Journal of Computers Vol. 30 No. 6, 2019, pp. 155-167
doi:10.3966/199115992019123006012

A Network Flow Based Energy-Efficient Backhauling Algorithm for mm-Wave Small Cell Networks

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Received 24 March 2018; Revised 20 July 2018; Accepted 5 September 2018

Abstract. The millimeter wave small cell backhaul network is one of the key solutions in 5G small cell backhaul. However, a lot of new challenges will be faced the multi-hop path planning is designed. In this paper, a flow network based energy efficient backhaul path planning algorithm (FBPA) is proposed for highly dense millimeter wave small cell networks so that the backhaul path planning with maximum throughput as well as minimum energy consumption is obtained. Firstly, the backhaul path planning problem is modelled as an integer programming (IP) problem, which is always a *NP*-hard problem. Then, a liner relaxation technique is used to make the problem be easier to resolve. Finally, the FBPA algorithm is proposed to find the path planning with minimum cost and maximum flow. Extensive simulations are conducted, the simulation results show that the backhaul throughput is improved by about 66.7% and energy efficiency is decreased by nearly 10% when the FBPA is compared to the existing path planning algorithm.

Keywords: 5G, backhaul, energy-efficient, millimeter-wave

1 Introduction

The backhaul network is composed of dedicated lines connecting the base station and the core network, which is an important part of the 5G system [1]. Millimeter wave (mm-Wave) has been paid more attention in the applications of cellular network due to large available communication bandwidth. However, the effective transmission distance of mm-Wave is usually around 200 meters because of its line-of-sight propagation characteristic. Therefore, the concept of the mm-Wave small cell (SC) is proposed to cope with the inefficiencies of the frequency band by mm-Wave and to cope with ultra dense deployment by small cells. Based on this, the idea of using mm-Wave technology into wireless backhaul of future 5G system is naturally proposed by people, namely mm-Wave small cell backhaul network [2]. Simultaneously, some new challenges is put forward for the mm-Wave backhaul network in terms of the metric parameters of the 5G system, such as the peak rate is at least 10Gbps, end-to-end delay is limited in 1ms and so on.

However, if each mm-Wave SC is connected to the core network with fiber as the traditional cellular

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network, the cost of construction and operation is unbearable, especially in densely deployed scenarios [3]. Therefore, a feasible backhaul way the industry believed is that let the SC transmit data to the sink node with millimeter-wave multi-hop wireless communication [4]. Note that in the mm-Wave small cell backhaul network, there exists multiple sink nodes and the mm-Wave links between small cells may be multi-hop [5]. The network scenario that considered in this paper is shown as Fig. 1. Suppose that the network is composed of N small cells (SCs) that connect with mm-Wave link, and M sink nodes that connect to the core network using fiber. Besides, there are multiple wireless links between adjacent nodes, e.g., links between SCs or links between SC and sink nodes. For simplicity, it is assumed that the number of links between two nodes is identical, which is denoted as K. To achieve the mm-Wave backhaul in the multi-hop scenario, the mm-Wave SCs forward data to sink nodes by means of cooperation with each other. In addition, the software defined network (SDN) controller located in the core network is responsible for planning the whole network backhaul path according to the network topology, and distributing the planning results to each SC through the sink nodes. Suppose that interferences between the mm-Wave beams can be ignored [6], so that the wireless link between a SC and its adjacent SC or a sink node may construct K independent mm-Wave backhaul links.

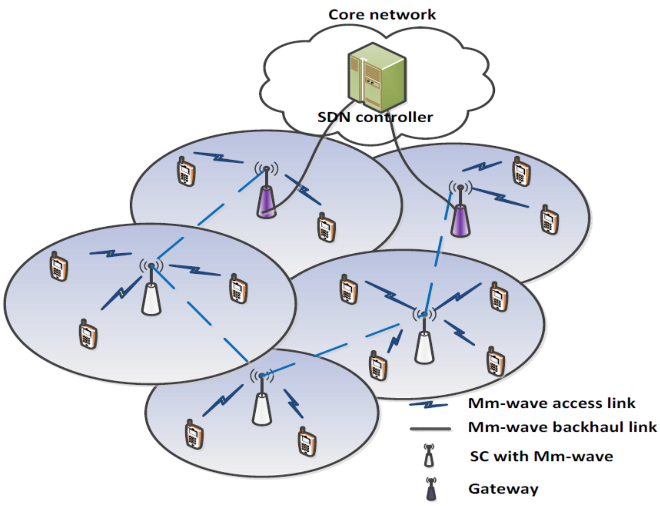

Fig. 1. Network scenario

Recently, work related to mm-Wave backhaul has gained more attention. The two types of backhaul schemes with mm-Wave are analyzed in [7] firstly. The feasibility, problems and corresponding underlying method for mm-Wave small cell backhaul network has been surveyed in [8] especially. All follow-up related studies on designing wireless backhaul scheme mainly focus on resolving two technical issues. The first issue is how to deploy the sink cells in the mm-Wave small cell backhaul network, the second issue is wireless backhaul path planning between small cells and the sink cells [9-10]. Note that deployment schemes of sink cells in the mm-Wave small cell backhaul network are the precondition of the research on path planning. Once the network scene is given, how to achieve energy efficient path planning requires to be deeply studied.

There is very little literature for the first issue. [11] proposed two optimized infrastructure-aware planning strategies for small cells and fiber backhaul. A cost-optimal small cells placement is identified first, then the corresponding minimum cost fiber backhaul deployment is determined accordingly. [12] proposed a joint cost optimal deployment method for the wireless backhaul with microwave (6G - 42G) and sub-6G bands. However, as far as the authors are aware, the deployment of sink nodes in existing millimeter-wave backhaul networks is mostly modeled as the Steiner tree problem.

Our work is belonged to the second question, and there is a few work related to our work. [13] modeled the distribution of access points with wireless backhauls and that of base stations with dedicated wired backhauls as two independent Poisson Point Processes, and a routing protocol that aims to maximize the network throughput is proposed. [14] proposed an optimization model that minimizes the total power consumption of 5G heterogeneous network deployments while providing the required capacity and coverage. [15] proposed a maximum flow model based route planning method for the static mesh network with directional antenna, so as to maximize the throughput of the network. [16] proposed a wireless backhaul solution for UDN deployment by considering Multi-Path-Multi-Hop (MPMH) backhaul architecture in mm-Wave frequency band, Backhaul capacity and line-of-sight probability of the proposed backhaul architecture for various picocell densities were compared with direct, multiple-association, and multi-hop backhaul schemes under interference limited scenarios in outdoor and indoor small cell deployments. [17] presented a general optimization framework for the design of policies that optimally solve the problem of where to associate a user, over which links to route its traffic towards which mesh gateway, and which base stations and backhaul links to switch off in order to minimize the energy cost for the network operator and still satisfy the user demands. [18] proposed a mathematical model that jointly solves the user association and backhaul routing problem in the aforementioned context, aiming at the spectrum efficiency maximization of the network. However, all of these are either highly complex or not take the consideration of network energy consumption and energy efficiency.

To the best knowledge of authors, there has been a few related works focusing on to design the energy efficient scheme for the mm-Wave backhaul, which reasonably motivates our work. This paper mainly focuses on studying the issue of energy efficient path planning with throughput maximization for the mm-Wave backhaul. The main contributions of this paper can be summarized as follows.

- Firstly, the problem of path planning for mm-Wave backhaul links that aiming at minimizing energy consumption is formulated as an integer programming problem (IP) [19] for mm-Wave small cell UDNs.
- Secondly, the IP problem is made easier to resolve using liner relaxation.
- Thirdly, a flow network based energy efficient backhaul path planning algorithm (FBPA) is proposed to solve the problem, by means of using network flow theory.
- Finally, simulation results show that the proposed algorithm outperforms the existing path planning algorithms, in terms of throughput and energy consumption.

The rest parts of the paper are organized as follows. The system model is introduced in Section 2. In Section 3, the formulation and transformation of backhaul path planning problems aiming at maximizing energy efficiency are described, considering the constraints of throughput maximization. The proposed algorithm, which is called FBPA, is introduced detailed in Section 4. We compare and analysis the simulation results in Section 5. Finally, Section 6 summarizes the paper with work to be carried out in the future.

2 System Model

2.1 Network Scenario Model

The network scenario that shown as Fig. 1 can be modelled as a undirected multi-graph, i.e., $\mathcal{G} = (\mathcal{V}; \mathcal{E})$, where $\mathcal{V} = \{\mathcal{V}_S; \mathcal{V}_G\}$ denotes the set of wireless nodes in the network (including mm-Wave SCs and sink nodes), and $\mathcal{E} = \{\mathcal{E}_{SS}; \mathcal{E}_{SG}\}$ denotes the set of wireless edges (including edges between SC and SC, and edges between SC and sink node), which are defined as

$$\begin{cases} \mathcal{V}_S = \left\{ s_i \middle| 1 \le i \le N \right\} \\ \mathcal{V}_G = \left\{ g_j \middle| 1 \le i \le M \right\} \\ \mathcal{E}_{SS} = \left\{ g^k_{s_{i_1} \leftrightarrow s_{i_2}} \middle| 1 \le i_1, i_2 \le N, i_1 \ne i_2, 1 \le k \le K \right\} \\ \mathcal{E}_{SG} = \left\{ g^k_{s_i \leftrightarrow g_j} \middle| 1 \le i \le N, 1 \le j \le M, 1 \le k \le K \right\} \end{cases} \quad (1)$$

Besides, denote $T^k_{i_1 i_2}$ and $t^k_{i_1 i_2}$ as the total number of available time slots and active slots on the k-th mm-Wave link $e^k_{s_{i_1} \to s_{i_2}}$ between s_{i_1} and s_{i_2}. Similarly, denote T^k_{ij} and t^k_{ij} as the total number of available time slots and active slots on the *k-th* mm-Wave link $e^k_{s_i \to g_j}$ between s_i and g_j, where $0 \le t^k_{i_1 i_2} \le T^k_{i_1 i_2}$ and $0 \le t^k_{ij} \le T^k_{ij}$.

2.2 Energy Consumption Model

Let R_{ij}^k be the transmission rate within a slot on the *k-th* mm-Wave link $e_{s_i \to g_j}^k$ between s_i and g_j, L_i is the backhaul load of s_i generated by cell users. S_j is the total receiving capacity of g_j. $P_{i_1 i_2}^k$ is the consumed energy within a time slot on the *k*-th mm-Wave link $e_{s_{i_1} \leftrightarrow s_{i_2}}^k$ between si1 and si2, and P_{ij}^k is the consumed energy within a time slot on the *k-th* mm-Wave link $e_{s_i \to g_j}^k$ between s_i and g_j.

According to [20], $P_{i_1 i_2}^k$ and P_{ij}^k that can be abbreviated as P, which is given by $P = P_{sta} + P_{\text{var}}$, P_{sta} is the fixed energy consumption of SC, e.g., power supply, cooling, and baseband unit operation. P_{var} is the load-dependent energy consumption of SC, which equals to the RF transmit energy consumption. P_{var} is given by

$$P_{\text{var}} = SINR + L_{loss} + I_L + N_{th} + N_F - G_t - G_r \quad \textbf{(2)}$$

Where $L_{loss} = 20\log_{10}(4\pi d/\lambda)$ represents the path loss with distance of d, λ is the signal wavelength, e.g., λ =0.005 m for 60 GHz, I_L is the implementation loss that may account for e.g., distortion, intermodulation and phase noise, N_{th} is the thermal noise, and N_F is the noise figure. G_t and G_r are the antenna gain of transmitting and receiving. Moreover, for mm-Wave, the generated interference can be negligible due to high path loss, and thus we have $SINR = 10\log_{10}(2^{r/B} - 1)$, where r is data rate, B is the bandwidth of the backhaul link.

3 Problem Formulation and Transformation

In this section, the backhaul path planning issue in the highly dense small cell networks is first modeled as an integer programming problem. Then, a linear programming (LP) problem is obtained through the relaxation techniques. Finally, the LP problem is solved using our proposed FBPA algorithm.

3.1 Problem Formulation

Under the constraint the backhaul link between adjacent mm-Wave SCs, the goal of high efficient backhauling is to plan the paths between each mm-Wave SC and sink node, which aims to maximize total backhaul network throughput with the minimum energy consumption. This issue can be modelled as a linear programming (LP) problem as follows.

$$\begin{aligned} &\min\left(\sum_{i_1=1}^{N}\sum_{i_2=1}^{N}\sum_{k=1}^{K} t_{i_1 i_2}^k * P_{i_1 i_2}^k + \sum_{i=1}^{N}\sum_{j=1}^{M}\sum_{k=1}^{K} t_{ij}^k * P_{ij}^k\right) \\ &s.t.\ \max \sum_{i=1}^{N}\sum_{j=1}^{M}\sum_{k=1}^{K} t_{ij}^k * R_{ij}^k \end{aligned} \quad \textbf{(3)}$$

$$s.t.\ \ 0 \le t_{i_1 i_2}^k \le T_{i_1 i_2}^k, 0 \le i_1, i_2 \le N, 0 \le k \le K \quad \textbf{(4)}$$

$$0 \le t_{ij}^k \le T_{ij}^k, 0 \le i \le N, 0 \le j \le M, 0 \le k \le K \quad \textbf{(5)}$$

$$t_{i_1 i_2}^k, t_{ij}^k \in \mathcal{Z} \quad \textbf{(6)}$$

$$L_i + \sum_{k=1}^{K}\sum_{i_1=1}^{N} t_{i_1 i}^k * R_{i_1 i}^k \le \sum_{k=1}^{K}\sum_{i_2=1}^{N} t_{i i_2}^k * R_{i i_2}^k \quad \textbf{(7)}$$

$$\sum_{k=1}^{K}\sum_{i=1}^{N} t_{ij}^{k} * R_{ij}^{k} \le S_j, \forall j, 1 \le j \le M \qquad \textbf{(8)}$$

where Eq. (3) is to maximize the backhaul network throughput. Eq. (4) and Eq. (5) mean that number of actual active slots within the mm-Wave links does not exceed the maximum number of active slots. Eq. (6) denotes that the number of actual active slots within the mm-Wave links is an integer, where $\mathcal{Z}$ is the set of integers. Eq. (7) denotes that for any one of mm-Wave 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. Eq. (8) represents that for any one of sink nodes, the total amount of data that flows into the sink node is no more than the maximum capacity of the fiber.

The issue that aims to maximize total backhaul network throughput using the minimum energy consumption is denoted as ***Problem-I***. Owing that the decision variables $t_{i_1 i_2}^{k}$ and t_{ij}^{k} are the integers, then ***Problem-I*** is a LP problem, which is always a NP-hard problem and the optimal solution can hardly be obtained within the polynomial time. Therefore, a new variable is introduced in this paper to make linear relaxation for the LP problem. After that, the LP problem can be resolved using flow network theory, and thus ***Problem-I*** can be solved.

3.2 Problem Transformation

In order to make linear relaxation for ***Problem-I***, a new variable $d_{i_1 i_2}^{k}$ is introduced, which denotes the amount of data on the *k-th* backhaul link between s_{i_1} and s_{i_2}, i.e., $e_{s_{i_1} \to s_{i_2}}^{k}$. Similarly, a new variable d_{ij}^{k} is introduced, which denotes the amount of data on the *k-th* backhaul link between s_i and g_j, i.e., $e_{s_i \to g_j}^{k}$. 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

$$\begin{cases} t_{i_1 i_2}^{k} = \left\lceil \dfrac{d_{i_1 i_2}^{k}}{R_{i_1 i_2}^{k}} \right\rceil \\ t_{ij}^{k} = \left\lceil \dfrac{d_{ij}^{k}}{R_{ij}^{k}} \right\rceil \end{cases} \qquad \textbf{(9)}$$

Besides, for the mm-Wave link between s_{i_1} and s_{i_2}, we have $0 \le d_{i_1 i_2}^{k} \le t_{i_1 i_2}^{k} * R_{i_1 i_2}^{k} \le T_{i_1 i_2}^{k} * R_{i_1 i_2}^{k}$, and for the mm-Wave link between s_i and g_j, we have $0 \le d_{ij}^{k} \le t_{ij}^{k} * R_{ij}^{k} \le T_{ij}^{k} * R_{ij}^{k}$. Then for anyone of s_i, we have

$$L_i + \sum_{k=1}^{K}\sum_{i_1=1}^{N} d_{i_1 i}^{k} = \sum_{k=1}^{K}\sum_{i_2=1}^{N} d_{i i_2}^{k} \qquad \textbf{(10)}$$

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 g_j, which are given as

$$\begin{cases} \eta_{i_1 i_2}^{k} = \dfrac{P_{i_1 i_2}^{k}}{R_{i_1 i_2}^{k}} \\ \eta_{ij}^{k} = \dfrac{P_{ij}^{k}}{R_{ij}^{k}} \end{cases} \qquad \textbf{(11)}$$

Until now, the total energy consumed is denoted as $\sum_{i_1=1}^{N}\sum_{i_2=1}^{N}\sum_{k=1}^{K} d_{i_1 i_2}^{k} * \eta_{i_1 i_2}^{k} + \sum_{i=1}^{N}\sum_{j=1}^{M}\sum_{k=1}^{K} d_{ij}^{k} * \eta_{ij}^{k}$, Therefore, by using the linear relaxation, ***Problem-I*** can be transformed as

$$\min\left(\sum_{i_1=1}^{N}\sum_{i_2=1}^{N}\sum_{k=1}^{K} d_{i_1 i_2}^{k} * \eta_{i_1 i_2}^{k} + \sum_{i=1}^{N}\sum_{j=1}^{M}\sum_{k=1}^{K} d_{ij}^{k} * \eta_{ij}^{k}\right)$$
$$s.t.\ \max \sum_{i=1}^{N}\sum_{j=1}^{M}\sum_{k=1}^{K} d_{ij}^{k} \tag{12}$$

$$s.t.\ 0 \le d_{i_1 i_2}^{k} \le T_{i_1 i_2}^{k} * R_{i_1 i_2}^{k}, 0 \le i_1, i_2 \le N, 0 \le k \le K \tag{13}$$

$$0 \le d_{ij}^{k} \le T_{ij}^{k} * R_{ij}^{k}, 0 \le i \le N, 0 \le j \le M, 0 \le k \le K \tag{14}$$

$$L_i + \sum_{k=1}^{K}\sum_{i_1=1}^{N} d_{i_1 i}^{k} = \sum_{k=1}^{K}\sum_{i_2=1}^{N} d_{i i_2}^{k} \tag{15}$$

$$\sum_{k=1}^{K}\sum_{i=1}^{N} d_{ij}^{k} \le S_j, \forall j, 1 \le j \le M \tag{16}$$

The LP problem above is denoted as ***Problem-II***. Note that Eq. (15) meets the demands of conservation in the flow network model, as well as Eq. (13) and (14) satisfy the 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 the ***Problem-II***, and this optimal solution is considered as an approximate solution of the ***Problem-I***.

4 The Proposed FBPA

Actually, a flow in a flow network can be viewed as a water flow in a water network, where the amount of water flow should be smaller than the capacity of the water pipes, and there may be some prices to pay for the water flowing from one point to another, e.g., abrasions for the pipes. Therefore, mm-Wave links between two adjacent nodes can be viewed as the water pipes, the data flow via the mm-Wave links can be viewed as the water flow in the pipes. Besides, the maximum capacity of the mm-Wave links can be considered as the capacity of pipes, and the energy that consumed during the transmission on the mm-Wave links can be considered as the abrasions for the pipes. Therefore, there are three attributes that include 'capacity', 'cost', and 'flow' in the flow network. Correspondingly, in the mm-Wave backhaul network, these three attributes correspond to 'the maximum amount of data on the mm-Wave backhaul link', 'energy consumed per bit data' and 'amount of data that carried on the backhaul link'. However, the network flow algorithm is only applicable to the directed simple graph, where there just a single edge between any two adjacent nodes.

Note that mm-Wave backhaul network $\mathcal{G}=(\mathcal{V};\ \mathcal{E})$ is an undirected graph where there exist multiple undirected edges between two adjacent nodes. Therefore, when the ***Problem-II*** is being resolved, the FBPA algorithm is proposed with the method of flow network, which is described as Algo.1. Firstly, the undirected multi-graph is transformed into a directed simple graph. Secondly, a virtual source node and a virtual destination node are added, the corresponding edges between these two nodes and the nodes in the directed simple graph are introduced as well. Moreover, the property value of the capacity, cost, and flow of the edges in the directed simple graph are assigned, and then the flow network graph is formed. Thirdly, the problem with minimum cost and maximum throughput of the flow network graph is solved using the Push-Relabel method. Finally, the solution of this problem is transformed and mapped into the solution of the original problem, i.e., the number of active slots on each of links between two neighboring small cells. The process of transforming undirected multi-graph into directed simple graph concludes two parts as follows.

4.1 The Undirected Multi-graph Is Transformed into a Directed Multi-graph

- Firstly, 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 $\{s_{i_1^{in}}, s_{i_1^{out}}\}$, $\{s_{i_2^{in}}, s_{i_2^{out}}\}$. $s_{i_1^{in}}$ 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 $\mathcal{V}_{s_{out}}$. $s_{i_1^{in}}$ and $s_{i_2^{in}}$ can be considered as the receiving module of s_{i_1} and s_{i_2}, $s_{i_1^{out}}$ and $s_{i_2^{out}}$ can be considered as the transmitting module of s_{i_1} and s_{i_2}.

- Secondly, the edges $e_{s_{i_1^{in}} \to s_{i_1^{out}}}$ and $e_{s_{i_2^{in}} \to s_{i_2^{out}}}$ that from the virtual entry nodes $s_{i_1^{in}}$, $s_{i_2^{in}}$ to the virtual export nodes $s_{i_1^{out}}$, $s_{i_2^{out}}$ are added respectively, where $e_{s_{i_1^{in}} \to s_{i_1^{out}}}$ and $e_{s_{i_2^{in}} \to s_{i_2^{out}}}$ are belong to the set $\mathcal{E}_{s_{in}s_{out}}$. Then the undirected edges (denoted as $e^k_{s_{i_1} \leftrightarrow s_{i_2}}$) between s_{i_1} and s_{i_2} are transformed into a directed edges set $\{e^k_{s_{i_1^{out}} \leftrightarrow s_{i_2^{in}}}, e^k_{s_{i_2^{out}} \leftrightarrow s_{i_1^{in}}}\}$. Where $e^k_{s_{i_1^{out}} \leftrightarrow s_{i_2^{in}}}$ is the directed edge from $s_{i_1^{out}}$ to $s_{i_2^{in}}$, $e^k_{s_{i_2^{out}} \leftrightarrow s_{i_1^{in}}}$ is the directed edge from $s_{i_2^{out}}$ to $s_{i_1^{in}}$. Specifically, $e^k_{s_{i_1^{out}} \leftrightarrow s_{i_2^{in}}}$ and $e^k_{s_{i_2^{out}} \leftrightarrow s_{i_1^{in}}}$ can be considered as the physical circuits from the receiving module to the transmitting module of s_{i_1} and s_{i_2}.

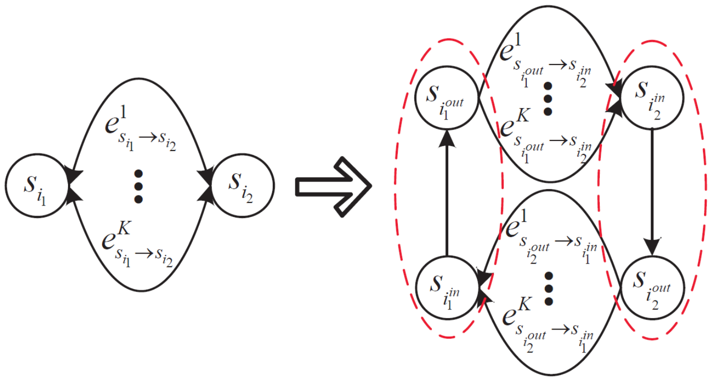

Fig. 2. Undirected multi-graph is transformed into directed multi-graph

4.2 The Directed Multi-graph Is Transformed into a Directed Simple Graph

- Firstly, as shown in Fig. 3, k virtual entry nodes $s^k_{i_1^{in}}$ and $s^k_{i_2^{in}}$ that belong to the set $\mathcal{E}_{s^k_{in}}$, are introduced for the nodes $s_{i_1^{in}}$ and $s_{i_2^{in}}$ in the directed multi-graph. Similarly, k virtual export nodes $s^k_{i_1^{out}}$ and $s^k_{i_2^{out}}$ that belong to the set $\mathcal{E}_{s^k_{out}}$, are introduced for the nodes $s_{i_1^{out}}$ and $s_{i_2^{out}}$. Specifically, $s^k_{i_1^{in}}$, $s^k_{i_2^{in}}$, $s^k_{i_1^{out}}$ and $s^k_{i_2^{out}}$ can be considered as the RF modules that forming k beams between s_{i_1} and s_{i_2}.

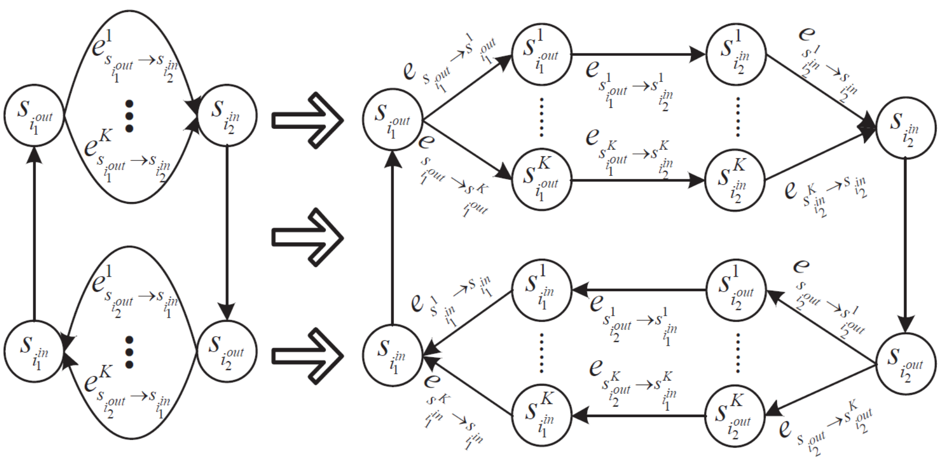

Fig. 3. Directed multi-graph is transformed into directed simple graph

- Secondly, the *k-th* edge from $s_{i_1^{out}}$ to $s_{i_2^{in}}$ in the directed multi-graph, i.e., $e^k_{s_{i_1^{out}} \to s_{i_2^{in}}}$, is transformed into a set of edges $\{e_{s_{i_1^{out}} \to s^k_{i_1^{out}}}, e_{s^k_{i_1^{out}} \to s^k_{i_2^{in}}}, e_{s^k_{i_2^{in}} \to s_{i_2^{in}}}\}$, where $e_{s_{i_1^{out}} \to s^k_{i_1^{out}}}$ is the edge from $s_{i_1^{out}}$ to $s^k_{i_1^{out}}$, $e_{s^k_{i_1^{out}} \to s^k_{i_2^{in}}}$ is the edge from $s^k_{i_1^{out}}$ to $s^k_{i_2^{in}}$, and $e_{s^k_{i_2^{in}} \to s_{i_2^{in}}}$ denotes the edge from $s^k_{i_2^{in}}$ to $s_{i_2^{in}}$. Similarly, the *k*-th edge from $s_{i_2^{out}}$ to $s_{i_1^{in}}$ in the directed multi-graph, i.e., $e^k_{s_{i_2^{out}} \leftrightarrow s_{i_1^{in}}}$, is transformed into a set of edges $\{e_{s_{i_2^{out}} \to s^k_{i_2^{out}}}, e_{s^k_{i_2^{out}} \to s^k_{i_1^{in}}}, e_{s^k_{i_1^{in}} \to s_{i_1^{in}}}\}$, where $e_{s_{i_2^{out}} \to s^k_{i_2^{out}}}$ is the edge from $s_{i_2^{out}}$ to $s^k_{i_2^{out}}$, $e_{s^k_{i_2^{out}} \to s^k_{i_1^{in}}}$ is the edge from $s^k_{i_2^{out}}$ to $s^k_{i_1^{in}}$, and $e_{s^k_{i_1^{in}} \to s_{i_1^{in}}}$ denotes the edge from $s^k_{i_1^{in}}$ to $s_{i_1^{in}}$.

For clarity, three sets are define as follow, $\mathcal{E}_{s_{in}s^k_{out}} = \{e_{s_{i_1^{out}} \to s^k_{i_1^{out}}}, e_{s_{i_2^{out}} \to s^k_{i_2^{out}}}\}$, $\mathcal{E}_{s^k_{out}s^k_{in}} = \{e_{s^k_{i_1^{out}} \to s^k_{i_2^{in}}}, e_{s^k_{i_2^{out}} \to s^k_{i_1^{in}}}\}$, $\mathcal{E}_{s^k_{in}s_{in}} = \{e_{s^k_{i_2^{in}} \to s_{i_2^{in}}}, e_{s^k_{i_2^{in}} \to s_{i_2^{in}}}\}$. Specifically, the elements in $\mathcal{E}_{s_{out}s^k_{out}}$ and $\mathcal{E}_{s^k_{in}s_{in}}$ can be considered as the part from the transmitting module to the RF module between s_{i_1} and s_{i_2}. The elements in $\mathcal{E}_{s^k_{out}s^k_{in}}$ in can be considered as the k mm-Wave links between s_{i_1} and s_{i_2}.

Until now, the directed simple graph is formed, and then the flow network is required to be formed.

4.3 The Flow Network Is Formed Based on Directed Simple Graph

- Step 1: a virtual source node *x* and a virtual destination node *y* are introduced. Correspondingly, the edges from *x* to $s_{i_1^{in}}$ and $s_{i_2^{in}}$ are introduced, i.e., $e_{x \to s_{i_1^{in}}}$ and $e_{x \to s_{i_2^{in}}}$, and the set of which is denoted as $\mathcal{E}_{s_{in}}$. Moreover, the edges from $g_{j^{out}}$ to y are introduced, i.e., $e_{g_{j^{out}} \to y}$, and the set of which is denoted as $\mathcal{E}_{g_{in}y}$. Actually, the virtual source node x can be regarded as a point that merges all of the users in the backhaul network, and the virtual destination node y can be considered as the core network. Therefore, elements in the $\mathcal{E}_{xs_{in}}$ can be seen as the access links from each user to the small cells, and elements in the $\mathcal{E}_{g_{in}y}$ can be seen as the fiber links from sink nodes to the core network. Then the directed simple graph after transformation can be given as $\mathcal{G}_m = (\mathcal{V}_m; \mathcal{E}_m)$, where

$$\begin{cases} \mathcal{V}_m = \{x, \mathcal{V}_{s_{out}}, \mathcal{V}_{s_{in}}, \mathcal{V}_{g_{out}}, \mathcal{V}_{g_{in}}, \mathcal{V}_{s^k_{out}}, \mathcal{V}_{s^k_{in}}, \mathcal{V}_{g^k_{in}}, y\} \\ \mathcal{E}_m = \{\mathcal{E}_{xs_{in}}, \mathcal{E}_{s_{in}s_{out}}, \mathcal{E}_{s_{out}s^k_{out}}, \mathcal{E}_{s^k_{out}s^k_{in}}, \mathcal{E}_{s^k_{in}s_{in}}, \mathcal{E}_{s^k_{out}g^k_{in}}, \mathcal{E}_{g^k_{in}g_{in}}, \mathcal{E}_{g_{in}g_{out}}, \mathcal{E}_{g_{out}y}\} \end{cases}$$

- Step 2: as mentioned before, there are three attributes for the edges of the flow network, i.e., “capacity”, “cost”, and “flow”. In the mm-Wave backhaul network, the three attributes correspond to “the maximum amount of data on the mm-Wave backhaul link”, “energy consumed per bit data” and “amount of data that carried on the backhaul link”. Therefore, according to the physical meaning of each edge in the backhaul network, the attributes of each edge in the directed simple graph can be assigned as follows.

  In the $\mathcal{E}_{xs_{in}}$, the capacity and cost of each edge are given as

$$\begin{cases} a(e_{x \to s_{i_1^{in}}}) = a(e_{x \to s_{i_2^{in}}}) = Inf \\ c(e_{x \to s_{i_1^{in}}}) = c(e_{x \to s_{i_2^{in}}}) = 0 \end{cases} \tag{17}$$

In the $\mathcal{E}_{s_{out}s^k_{out}}$, $\mathcal{E}_{s^k_{in}s_{in}}$ and $\mathcal{E}_{g^k_{in}g_{in}}$, the capacity and cost of each edge are given as Eq. (17). In the $\mathcal{E}_{s_{in}s_{out}}$ and $\mathcal{E}_{g_{in}g_{out}}$, the capacity and cost of each edge are given as

$$\begin{cases} a(e_{s_{i_1}^{in} \to s_{i_1}^{out}}) = a(e_{s_{i_2}^{in} \to s_{i_2}^{out}}) = a(e_{g_j^{in} \to g_j^{out}}) = Inf \\ c(e_{s_{i_1}^{in} \to s_{i_1}^{out}}) = c(e_{s_{i_2}^{in} \to s_{i_2}^{out}}) = c(e_{g_j^{in} \to g_j^{out}}) = 0 \end{cases} \quad (18)$$

In the $\mathcal{E}_{s_{out}^k s_{in}^k}$ and $\mathcal{E}_{s_{out}^k g_{in}^k}$, the capacity and cost of each edge are given as Eq. (18). Besides, in the $\mathcal{E}_{g_{out} y}$, the capacity and cost of each edge are given as

$$\begin{cases} a(e_{g_j^{out} \to y}) = Inf \\ c(e_{g_j^{out} \to y}) = 0 \end{cases} \quad (19)$$

After this, 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, values of data flow on each edge of the ***Problem-II*** is obtained as $\mathcal{F}_m = \{f_{i_1^{out} i_2^{in}}^k, f_{i^{out} j^{in}}^k\}$.

4.4 Solution Transformation

According to the solution of the ***Problem-II***, it can be transformed into the solution of the ***Problem-I*** as follows

$$\begin{cases} t_{i_1 i_2}^k = \left\lceil \dfrac{f_{i_1^{out} i_2^{in}}^k}{R_{i_1 i_2}^k} \right\rceil \\ t_{ij}^k = \left\lceil \dfrac{f_{i^{out} j^{in}}^k}{R_{ij}^k} \right\rceil \end{cases} \quad (20)$$

Furthermore, the maximum amount of data that been backhauled and the minimum energy consumption in the network are given as

$$\begin{cases} d_{\max} = \sum_{i=1}^{N} \sum_{j=1}^{M} \sum_{k=1}^{K} t_{ij}^k * R_{ij}^k \\ P_{\min} = \sum_{i_1=1}^{N} \sum_{i_2=1}^{N} \sum_{k=1}^{K} t_{i_1 i_2}^k * P_{i_1 i_2}^k + \sum_{i=1}^{N} \sum_{j=1}^{M} \sum_{k=1}^{K} t_{ij}^k * P_{ij}^k \end{cases} \quad (21)$$

5 Simulation Results

5.1 Simulation Settings

In the simulations, SCs are uniformly distributed within 500m × 500m square, and the maximum distance between two SCs or SC and sink node is 120m. There exist four sink nodes, the coordinates of which are (125,125), (125,375), (375,125), (375,375), respectively. Besides, it is assumed that line-of-sight (LOS) mm-Wave links are located at 60 GHz, the bandwidth of each is 2G Hz, and interferences of directional wireless links between two nodes can be neglected. Other simulation parameters are summarized in Table I [6, 14].

Table 1. Simulation parameters

Parameters	Value
N_{th}	-174 *dB/Hz*
N_F	5 *dB*
G_t	5 *dB*
G_r	5 *dB*

5.2 Simulation

In this section, we compare our proposed FBPA algorithm with the shortest path algorithm and exhaustive algorithm. In the shortest path algorithm, the path with shortest distance between two nodes is prone to be selected. In the exhaustive algorithm, all the active slots are exhausted to obtain the optimal solution of Eq. (12).

Fig. 4 and Fig. 5 are the path selection results generated from shortest path algorithm and the FBPA. The number of small cells (SCs) is 50, the traffic load of each SC varies from 10 Gbits to 15 Gbits. Note that the amount of data transmitted via the link between two nodes is proportional to the line width. It can be seen that the FBPA can establish multiple paths to multiple sink nodes, e.g., SC that marked with rectangle in Fig.5 can be connected to multiple sink nodes. However, the same SC that marked with rectangle in Fig.4 can not be connected with either sink node. Therefore, FBPA outperforms the shortest path algorithm and is more beneficial to backhaul throughput enhancement.

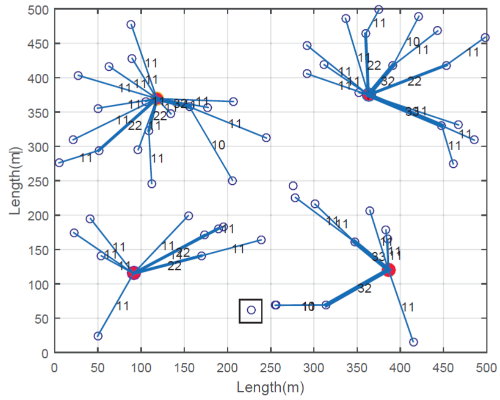

Fig. 4. Shortest distance path selection

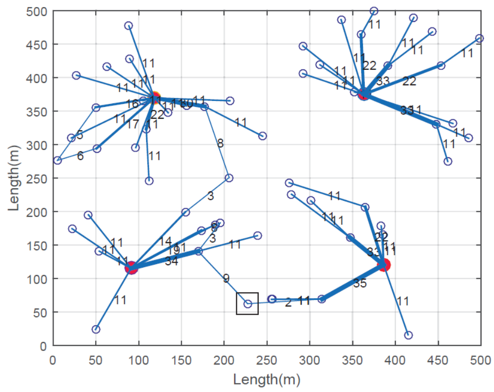

Fig. 5. Higher energy efficient path selection

Fig. 6 and Fig. 7 show the backhaul throughput and energy consumption against backhaul load of each SC. As shown in Fig. 6, the backhaul throughput of three algorithms increase slowly when the backhaul load is relatively small. With the constantly increasing of the backhaul load, FBPA and exhaustive algorithm outperform the shortest path algorithm, this is because the SC in both algorithms can select multiple paths to different sink nodes, when the backhaul load of each SC exceeds 14 Gbit. The backhaul throughput of FBPA outperforms the shortest path algorithm by nearly 70% and is close to the exhaustive algorithm, the difference of which is less than 4%. As shown in Fig. 7, it can be seen that the energy consumption for all of 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 13 Gbits, this is because the path selection in the shortest path algorithm is only based on the distance, but the energy consumption is not considered. Moreover, we can observe that the gap between FBPA and the exhaustive algorithm is small, which is about 15%.

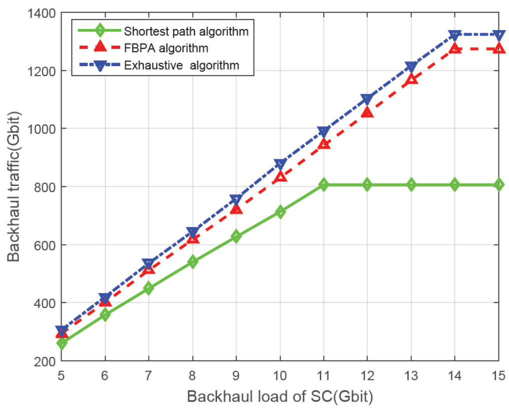

Fig. 6. Backhaul throughput against backhaul load of SC

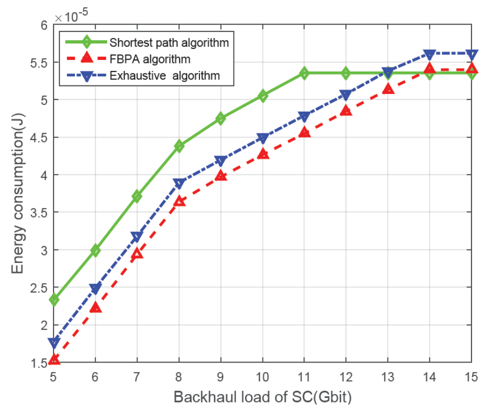

Fig. 7. Energy consumption against backhaul load of SC

Fig. 8 shows the average energy efficiency of three algorithms against number of SCs, where the traffic load of each SC is 10 Gbits, and the number of SCs varies from 50 to 75. The average energy efficiency in this paper is defined as the energy consumption per bit. As we can see from Fig. 8, with the increase number of SCs in the network, the average energy efficiency of three algorithm decline, and FBPA is much lower than the shortest path algorithm. This is because our algorithm aims to select multiple paths with lowest energy consumption, but maximize the network throughput. Besides, it is worth noting that when the number of SCs is 60, average network energy efficiency using both the three algorithms are increased slightly. This is because the network topology is generated randomly, and the sink node is fixed, therefore fixed sink nodes location may be not necessarily suitable for random network topology, and then result in the average network energy efficiency increased instead.

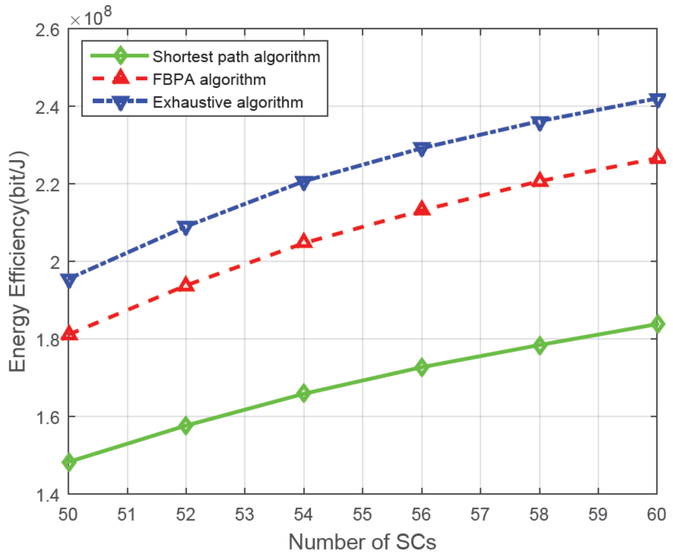

Fig. 8. Energy efficiency against number of SCs

6 Conclusion

In this paper, a flow network based energy-efficient backhaul path planning algorithm for millimeter-wave cell backhaul networks is studied. To explore the path planning with maximum throughput but minimum energy consumption, the backhaul path planning problem is modeled as an integer programming (IP) problem, which is a *NP-hard* problem. In order to solve the problem in polynomial time, the IP problem is transformed into an easier LP using liner relaxation, and a flow network based energy efficient backhaul path planning algorithm is proposed to solve this problem. Extensive simulations are conducted and the effectiveness as well as the efficiency of the proposed algorithm are demonstrated.

For any SC, the backhaul path depends largely on the load of the SCs in the network, and user association is a key factor for the SC load. So, as the future work, we plan to study the aforementioned problem in the consideration of user association, and the joint user association and backhaul path planning for mm-Wave small cell backhaul network will be studied in the future.

Acknowledgements

This work was supported in part by the National Natural Science Foundations of China (grant no. 61763028), Youth Natural Science Foundations of Gansu (grant no. 18JR3RA231 and 1610RJYA021), Science and Technology Plan Project of Lanzhou (grant no. 2017-4-101), Innovation Ability Promotion Project of Gansu Universities (grant no. 2019A-144), Reform Research Project in Innovation and Entrepreneurship Education of Gansu Universities (grant no. 2019-26), Cooperative Education Project of the Chinese Ministry of Education (grant no. 201802048017), ‘‘Qizhi’’ Talent Cultivation Project of

Lanzhou Institute of Technology (grant no. 2019QZ-03) and Gansu University Research Project (grant nos 2016A-98 and 2017A-104).

References

[1] M. Jaber, F.J. Lopez-Martinez, M.A. Imran, A. Sutton, A. Tukmanov, R. Tafazolli, Wireless backhaul: performance modeling and impact on user association for 5G, IEEE Transactions on Wireless Communications 17(5)(2018) 3095-3110.

[2] M.N. Kulkarni, J. G. Andrews, A. Ghosh, Performance of dynamic and static TDD in self-backhauled millimeter wave cellular networks, IEEE Transactions on Wireless Communications 16(10)(2017) 6460-6478.

[3] X. Ge, S. Tu, G. Mao, C.X. Wang, T. Han, 5G ultra-dense cellular networks, IEEE Wireless Communications 23(1)(2016) 72-79.

[4] Y. Niu, Y. Li, M. Chen, D. Jin, S. Chen, A cross-layer design for a software-defined millimeter-wave mobile broadband system, IEEE Communications Magazine 54(2)(2016) 124-130.

[5] G. Zhang, T.Q.S. Quek, M. Kountouris, A. Huang, H. Shan, Fundamentals of heterogeneous backhaul design-analysis and optimization, IEEE Transactions on Communications 64(2)(2016) 876-889.

[6] A. Mesodiakaki, F. Adelantado, L. Alonso, Energy and spectrum-efficient user association in millimeter-wave backhaul small-cell networks, IEEE Transactions on Vehicular Technology 66(2)(2017) 1810-1821.

[7] M. Xiao, Millimeter wave communications for future mobile networks, IEEE Journal on Selected Areas in Communications 35(9)(2017) 1909-1935.

[8] A. Mesodiakaki, E. Zola, R. Santos, Optimal user association, backhaul routing and switching off in 5G heterogeneous networks with mesh millimeter wave backhaul links, Ad Hoc Networks 78(2018) 99-114.

[9] S.A. Busari, S. Mumtaz, S. Al-Rubaye, J. Rodriguez, 5G millimeter-wave mobile broadband: performance and challenges, IEEE Communications Magazine 56(6)(2018) 137-143.

[10] H. Liu, S. Hao, J. Li, Routing and heuristic scheduling algorithm for millimeter wave wireless backhaul networks, in: Proc. 2017 IEEE 2nd Information Technology, Networking, Electronic and Automation Control Conference, 2017.

[11] E. Zola, A.J. Kassler, W. Kim, Joint user association and energy aware routing for green small cell mm-wave backhaul networks, in: Proc. 2017 IEEE Wireless Communications and Networking Conference, 2017.

[12] J. Chávez, J. Escobar, M. Echeverri, A heuristic algorithm based on Tabu search for vehicle routing problems with backhauls, Decision Science Letters 7(2)(2018) 171-180.

[13] D. Yuan, H.-Y. Lin, J. Widmer, M. Hollick, Optimal joint routing and scheduling in millimeter-wave cellular networks, Proceedings of INFOCOM '18, 2018.

[14] J. Kim, A.F. Molisch, Quality-aware millimeter-wave device-to-device multi-hop routing for 5G cellular networks, in: Proc. 2014 IEEE International Conference on Communications, 2014.

[15] V. Yazıcı, U.C. Kozat, M.O. Sunay, A new control plane for 5G network architecture with a case study on unified handoff, mobility, and routing management, IEEE Communications Magazine 52(11)(2014) 76-85.

[16] Y. Nishiyama, M. Ishino, Y. Koizumi, Routing-based mobility architecture for future 5G cellular networks, IEICE Transactions on Communications 100(10)(2017)1789-1797.

[17] Y.H. Chiang, W. Liao, mw-HierBack: a cost-effective and robust millimeter wave hierarchical backhaul solution for HetNets, IEEE Transactions on Mobile Computing 16(12)(2017) 3445-3458.

[18] B.P.S. Sahoo, C.H. Yao, H.Y. Wei, Millimeter-wave multi-hop wireless backhauling for 5G cellular networks, in: Proc. 2017 IEEE Vehicular Technology Conference, 2017.

[19] Y. Li, E. Pateromichelakis, N. Vucic, Radio resource management considerations for 5G millimeter wave backhaul and access networks, IEEE Communications Magazine 55(6)(2017) 86-92.

[20] J. García-Rois, R. Banirazi, F.J. González-Castaño, B. Lorenzo, J.C. Burguillo, Delay-aware optimization framework for proportional flow delay differentiation in millimeter-wave backhaul cellular networks, IEEE Transactions on Communications, 66(5)(2018) 2037-2051.