



A Flow Network Based Backhaul Path Planning Algorithm for mmWave Small Cell Networks (Invited Paper)

Zhongyu Ma^{1,2,3}, Bo Li¹, Zhongjiang Yan^{1(✉)}, Mao Yang¹, Xiaoya Zuo¹,
and Bo Yang¹

¹ Northwestern Polytechnical University, Xi'an 710072, China
mazy@mail.nwpu.edu.cn, {libo.npu,zhjyan,yangmao,zuoxy}@nwpu.edu.cn

² Lanzhou Institute of Technology, Lanzhou 730050, China

³ Science and Technology on Communication Networks Laboratory,
Shijiazhuang 053200, China

Abstract. In this paper, a flow network based backhaul path planning algorithm (FBPA) is proposed for mmWave small cell networks, to obtain the backhaul path with minimum energy consumption on the basis of maximum backhaul traffic. Firstly, the backhaul path planning problem is formulated as an integer programming (IP) problem, which is always an NP-hard problem. Then, to obtain the near-optimal solution of the proposed IP problem, a liner relaxation technique is used to make it be a liner problem. Finally, the FBPA algorithm is proposed to find the minimum energy consumption solution on the basis of maximum backhaul traffic based on the flow network theory for the IP. Extensive simulations are conducted and the simulation results show that the FBPA outperforms other traditional backhaul path planning algorithm in terms of energy efficiency and backhaul traffic.

Keywords: 5G · mmWave backhaul · Flow network

1 Introduction

With millimetre Wave (mmWave) small cells densely deployed in 5G for the applications, such as Internet of Things, Virtual Reality and so on, it is costly to connect the small cells with the core network, and to forward data to the gateway using fiber based backhaul [1]. Although mmWave wireless backhaul can be a competitive backhaul solution for the small cells in 5G networks, backhaul path planning is an important issue that needs to be addressed.

Recently, there is a few related works on designing wireless backhaul path. A joint routing and scheduling algorithm of backhaul link for ultra dense mmWave network is proposed in [2], and an maximum flow model based path planning method for the static mesh network with directional antenna is proposed in [3]. However, both of them do not consider the energy conservation issues. Ref.

[4] presents a cognitive green topology management mechanism in 5G network. However, each node in the algorithm is assumed to be with cognitive ability, and the algorithm is not suitable to the scenes with massive data transmissions for mmWave backhaul network. Ref. [5] proposes an energy saving method which dynamically change the operating states of the small cells. Although the energy consumption can be saved, the algorithm assumed that all of the mmWave small cells could be connected to macro base station in one hop, so the path planning problem of the multi hop backhaul is not considered.

To the best knowledge of ours, there has been few related works focusing on designing the backhaul path with minimum energy consumption based on the maximum traffic in given time period for mmWave small cells, which reasonably motivates our work. The main contributions of this paper can be summarized as follows. Firstly, the problem of path planning which is aiming at minimizing energy consumption on the basis of maximizing the backhaul traffic is formulated as an integer-programming (IP) problem for ultra dense mmWave small cells. Secondly, the IP problem is made more easier to resolve using liner relaxation. Thirdly, a flow network based backhaul path planning algorithm (FBPA) is proposed to solve the problem. Finally, simulation results show that the proposed algorithm outperforms the existing path planning algorithms, in terms of backhaul traffic and energy consumption.

2 System Modelling and Problem Formulation

The network scenario that considered in this paper is shown in Fig. 1. Suppose that the network is composed of N small cells (SCs) that connect with mmWave link, and M gateway nodes that connect the core network using fiber. Without loss of generality, the number of the mmWave links between adjacent nodes can be equal, which is denoted as K .

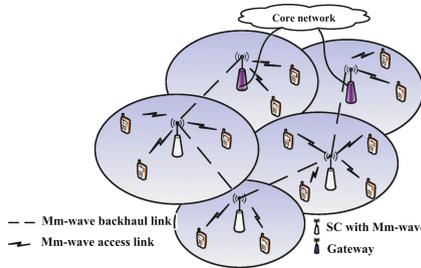


Fig. 1. Network scenario.

The network that shown in Fig. 1 can be modelled as an unidirectional multi-graph, i.e., $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, $\mathcal{V} = \{\mathcal{V}_S, \mathcal{V}_G\}$, where $\mathcal{V}_S = \{s_i | 1 \leq i \leq N\}$ denotes the node set of SCs, $\mathcal{V}_G = \{g_j | 1 \leq j \leq M\}$ denotes the node set of gateways,

and $\mathcal{E} = \{\mathcal{E}_{SS}, \mathcal{E}_{SG}\}$, where $\mathcal{E}_{SS} = \{e_{s_{i_1} \leftrightarrow s_{i_2}}^k | 1 \leq i_1, i_2 \leq N, i_1 \neq i_2, 1 \leq k \leq K\}$, while $\mathcal{E}_{SG} = \{e_{s_i \rightarrow g_j}^k | 1 \leq i \leq N, 1 \leq j \leq M, 1 \leq k \leq K\}$ denotes the set of wireless edges from SC to gateway. Besides, denote $T_{i_1 i_2}^k$ and $t_{i_1 i_2}^k$ as the total number of available time slots and active slots on the k -th mmWave link $e_{s_{i_1} \leftrightarrow s_{i_2}}^k$. Similarly, denote T_{ij}^k and t_{ij}^k as the total number of available time slots and active slots on the k -th mmWave link $e_{s_i \rightarrow g_j}^k$, where $0 \leq t_{i_1 i_2}^k \leq T_{i_1 i_2}^k$ and $0 \leq t_{ij}^k \leq T_{ij}^k$. Let $R_{i_1 i_2}^k, R_{ij}^k$ be the transmission rate within a slot on the k -th mmWave link $e_{s_{i_1} \leftrightarrow s_{i_2}}^k, e_{s_i \rightarrow g_j}^k$. L_i is the backhaul load of s_i generated by cell users. S_j is the total receiving capacity of g_j . $P_{i_1 i_2}^k, P_{ij}^k$ is the consumed energy within a time slot on the k -th mmWave link $e_{s_{i_1} \leftrightarrow s_{i_2}}^k, e_{s_i \rightarrow g_j}^k$.

The goal of the proposed problem is to plan the backhaul paths between each mmWave SC and gateway node, which aims to minimize the total energy consumption with maximum backhaul traffic in given time period. The problem is formulated as follows.

$$\min \left(\sum_{i_1=1}^N \sum_{i_2=1}^N \sum_{k=1}^K t_{i_1 i_2}^k \times P_{i_1 i_2}^k + \sum_{i=1}^N \sum_{j=1}^M \sum_{k=1}^K t_{ij}^k \times P_{ij}^k \right) \quad (1)$$

$$s.t. \max \sum_{i=1}^N \sum_{k=1}^K \sum_{j=1}^M t_{ij}^k \times R_{ij}^k, \quad (2)$$

$$s.t. 0 \leq t_{i_1 i_2}^k \leq T_{i_1 i_2}^k, 1 \leq i_1, i_2 \leq N, 1 \leq k \leq K, \quad (3)$$

$$0 \leq t_{ij}^k \leq T_{ij}^k, 1 \leq i \leq N, 1 \leq j \leq M, 1 \leq k \leq K, \quad (4)$$

$$t_{i_1 i_2}^k, t_{ij}^k \in \mathcal{Z} \forall i, 1 \leq i \leq N, \quad (5)$$

$$L_i + \sum_{k=1}^K \sum_{i_1=1}^N t_{i_1 i}^k \times R_{i_1 i}^k \leq \sum_{k=1}^K \sum_{i_2=1}^N t_{i i_2}^k \times R_{i i_2}^k, \quad (6)$$

$$\sum_{k=1}^K \sum_{i=1}^M t_{ij}^k \times R_{ij}^k \leq S_j, \forall j, 1 \leq j \leq M, \quad (7)$$

The problem is denoted as *Problem-I*, where Eqs. (3) and (4) mean that number of actual active slots within the mmWave links do not exceed the maximum number of active slots. Equation (5) denotes that the number of actual active slots is an integer, where \mathcal{Z} is the set of integers. Equation (6) denotes that for any one of mmWave SCs, the total amount of data being sent out is no less than total amount of data being received and the traffic loads that generated by itself. Equation (7) represents that the total amount of data that flows into the gateway node is no more than the maximum capacity of the fiber. Problem-I is an IP problem, which is always an NP-hard problem. A new variable $d_{i_1 i_2}^k$ is introduced, which denotes the amount of data on the k -th backhaul link from s_{i_1} to s_{i_2} , i.e., $e_{s_{i_1} \rightarrow s_{i_2}}^k$. Similarly, the other variable d_{ij}^k is also introduced, which

denotes the amount of data on the k -th backhaul link from s_i to g_j , i.e., $e_{s_i \rightarrow g_j}^k$. The relationship between variables $d_{i_1 i_2}^k$, d_{ij}^k and $t_{i_1 i_2}^k$, t_{ij}^k can be obtained as

$$t_{i_1 i_2}^k = \left\lceil \frac{d_{i_1 i_2}^k}{R_{i_1 i_2}^k} \right\rceil, t_{ij}^k = \left\lceil \frac{d_{ij}^k}{R_{ij}^k} \right\rceil. \tag{8}$$

Then, the Eq. (2) can be rewritten as

$$\max \sum_{i=1}^N \sum_{j=1}^M \sum_{k=1}^K d_{ij}^k. \tag{9}$$

The Eqs. (3)–(4) can be rewritten as

$$0 \leq d_{i_1 i_2}^k \leq T_{i_1 i_2}^k \times R_{i_1 i_2}^k, 1 \leq i_1, i_2 \leq N, 1 \leq k \leq K, \tag{10}$$

$$0 \leq d_{ij}^k \leq T_{ij}^k \times R_{ij}^k, 0 \leq i \leq N, 1 \leq j \leq M, 1 \leq k \leq K, \tag{11}$$

respectively. For each s_i , Eq. (6) can be rewritten as

$$L_i + \sum_{k=1}^K \sum_{i_1=1}^N d_{i_1 i}^k = \sum_{k=1}^K \sum_{i_2=1}^N d_{i i_2}^k, \forall i, 1 \leq i \leq N, \tag{12}$$

and the constraint (7) can be rewritten as

$$\sum_{k=1}^K \sum_{i=1}^M d_{ij}^k \leq S_j, \forall j, 1 \leq j \leq M. \tag{13}$$

Finally, denote $\eta_{i_1 i_2}^k$ and η_{ij}^k as the energy efficiency¹ on the k -th transmission link between s_{i_1} and s_{i_2} , s_i and s_j , which are given as $\eta_{i_1 i_2}^k = \frac{P_{i_1 i_2}^k}{R_{i_1 i_2}^k}$, $\eta_{ij}^k = \frac{P_{ij}^k}{R_{ij}^k}$. Thus, the objective of *Problem-I* defined in formula (1), can be rewritten as

$$\sum_{i_1=1}^N \sum_{i_2=1}^N \sum_{k=1}^K d_{i_1 i_2}^k \times \eta_{i_1 i_2}^k + \sum_{i=1}^N \sum_{j=1}^M \sum_{k=1}^K d_{ij}^k \times \eta_{ij}^k. \tag{14}$$

Therefore, *Problem-I* can be transformed as a linear program (LP) problem. The LP problem above is denoted as *Problem-II*. Note that Eq. (12) satisfy the demands of flow conservation in the flow network model, Eqs. (10) and (11) satisfy the capacity constraints of the flow network model. Therefore, the method named minimum cost maximum flow in the flow network model is used to obtain the optimal solution of *Problem-II*, and this optimal solution is considered as an approximate solution of the *Problem-I*.

¹ Energy efficiency is the energy consumed by transmission one bit.

3 The Proposed FBPA Algorithm

Note that mmWave backhaul network $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ is an undirected multi graph, where there exist multiple undirected edges between two adjacent nodes. Therefore, to solve *Problem-II*, the FBPA algorithm is proposed. Firstly, the undirected multigraph is transformed into a directed multi-graph. Secondly, the directed multi-graph is transformed into a directed simple graph. Thirdly, a flow network graph is constructed based on the transformed directed simple graph, the problem with minimum cost and maximum traffic of the flow network graph is solved using the Push-Relabel method.

- *Step 1:* As shown in Fig. 2, any two connected nodes s_{i_1} and s_{i_2} in the undirected multi-graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ are transformed into two node sets $\{s_{i_1^{in}}, s_{i_1^{out}}\}$, $\{s_{i_2^{in}}, s_{i_2^{out}}\}$, where $s_{i_1^{in}}$ and $s_{i_2^{in}}$ are virtual entry nodes, which are belong to the set $\mathcal{V}_{s_{in}}$. In addition, $s_{i_1^{out}}$ and $s_{i_2^{out}}$ are virtual export nodes, which are belong to the set $\mathcal{V}_{s_{out}}$.
- *Step 2:* The edges $e_{s_{i_1^{in}} \rightarrow s_{i_1^{out}}}$ and $e_{s_{i_2^{in}} \rightarrow s_{i_2^{out}}}$ are added respectively, where $e_{s_{i_1^{in}} \rightarrow s_{i_1^{out}}}$ and $e_{s_{i_2^{in}} \rightarrow s_{i_2^{out}}}$ are belong to the set $\mathcal{E}_{s_{in}s_{out}}$. Then the undirected edges (denoted as $e_{s_{i_1} \leftrightarrow s_{i_2}}^k$) between s_{i_1} and s_{i_2} are transformed into a directed edges set $\{e_{s_{i_1^{out}} \rightarrow s_{i_2^{in}}}^k, e_{s_{i_2^{out}} \rightarrow s_{i_1^{in}}}^k\}$.

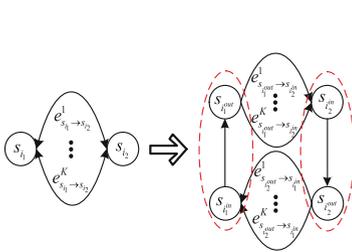


Fig. 2. Undirected multi-graph is transformed into directed multi-graph.

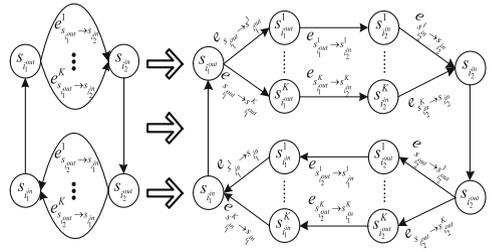


Fig. 3. Directed multi-graph is transformed into directed simple graph.

- *Step 3:* As shown in Fig. 3, k virtual entry nodes $s_{i_1^{in}}^k$ and $s_{i_2^{in}}^k$ that belong to the set $\mathcal{V}_{s_{in}^k}$, are added for $s_{i_1^{in}}$ and $s_{i_2^{in}}$ in the directed multi-graph. Similarly, k virtual export nodes $s_{i_1^{out}}^k$ and $s_{i_2^{out}}^k$ that belong to the set $\mathcal{V}_{s_{out}^k}$, are introduced for $s_{i_1^{out}}$ and $s_{i_2^{out}}$.
- *Step 4:* The k -th edge from $s_{i_1^{out}}$ to $s_{i_2^{in}}$ in the directed multi-graph, i.e., $e_{s_{i_1^{out}} \rightarrow s_{i_2^{in}}}^k$ is transformed into a set of edges $\{e_{s_{i_1^{out}} \rightarrow s_{i_1^{out}}^k}, e_{s_{i_1^{out}}^k \rightarrow s_{i_2^{in}}^k}, e_{s_{i_2^{out}}^k \rightarrow s_{i_2^{in}}^k}\}$, $e_{s_{i_2^{out}} \rightarrow s_{i_1^{in}}}$ is transformed into a set of edges $\{e_{s_{i_2^{out}} \rightarrow s_{i_2^{out}}^k}, e_{s_{i_2^{out}}^k \rightarrow s_{i_1^{in}}^k}, e_{s_{i_1^{in}}^k \rightarrow s_{i_1^{in}}}\}$. For clarity, the sets

are separately defined as $\mathcal{E}_{s_{out}s_{out}^k} = \{e_{s_{i_1out} \rightarrow s_{i_1out}^k}, e_{s_{i_2out} \rightarrow s_{i_2out}^k}\}$, $\mathcal{E}_{s_{out}^k s_{in}^k} = \{e_{s_{i_1out}^k \rightarrow s_{i_1in}^k}, e_{s_{i_2out}^k \rightarrow s_{i_2in}^k}\}$, $\mathcal{E}_{s_{in}^k s_{in}^k} = \{e_{s_{i_1in}^k \rightarrow s_{i_1in}^k}, e_{s_{i_2in}^k \rightarrow s_{i_2in}^k}\}$.

- *Step 5:* A virtual source node x and a virtual destination node y are introduced. Correspondingly, the edges from x to s_{i_1in} and s_{i_2in} are introduced, i.e., $e_{x \rightarrow s_{i_1in}}$ and $e_{x \rightarrow s_{i_2in}}$, and the set of which is denoted as $\mathcal{E}_{xs_{in}}$. Moreover, the edges from g_{jout} to y are introduced, i.e., $e_{g_{jout} \rightarrow y}$, and the set of which is denoted as $\mathcal{E}_{g_{out}y}$.
- *Step 6:* The attributes of each edge in the directed simple graph can be assigned as follows. In $\mathcal{E}_{xs_{in}}$, the capacity and cost of each edge are given as $a(e_{x \rightarrow s_{i_1in}}) = L_i, c(e_{x \rightarrow s_{i_1in}}) = 0$. In $\mathcal{E}_{s_{in}^k s_{in}^k}$, $\mathcal{E}_{s_{in} s_{out}}$, $\mathcal{E}_{s_{out} s_{out}^k}$, $\mathcal{E}_{g_{in}^k g_{in}}$ and $\mathcal{E}_{g_{in} g_{out}}$, the capacity and cost of each edge are given in Eq. (15). In $\mathcal{E}_{s_{out}^k s_{in}^k}$ and $\mathcal{E}_{s_{out}^k g_{in}^k}$, the capacity and cost of each edge are given in Eq. (16). Besides, in $\mathcal{E}_{g_{out}y}$, the capacity and cost of each edge are given as $a(e_{g_{jout} \rightarrow y}) = S_j, c(e_{g_{jout} \rightarrow y}) = 0$.

$$\begin{cases} a(e_{s_{i_1in}^k \rightarrow s_{i_1in}^k}) = a(e_{s_{i_1in} \rightarrow s_{i_1out}}) = a(e_{s_{i_1out} \rightarrow s_{i_1out}^k}) = a(e_{g_{j_1in}^k \rightarrow g_{j_1in}}) = a(e_{g_{j_1in} \rightarrow g_{j_1out}}) = Inf \\ c(e_{s_{i_1in}^k \rightarrow s_{i_1in}^k}) = c(e_{s_{i_1in} \rightarrow s_{i_1out}}) = c(e_{s_{i_1out} \rightarrow s_{i_1out}^k}) = c(e_{g_{j_1in}^k \rightarrow g_{j_1in}}) = c(e_{g_{j_1in} \rightarrow g_{j_1out}}) = 0 \end{cases} \quad (15)$$

$$\begin{cases} a(e_{s_{i_1out}^k \rightarrow s_{i_2in}^k}) = a(e_{s_{i_2out}^k \rightarrow s_{i_1in}^k}) = T_{i_1i_2}^k \times R_{i_1i_2}^k, a(e_{s_i \rightarrow g_j}) = T_{ij}^k \times R_{ij}^k \\ c(e_{s_{i_1out}^k \rightarrow s_{i_2in}^k}) = c(e_{s_{i_2out}^k \rightarrow s_{i_1in}^k}) = \eta_{i_1i_2}^k, c(e_{s_i \rightarrow g_j}) = \eta_{ij}^k \end{cases} \quad (16)$$

- *Step 7:* The minimum cost with maximum flow of $\mathcal{G}_m = (\mathcal{V}_m, \mathcal{E}_m)$ can be obtained, using the Push-Relabel algorithm. Therefore, the values of data flow on each edge of the *Problem-II* is obtained as $\mathcal{F}_m = \{f_{i_1out i_2in}^k, f_{i_1out j_1in}^k\}$.

According to the solution of the *Problem-II*, it can be transformed into the solution of the *Problem-I* as $t_{i_1i_2}^k = \left\lceil \frac{f_{i_1out i_2in}^k}{R_{i_1i_2}^k} \right\rceil, t_{ij}^k = \left\lceil \frac{f_{i_1out j_1in}^k}{R_{ij}^k} \right\rceil$. The maximum amount of data and the minimum energy consumption are given as

$$\begin{cases} d_{\max} = \sum_{i=1}^N \sum_{j=1}^M \sum_{k=1}^K t_{ij}^k \times R_{ij}^k \\ P_{\min} = \sum_{i_1=1}^N \sum_{i_2=1}^N \sum_{k=1}^K t_{i_1i_2}^k \times P_{i_1i_2}^k + \sum_{i=1}^N \sum_{j=1}^M \sum_{k=1}^K t_{ij}^k \times P_{ij}^k \end{cases}$$

4 Simulation Results

In the simulations, SCs are uniformly distributed within 500 m * 500 m square, and the maximum distance between two SCs or SC and gateway node is 120 m. There exist four gateway nodes respectively. Besides, it is assumed that line-of-sight (LOS) mmWave links are located at 60 GHz, the bandwidth of each is

2G MHz. Other simulation parameters are given [6]. We compare our proposed FBPA algorithm with the shortest path algorithm and exhaustive algorithm.

Figure 4 are the path selection results generated from FBPA algorithm. It can be seen that FBPA algorithm can establish multiple paths to multiple gateway nodes, e.g., SC that marked with rectangle in Fig. 4.

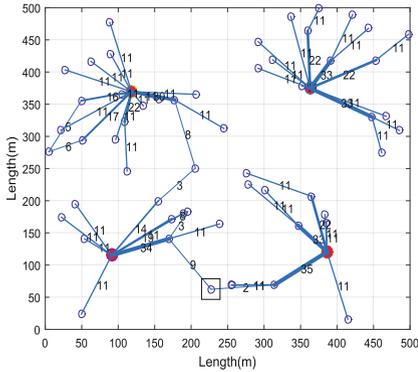


Fig. 4. FBPA path selection.

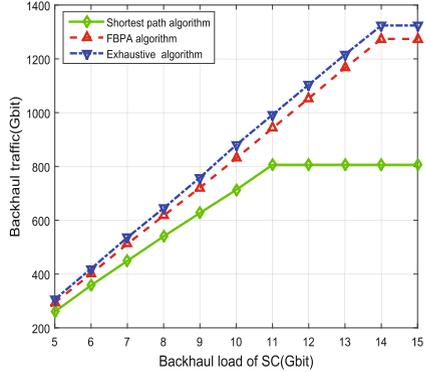


Fig. 5. Backhaul traffic vs load of SC.

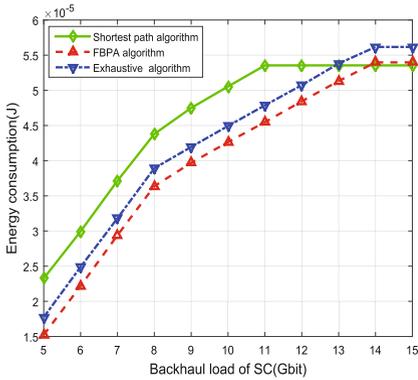


Fig. 6. EC vs load of SC.

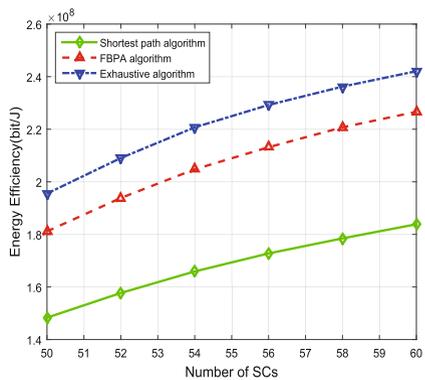


Fig. 7. EE vs number of SCs.

Figures 5 and 6 show the backhaul traffic and energy consumption against backhaul load of each SC. As shown in Fig. 5, with the constantly increasing of the load, the proposed FBPA algorithm and the exhaustive algorithm outperform the shortest path algorithm, this is because the SCs in both algorithms can select multiple paths to different gateway nodes. When the backhaul load of each SC exceeds 14 Gbit, the backhaul traffic of the proposed FBPA algorithm outperforms the shortest path algorithm by nearly 62% and is close to

the exhaustive algorithm, the difference of which is less than 5%. As shown in Fig. 6, the energy consumption for the three algorithms increase when the backhaul load is relatively small, and the network energy consumption using shortest path algorithm is almost highest until the backhaul load is about 11 Gbit, this is because the path selection in the shortest path algorithm is only based on the distance, the energy consumption is not considered. Moreover, the gap between the FBPA algorithm and the exhaustive algorithm is small, which is about 10%.

Figure 7 shows the average energy efficiency of three algorithms against the number of SCs, where the traffic load of each SC is 10 Gbits, and the number of SCs varies from 50 to 60. The average energy efficiency is defined as amount of transmission traffic within unit joule. As we can see from Fig. 7, with the increase number of SCs, the average energy efficiency of three algorithm increase. Although the average energy efficiency of the FBPA algorithm is lower than the exhaustive algorithm's, it much better than the shortest path algorithm. The gain between FBPA algorithm and the shortest path algorithm is nearly 18%.

5 Conclusions

We have studied the backhaul path planning problem in a mmWave small cell network. We aimed at exploring the path planning with minimum energy consumption based on maximum traffic in given time slot. The problem is formulated as an IP problem, then the IP problem is transformed into a easier LP using liner relaxation. FBPA is proposed to find the approximate solution of the IP problem. Extensive simulation are conducted and the efficiency of the proposed algorithm are demonstrated.

Acknowledgment. This work was supported in part by the Science and Technology on Communication Networks Laboratory Open Projects (Grant No. KX162600031, KX172600027), the National Natural Science Foundations of CHINA (Grant No. 61271279, and No. 61501373), the National Science and Technology Major Project (Grant No. 2016ZX03001018-004), and the Fundamental Research Funds for the Central Universities (Grant No. 3102017ZY018).

References

1. Niu, Y., Li, Y., Jin, D., et al.: A survey of millimeter wave communications (mmWave) for 5G: opportunities and challenges. *J. Wirel. Netw.* **21**(8), 2657–2676 (2015)
2. Pateromichelakis, E., Shariat, M., Quddus, A.U., et al.: Joint routing and scheduling in dense small cell networks using 60 GHz backhaul. In: 16th IEEE International Conference on Communication Workshop (ICCW), London, pp. 2732–2737. IEEE Press (2015)
3. Zhang, G., Quek, T.Q.S., Kountouris, M., et al.: Fundamentals of heterogeneous backhaul design-analysis and optimization. *J. IEEE Trans. Commun.* **64**(2), 876–889 (2016)

4. Lun, J., Grace, D.: Cognitive green backhaul deployments for future 5G networks. In: 1st International Workshop on Cognitive Cellular Systems (CCS), Germany, pp. 1–5. IEEE Press (2014)
5. Cai, S., Che, Y., Duan, L., et al.: Green 5G heterogeneous networks through dynamic small-cell operation. *IEEE J. Sel. Areas Commun.* **34**(5), 1103–1115 (2016)
6. Auer, G., Giannini, V., Desset, C., et al.: How much energy is needed to run a wireless network? *J. IEEE Wirel. Commun.* **18**(5), 40–49 (2011)