Millimeter-Wave Multi-Hop Wireless Backhauling for 5G Cellular Networks

B. P. S. Sahoo, Chun-Han Yao, and Hung-Yu Wei*
Graduate Institute of Electrical Engineering, National Taiwan University, Taiwan
*hywei@cc.ee.ntu.edu.tw

***Abstract*—The millimeter-wave (mmWave) bands, roughly referred to 30–300 GHz, have been widely recognized as a promising candidate for dense deployment of small-cells backhaul network. The dense small-cell deployment produces a huge amount of backhaul traffic, and directional communication poses a significant challenge. In this paper, we propose a dynamic frame reconfiguration scheme which provides greater flexibility for dynamic traffic adaptation in multi-hop mmWave relay backhaul. This allows better exploitation of the traffic dynamics in small-cell. In addition, we present a traffic load and link-quality aware multi-hop relay backhaul scheduling algorithm to maximize the overall system performance. The extensive simulation results demonstrate the superiority of our proposed algorithm when compared with other schemes.**

I. Introduction

Globally, the demand for higher data-rate is continually increasing. This, in turn, has led to a significant increase in capacity requirements for the backhaul network. In traditional wireless system, the multi-hop aided transmission has been considered as an effective way to increase the coverage, throughput and transmission reliability of networks [1][2]. Thus, the multi-hop relaying is likely to play a significant role in mmWave cellular systems for self backhauling. The designing of scheduling policies for these systems is challenging due both adaptive directional transmissions and dynamic time-division duplexing schedules, which are key enabling features of mmWave systems [2].

For designing scheduling policies, there are two aspects of challenges in the backhaul network of relay aided mmWave systems. In the first aspect, providing greater flexibility in dynamic adaptation for beam-specific transmit/receive selection to cater the huge backhaul traffic. In the second, the inter-BS scheduling mechanism should serve the maximum backhaul traffic demand and provide higher throughput. The scheduling mechanism should be able to ensure fair transmission opportunity for each BS with non-uniform traffic load in the relay system which is a challenging task.

In this paper, we investigate the multi-hop relaying transmission challenges for mmWave systems. We discuss three solutions based on the point-to-point (P2P) link-quality and traffic-load at each BS that optimizes the overall network performance. Firstly, we present Load-iBS, a traffic-load based inter-BS scheduling mechanism. This approach uses the traffic-load metrics to maximize the performance without acquiring link-state information. Secondly, we present Link-iBS, a link-quality based inter-BS scheduling mechanism. This approach uses the link-quality metric to determine the scheduling decision to maximize the performance. Finally, we present throughput-optimal inter-BS, TO-iBS, a combined version of both Load-iBS and Link-iBS mechanism. This approach uses both the traffic-load and link-quality metrics, and subsequently reallocate the power proportional to the transmission requirements to determine the scheduling decision. Henceforth, the main contribution are summarized as follows:

- We propose a frame reconfiguration scheme which provides greater flexibility in dynamic traffic adaptation.
- We formulate the inter-BS scheduling problem into a non-linear integer programming, i.e. to maximize the number of flows to meet the traffic demand.
- We present a novel heuristic scheduling algorithm with adaptive power allocation method for multi-hop relaying by extensively considering the traffic load at each BS.
- The proposed inter-BS scheduling mechanism showcase superior performance compared with other schemes.

Related Work: There are ample of existing MAC protocols recently proposed for mmWave system [3][5][8] that are based on TDMA including several scheduling algorithms that supports concurrent transmissions [7][9], and dynamic TDD algorithms [6][11] designed to take the advantage of beamforming. In [7], the authors propose a spatial-time division multiple access (STDMA) algorithm that schedules both non-interfering and interfering links simultaneously. It aims to maximize the overall system throughput. However, it does not allow the exploitation of the traffic dynamics. Recently, authors in [9] proposed a QoS-aware scheduling algorithm that partially considers the traffic dynamics, however, it does not exploit the flexibility to adapt fluctuating capacity requirements in the backhaul. A fundamental problem is thus to exploit the traffic dynamics and fluctuating capacity requirements to determine the backhaul scheduling decision. In this work, a dynamic duplexing scheme is considered, where each BS determine its transmit-receive duplex pattern.

II. System Overview

A. Network Model

We consider a multi-hop cellular network consisting of a set of mmWave-enabled small-cell eNodeB (SeNB), where a macrocell eNodeB (MeNB) provides a root from which connections goes to the SeNB at the edge via relay SeNBs that are self-backhauled on mmWave band as shown in Fig. 1.

The backhaul network, $\mathcal{N}(\mathcal{B}, \mathcal{L})$, operates in slotted time $t \in \{0, 1, 2, \dots\}$, where $\mathcal{B} \triangleq \{1, \dots, B\}$ denotes the set of SeNBs and $\mathcal{L} \triangleq \{1, \dots, L\}$ denotes the set of P2P links, indexed by b and ℓ respectively. We denote the cardinalities of these sets as B and L respectively.

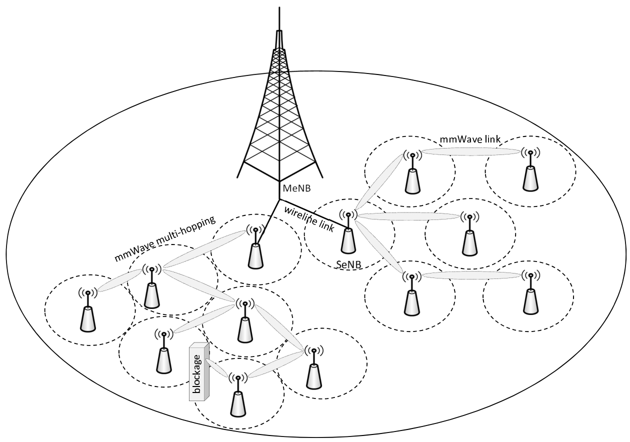


Fig. 1: Illustration of 5G mmWave self-backhaul network.

We assume, all the nodes have adaptive beamforming capabilities, and are able to transmit to *or* receive from multiple neighbors concurrently. The transmission over each link is defined by the general half-duplex constrained. The channel condition remains the same throughout a frame, but may vary dynamically from frame to frame. The system runs a bootstrapping program by which each node is capable of detecting and identifying its set of neighbors.

B. Physical Model

For mmWave communications based on the abstraction used in the prior study [2], the received power at receiver $v \in \mathcal{B}$ from a transmitter $u \in \mathcal{B}$ with transmitting power $P_t(u, v)$, can be calculated as:

$$P_r(u, v) = P_t(u, v)\psi(u, v)PL(u, v)^{-1} \quad (1)$$

where ψ is the combined antenna gain of the receiver and transmitter, and $PL(u, v)^{-1}$ is the associated path-loss in dB.

Without loss of generality, we consider the Line-of-Sight (LOS) model, expressed in (2), since Non-Line-of-Sight (NLOS) transmissions suffers from higher attenuation than LOS transmission, hence, not suitable for backhaul transmission [9]. It is noted that an extension to include both LOS and NLOS model is straightforward.

$$PL(u, v)[dB] = \alpha + 10\beta \log_{10} ||u - v|| + \xi \quad (2)$$

where $\xi \sim N(0, \sigma^2)$, and α and β are provided in Table I.

Let G^2_{max} be the maximum gain on the desired backhaul link $u \to v$. We assume, $SINR_{u \to v}$ is the instantaneous SINR value of link $u \to v$, which is computed based on the active links in the current network schedule at t. This ratio is defined in the expression (3) as below

$$SINR_{u \to v} = \frac{P_t(u, v)G^2_{max}PL(u, v)^{-1}}{I_0 + \sigma^2_N} \quad (3)$$

where $P_t(u, v)$ is the transmitting power from node u to node v, assuming I_0 is the interference due to concurrent transmission, and σ^2_N is the thermal noise power.

Given the SINR and allocated bandwidth, we assume that the maximum data rate on link $u \to v$, i.e., the achievable capacity, expressed in (4), can be estimated as

$$R_{u \to v} = \eta W \log_2(1 + SINR_{u \to v}) \quad (4)$$

where W is the mmWave system bandwidth allocated to the link, η is the bandwidth overhead.

C. Backhaul Traffic Flows

Let data that is destined for node $v \in \mathcal{B}$ be labeled as $Q^{(v)}$. Every node keeps internal queues that store data according to its destination. Let $Q^{(v)}_u(t)$ be the current amount of data for node v in node u, where $v \in N(u)$, the set of neighbour nodes of u. The units of $Q^{(v)}_u(t)$ can be integer units of packets or real valued units of bits. Specifically, we define $\boldsymbol{Q}_u(t) = \left(Q^{(N(u))}_u(t)\right)$ as the matrix of current queue backlogs at u. We assume that $Q^{(u)}_u(t) = 0$ for all slots t, as no queue stores data destined for itself. The queue backlogs from one slot to the next satisfy the following, for all $u, v \in \mathcal{B}$, such that $u \neq v$:

$$Q^{(v)}_u(t+1) \leq \max\left[\boldsymbol{Q}_u(t) - \sum_{v=1}^{|N(u)|} Q^{(v)}_u(t), 0\right] + A^{(v)}_u(t) \quad (5)$$

where $A^{(v)}_u(t)$ is the amount of new data that arrives at node u from $v \in N(u)$ on slot t.

Let $A^{(v)}_u(t)$ be the matrix exogenous arrival on t, for the node $u \in \mathcal{B}$, it is calculated by adding the traffic from access network (UE $\rightleftharpoons$ BS) and the traffic from all other backhaul nodes (BS $\rightleftharpoons$ BS) as

$$A^{(v)}_u(t) = \lambda^0_u + \sum_{v=1}^{|N(u)|} \lambda^{(v)}_u p_{vu} \quad (6)$$

where λ^0_u is the traffic from access network to node u, and p_{vu} is the probability that the traffic is transmitted from node v to u, where $v \in N(u)$. We assume that $\lambda^{(u)}_u = 0$ for all $u \in \mathcal{B}$, as no data arrives that is destined for itself. Thus, $A^{(v)}_u(t)$ is a $|N(u)| \times |N(u)|$ matrix of non-negative real numbers, with zeros on the diagonal.

D. TDD Frame Reconfigurations for Backhauling

To better exploit the traffic variations, enhanced Interference Mitigation and Traffic Adaptation (eIMTA) was introduced [4], which notably allows dynamic adaptation of the TDD pattern. Each TD-LTE frame consists of 10 subframes, which is pre-configured for downlink (D) or for uplink (U) resources. LTE offers 7 different patterns to statically configure the subframes as D, or L, as shown in Fig. 2. On the downside, it suffers from unbalanced allocation of UL and DL time-slots in neighbouring nodes. On the other hand, with an increased focus on small-cell deployments, the basis for the backhaul resource allocation design should be dynamic TDD where a subframe carrying data (or the whole frame) should be assigned either for transmission or for reception as part of the dynamic scheduling decisions. We proposed a novel dynamic frame reconfiguration mechanism, where each subframe could be allowed to transmit to or receive from multiple nodes concurrently, a maximum-size data frame according to the channel capacity. This allows better exploitation of the traffic dynamics in small-cell deployments.

Uplink-Downlink Structure	Subframe Number									
	0	1	2	3	4	5	6	7	8	9
0	D	S	U	U	U	D	S	U	U	U
1	D	S	U	U	D	D	S	U	U	D
2	D	S	U	D	D	D	S	U	D	D
3	D	S	U	U	U	D	D	D	D	D
4	D	S	U	U	D	D	D	D	D	D
5	D	S	U	D	D	D	D	D	D	D
6	D	S	U	U	U	D	S	U	U	D

10 ms

Fig. 2: The LTE TDD configurations.

Specifically, our proposed scheme includes two steps: firstly, we assume a mechanism is in place to poll the transmission requests from neighbouring nodes, so that each node could be aware of the traffic demand of its neighbour nodes; secondly, the subframes are reconfigured dynamically as part of the dynamic scheduling algorithm.

E. Problem Formulation

The scheduling of subframes is the TDD configuration that is used for inter-BS data communication. We consider a queued traffic network where an end-to-end flow with a minimum throughput requirement is transmitted through multiple hops. We calculate the traffic load at each BS and establish a schedule to carry inter-BS data by exploiting concurrent transmissions. For this purpose, we present a scheduling mechanism to find the set of transmitting and receiving nodes, $\mathcal{T}$ and $\mathcal{R}$, respectively.

Assuming the current amount of traffic that is destined to node v from u is $Q_u^{(v)}(t)$ on slot t. Let $\max_{\mu_{uv}} Q_u^{(v)}(t)$ be the maximum amount of traffic that can be delivered from $u \rightarrow v$ with the current P2P link condition μ_{uv} on t. It means choosing a higher μ_{uv} is amounts to maximizing the amount of traffic than can be transmitted. Thus, we want to choose an improved μ_{uv} for each P2P link so as to maximize the amount of traffic that can be delivered on slot t over the whole network.

We assume the traffic demand is $Q_u^{N(u)}(D)$ on each link $u \rightarrow N(u)$, we aim to maximize the total amount of traffic demand served over the whole network by allowing concurrent transmission under the current channel conditions, and half-duplex transmission constraints. Given the huge traffic load at each BS in the backhaul network, and the limited number of timeslots; the optimal schedule, while providing a fair transmission opportunity for each BS, should also served as much traffic demands as possible. The optimal backhaul traffic scheduling problem can be formulated as follows.

$$Q^* = \arg\max_{\mu_{uv}} \sum_{b=1}^{B} \sum_{\ell=1}^{L} Q_u^{(v)} \ \mu_{uv} \tag{7}$$

subject to

$$\sum_{u=1}^{|N(u)|} P_t(u) \leq P_{max}, \quad \forall\ u \in \mathcal{B} \tag{8}$$

$$\sum_{u=1}^{|N(u)|} W \leq W_{max}, \quad \forall\ u \in \mathcal{B} \tag{9}$$

$$\ell_u^t + \ell_v^t \leq 1, \text{if node } u \text{ and } v \text{ are adjacent}; \forall\ u, v \tag{10}$$

This is a non-linear integer programming problem, and is NP-hard. Constraint (8) indicates the total power is shared during concurrent transmission, (9) indicates the total bandwidth is shared among multiple links, and (10) indicates the half-duplex assumption, where adjacent links cannot be scheduled concurrently in the same schedule.

Since it is difficult to solve the problem (7) in polynomial time, we propose a distributed heuristic algorithm instead to solve this in Section III.

III. The Scheduling Policy

The proposed heuristic algorithm yields the $\mathcal{T}$ and $\mathcal{R}$ set for each subframes of Flexible Frame, while enabling the spatial reuse to maximize the total throughput of the system.

A. Set Membership Metric

To achieve high transmission data rate for each traffic flow, links with higher channel quality are usually preferred in link activation selection. Therefore, nodes involved in each active flow can transmit or receive maximum traffic. In addition, considering a queued network, when traffic aggregates at some nodes, congestion may occur and these nodes become bottleneck of the network. Therefore, selection of appropriate nodes for transmission or reception is important to improve the network throughput, considering both the link quality and the traffic loads at the node.

When a node receives a transmission traffic request, it calculates the traffic load at each neighbouring node using the local one-hop information, including the P2P channel statistics. Based on this metric, we categorise our proposed scheduling algorithm into three parts and describe it in next subsection.

B. The Proposed Scheduling Policy

1) Load-based inter-BS Scheduler (Load-iBS): As the name suggests, in Load-iBS we consider the traffic load at each BS to determine the $\mathcal{T}$ and $\mathcal{R}$ set. BS with maximum traffic to transmit is selected as a member of $\mathcal{T}$ in the current subframe. Therefore, the network can transmit maximum aggregate traffic at any subframe. Note that the successful reception is proportional to the transmission requirement and channel quality. The selection metric (hereinafter weight, ω) is calculated as below

$$\omega_{uv} = Q_u^{(v)}, \forall v \in N(u) \tag{11}$$

2) Link Quality-based inter-BS Scheduler (Link-iBS): In the Link-iBS, to achieve the higher transmission data rate in each P2P link, the links with higher channel quality is activated for current subframe. Therefore, the total traffic transmitted over each higher-quality P2P link is amounts to maximizing the overall network throughput. However, this mechanism may lead to wastage transmission slot due to no traffic demand from nodes associated with that link.

$$\omega_{uv} = \mu_{uv} \tag{12}$$

3) Throughput-Optimal inter-BS Scheduler (TO-iBS): Considering either the load of each node or the P2P link quality may not lead to near-optimal throughput performance in the network. Hence, differently from above two scheme, the TO-iBS implements Load-iBS mechanism to obtain the $\mathcal{T}$ and $\mathcal{R}$ sets, and subsequently implements a power reallocation mechanism to improve the active P2P link quality. We can calculate the weight as

$$\omega_{uv} = \min\left[Q_u^v, \mu_{uv}\right] \tag{13}$$

We utilize a proportional power allocation scheme with fractional path loss compensation for improving the link quality. We will describe it briefly.

Let P_{max} represents the maximum transmission power of the BS; PL represents the path loss between BS; $SINR_{target}$ represents the targeted received power level and P_{noise} represents the noise power level. Then, the BS's transmitting power P_t is set to

$$SINR_{target} = P_t - P_{noise} - PL \tag{14}$$

$$P_t = \varphi \cdot PL, P_{min} \leq P_t \leq P_{max} \tag{15}$$

where φ is the compensation factor and is set to $\varphi \in [0, 1]$ in LTE standard with $SINR_{target}$ between 0 and 30dB. The pseudo-code of the scheduling algorithm is presented in Algorithm 1.

Algorithm 1: Millimeter-Wave Inter-BS Scheduler

Input : $\mathcal{N}(\mathcal{B}, \mathcal{L}, Q)$
Output: $Set(\mathcal{T}, \mathcal{R})$
Implements at each SCBS $b \in \mathcal{B}$.
Initialize: $\mathcal{T} = \mathcal{R} = \phi$, and $U = \mathcal{B}$
while $U \neq \phi$ **do**
  Calculate $\mathcal{W} = \max_{v \in N(u)} |\omega_{uv} - \omega_{vu}|$;
  foreach $u \in U$ **do**
    $v \leftarrow \arg\max_{v \in N(u)} \mathcal{W}(v)$;
    if $\mathcal{W}(u) > \mathcal{W}(v)$ **then**
      if $\sum_v \omega_{uv} - \sum_v \omega_{vu} > 0$ **then**
        $\mathcal{T} = \mathcal{T} \cup \{u\}$;
         $U = U \backslash \{u\}; Q_v^{(u)} = 0 \forall v \in N(u)$;
        $v_{maxQ} \leftarrow \max_{v \in \left(N(u) \cup U\right)} \left(Q_u^{(v)}\right)$;
        $\mathcal{R} = \mathcal{R} \cup \{v_{maxQ}\}$;
         $U = U \backslash \{v_{maxQ}\}; Q_{v_{maxQ}}^{(u)} = 0, \forall u \in N(v_{max}Q)$;
      else
        $\mathcal{R} = \mathcal{R} \cup \{u\}$;
         $U = U \backslash \{u\}; Q_u^{(v)} = 0, \forall v \in N(u)$;
        $v_{maxQ} \leftarrow \max_{v \in \left(N(u) \cup U\right)} \left(Q_v^{(u)}\right)$;
        $\mathcal{T} = \mathcal{T} \cup \{v_{maxQ}\}$;
         $U = U \backslash \{v_{maxQ}\}; Q_u^{(v_{maxQ})} = 0, \forall u \in N(v_{max}Q)$;
      end
    end
  end
end
return $Set(\mathcal{T}, \mathcal{R})$;

TABLE I: Simulation Parameters

Parameter	**Value**
Carrier frequency	28 GHz
Duplex Mode	TDD
System Bandwidth	2 GHz
BS Transmit Power	30 dBm
BS Antenna Gain	10 dBi
Pathloss Parameter (PL), $PL = \alpha + 10\beta \log_{10}(d)$ [dB], d in meters	$\alpha = 72.0$ $\beta = 2.92$
Beam-width	45°

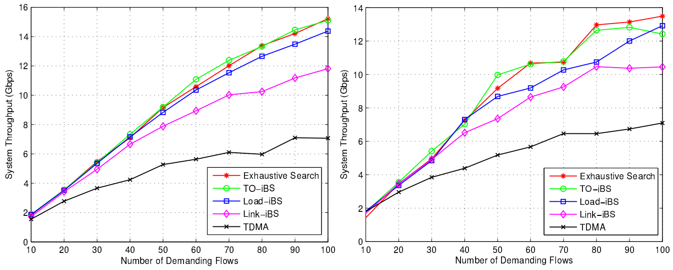
IV. Performance Evaluation

We considered a tree-structured backhaul network with m-hop i.e., the depth of the tree. We assume each node completes the traffic demand polling in the Anchor Frame. The basic system parameters used for simulation are listed in Table I. The related parametres are based on [8]. In the simulation, we set two kinds of traffic model such as: Poisson Process (PP), where each flow arrive follows a PP with arrival rate (6), and Interrupted Poisson Process (IPP), where each flow arrive follows an IPP represented by an ON-OFF process. In the ON state, a packet arrives in each time slot according to a Bernoulli distribution. In the OFF state, packets do not arrive. IPP traffic is typically bursty traffic.

In order to show the advantages of our proposed scheme, we implemented the TDMA, and the Exhaustive Search method for performance comparison.

We plot the network throughput of five schemes under the increasing number of flows in Fig. 3. It indicates the total throughput of the backhaul network i.e., the average sum of the throughput of all successful flows. We observe the performance trend of our proposed algorithm; more the demanding flows, more the aggregate transmission of data, and thus higher the system throughput.

In Fig. 4, we plot the number of successful flows under

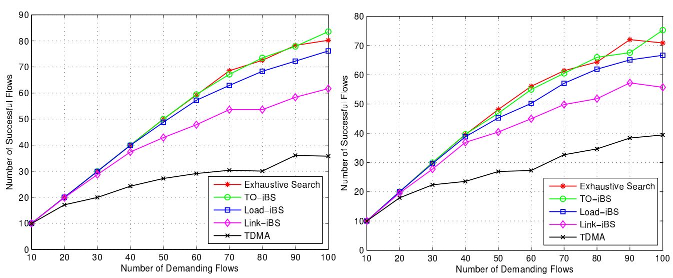


(a) Poisson traffic

(b) IPP traffic

Fig. 3: System throughput under different traffic model

different traffic types and loads with varying number of flows from 10 to 100. The end-to-end flow that successfully reached its destination node and also achieved its throughput requirement is counted as successful flow. Under light load, the number of successful flows keep increases with the traffic load. Under Poisson traffic, the Exhaustive Search and TO-iBS improves the success rate about 10% compared with IPP traffic, under light load.

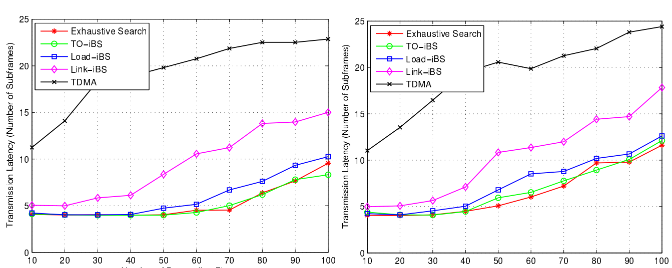


(a) Poisson traffic

(b) IPP traffic

Fig. 4: No. of successful flows under different traffic model

Fig. 5 demonstrates the bursty traffic and Poisson traffic in general experiences very similar average delay due to the node having traffic to transmit is more likely to have the transmission opportunity at the current subframe. Therefore, the flow that arrives non-uniformly, in IPP arrival case, easily misses the channel to transmit.



(a) Poisson traffic

(b) IPP traffic

Fig. 5: Transmission delay under different traffic model

In summary, compared with TDMA and Exhaustive Search, the proposed scheme, TO-iBS, has clear edge. TDMA has a static frame configuration so it cannot accommodate fluctuating capacity requirements. We can observe, the difference between TO-iBS and Exhaustive Search is minor, both scheme almost accommodate similar number of demanding flows. The Exhaustive Search iteratively select the best node from the network and add it to the $\mathcal{T}$ and $\mathcal{R}$ set. The superiority of our proposed scheme comes from two facts. First, it uses local information to acquire the knowledge of traffic information at each node and subsequently makes the scheduling decision. Secondly, the power reallocation proportional to the throughput requirements contributes to the overall performance.

V. Conclusion

In this paper, we consider the problem of providing greater transmission/reception flexibility in the mmWave backhaul network and design a dynamic frame reconfiguration mechanism to overcome the static duplexing. We have formulated the selection of duplex schedules as an optimization problem and proposed an efficient algorithm to solve this by extensively considering the traffic load at each BS. Extensive simulation shows the superiority of our algorithm in achieving similar network throughput and number of successful flows comparing with optimal algorithm, under fairly uniform traffic.

Acknowledgement

This work was financially supported by the Ministry of Science and Technology of Taiwan under Grants MOST 103-2622-E-002-034, and sponsored by MediaTek Inc., Hsinchu, Taiwan.

References

[1] Z. Pi, F. Khan, "An Introduction to Millimeter-Wave Mobile Broadband Systems," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 101–107, Jun. 2011.

[2] S. Singh, *et al.* "Tractable Model for Rate in Self-Backhauled Millimeter Wave Cellular Networks," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 10, pp. 2196–2211, Oct. 2015.

[3] S. Singh, R. Mudumbai, U. Madhow, "Distributed Coordination with Deaf Neighbors: Efficient Medium Access for 60 GHz Mesh Networks", *Proceedings IEEE INFOCOM*, pp. 1–9, Mar 2010.

[4] Volker Pauli, Yi Li, Eiko Seidel, "Dynamic TDD for LTE-A and 5G", *Nomor Research GmbH*, Sept. 2015.

[5] Chan-Yu Tung, Chun-Yen Chen, and Hung-Yu Wei, "Next-Generation Directional mmWave MAC Time-Spatial Resource Allocation", *11th Int'l Conf. on Heterogeneous Networking for Quality, Reliability, Security and Robustness (Qshine 2015)*, Taipei, Taiwan, Aug. 2015

[6] R. Ford, *et al.* "Dynamic Time-domain Duplexing for Self-backhauled Millimeter Wave Cellular Networks," *IEEE International Conference on Communication Workshop (ICC)*, pp. 13–18, June. 2015.

[7] J. Qiao, LX Cai, X. Shen, JW Mark, "STDMA-based Scheduling Algorithm for Concurrent Transmissions in Directional Millimeter Wave Networks," *IEEE Int'l Conf. on Comms.*, pp. 5221–5225, June 2012.

[8] C.Y. Chen, Y.Y. Chen, and H.Y. Wei, "Multi-Cell Interference Coordinated Scheduling in mmWave 5G Cellular Systems," *8th Int'l Conf. on Ubiquitous and Future Networks (ICUFN 2016)*, pp. 912-917, Jul. 2016

[9] Y. Zhu, Y. Niu, J. Li, D. O. Wu, Y. Li, D. Jin, "QoS-aware Scheduling for Small Cell Millimeter Wave Mesh Backhaul," *IEEE International Conference on Communications (ICC)*, pp. 1–6, May. 2016.

[10] Hung-Yu Wei, Samrat Ganguly, Rauf Izmailov, and Zygmunt Haas, "Interference-Aware IEEE 802.16 WiMax Mesh Networks," *The 61st IEEE Vehicular Technology Conference (VTC Spring'05)*, May 2005

[11] J. Garcia-Rois, *et al.* "On the Analysis of Scheduling in Dynamic Duplex multi-hop mmWave Cellular Systems," *IEEE Transactions on Wireless Communications*, vol. 14, no. 11, pp. 6028–6042, Nov. 2015.