact, the Poisson distribution in a circle is a kind of uniform distribution without border effects. A possible approach to simulate Poisson distribution nodes in a circle can be found in [14].

Fig. 3 illustrates the minimum average hop number with respect to the density of small cell BSs considering different numbers of gateways in wireless backhaul networks. The minimum average hop number decreases with the increase of the density of small cell BSs. Moreover, the minimum average hop number decreases with the increase of the number of gateways. Comparing curves in Fig. 3(a) and Fig. 3(b), the minimum average hop number with the Poisson distribution of small cell BSs is larger than the minimum average hop number with the uniform distribution of small cell BSs when the density of small cell BSs is less than or equal to 150. When the density of small cell BSs is larger than 150, the minimum average hop number approaches the same for wireless backhaul networks with the Poisson and uniform distributions of small cell BSs.

Fig. 4 shows the backhaul network capacity with respective to the density of small cell BSs considering different numbers of gateways in wireless backhaul networks. The backhaul network capacity increases with the increase of the number of gateways in wireless backhaul networks. Moreover, the backhaul network capacity increases with the initial increase of density of small cell BSs but approaches a stationary value when the density of small cell BSs is larger than a specified threshold. When the backhaul network capacity

Algorithm 1 MAN.

Input: M, N, the locations of all small cell BSs $\{(BS_1\_x, BS_1\_y), ..., (BS_N\_x, BS_N\_y)\}$ and the locations of all gateways $\{(GW_1\_x, GW_1\_y), ..., (GW_M\_x, GW_M\_y)\}$;

Initialization: For all small cell BSs, $state(i) = 0, 1 \le i \le N$; All gateways are configured as 0 hop nodes.

Begin:

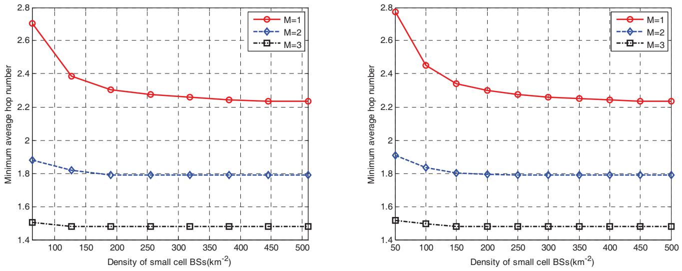
1) **for** $j = 1 : M$ **do**
   Empty all sets Φ_h, variable $h \leftarrow 0$; Put the gateway GW_j into the set Φ_0:
   $$\Phi_h = \Phi_h + \{GW_j\};$$
   while Φ_h **do**
   for $k \in \Phi_h$ **do**
   for $i = 1 : N$ **do**
   if $h == 0$ **then**
   the node k is a gateway, i.e., GW_k and the distance D_{ik} between the small cell BS BS_i and the gateway GW_k is calculated by
   $$D_{ik} = \sqrt{(BS_i\_x - GW_k\_x)^2 + (BS_i\_y - GW_k\_y)^2};$$
   else
   the node k is a small cell BS, i.e., BS_k and the distance D_{ik} between the small cell BS BS_i and the small cell BS BS_k is calculated by
   $$D_{ik} = \sqrt{(BS_i\_x - BS_k\_x)^2 + (BS_i\_y - BS_k\_y)^2};$$
   end if
   if $state(i) == 0 \&\& D_{ik} \le D_0$ **then**
   The minimum hop number between the small cell BS BS_i and the gateway GW_j is $h + 1$, then put the small cell BS BS_i into the set Φ_{h+1} and change the state $state(i)$ of the small cell BS BS_i into 1:
   $$hop(i, j) \leftarrow h + 1; \Phi_{h+1} = \Phi_{h+1} + \{BS_i\};$$
   end if
   end for
   end for
   Search small cell BSs whose minimum hop number for backhauling to the gateway GW_j is $h + 1$:
   $$h \leftarrow h + 1;$$
   end while
   end for
2) The routing link with minimum hop number is selected for relaying the wireless backhaul traffic between the small cell BS and the corresponding gateway:
   $$min\_hop(i) \leftarrow \min_{1 \le j \le M} hop(i, j)$$
3) The minimum average hop number of wireless backhaul network is calculated by
   $$\min_{\chi \in \Omega} Y^{\chi}(M, N) \leftarrow \frac{\sum_{i=1}^{N} min\_hop(i)}{N}$$

end Begin

Output: $\min_{\chi \in \Omega} Y^{\chi}(M, N)$.

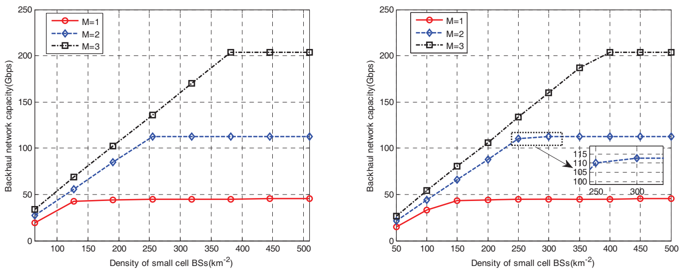
with the uniform distribution of small cell BSs achieves the stationary values in Fig.4 (a), the density thresholds of small cell BSs are 75, 260 and 380 which corresponds to the number of gateways M=1, 2 and 3, respectively. When the backhaul network capacity with the Poisson distribution of small cell BSs achieves the stationary values in Fig.4 (a), the density thresholds of small cell BSs are 150, 300 and 400 which corresponds to the number of gateways M=1, 2 and 3, respectively.

Fig. 5 describes the energy efficiency of wireless backhaul networks with respect to the density of small cell BSs considering different numbers of gateways. The energy efficiency of wireless backhaul networks increases with the increase of the number of gateways in wireless backhaul networks. The energy efficiency of wireless backhaul networks first increases with the density of small cell BSs and then decreases with the density of small cell BSs after the density of small cell BSs is larger than the specified thresholds. When small cell BSs is governed by the uniform distribution in Fig. 5(a), the maximum energy efficiency values are 25, 33 and 40 Mbps/GJ, corresponding to the density of small cell BSs of 135, 260 and 380, respectively. When small cell BSs is governed by the Poisson distribution in Fig. 5(b), the maximum energy efficiency values are 24, 32 and 38 Mbps/GJ, corresponding to the density of small cell BSs of 100, 250 and 350, respectively.



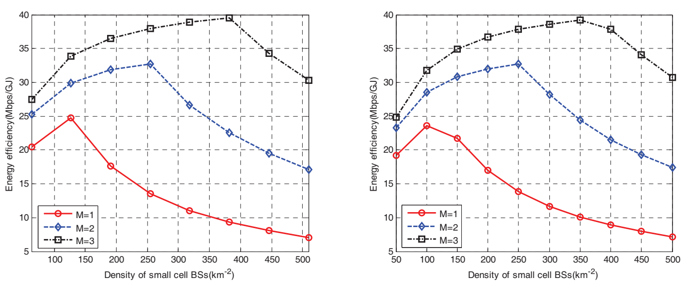
(a)Uniform distribution (b)Poisson distribution

Fig. 3. Minimum average hop number with respect to the density of small cell BSs considering different numbers of gateways in wireless backhaul networks.



(a)Uniform distribution (b)Poisson distribution

Fig. 4. Backhaul network capacity with respective to the density of small cell BSs considering different numbers of gateways in wireless backhaul networks.



(a)Uniform distribution (b)Poisson distribution

Fig. 5. Energy efficiency of wireless backhaul networks with respect to the density of small cell BSs considering different numbers of gateways.

VI. Conclusion

When the backhaul traffic of 5G ultra-dense cellular networks is transmitted by the wireless multi-hop relay method to the core network, a theorem of backhaul network capacity is proposed for wireless backhaul networks with multi-gateways. A MAN algorithm is developed for wireless backhaul traffic transmission in 5G ultra-dense cellular networks. Simulation results indicate that the backhaul network capacity and energy efficiency increase with the increase of the number of gateways in wireless backhaul networks. There exist a stationary value of backhaul network capacity and a maximum energy efficiency of wireless backhaul networks when the density of small cell BSs is larger than a specified threshold in 5G ultra-dense cellular networks. Our results provide some guidelines for the wireless backhaul traffic design for future 5G ultra-dense cellular networks.

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