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Energy-Efficient Wireless Backhaul Algorithm in Ultra-Dense Networks

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Abstract

Ultra-dense networks (UDNs) are expected to be applied for the fifth generation wireless system (5G) to meet the requirements of very high throughput density and connections of a massive number of users. Considering the large amount of small base stations (SBSs), how to choose proper backhaul links is an important problem under investigation. In this paper, we propose a wireless backhaul algorithm to find an effective backhaul method for densely-deployed SBSs and to maximize energy efficiency of the system. We put forward adaptive backhaul methods of indirect and direct modes. The SBS can select the direct backhaul which connects to the macro base station (MBS) directly, or the indirect backhaul which selects an idle SBS as a relay based on the backhaul channel condition. The algorithm also allocates network resources, including the power of SBSs and system bandwidth, to solve the serious interference problem in UDN. Finally, the simulation results show that the proposed wireless backhaul algorithm has desired performance to achieve higher energy efficiency with required data rate.

Keywords

UDN; wireless backhaul; energy efficiency; recourse allocation

1 Introduction

The fifth generation wireless system (5G) is predicted to be commercialized by 2020 [1]. In order to meet the expected 1000 times increase in capacity of existing cellular networks, experts believe that technology innovation is necessary [2]. Ultra-dense networks (UDNs) are proposed to improve system throughput by densely deploying small base stations (SBSs) in the network. On the other hand, it brings huge backhaul traffic load, especially for wireless links. It also indicates more energy consumption of the backhaul process for huge traffic.

Energy efficiency is an important indicator of network performance and a challenge for UDN, which has been studied by many researchers. For examples, in [3], the network energy efficiency of some open channels in a small-area network is discussed and evaluated. In [4], the energy efficiency is improved by power allocation and load balance constraints. In [5], the energy efficiency of SBSs and regional energy efficiency can be improved by deploying SBSs and reducing the transmission power of macro base stations (MBSs). Most of the existing studies about UDN focus on optimizing the energy efficiency of the access network. However, the backhaul capacity is also a constraint on the overall network throughput.

With the intensive deployment of the SBSs in UDN, most of the user devices choose to access the SBS rather than MBS in order to obtain a higher data rate, so the number of small cell user equipment (SUE) is much larger than that of macro cell user equipment (MUE). Furthermore, due to the short inter site distance (ISD) between SBSs, the interference environment and resource allocation are quite complex for wireless backhaul transmission. When the limited capability of SBSs and energy consumption during the transmission are considered, how to choose proper backhaul routing is an important problem and still under investigation by researchers. In [6], backhaul constraint is considered as an important constraint for network performance while modeling a heterogeneous network.

Some research in backhaul has been published. In [7], a new wireless backhaul architecture of dense small cell network is proposed, which optimizes the backhaul path selection and wireless backhaul link scheduling. And in [8], the requirement of the backhaul traffic is evaluated, which indicates that the cooperation between MBSs and SBSs could improve the network performance. In [9], the resource management for wireless backhaul is studied to optimize performance of UDN. In [10], a joint optimization mechanism for forward and backhaul links is proposed which takes into account both the transmission power

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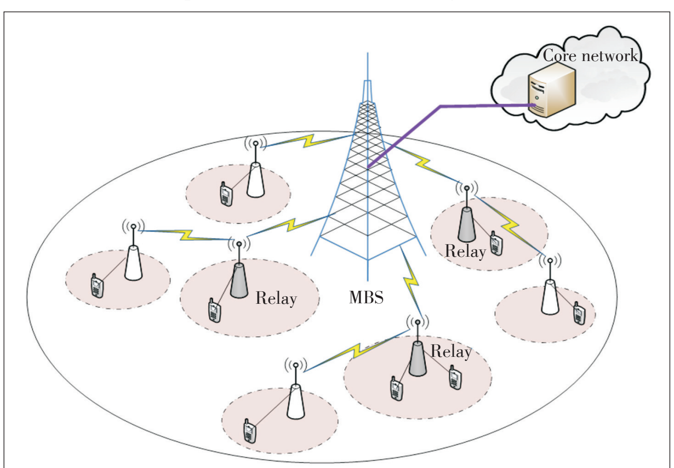
and the backhaul data rate. However, the wireless backhaul transmission with consideration on energy efficiency is still an open issue and needs further investigation.

In this paper, we propose a wireless backhaul algorithm in UDN to maximize the system energy efficiency. The proposed algorithm considers the channel condition, the backhaul rate requirement and the interference factors between SBSs for selecting an appropriate backhaul mode. There are two types of backhaul modes. One is that the SBS connects to the MBS directly, which is denoted as direct backhaul. The other is indirect backhaul in which the backhaul data is sent to the relay base station acted by surrounding free SBSs and then to the MBS. In [11], the advantages of relay in energy efficiency is described. Meanwhile, Combining the content of [3]–[5], the sub-channels and transmit power are allocated to the backhaul nodes along the route, to meet the data requirement and enhance the overall network energy efficiency. Simulation results have proved the effectiveness of the proposed algorithm.

2 System Model

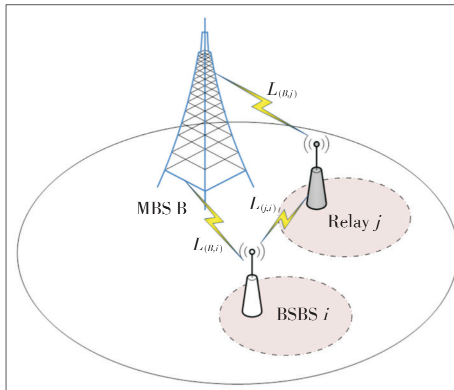
We consider a two-tier heterogeneous UDN scenario shown in **Fig. 1**. It contains a MBS and several SBSs densely deployed in the coverage. In this paper, the SBS with user accessing and backhaul requirement is defined as the backhaul small base station (BSBS), and the SBS without user accessing is defined as the idle small base station (ISBS). The MBS communicates with the core network through a fiber link. The BSBS obtains the data information required by the user through the wireless backhaul link with the MBS for the cost of the optical fiber between a lot of SBSs and the MBS is expensive. [12] We focus on planning the wireless backhaul link of the BSBS in a centralized manner. Also, we summarize the data rate requirement required by the BSBS users as the backhaul rate requirement of the BSBS.

The BSBS for possible backhaul routing is shown in **Fig. 2**.



MBS: macro base station

▲Figure 1. Wireless backhaul in UDN.



BSBS: backhaul small base station MBS: macro base station

Figure 2.▶ Backhaul link selection for a BSBS.

We assume that there are n sub-channels in the system, denoted by the set K as: $K = \{k_1, k_2, \cdots, k_n\}$. Only one MBS which is denoted as B and a total of z SBSs are in the system. It is assumed that at some points, the number of BSBSs in the system is p, which is expressed as the set I, $I = \{i_1, i_2, ..., i_p\}$. The number of free base stations is q, which is expressed by the set J, $J = \{j_1, j_2, ..., j_q\}$. As shown in Fig. 2, the base station i is a BSBS and the base station j is an ISBS. The backhaul data, which is required by any UE access to i, needs transmitting from i to the MBS. One way is direct backhaul and the wireless link between B and i is denoted as $L_{(B,i)}$). Another way is indirect backhaul where j acts as a relay base station through the wireless backhaul link; the wireless link between B and j is denoted as $L_{(B,j)}$ and the wireless link between j and i is denoted as $L_{(j,i)}$.

MBS is used here as a centralized control node for the backhaul routing design for deployment convenience. It plays the role of backhauling management for all the SBSs within its coverage, focusing on backhaul data rate requirement, wireless link interference and resource allocation. Moreover, it is assumed that the base station i in the system could only select one method from the direct and indirect backhaul modes for backhaul.

3 Problem Formulation

3.1 Problem Description

In the network, the BSBS may be far from the MBS in Euler distance with poor quality channel, or the interference of backhaul link may be serious, resulting in that the BSBS is not able to meet the backhaul rate demand of users. In such cases, we will choose a proper ISBS as relay for backhaul.

The direct mode for transmitting data back to the core network is simple and easy. However, the available resource is limited and its backhaul network throughput is lower than that of the indirect mode. Although the indirect mode is more complicated with higher cost than the direct mode, we can organize the backhaul network well. In the indirect mode, more resources are available so that the network throughput can be greatly improved. At the same time, the energy efficiency of the network can be improved by making full use of the resources reasonably.

The association matrix **X** is defined to characterize whether a wireless backhaul link is established between the base stations. In the association matrix **X**, $x_{(B,i)}=1$ indicates that a wireless backhaul link, $L_{(B,i)}$, is established between B and i, which is a direct backhaul mode. $x_{(B,j)}=1$ and $x_{(j,i)}=1$ mean that there are wireless backhaul links established between B and j, as well as between j and i. It is an indirect backhaul mode.

The association matrix **A** is defined to characterize whether particular sub-channel resource is occupied by a particular wireless backhaul link. In the association matrix **A**, $a^k_{(B,i)}=1$ indicates that B occupies the sub-channel k when transmitting the data to i through $L_{(B,i)}$, and vice versa $a^k_{(B,i)}=0$ means that the sub-channel k is not occupied by B when transmitting the data to i through $L_{(B,i)}$.

3.2 Problem Modeling

Based on the assumption, it can be deduced that on $L_{(B,i)}$, when B transmits data through the sub-channel k, i receives the signal to interference plus noise ratio (SINR) which is:

$$SINR^k_{(B,i)}=x_{(B,i)}\frac{a^k_{(B,i)}p^k_{(B,i)}h^k_{(B,i)}}{\sum_{j\in J}x_{(j,i)}a^k_{(j,i)}p^k_{(j,i)}h^k_{(j,i)}+\sigma^2}, \tag{1}$$

where $p^k_{(j,i)}$ is the transmit power of j on the sub-channel k when the wireless backhaul link is established by j, which is limited by the maximum transmit power of the SBS. $h^k_{(j,i)}$ represents the channel gain on the sub-channel k of the wireless backhaul link between j and i. The sum in the denominator is the interference from the surrounding SBSs when i receives the data transmitted from B by the sub-channel k. σ^2 is additive white Gaussian noise (AWGN), which can also be written as $\sigma^2=N_0B$.

Based on (1), the rate of i provided by B can be expressed as:

$$r_{(B,i)}=\sum_k b\log_2(1+SINR^k_{(B,i)}), \tag{2}$$

where b represents the bandwidth of the sub-channel.

Similarly, the data rate on $L_{(B,j)}$ can be expressed as:

$$r_{(B,j)}=\sum_k b\log_2(1+SINR^k_{(B,j)}). \tag{3}$$

When j receives the data transmitted by B through the sub-channel k, the SINR is:

$$SINR^k_{(B,j)}=x_{(B,j)}\frac{a^k_{(B,j)}p^k_{(B,j)}h^k_{(B,j)}}{\sum_{j\in J}x_{(j,i)}a^k_{(j,i)}p^k_{(j,i)}h^k_{(j,i)}+\sigma^2}. \tag{4}$$

Likewise, the data rate on $L_{(j,i)}$ is:

$$r_{(j,i)}=\sum_k b\log_2(1+SINR^k_{(j,i)}). \tag{5}$$

The SINR of i on sub-channel k is:

$$\begin{cases} SINR^k_{(j,i)}=x_{(B,j)}\dfrac{a^k_{(B,j)}p^k_{(B,j)}h^k_{(B,j)}}{I^k_{(j',i)}+I^k_{(B,i)}+I^k_{(B,j)}+\sigma^2} \\ I^k_{(j',i)}=\sum_{j'\neq j}x_{(j',i)}a^k_{(j',i)}p^k_{(j',i)}h^k_{(j',i)} \\ I^k_{(B,i)}=\sum_i x_{(B,i)}a^k_{(B,i)}p^k_{(B,i)}h^k_{(B,i)} \\ I^k_{(B,j)}=\sum_j x_{(B,j)}a^k_{(B,j)}p^k_{(B,j)}h^k_{(B,j)} \end{cases}. \tag{6}$$

The first sum in the denominator, $I^k_{(j',i)}$, in (6) indicates that i is disturbed by the other relay base stations on the same sub-channel. The second and third summations, $I^k_{(B,i)}$ and $I^k_{(B,j)}$, mean that i is disturbed by B. In all the backhaul links $L_{(B,j)}$ and $L_{(B,i)}$, up to one backhaul link occupies the sub-channel k, so either the second or third summation must be zero.

It can be analyzed that in the whole network, the total wireless backhaul throughput is provided by B and the relay base stations. By (1)–(6), the total throughput in the system can be calculated as:

$$R=\sum_i r_{(B,i)}+\sum_j r_{(B,j)}+\sum_j\sum_i r_{(j,i)}. \tag{7}$$

The power consumed by B can be expressed as:

$$P_B=\sum_k\left(\sum_i x^k_{(B,i)}a^k_{(B,i)}p^k_{(B,i)}+\sum_j x^k_{(B,j)}a^k_{(B,j)}p^k_{(B,j)}\right), \tag{8}$$

where the left half of the plus sign indicates the total power which is consumed by B to provide the data rate for i, and the right half is expressed as the power consumed on the wireless backhaul link of j. It must be ensured that B only provides service for only one SBS on a sub-channel when allocating sub-channels.

Similarly, the power consumed by j can be expressed as:

$$P_j=\sum_k\sum_i x^k_{(j,i)}a^k_{(j,i)}p^k_{(j,i)}. \tag{9}$$

It can be seen that the total energy consumption in the system is the sum of the power consumption of the wireless backhaul link on the MBS and the relay base stations:

$$P_{total}=P_B+\sum_j P_j. \tag{10}$$

The optimization goal is the overall energy efficiency of the system backhaul:

$$\arg\max\frac{R}{P_{total}}. \tag{11}$$

The system energy efficiency is constrained by the following:

$$C_1: r_{(B,i)} + \sum_j r_{(j,i)} \geqslant r_i^{req}, \forall i, \tag{12}$$

$$C_2: r_{(B,j)} \geqslant \sum_i r_{(j,i)}, \forall j, \tag{13}$$

$$C_3: P_j \leqslant P_j^{\max}, \forall j, \tag{14}$$

$$C_4: P_B \leqslant P_B^{\max}, \tag{15}$$

$$C_5: 1 - x_{(B,i)} = x_{(j,i)}, \forall i, \exists j, \tag{16}$$

$$C_6: x_{(j,i)} = x_{(B,j)}, \forall j, \exists i, \tag{17}$$

$$C_7: \sum_i x_{(B,i)} a_{(B,i)}^k + \sum_i x_{(B,j)} a_{(B,j)}^k \leqslant 1, \forall k, \tag{18}$$

$$C_8: x_{(j,i)}, x_{(B,j)}, x_{(B,i)} \in \{0,1\}, \forall j,i, \tag{19}$$

$$C_9: a_{(B,i)}^k, a_{(B,j)}^k, a_{(j,i)}^k \in \{0,1\}, \forall j,i,k. \tag{20}$$

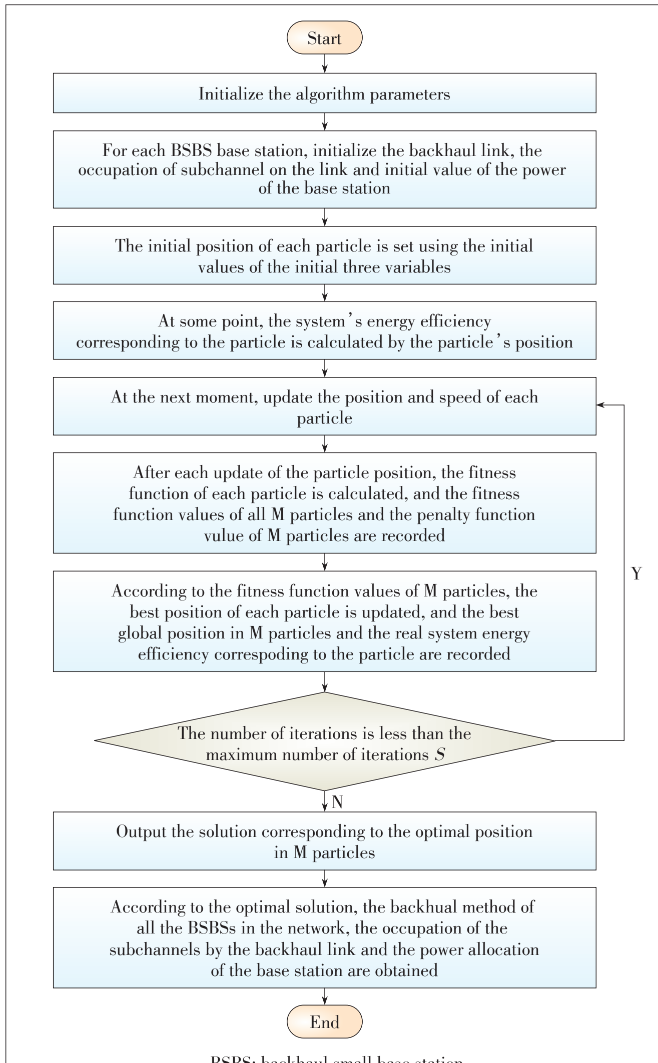
In these constraint conditions, the traffic load of all the users accessing i is expressed as r_i^{req}. C_1 indicates that it must be ensured that the data rate of the backhaul is higher than or equal to the user traffic load of i whether selecting direct backhaul or indirect backhaul. C_2 means that when j provides an indirect backhaul service for i as the relay, it is necessary to ensure that the data rate received by j is equal to or higher than the data rate sent out of j, which is reasonable and effective. When the rate on $L_{(B,j)}$ is higher than the data rate provided by j for i, j can still cache the data and then forward it to i gradually. C_3 indicates that the sum of the total power of j on each sub-channel is smaller than the maximum power of the SBS. Similarly, C_4 indicates that the sum of the total power of B on each sub-channel is smaller than the maximum power of the MBS. C_5 and C_6 represent the choice of the backhaul mode of all BSBSs in UDN. C_5 indicates that i either selects direct backhaul or is provided with an indirect backhaul by at least one ISBS, j. And C_6 indicates that j must create a backhaul link with B as long as there is a BSBS receiving the backhaul data from j. C_7 indicates that any sub-channel can only be occupied at most once on the wireless backhaul link of B. C_8 and C_9 mean that the establishment of the radio backhaul link and the occupancy of backhaul link to the sub-channels are binary discrete variables. The value of these variables can only be 0 or 1.

4 Problem Resolving

The problem established by (11) to (20) is the joint optimization problem of backhaul mode selection, base station power allocation and sub-channel assignment. It is a non-deterministic polynomial-hard (NP-hard) problem [13]. Considering the computational cost, we introduce the quantum behavior particle swarm optimization (QPSO) algorithm [14] to solve the problem.

Fig. 3 shows the problem solving based on the QPSO algorithm. The concrete steps are described as follows:

1) The parameters for QPSO are initialized, including particle position, the total number of particles, and the maximum number of iterations. Each particle location includes three parts of information: the backhaul mode selection results of all base stations in the system, the occupancy results of all sub-channels on the wireless backhaul link, and the power allocation results of the base stations on each sub-channel. The total number of particles is M and the maximum number of iterations is S.
2) An initial value, $\mathbf{X}_m(0)(m = 1, \ldots, M)$, is assigned to all variables of each particle. The zero-variable for the backhaul link establishment and sub-channel occupancy is set by random initialization, then compared to 0.5. If the random number is larger than 0.5, it is set to 1 and if less than 0.5, it is set to 0. The transmit power of the base station is assigned by taking a random value between 0 and the maximum pow-



BSBS: backhaul small base station

▲**Figure 3. The problem resolving based on the QPSO algorithm.**

er. We define the initial value of every parameter in every particle in this step.

3) All the particles are iterated. In the process of iteration, the energy efficiency of the system corresponding to the particle is calculated by the position of each particle at a certain time. We get the first indecisive result in this step.

4) The position and velocity of each particle are updated according to the characteristics of the QPSO algorithm. The next position of the particle is determined by the current position and velocity of the particle. We change the location of every particle to find the better solution.

5) After the particle is updated, the fitness function of each particle is calculated and the fitness function value and the corresponding penalty function value of all M particles are recorded. In this step, we get the result of each particle.

6) The optimal position of each particle is updated according to the fitness function of M particles. The global optimal position and the optimal position corresponding to the real energy efficiency maximum of M particles are recorded. According to the result of each particle, we find the best result in these particles.

7) It is determined whether the number of iterations s reaches the maximum number of iterations S. Reaching the maximum number of iterations makes the output $\mathbf{X}_m^*$ and the corresponding solution of the optimal position of M particles $\mathbf{G}(s)$, then we go to step (8); otherwise, return to step (5). We loop the iteration of these particles to get better results.

8) According to $\mathbf{X}_m^*$, the optimal solution of the optimal position $\mathbf{G}(s)$, the backhaul mode of all the BSBSs, the occupancy of all the sub-channels on the backhaul link, and the power allocation results of the base stations on each sub-channel are obtained. We finally get the best solution.

5 Simulation Results

The simulation scenario is shown in Fig. 1. The MBS can cover an entire 100 m × 100 m network, and the SBSs coverage radius is 40 meters.

The wireless channel model includes two parts, small-scale Rayleigh fading and large-scale path loss, which can be expressed as $h_{(j,i)} = h_0^2 d^{-\alpha}$. h_0 is the complex Gaussian channel coefficient, d is the distance between the BSBS and the MBS or relay base station, and the path loss factor $\alpha = 4$. The specific simulation parameters are shown in **Table 1**.

The backhaul method proposed in this paper is a combined one of the direct and indirect backhaul, while the most existing centralized backhaul in the real networks uses the direct mode. Therefore, we choose a direct backhaul algorithm to compare with the proposed wireless backhaul algorithm to verify the performance of the proposed algorithm.

It can be seen from **Fig. 4** that the proposed algorithm has converged. As the number of iterations increases, the maximum system energy efficiency is increasing. This is because with the operation of the quantum particle swarm optimization algorithm, the current optimal solution is constantly updated, and the energy efficiency of the system obtained by the current optimal solution also increases, indicating that the particle continuously approximates the suboptimal solution of the QPSO algorithm. The algorithm has reached the maximum system energy efficiency at about 700th iteration.

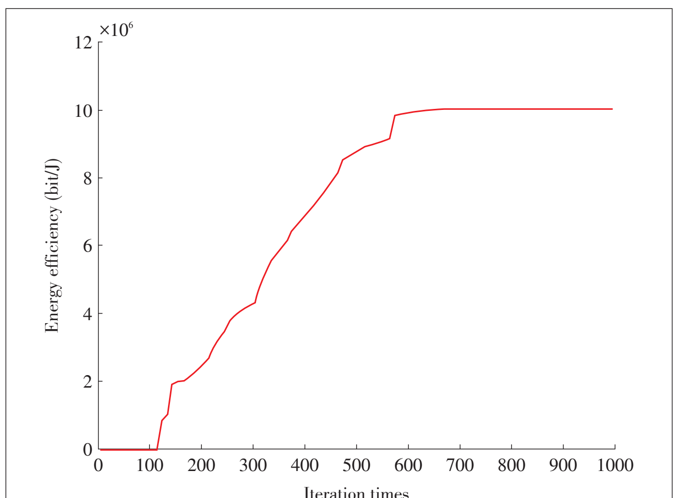
Fig. 5 shows the relationship between the number of BSBSs and the system energy efficiency. The number of BSBSs increases from 5 to 10 and the total number of SBSs in the system grows from 10 to 20, so that each BSBS has one or two ISBSs that can serve as its relay. The total energy efficiency of the system decreases gradually with the increase in the number of BSBSs. The system energy is consumed by the transmission of the MBS and the relay base stations on their respective wireless backhaul links.

When the number of BSBSs is small, the energy consumption of the system is almost from the MBS, which results in

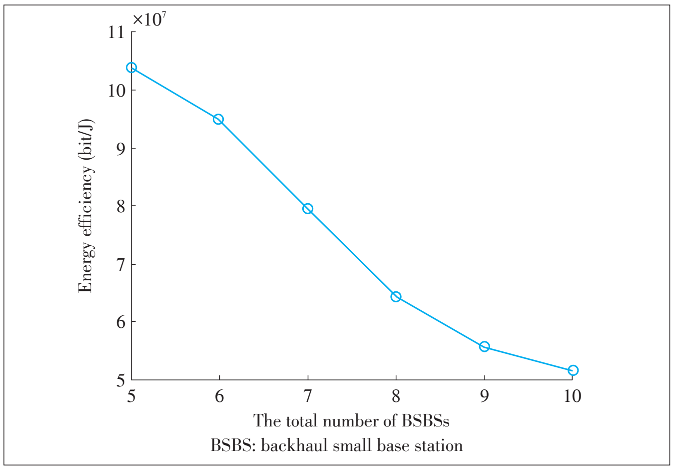
▼**Table 1. System simulation parameters**

Parameters	Value
MBS maximum transmit power	1 W
SBS maximum transmit power	0.3 W
MBS coverage	100 m
SBS coverage	40 m
The total number of SBSs	10–20
BSBS backhaul rate requirement	10 Mbit/s
System bandwidth	10 M
The number of sub-channels	20
Sub-channel bandwidth	500 kHz
Noise power spectral density	-174 dBm/Hz
Path loss factor	4

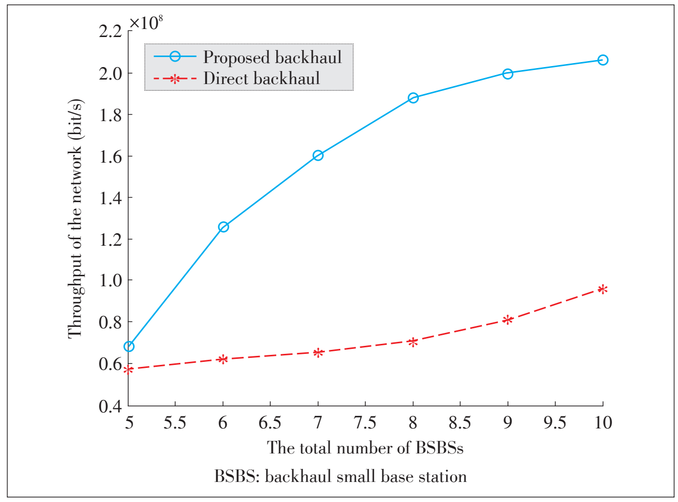
BSBS: backhaul small base station SBS: small base station
MBS: macro base station



▲**Figure 4. Convergence curve of the proposed algorithm.**



▲Figure 5. Relationship between the number of BSBSs and the system energy efficiency.

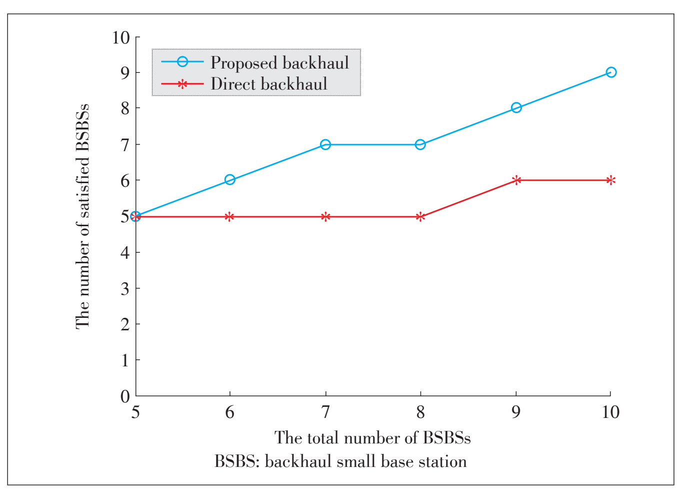


▲Figure 6. Relationship between the number of BSBSs and the system throughput.

high energy efficiency with higher throughput and lower energy consumption in the system. With the gradual increase in the number of BSBSs, the transmission power of the MBS could not meet the backhaul rate requirement of those BSBSs with poor channel quality, so that the energy consumption of the system also occurs in the relay base stations; the system energy consumption relatively increases with a large amount. Compared to the energy consumption, the increase of system throughput is relatively small, so that the system energy efficiency gradually reduces. In spite of this, the algorithm achieves the highest energy efficiency in the system by optimizing the backhaul mode and system resource allocation under the premise of ensuring the BSBS backhaul rate requirement at the specific time, the specific BSBS number and backhaul rate requirement.

Fig. 6 shows the relationship between the number of BSBSs and the system throughput. As can be seen in Fig. 6, using whether the direct backhaul or the proposed backhaul, the system throughput increases with the number of BSBSs increasing. Assuming that the backhaul rate requirement of each BSBS in the system is the same, with the increase in the number of BSBSs, the total backhaul rate requirement of the system will gradually increase, so that using whether the direct backhaul or the proposed backhaul, the system throughput will gradually increase. However, the rate of increase in system throughput in the proposed backhaul mode is greater than that in the direct backhaul mode, because there are some cases that the quality of the channels between these BSBSs and the MBS is poor in the network. The proposed backhaul can also provide the backhaul service for the BSBS by the relay base station, which makes the system throughput growth rate even greater. It can be seen that the proposed backhaul provides greater system throughput as the number of BSBSs increases compared to the direct backhaul.

Fig. 7 shows the relationship between the number of BSBSs and the number of BSBSs that meet the backhaul rate requirement. Likewise, the direct backhaul is compared to the proposed backhaul. With the increase in the total number of BSBSs, the number of BSBSs that meet the backhaul rate requirement is increasing whether using the direct backhaul or proposed backhaul. When the number of BSBSs is small, the total backhaul traffic load in the system is not very large. And the MBS is sufficient to meet the demand of the total backhaul rate of the whole system. Therefore, both backhaul modes can meet the requirement of all BSBS backhaul tasks, such as in the case that the number of BSBSs is 5. When the number of BSBSs increases, the total backhaul flow load increases in the system. The MBS may not be enough to support the gradually increasing backhaul traffic load. At this time, the ISBSs serve as relay base stations for BSBSs by proposed algorithm. Although the backhaul rate of some BSBSs can't be satisfied using whether the direct backhaul or proposed backhaul algorithm, the number of BSBSs satisfied by proposed backhaul is greater than by direct backhaul. It can be seen that the pro-



▲Figure 7. Relationship between the number of BSBSs and the number of BSBSs that meet the backhaul requirements.

posed backhaul performs better on supporting the backhaul traffic load of the entire system.

6 Conclusions

In this paper, a wireless backhaul algorithm for maximizing energy efficiency is proposed in UDN. We propose a model of combining direct backhaul and indirect backhaul, with consideration on the limited capability of SBSs, energy consumption during the transmission, channel quality and other factors. The corresponding sub-channels and transmit power are also allocated to maximize the system energy efficiency. The problem is a mixed integer nonlinear programming problem and solved by QPSO algorithm in this paper. The simulation results show that the proposed algorithm has desired performance to guarantee the high energy efficiency of the system and to effectively meet the BSBS backhaul rate requirement in the system. In the future, other factors for wireless backhaul routing may be considered such as load balance of the relay SBSs.

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