Traffic Adaptive Formation of mmWave Meshed Backhaul Networks

Hiroaki Ogawa
Tokyo Institute of Technology
ogawa@mobile.ee.titech.ac.jp

Gia Khanh Tran
Tokyo Institute of Technology
khanhtg@mobile.ee.titech.ac.jp

Kei Sakaguchi
Tokyo Institute of Technology / Fraunhofer HHI
kei.sakaguchi@hhi.fraunhofer.de

Thomas Haustein
Fraunhofer HHI
thomas.haustein@hhi.fraunhofer.de

***Abstract*—MmWave meshed network is a promising architecture for cost-efficient wireless backhaul of millimeter-wave overlay heterogeneous network (mmWave overlay HetNet). As user distribution in practice is time-variant and spatially non-uniform, mmWave meshed backhaul should be controlled adaptively. This paper proposes a novel method to control mmWave meshed backhaul for efficient operation of mmWave overlay HetNet. Our algorithm is featured by two functionalities, i.e. backhauling route multiplexing for overloaded mmWave small cell base stations (SC-BSs) and mmWave SC-BSs' ON/OFF status switching for underloaded spot. Considering practical user distribution, radio backhaul resources should be concentrated on overloaded mmWave SC-BSs. Inversely, underloaded mmWave SC-BSs should be deactivated for saving power. The performance of mmWave meshed backhaul controlled by the proposed algorithm is evaluated by system level simulation. Numerical results show that the proposed algorithm can cope with the locally intensive traffic, network scalability, and can reduce energy consumption.**

I. Introduction

Nowadays as mobile terminals like smartphones or tablets become commonplace, the amount of mobile traffic has been increasing exponentially. According to [1], the increase speed is about 53% per year, and the increase will surely continue. In order to keep up with this growth, 5G communication network is required to support enhanced mobile broadband (eMBB) services. One of promising architectures to realize eMBB is millimeter-wave overlay heterogeneous network (mmWave overlay HetNet) proposed in [2],[3]. In mmWave overlay HetNet, mmWave small-cell Base Stations (SC-BSs) are deployed in the coverage of a macro BS. [4] shows that it can achieve 1000 times higher capacity compared with conventional systems on the assumption that all SC-BSs have ideal backhaul. However, it is extremely costly to equip ideal backhaul such as optical fibers, because a large number of SC-BSs are required to be introduced in a macro cell [4].

One of possible solutions to reduce CAPEX (capital expenditure) is wireless backhaul. The capacity of wireless backhaul should be larger than that of access, thus [5],[6] attempted to use mmWave band for backhaul. As mmWave wireless links with highly directional antennas can be modeled as pseudo-wired links, we can operate mmWave meshed backhaul especially in dense deployment of mmWave SC-BSs. As one way to operate mmWave meshed backhaul, [7] introduced anchored BSs that have wired backhaul like fibers as a gateway for other BSs. However, [7] dealt with only single-hop scheme i.e. without considering any relay. According to [8], user distribution in practice is time-variant and spatially non-uniform. Therefore, it occurs in practical scenarios that there will be some overloaded and underloaded mmWave SC-BSs. The overloaded SC-BSs need much radio backhaul resources to satisfy huge traffic demand. For such case, backhauling route multiplexing, i.e. concentration of radio backhaul resources on the overloaded spots, is effective through the method of load balancing as conducted in [9].

In another aspect, [10] showed that power consumption of ICT (information and communication technology) industry is increasing up to 3% of power consumption of the world. In addition, 90% of the amount are consumed by wireless network BSs, 4G LTE or Wi-Fi access points [11]. Therefore it is crucial to manage power consumption of BSs to realize energy-efficient wireless network systems. As there are some underloaded SC-BSs in mmWave overlay HetNet, adaptive switching of BSs' ON/OFF status are effective as conducted in [12],[13]. These works consider power consumed by only RAN (Radio Access Network). Another work tried to reduce power consumption of wired backhaul by solving flow optimization problem in graphically modeled network [14]. However, [14] does not consider joint power consumption optimization of RAN and backhaul, and also does not consider direction selectivity as assumed in the case of mmWave backhaul links. As we can use directional antennas for mmWave meshed backhaul networks, combinatorial optimization of the directions of mmWave links should be required in addition to flow optimization. However, there are too many candidates of link direction combination, thus it is impossible to find the best combination of mmWave backhaul links and SC-BSs' ON/OFF status for the best link direction combination.

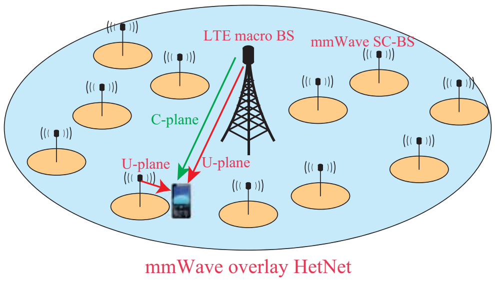

Fig. 1. C/U splitting architecture of the evaluated network.

For these reasons, this paper proposes an algorithm to control mmWave meshed backhaul, i.e. finding a heuristic combination of mmWave backhaul links, SC-BSs' ON/OFF status, and link directions. The assumed scenario is a large hotspot (an overloaded spot) like a scramble intersection in front of Shibuya station in Tokyo. The purpose is to satisfy user's traffic demand while reducing network power consumption. Our algorithm will control mmWave backhaul links and mmWave BSs' ON/OFF status so that the overloaded mmWave SC-BSs are allocated large backhaul radio resources and inversely the underloaded mmWave SC-BSs are deactivated to reduce power consumption considering multi-RAT (Radio Access Technology) selectivity of microwave LTE and mmWave network. To the best of our knowledge, the proposed method is the first work on controlling both of wireless backhaul links and ON/OFF status switching in mmWave meshed network considering direction selectivity of mmWave backhaul links. In addition, system level simulation is conducted to evaluate the performance of mmWave meshed backhaul controlled by the proposed algorithm. The interval of network switching control is the order of seconds corresponding to the period of change of user distribution. Investigation on specified transmission protocols for mmWave backhaul meshed network are out of scope of this paper.

II. Adaptive Backhaul Control

A. Network topology

We employ mmWave overlay HetNet shown in Fig. 1 as a network topology. In the mmWave overlay HetNet, LTE is assumed to manage the C-plane information, i.e. user's location, movement, and traffic demand. This paper introduces one mmWave gateway as a source base station for mmWave SC-BSs, and focuses only on downlink communications.

B. Wireless Bakchaul

As this paper assumes time-variant and spatially non-uniform user distribution, wireless backhaul should be controlled adaptively in accordance with traffic distribution. Relay scheme can realize adaptive backhaul control and can conduct backhauling route multiplexing. This section presents two types of wireless backhaul schemes,

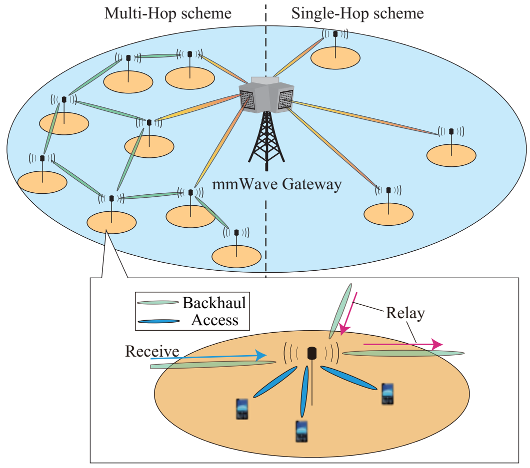

Fig. 2. Single-Hop scheme and Multi-Hop scheme.

i.e. Single-Hop and Multi-Hop schemes summarized in Fig. 2.

1) Single-Hop scheme: In this scheme, there are only direct connections between gateway and SC-BSs, thus all backhaul links are fixed. If locally intensive traffic demand exists, this scheme will fail to cope with such scenario due to limited capacity of each wireless backhaul link. In addition, this scheme is inappropriate for a large coverage network because the effect of path loss attenuation is inherent in mmWave links.

2) Multi-Hop scheme: In Multi-Hop scheme, gateway is connected to each SC-BS not only directly but also indirectly with relay scheme. This scheme can operate adaptive topology backhaul, and also can conduct backhauling route multiplexing on an arbitrary spot. Furthermore, relay scheme can compensate path loss attenuation by amplification when signals are relayed. For stable communications and ease of analysis, this paper allows Multi-Hop scheme to be formed among only links which can achieve maximum data rate of IEEE 802.11ad standard.

C. Proposed Algorithm

In order to take advantage of Multi-Hop scheme described in the previous section, we have to control relay properly. This section presents an algorithm to determine the appropriate backhaul links and SC-BSs' ON/OFF status in accordance with traffic distribution. As it is hard to determine backhaul links and SC-BSs' ON/OFF status all at once, this algorithm is divided into three steps summarized in Fig. 3. In the description of the proposed algorithm, mmWave gateway and SC-BSs are called simply GW and AP.

(i) Determine tentative ON/OFF status based on traffic distribution:

Step (i) determines tentative ON/OFF status of each AP considering multi-RAT selectivity of microwave LTE and mmWave network and the goal is to reduce the total

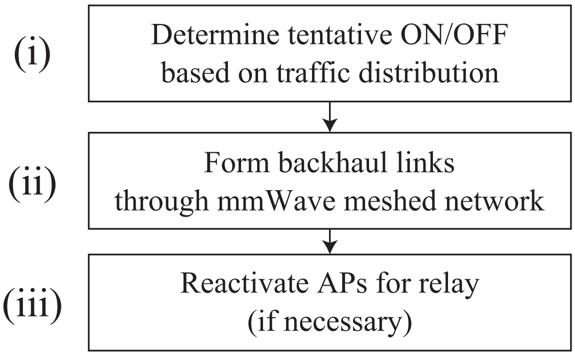

Fig. 3. Algorithm flow chart.

power consumption of mmWave network as much as possible. In order to minimize the total power consumption, LTE should accommodate as many users as possible within its available bandwidth B_{LTE} and underloaded APs should be set OFF. As it is complicated to consider each user individually, all APs are activated at first and all users are accommodated by their nearest APs. Then AP_i has an aggregated traffic demand T_i. If T_i can be instead accommodated by macro LTE, LTE needs to allocate some bandwidth b_i given by Shannon's capacity as follows.

$$b_i = T_i / \log_2(1+\gamma_i) \tag{1}$$

γ_i is the approximated SINR (Signal to Interference plus Noise power Ratio) of signals from LTE macro BS to AP_i considering only path loss attenuation. Therefore, in order to determine tentative ON/OFF status of AP, we have only to determine which system of LTE or mmWave network should accommodate T_i. When we define $i \in G_k$ as a state that users around AP_i are accommodated by the k-th sector of LTE macro BS, the problem to be solved is as follows.

for $k = 1, 2, 3$
find: group G_k s.t.
maximize: $|G_k|$
subject to: $\sum_{i \in G_k} b_i \leq B_{\mathrm{LTE}}$

where $|G_k|$ expresses the number of APs included in G_k. As a result, if T_i is accommodated by LTE, the corresponding users around AP_i will be accommodated by LTE, and AP_i can be set OFF to reduce power consumption. If AP_i is set ON, all the 3 sectors for AP_i's access structure will be activated regardless of the number of users in the coverage of AP_i and the user location. In the following steps, we shall focus on only mmWave meshed network.

(ii) Form backhaul links through mmWave meshed network:

In step (ii), mmWave backhaul links are formed among APs that are set ON in step (i) to satisfy user's traffic demand. In order to form backhaul links, we have to determine appropriate backhauling routes from any sector of GW to AP. If the combination of sources and destinations is given, graph-theoretical expression of AP and connectivity between APs as node and edge enables us to find the shortest path easily. Thus the problem of backhauling route can be substituted for another problem to find the optimal combination of the source sector of GW and destination AP. Figure 4 presents a simple example to derive the combination of transmitter sector of GW and receiver AP. The filled cell is a hotspot and has an aggregated traffic demand T that is larger than the capacity of one sector of GW. In such a case, we have to conduct backhauling route multiplexing on the hotspot from several sectors of GW to satisfy user's request as the load balancing conducted in [9]. To cope with the locally intensive traffic T, we consider a simple solution that one sector of GW is assigned x_1 of T and the other is assigned x_2 of T. A reasonable way to determine the value of x_1 and x_2 is to minimize "Total Hop" defined as Total Hop $=$ Data $\times$ Hop, where Hop is the distance of the shortest path to transmit Data from transmitter to receiver. And x_1, x_2 should satisfy three constraints below.

[A] $x_1, x_2 \leq C_{\mathrm{S}}$
[B] $x_1 + x_2 \geq T$
[C] $x_1, x_2 \geq 0$

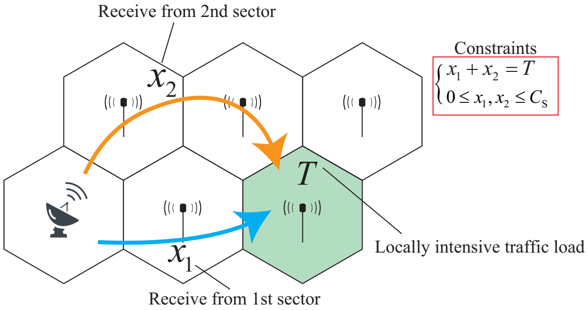

Fig. 4. The concept of backhauling route multiplexing.

where [A] means the capacity of each sector of GW, [B] ensures satisfaction of user's request, [C] assures that the value of traffic is not negative. If this example is generalized to a whole network, a linear programming as follows is defined.

find: $\boldsymbol{x}$ s.t.
minimize: Total Hop$=\boldsymbol{f}^{\mathrm{T}}\boldsymbol{x}$
subject to: [A] $\boldsymbol{t}_{\mathrm{S}}=\boldsymbol{W}_{\mathrm{S}}\boldsymbol{x} \leq C_{\mathrm{S}}\mathbf{1}$
[B] $\boldsymbol{t}_{\mathrm{AP}}=\boldsymbol{W}_{\mathrm{AP}}\boldsymbol{x} \geq \boldsymbol{a} \odot \boldsymbol{T}_{\mathrm{D}}$
[C] $\boldsymbol{x} \geq 0$

where $\odot$ means Hadamard product. When the number of AP and the number of sectors of GW are denoted by N_{S} and N_{AP} respectively, total number of flow N_{V} is defined as $N_{\mathrm{V}} = N_{\mathrm{S}} \times N_{\mathrm{AP}}$. $\boldsymbol{x} \in \mathbb{R}^{N_{\mathrm{V}}}$ means the data amount to be transmitted from any sector of GW to any AP, $\boldsymbol{f} \in \mathbb{R}^{N_{\mathrm{V}}}$ weights the number of relay hop against $\boldsymbol{x}$, $\boldsymbol{t}_{\mathrm{S}} \in \mathbb{R}^{N_{\mathrm{S}}}$ is the summation of traffic load accommodated by each sector of GW, $\boldsymbol{t}_{\mathrm{AP}} \in \mathbb{R}^{N_{\mathrm{AP}}}$ is the summation of traffic supplied to each AP, $\boldsymbol{a} \in \mathbb{R}^{N_{\mathrm{AP}}}$ expresses the ON/OFF state, in other words, $i(i \notin \bigcup(G_k))$-th component is 1, and the others are 0, $\boldsymbol{T}_{\mathrm{D}} \in \mathbb{R}^{N_{\mathrm{AP}}}$ is the aggregated traffic demand of each AP, $\boldsymbol{W}_{\mathrm{AP}} \in \mathbb{R}^{N_{\mathrm{V}} \times N_{\mathrm{AP}}}$ is a mapping matrix between $\boldsymbol{t}_{\mathrm{AP}}$ and $\boldsymbol{x}$, $\boldsymbol{W}_{\mathrm{S}} \in \mathbb{R}^{N_{\mathrm{V}} \times N_{\mathrm{S}}}$ is a mapping matrix between $\boldsymbol{t}_{\mathrm{S}}$ and $\boldsymbol{x}$. The constraint [A] means the capacity of each sector of GW, [B] ensures satisfaction of user's request, [C] assures that the value of traffic is not negative. We then get the optimal combination of transmitter sector of GW and receiver AP from solving for $\boldsymbol{x}$. As Multi-Hop scheme can only form among links assuring maximum data rate of IEEE 802.11ad standard, the constraint [A] is sufficient to satisfy the capacity constraint of each mmWave backhaul link.

(iii) Reactivate APs for relaying (if necessary)

To confirm whether we should reactivate some APs for relaying or not, we first find "parent" for each activated AP in step (i). Parent of AP_i is an upper AP on the backhauling route from GW to AP_i, and satisfies the following requirements.

Requirements for the parent of AP_i

1) Can communicate with AP_i at the maximum data rate
2) Nearest to GW in terms of Hop among APs that satisfy 1)
3) If AP_i has no parent that satisfies 1) and 2), AP_i is regarded as "isolated"

If a parent succeeds in connection with GW, the corresponding subordinate AP will also succeed. Thus, if there is no isolated AP, reactivation is not necessary. On the other hand, if there are some isolated APs, we have only to reactivate appropriate APs for them.

From the viewpoint of power consumption, it is desirable that a small number of APs are reactivated. In order to minimize the number of such reactivated APs, we determine the best combination of APs to be newly activated by the following procedure.

Procedure to determine AP to be reactivated

1) Identify isolated APs for each sector of GW
2) Generate the shortest paths from GW to isolated APs through all available APs
3) Consider all combinations of the shortest paths and count the number of APs needed to be reactivated for each combination
4) Adopt the combination that minimizes the number of reactivated APs

By this procedure, all isolated APs that is set ON can be connected with GW. For APs that are set ON, the number of activated sectors of AP_i's backhaul structure depends on whether AP_i plays a role of relay AP for other APs or not. If AP_i does not have any relay links, the number of activated sectors of AP_i will be one; otherwise it will be two or three.

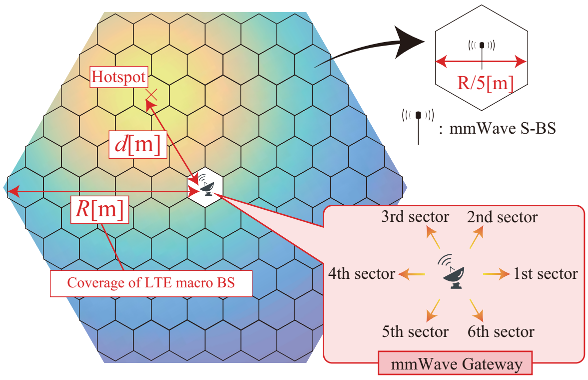

Fig. 5. Deployment of SC-BSs in a macro cell.

III. Simulation Study

In order to evaluate the performance of mmWave meshed backhaul controlled by the proposed algorithm, numerical analysis is conducted in system level simulation. Simulation settings are as follows.

A. Base stations

The deployment of mmWave gateway and SC-BSs is presented in Fig. 5. One mmWave gateway and ninety mmWave SC-BSs are deployed in a LTE macro cell.

1) LTE macro BSs: LTE macro cell, which is hexagonal, has $R = 250m$ coverage and three sectors. Indeed this paper evaluates only one macro cell, but introduces six more macro cells around the evaluated macro cell in order to consider the effects of interference by other macro BSs.

2) mmWave small-cell base stations: MmWave SC-BSs have mmWave access structure with three sectors and mmWave backhaul structure also with three sectors, and access and backhaul structure are operated independently. Note that all mmWave SC-BSs do not have wired backhaul.

3) mmWave Gateway: MmWave gateway is the only base station with wired backhaul in our mmWave meshed network, and plays a role of source to mmWave SC-BSs. MmWave gateway is assumed to be equipped with massive MIMO antenna that has six sectors, and for simplicity each sector can form one beam.

B. Traffic demand

In order to reproduce non-uniform user distribution, user location is assumed to follow 2-dimensional Gaussian distribution whose form is determined by mean vector $\boldsymbol{\mu}$ and covariance matrix $\boldsymbol{\Sigma}$. $\boldsymbol{\mu}$ corresponds to the location of hotspot, and $\boldsymbol{\Sigma}$ can be interpreted as non-uniformity of user distribution. Here, $\boldsymbol{\Sigma}$ is assumed to be isotropic, i.e. $\boldsymbol{\Sigma}= \sigma^2 \boldsymbol{I}$ where σ is standard deviation. This paper employs the models for packet generation interval and the length of each packet as shown in [8], and assumes that the traffic demand grows about twice every year and then 10 years later it will become 1000 times higher.

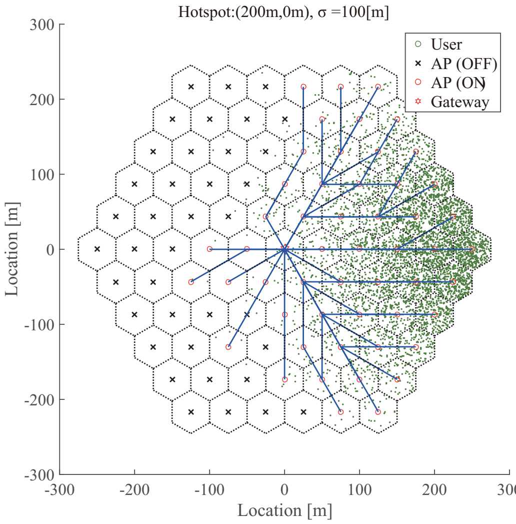

Fig. 6. Backhaul links and ON/OFF status when $\sigma = 100$.

C. Frequency

This work assumes 57-66GHz band use and communication scheme follows the channel allocation defined by IEEE 802.11ad standard. This standard divides 57-66GHz band into four channels [15]. As there are many wireless links in mmWave meshed backhaul, severe interference between access and backhaul may occur. In this paper, for stable communications two channels are used for backhaul, and the others for access. Note that CSMA/CA is not suitable for mmWave meshed backhaul scenario, thus ideal protocol is assumed instead.

D. Example

Figure 6 presents the result of adaptively controlled backhaul links and ON/OFF status in the case of $\sigma = 100m$ where the hotspot is centered at (200[m],0[m]). From this result, we can confirm that SC-BSs which are distant from the hotspot are deactivated, and radio backhaul resources are concentrated on the area of the hotspot. Following the above, three types of numerical analyses are conducted at system level simulation i.e. Backhauling Route Multiplexing, Scalability, and Power Consumption. Also two types of evaluation criteria i.e. system satisfaction ratio (SSR) and power consumption are defined as follows.

$$\mathrm{SSR} = \left[\frac{\text{Supplied Backhaul Data}}{\text{Demanded Backhaul Data}} \right] \tag{2}$$

$$\text{Power Consumption} = \sum_{i}^{N_{\mathrm{AP}}} (N_i^{\mathrm{on}} P_{\mathrm{on}} + N_i^{\mathrm{off}} P_{\mathrm{off}}) \tag{3}$$

Here, N_i^{on}, the number of ON sectors of i-th SC-BS for access and backhaul structure, and N_i^{off}, the number of OFF sectors of i-th SC-BS, should satisfy $N_i^{\mathrm{on}} + N_i^{\mathrm{off}} = 6$, because each SC-BS has three sectors for access structure and also three sectors for backhaul. The second criterion evaluates only the power consumption of mmWave network, calculated by the summation of power consumption of both access and backhaul structure.

TABLE I
SYSTEM PARAMETER.

Parameter	LTE Macro	mmWave network
Bandwidth	10MHz	2×2.16GHz
Carrier freq.	2.0GHz	60GHz
Antenna gain	17dBi	26dBi
Antenna height	25m	4m/25m(AP/GW)
Tx power	46dBm	10dBm
Beam pattern	[18]	[17]
Path loss	[18]	[19]
# of BSs	1	90
# of users	5000	
Noise density	-174dBm/Hz	-174dBm/Hz

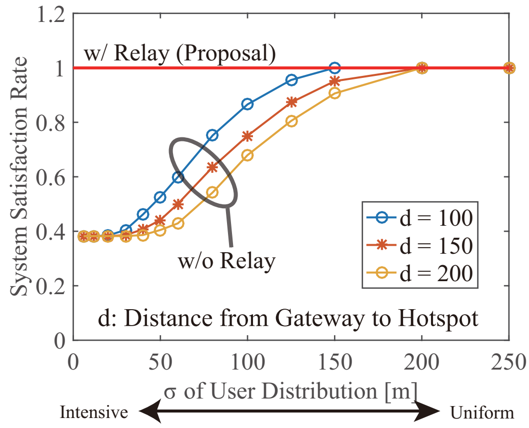

Fig. 7. SSR against σ of user distribution.

E. Backhauling Route Multiplexing

Here we evaluate SSR by changing the standard deviation σ of the 2-dimensional Gaussian user distribution. Then, the smaller σ becomes, the more users are distributed intensively near the hotspot, i.e. the center of the 2-dimensional Gaussian distribution. On the other hand, the larger σ becomes, the more uniform user distribution becomes. Figure 7 shows SSR values in changing σ from $1m$ to $250m$. From this result, we can see that even though users are distributed intensively, Multi-Hop scheme with the proposed algorithm can maintain high SSR by backhauling route multiplexing and compensation of path loss by amplification relay. Conversely, Single-Hop scheme cannot deal with the intensive traffic, because of limited capacity of only some gateway sectors able to be directed toward the hotspot. The performance of Single-Hop scheme and Multi-Hop scheme depends on the number of routes to receive backhaul data. In Single-Hop scheme, SC-BS can receive backhaul data with only one sector, whereas in Multi-Hop scheme, SC-BS can receive with three sectors at most. Thus Multi-Hop scheme can cope with three times higher traffic demand compared with Single-Hop scheme, and this can be confirmed from SSR when σ goes to $1m$. In addition, this result suggests that

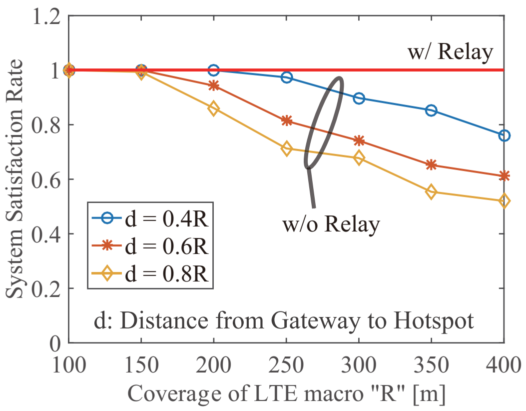

Fig. 8. SSR against macro radius.

Multi-Hop scheme with the proposed algorithm can control adaptively mmWave meshed backhaul and ON/OFF status of SC-BSs following time-variant and spatially non-uniform user distribution.

F. Scalability

Figure 8 presents SSR by changing the coverage R of LTE macro BS and fixing σ to $100m$. Multi-Hop scheme can cope with the expansion of the network scale, whereas Single-Hop scheme cannot due to path loss attenuation.

G. Power Consumption

Here we evaluate power consumption calculated by (3). Three types of criteria for SC-BS activation are compared. The first one is defined by the proposed algorithm considering multi-RAT selectivity of microwave LTE and mmWave network and SC-BSs' ON/OFF status switching. The second one is "User centric ON" considering only ON/OFF status switching i.e. without multi-RAT. In the case of "User centric ON", mmWave AP_i will be deactivated only when AP $_i$ has no associated user. The last one is "Always ON" considering neither of multi-RAT selectivity nor ON/OFF status switching. Figure 9 shows power consumption by changing σ of user distribution where the hotspot is centered at (200[m],0[m]). The proposed algorithm can even reduce power consumption against "User centric ON" in most scenarios. Figure 10 shows power consumption by changing the number of users in the evaluated area and fixing σ of user distribution. The proposed algorithm and "User centric ON" can reduce power consumption significantly as compared with "Always ON". As the proposed algorithm introduces multi-RAT selectivity as well as ON/OFF status switching, it can even reduce more power consumption than "User centric ON".

IV. Conclusion and Future Works

Dealing with practical user distribution, this paper employed multi-RAT selectivity of microwave LTE and mmWave network, and SC-BSs' ON/OFF status switching, to propose an algorithm which can realize adaptive

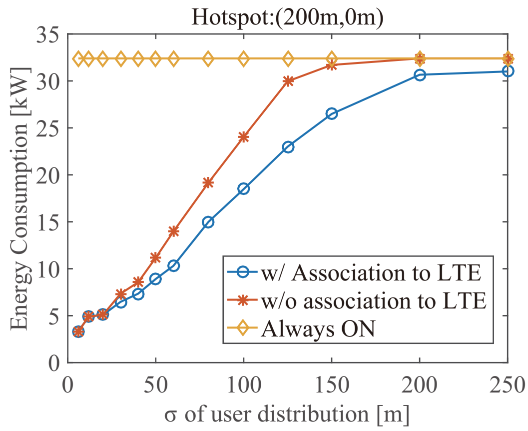

Fig. 9. Power consumption against σ of user distribution.

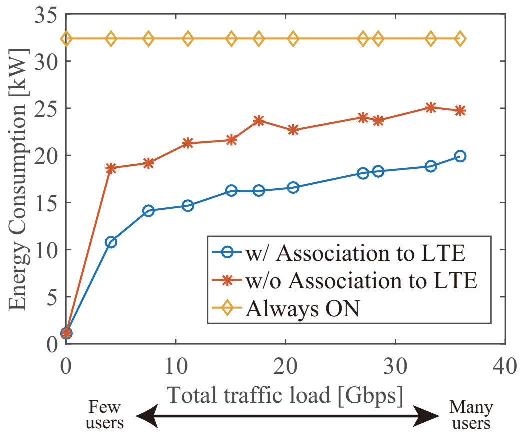

Fig. 10. Power consumption against total traffic load.

control of mmWave meshed backhaul. To the best of our knowledge, the presented method is the first work on controlling both of wireless backhaul links and ON/OFF status switching in mmWave meshed network. Numerical results showed that proposed method can satisfy users' traffic demand and reduce power consumption, and also confirmed the effect of backhauling route multiplexing and ON/OFF status switching. In our future works, we will investigate the performance gap between the optimal one and the proposed heuristic approach. Furthermore, transmission scheduling including pre-fetching and caching will also be introduced. In addition, simulation study and experiments on more practical settings, e.g. backhauling delay, uplink communication, should be conducted.

V. Acknowledgement

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