Minimum Time Length Scheduling under Blockage and Interference in Multi-hop mmWave Networks

†Zhifeng He, †Shiwen Mao, ‡Sastry Kompella, and §Ananthram Swami
†Department of Electrical and Computer Engineering, Auburn University, Auburn, AL 36849-5201
‡Information Technology Division, Naval Research Laboratory, Washington, DC 20375
§Army Research Laboratory, Adelphi, MD 20783
Email: zzh0008@tigermail.auburn.edu, smao@ieee.org, sk@ieee.org, a.swami@ieee.org

***Abstract*—We study the problem of minimizing the scheduling time length to serve users' traffic demand by link scheduling in multi-hop mmWave wireless networks. We formulate a constrained Binary Integer Programming (BIP) problem incorporating a flexible interference model for directional transmissions and a Markov chain based blockage model. Since the problem is NP hard, we propose a heuristic algorithm with greatly reduced complexity, which first finds the optimal streaming path for each data flow and then maximizes the instant network throughput by optimizing the link scheduling at each time slot. The performance of the heuristic algorithm is validated with simulations.**

I. Introduction

Millimeter wave (mmWave) communications in the 60GHz band has become a research hot spot recently. The huge amount of license-free spectrum (i.e., up to 7GHz in many countries in the 60GHz band) makes mmWave communications a promising technique to satisfy the fast growing demand for wireless capacity [1]. There have been significant standardization efforts on mmWave communications [2], [3] recently.

Before one can deploy these mmWave networks, many challenges need to be addressed. Wireless signal attenuation in mmWave (e.g., 60GHz) channels is a serious issue, much more than in the case of 5GHz or 2.5GHz channels [4], thereby making beamforming indispensable. Because of the small wavelength, large antenna arrays are feasible. The authors in [5] show that the highly directional links, especially in the outdoor environment, can be regarded as "pseudowired" with negligible collision probabilities. Although this characteristic is very attractive for spatial reuse, network coordination and scheduling become extremely challenging with such narrow beamwidths [6]. In the indoor environment, the beamwidth is usually wider than that in outdoor networks due to smaller transmission distances. The interference among neighboring links should be considered since the pseudowired assumption may not hold in this case.

Furthermore, mmWave signals usually do not diffract around or penetrate obstacles. A line-of-sight (LOS) path between the transmitter and receiver is required for successful transmission. However, in practical networks, a LOS path may not always exist; besides, it is possible that a LOS path can be blocked (e.g., by a human body) from time to time. In that case, relay nodes would be needed to forward data to a distant or blocked receiver [7], by setting up a LOS path between the transmitter and relay, and then between the relay and receiver. Second, the blockage between two nodes may appear or disappear intermittently due to the movement of objects between them or the movement of the nodes themselves [8], [9]. A realistic mmWave network protocol should consider the multi-hop path model and dynamic blockages between nodes.

In this paper, we investigate the problem of link scheduling in multi-hop mmWave networks. The mmWave network consists of one Piconet coordinator (PNC), which is the central coordinator, and multiple devices (DEVs). The PNC schedules the downlink transmission to DEVs based on their traffic demands and the possible state of the mmWave links at each time slot. Note that this is different from the standard downlink, in that multi-hop in the peer network may be needed due to blocking of the LOS path to a DEV, or when the DEV is out of range of the PNC. In this case, the PNC then needs to find intermediate DEVs to relay the downlink traffic to a DEV (either out of range or blocked by an obstacle). A successful transmission between two nodes requires unblocked LOS path between them as well as a good Signal to Interference plus Noise Ratio (SINR) at the receiver.

Using blockage and directional interference models, the link scheduling problem is formulated as a constrained Binary Integer Programming (BIP) problem, which aims to deliver data flow to all DEVs within a minimum number of time slots. In our proposed algorithm, we first determine the optimal streaming path for each data flow, and then determine which links on the designated paths should be activated, in order to maximize the instantaneous network throughput. We examine two cases of mmWave transmissions. In the first case, all DEVs work in the HD (Half-Duplex) mode, where a relay cannot receive and forward data simultaneously. In the second case, the same DEVs can work in the FD (Full-Duplex) mode, where a relay can receive from the upstream node while simultaneously forwarding the data to the downstream node using two different beams. We have developed a solution approach with greatly reduced computational complexity for both cases. The performance of the proposed algorithms is validated by comparing them with a benchmark scheme via simulations.

The remainder of this paper is organized as follows. The system model and problem formulation are presented in Section II. The proposed algorithms are described in Section III and evaluated in Section IV. Related work is reviewed in Section V and some conclusions are provided in Section VI.

II. System Model and Problem formulation

A. System Model

We consider a 60GHz network consisting of one PNC and multiple DEVs [2], where directional antennas are used to overcome the high attenuation. We use the term $node$ to refer to a PNC or DEV when there is no need to distinguish between them. The PNC is indexed by 1 and the total number of nodes is N. We consider the downlink scenario where all data traffic originates from the PNC and each DEV has its own traffic demand. We use session z to refer to the data flow z whose destination is DEV z, which can also refer to the transmission path of data flow z.

Assume that time is slotted with unit length time slots. The PNC collects the traffic demand (e.g., the backlog or requests) and statistical link data from the DEVs, based on which, it then determines the link transmission schedule and transmits data to the DEVs in each time slot, until all the traffic demands are served. Using feedback (i.e., ACKs) from the DEVs, the PNC obtains the state of each link at the end of the current time slot and then it updates the remaining traffic demand. We assume that there is a dedicated control channel (e.g., over a lower frequency interface) for the PNC and DEVs to exchange control messages such as traffic demand, ACK, and transmission schedules. We further assume the PNC is able to transmit (receive) to (from) multiple DEVs at the same time.

We use the directional antenna gain model shown in Fig. 1 for co-channel interference (CCI), where h_{ij} is the maximum gain for link ij when their beams are exactly pointing to each other, θ is the angle offset from the peak gain direction, and $\Gamma(\theta)$ is a non-negative, non-increasing function of θ in [0,1] with $\Gamma(0) = 1$. When the transmit power is P_t, the received signal on link ij is $P_t|h_{ij}|^2\Gamma(0)\Gamma(0) = P_t|h_{ij}|^2$. The interference from link i^*j^* to link ij is $P_t|h_{i^*j}|^2\Gamma(\theta(i^*j, i^*j^*))\Gamma(\theta(i^*j, ij))$, where $\theta(i^*j, i^*j^*)$ is the angle between i^*j and i^*j^*, and $\Gamma(\theta(i^*j, ij))$ is the angle between i^*j and ij, as shown in Fig. 1. Let $\Omega(i)$ denote the set of DEVs within one hop distance to node i, $1 \le i \le N$, excluding node i itself, and assume that $j \in \Omega(i)$ in the following. Note that $j \in \Omega(i)$ implies $i \in \Omega(j)$. Transmission on an unblocked link ij will be successful if and only if the SINR exceeds a fixed threshold γ. In the worst case when all the links are activated, this condition can be expressed as

$$\frac{|h_{ij}|^2 P_t}{\sum_{i^*j^* \neq ij} |h_{i^*j}|^2 \Gamma(\theta(i^*j, i^*j^*))\Gamma(\theta(i^*j, ij))P_t + \sigma^2} \ge \gamma, \quad \text{for all } 1 \le i \le N, j \in \Omega(i). \tag{1}$$

where σ^2 is the noise power.

We also model the dynamic blockage of a 60GHz link as a Markov chain. For link ij, let G denote the good state (unblocked) and B denote the bad state (blocked); p_{ij} and q_{ij} are the transition probabilities from G to B and from B to G, respectively; $\bar{p}_{ij} = 1 - p_{ij}$ and $\bar{q}_{ij} = 1 - q_{ij}$ are the transition probabilities from G to G and from B to B, respectively

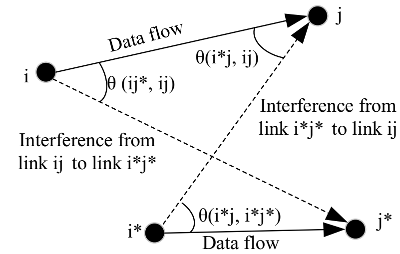

Fig. 1. Interference between two links

B. Problem Formulation

During each time slot, the PNC may or may not receive an ACK from a DEV, depending on whether the PNC transmits to the DEV and the channel state of the link. Define the link state variable s_{ij} as

$$s_{ij} = \begin{cases} 1, & \text{link } ij \text{ is in the good state} \\ 0, & \text{otherwise,} \end{cases} \quad \text{for all } 1 \le i \le N, j \in \Omega(i), \tag{2}$$

and index variable a as

$$a = \begin{cases} 1, & \text{an ACK is received by the PNC} \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

Let $U^m(a|s_{ij})$ be the probability that when link ij is activated during time slot m, the ACK status is a, conditioned on the possibility that the state of link ij is s_{ij} in that time slot. Assuming error-free ACKs, we then have

$$U^m(1|s_{ij}) = s_{ij} \tag{4}$$
$$U^m(0|s_{ij}) = 1 - U^m(1|s_{ij}) = 1 - s_{ij}. \tag{5}$$

Therefore we have that $U^m(a|s_{ij})$ is 1 when ACK is received and 0 when ACK is missing.

Define scheduling index variables x_{ij}^{mz} as

$$x_{ij}^{mz} = \begin{cases} 1, & \text{link } ij \text{ is activated to transmit session } z \\ & \text{traffic in time slot } m \\ 0, & \text{otherwise,} \end{cases} \quad \text{for all } 1 \le i \le N, 2 \le z \le N, z \neq i, j \in \Omega(i), m \ge 1. \tag{6}$$

Since a link can carry at most one session's traffic in each time slot, we have

$$\sum_{z=2, z\neq i}^{N} x_{ij}^{mz} \le 1, \text{for all } 1 \le i \le N, j \in \Omega(i), m \ge 1. \tag{7}$$

Recall that $z = 1$ refers to the PNC.

The probability that the state of link ij is s_{ij} during the time slot $m+1$, denoted as $\lambda^{m+1}_{s_{ij}}$, can be derived as

$$\lambda^{m+1}_{s_{ij}} = \left(\sum_{z=2,z\neq i}^{N} x_{ij}^{(m+1)z}\right)(1-a-s_{ij}-2as_{ij})+ \left(1-\sum_{z=2,z\neq i}^{N} x_{ij}^{(m+1)z}\right)\sum_{s'_{ij}=0}^{1}\lambda^{m}_{s'_{ij}}\Pr(s_{ij}|s'_{ij}),$$

where $\Pr(s_{ij}|s'_{ij})$ is the probability that link ij is in state s'_{ij} at the current time slot and then switches to state s_{ij} at the next time slot, i.e., the channel state transition probability.

We use the steady state distribution of the discrete-time Markov chain as the channel state probability of link ij at time slot 0, i.e., $\lambda^0_{s_{ij}}$:

$$\lambda^0_{s_{ij}} = \begin{cases} \frac{q_{ij}}{p_{ij}+a_{ij}} \doteq \pi(G_{ij}), & s_{ij}=1 \\ \frac{p_{ij}}{p_{ij}+q_{ij}}, & s_{ij}=0, \end{cases} \tag{8}$$

Also define the time slot index variable t^m for time slot m as

$$t^m = \begin{cases} 1, \text{ at least one link is activated in slot } m \\ 0, \text{ otherwise.} \end{cases} \tag{9}$$

From the definitions of x^{mz}_{ij} and t^m we can see that $\sum_{z=2}^{N}\sum_{i=1,i\neq z}^{N}\sum_{j\in\Omega(i)} x^{mz}_{ij} \geq 1$, if $t^m = 1$; and $\sum_{z=2}^{N}\sum_{i=1,i\neq z}^{N}\sum_{j\in\Omega(i)} x^{mz}_{ij} = 0$, otherwise.

Let $V^{mz}_{ij}(\lambda^m_{s_{ij}})$ be the expected amount of traffic of session z delivered by link ij from time slot m to a future time slot M. We have

$$V^{mz}_{ij}(\lambda^m_{s_{ij}}) = \sum_{s_{ij}=0}^{1}\lambda^m_{s_{ij}}\sum_{a=0}^{1}U^m(a|s_{ij})\left[ar_{ij}x^{mz}_{ij}+ V^{(m+1)z}_{ij}(\lambda^{m+1}_{s_{ij}})\right], \text{ for all } 1\leq m\leq M-1, \tag{10}$$

where r_{ij} is the number of packets that can be delivered by link ij if the transmission on link ij is successful.

The expected amount of traffic delivered by link ij for session z from time slot 1 to M can be derived as

$$V^{1z}_{ij}(\lambda^1_{s_{ij}}) = \sum_{m=1}^{M} c^{mz}_{ij}x^{mz}_{ij}, \tag{11}$$

where

$$c^{mz}_{ij} = \sum_{s_{ij}=0}^{1}\lambda^1_{s_{ij}}\sum_{a=0}^{1}U^1(a|s_{ij})\left(\sum_{s_{ij}=0}^{1}\lambda^2_{s_{ij}}\sum_{a=0}^{1}U^2(a|s_{ij}) \dots\left(\sum_{s_{ij}=0}^{1}\lambda^m_{s_{ij}}\sum_{a=0}^{1}U^m(a|s_{ij})ar_{ij}\right)\right). \tag{12}$$

Recall that $\Omega(i)$ is the set of one hop neighbors of node i and $i=1$ refers to the PNC. For the PNC, the following holds true, where D_z is the traffic demand of node z.

$$\sum_{m=1}^{M}\sum_{j\in\Omega(1)} c^{mz}_{1j}x^{mz}_{1j} \geq D_z, \text{ for all } 2\leq z\leq N. \tag{13}$$

If node j is the intermediate relay for session z and m^* is a time slot, then we have

$$\sum_{m=1}^{m^*}\sum_{i\in\Omega(j)} c^{mz}_{ij}x^{mz}_{ij} \geq \sum_{m=1}^{m^*}\sum_{k\in\Omega(j)} c^{mz}_{jk}x^{mz}_{jk}, \text{ for all } 2\leq j,k,z\leq N, k,z\neq i,j, 1\leq m^*\leq M, \tag{14}$$

which means that the data traffic received by an intermediate should be no less than the data traffic it forwarded to a destination in a time slot. In the HD mode, a DEV cannot transmit and receive at the same time. So the following capability constraint holds for a relay node.

$$\sum_{i\in\Omega(j)}\sum_{z=2,z\neq i,j}^{N} x^{mz}_{ij} + \sum_{k\in\Omega(j)}\sum_{z=2,z\neq j}^{N} x^{mz}_{jk} \leq 1, \text{ for all } 2\leq j\leq N. \tag{15}$$

The FD mode we adopt here is as proposed in [18]. In the FD mode, linear antenna arrays are deployed at both transmitter and receiver, and the transmit and receive arrays can be arranged either on a single plane or on two different planes, thus a DEV relay can receive and transmit to two different DEVs at the same time. A DEV is not allowed to simultaneously transmit and receive from the same DEV, since the mutual interference between the two beams will be significantly high. Therefore, the following capability constraint holds true for a relay:

$$\sum_{i\in\Omega(j)}\sum_{z=2,z\neq i,j}^{N} x^{mz}_{ij} \leq 1; \quad \sum_{k\in\Omega(j)}\sum_{z=2,z\neq j}^{N} x^{mz}_{jk} \leq 1, \text{ for all } 2\leq j\leq N. \tag{16}$$

DEV z is the destination of session z. If j is the previous hop of DEV z for session z, then we have

$$\sum_{m=1}^{M}\sum_{j\in\Omega(k)} c^{mz}_{jz}x^{mz}_{jz} \geq D_z, \text{ for all } 2\leq z\leq N. \tag{17}$$

The SINR constraint (1) can be rewritten as (18), which guarantees that the SINR of each activated link in each time slot is above the SINR threshold.

Our goal is to minimize the total amount of time slots used to serve the traffic demands under SINR and blockage constraints. When the relay nodes can only operate in the HD mode, the problem can be formulated as

$$\underline{\text{P0}}: \min: \ \tau = \sum_{m=1}^{M} t^m \tag{19}$$

$$\text{s.t. Constraints (7), (13), (14), (15), (17), (18)} \tag{20}$$

$$t^m \begin{cases} = 1, & \text{if } \sum_{ij} x^{mz}_{ij} \geq 1 \\ = 0, & \text{otherwise,} \end{cases} \text{ for all } m \tag{21}$$

$$t^m \geq t^{m+1}, \text{for all } m \tag{22}$$

$$x^{mz}_{ij} \in \{0,1\}, \text{for all } 1\leq i\leq N, j\in\Omega(i), 2\leq z\leq N, z\neq i. \tag{23}$$

$$\sum_{2\le z\le N, z\ne i}\sum_{i^*j^*\ne ij}|h_{i^*j}|^2\Gamma(\theta(i^*j,i^*j^*))\Gamma(\theta(i^*j,ij))P_t x_{i^*j^*}^{mz}+$$
$$\left(\sum_{2\le z\le N, z\ne i}\sum_{i^*j^*\ne ij}|h_{i^*j}|^2\Gamma(\theta(i^*j,i^*j^*))\Gamma(\theta(i^*j,ij))P_t+\sigma^2-\gamma^{-1}|h_{ij}|^2P_t\right)x_{ij}^{mz}$$
$$\le\sum_{2\le z\le N, z\ne i}\sum_{i^*j^*\ne ij}|h_{i^*j}|^2\Gamma(\theta(i^*j,i^*j^*))\Gamma(\theta(i^*j,ij))P_t, \text{for all } 1\le i\le N, j\in\Omega(i), 2\le z\le N, z\ne i. \quad (18)$$

To formulate the problem when the DEVs can operate in the FD mode, we only need to replace constraint (15) with constraint (16) in Problem P0. Constraints (9) and (22) assure that the scheduling time length is minimized, while during the entire scheduled time all time slots are activated. Further, the value of M could be sufficiently large so that there is always a feasible solution. As will be shown later, with the proposed algorithms, the value of M doesn't affect the solution and objective value as long as it is sufficiently large.

III. Solution Algorithms

Problem P0 is a BIP problem, which is NP-hard in general. Since the constraint matrix is so huge, it is infeasible to list all the columns of the constraint matrix to apply an exhaustive search method, which requires a huge memory to store the constraint matrix. We propose a heuristic algorithm to solve the problem with significantly reduced computation complexity. The basic idea of the heuristic algorithm is that, first, the PNC determines the optimal transmission path for each data flow based on a certain stability criterion. Next, the PNC maximizes the overall throughput of all the data flows by deciding the set of links to be activated in the current time slot, based on the possible state of the links and the interference among them.

A. Path Selection Algorithm

To simplify our problem, we restrict each data flow to be carried by one and only one path. Denote a path from the PNC to DEV z as $\mathcal{P}(z)$ and the set of directional links that belong to $\mathcal{P}(z)$ as $\mathcal{L}(\mathcal{P}(z))$. We define the stationary probability of $\mathcal{P}(z)$ as the joint stationary probability of all the links along $\mathcal{P}(z)$, i.e.,

$$\pi(G(\mathcal{P}(z)))=\prod_{ij\in\mathcal{L}(\mathcal{P}(z))}\pi(G_{ij})=\prod_{ij\in\mathcal{L}(\mathcal{P}(z))}\frac{q_{ij}}{p_{ij}+q_{ij}}. \quad (24)$$

Naturally, if we define the link weight (for those valid links ij) as $\omega_{ij}=-\log(\pi(G_{ij}))$, then a shortest path routing algorithm will find the path $G(\mathcal{P}(z))$ with the largest $\pi(G(\mathcal{P}(z)))$, i.e., the most reliable path. Here, we use *Dijkstra's Algorithm* to find the shortest path between the PNC and each DEV in the network, which has the largest stationary probability among all possible paths.

B. Link Scheduling Algorithm

1) HD Case : After determining the path for each data flow, PNC will decide which links to activate at each time slot. Let the current time slot be m^*, and denote the sets of sessions whose traffic demands have not been satisfied yet at time slot m^* as $H(m^*)$. Let session $z\in H(m^*)$. Denote the number of packets that link ij has delivered for session z at time slot m as f_{ij}^{mz}, $1\le m\le m^*$, and $\{\mathcal{L}(\mathcal{Q}(z)):ij\in\mathcal{L}(\mathcal{Q}(z)), \text{ s.t. } \sum_{m=1}^{m^*}f_{ij}^{mz}<D_z\}$ be the set of links ij such that it's on path $\mathcal{Q}(z)$ and the traffic it had carried up to time slot m^* is less than the demand D_z. Denote the set of relay nodes on path $\mathcal{Q}(z)$ as $\mathcal{R}(\mathcal{Q}(z))$. PNC aims to maximize the instantaneous overall throughput of links that are in $\mathcal{L}(\mathcal{Q}(z)),\forall z\in H(m^*)$ at time slot m^*, by solving Problem SP$(m^*)s$ defined as follows.

$$\min:\ \sum_{z\in H(m^*)}\sum_{ij\in\mathcal{L}(\mathcal{Q}(z))}c_{ij}^{m^*z}x_{ij}^{m^*} \quad (25)$$

s.t. SINR Constraint (28)(at top of the next page)

$$\sum_{m=1}^{m^*-1}f_{ij}^{mz}+c_{ij}^{m^*z}x_{ij}^{m^*z}\le\sum_{m=1}^{m^*-1}f_{jk}^{mz}, \text{for all } ij,$$
$$jk\in\mathcal{L}(\mathcal{Q}(z)), j\in\mathcal{R}(\mathcal{Q}(z)), z\in H(m^*) \quad (26)$$
$$\sum_{z\in H(m^*)}\sum_{ij\in\mathcal{L}(\mathcal{Q}(z))}x_{ij}^{m^*z}+\sum_{z\in H(m^*)}\sum_{jk\in\mathcal{L}(\mathcal{Q}(z))}x_{jk}^{m^*z}\le 1,$$
$$\text{for all } j\in\mathcal{R}(\mathcal{Q}(z)), z\in H(m^*) \quad (27)$$
$$x_{ij}^{mz}\in\{0,1\}, \text{for all } ij\in\mathcal{L}(\mathcal{Q}(z)), z\in H(m^*).$$

Constraint (26) indicates the flow conservation condition for each relay node, i.e., the volume of transmitted data must not exceed the volume of received data. Constraint (27) corresponds to the HD constraint (15) in Problem P0.

2) FD Case : In the FD mode, the flow conservation constraint and capability constraint for a relay node $j\in\mathcal{R}(\mathcal{Q}(z))$ becomes

$$\sum_{m=1}^{m^*-1}f_{ij}^{mz}+c_{ij}^{m^*z}x_{ij}^{m^*z}\le\sum_{m=1}^{m^*-1}f_{jk}^{mz}+c_{jk}^{m^*z}x_{jk}^{m^*z},$$
$$\text{for all } ij,jk\in\mathcal{L}(\mathcal{Q}(z)), j\in\mathcal{R}(\mathcal{Q}(z)), z\in H(m^*) \quad (29)$$
$$\sum_{z\in H(m^*)}\sum_{ij\in\mathcal{L}(\mathcal{Q}(z))}x_{ij}^{m^*z}\le 1;\quad \sum_{z\in H(m^*)}\sum_{jk\in\mathcal{L}(\mathcal{Q}(z))}x_{jk}^{m^*z}\le 1,$$
$$\text{for all } j\in\mathcal{R}(\mathcal{Q}(z)), z\in H(m^*). \quad (30)$$

Replacing constraints (26) and (27) in SP(m^*) with constraints (29) and (30) leads to the instantaneous throughput maximization problem for the FD case, denoted as Problem SP'(m^*).

3) Solution : Denote the total number of links in the network as υ. The size of the constraint matrix of Problem P0 is at least $(M\upsilon N+MN)\times(\upsilon N)$ (Constraints (14) and (18)).

$$\sum_{z\in H(m^*)}\sum_{i^*j^*\in\mathcal{L}(\mathcal{Q}(z)),i^*j^*\neq ij}|h_{i^*j}|^2\Gamma(\theta(i^*j,i^*j^*))\Gamma(\theta(i^*j,ij))P_t x_{i^*j^*}^{m^*z}+$$
$$\sum_{z\in H(m^*)}\sum_{i^*j^*\in\mathcal{L}(\mathcal{Q}(z)),i^*j^*\neq ij}\left(|h_{i^*j}|^2\Gamma(\theta(i^*j,i^*j^*))\Gamma(\theta(i^*j,ij))P_t+\sigma^2-\gamma^{-1}|h_{ij}|^2P_t\right)x_{ij}^{m^*z}$$
$$\leq\sum_{z\in H(m^*)}\sum_{i^*j^*\in\mathcal{L}(\mathcal{Q}(z)),i^*j^*\neq ij}|h_{i^*j}|^2\Gamma(\theta(i^*j,i^*j^*))\Gamma(\theta(i^*j,ij))P_t,\text{ for all } ij\in\mathcal{L}(\mathcal{Q}(z)),z\in H(m^*). \quad (28)$$

Denote the number of hops of session z as υ_z and we have $\upsilon_z \leq N$. Dijkstra's algorithm has a complexity of $\mathcal{O}(N^2)$. The size of the constraint matrix of Problem SP(m^*) (or SP'(m^*)) is $(3\upsilon_z\,\|H(m^*)\|)\times(2\upsilon_z\,\|H(m^*)\|)\leq 6\upsilon_z^2N^2$. Therefore, we conclude that the complexity of Problem SP(m^*) (or SP'(m^*)) is considerably lower than that of Problem P0. Both problems can be solved by *Binary Integer Programming* techniques.

The iterative algorithm for the HD mode problem SP(m^*) is presented in Algorithm 1, which is executed at the PNC. In Lines 1 and 2, Dijkstra's Algorithm is used to find the most reliable path between the PNC and each DEV. The link scheduling problem is solved in Lines 3 to 15. An LP solver is used to solve SP(m^*) first. Once the $x_{ij}^{m^*z}$'s are obtained, the PNC schedules transmissions in the current time slot according to $x_{ij}^{m^*z}$, for all ij (i.e., if $x_{ij}^{m^*z}=1$, then link ij is scheduled for transmission at time slot m^*, otherwise it is not allowed to transmit). Thus a feasible schedule at time slot m^* is obtained. With feedback from the DEVs, the PNC will know $\lambda_{ij}^{m^*+1}$ and $c_{ij}^{(m^*+1)z}$, for all ij, with which it can solve problem $SP(m+1)$ to obtain $x_{ij}^{(m^*+1)z}$, for all ij. And so forth, until H^{m^*} becomes empty. Denote the last time slot in which link ij was active as m_{ij}^*. Then in line 13 of Algorithm 1, $c_{ij}^{m^*z}$ should be updated as in (31) on the top of the next page.

The FD mode problem SP'(m^*) can be solved with an algorithm similar to Algorithm 1. Note that the algorithm is suboptimal, since the path selection and scheduling problems are separately solved, and the scheduling algorithm only aims to maximize the instantaneous throughput of the current time slot, without considering the impact on future time slots. In the next section, we validate the performance of the proposed algorithms with simulations.

Algorithm 1: Iterative Solution Algorithm for the HD Mode Problem SP(m^*)

1 Set link weights to $-\log(\pi(G_{ij}))$ for all valid link ij;
2 Use Dijkstra's Algorithm to find the shortest path between the PNC and each DEV;
3 $m^*=1$;
4 **while** $H(m^*)$ *is not empty* **do**
5   Solve SP(m^*) to obtain $x_{ij}^{m^*}$, for all ij;
6   PNC schedules link transmissions according to $x_{ij}^{m^*}$'s, for all ij;
7     $m^*=m^*+1$;
8   PNC Updates H^{m^*} and $\mathcal{L}(\mathcal{Q}(z))$, for all $z\in H^{m^*}$;
9   **for** $ij\in\mathcal{L}(\mathcal{Q}(z))$, *for all* $z\in H(m^*)$ **do**
10   **for** $s_{ij}=0:1$ **do**
11   Update $\lambda_{s_{ij}}^{m^*}$;
12   **end**
13   Update $c_{ij}^{m^*z}$;
14   **end**
15 **end**

TABLE I
SIMULATION PARAMETERS

Parameter	*Value*
P_t	1
$\|h_{ij}\|^2\Gamma(\theta(i^*j,i^*j^*))\Gamma(\theta(i^*j,ij))$	[0, 1], for all ij, $i^*j^*, ij\neq i^*j^*$
σ^2	0.1
r_{ij}	10, for all ij
D_z	$[50,60]$, for all z

IV. Simulation Study

In this section, we perform numerical simulations using Matlab to validate the performance of the proposed algorithms. Unless otherwise specified, the values of simulation parameters are as shown in Table I. Each simulated point in the figures is obtained by repeating the simulation 50 times with different random seeds, and 95% confidence intervals are computed and plotted in the figures. We compare the proposed algorithms with a benchmark scheme proposed in [11]. The benchmark scheme does not consider link blockages when making path selection and solving the problems with a greedy method, meaning that $\pi(G_{ij})=1$, for all ij, in path selection (it randomly selects a path from those with the minimum number of hops), $c_{ij}^{m^*z}=1$, for all ij and m^* in Problems SP(m^*) and SP'(m^*).

In Fig. 2, we compare the scheduling time to clear all traffic demands for our proposed algorithm with that of the benchmark scheme for different number of DEVs in the network. Although there is some fluctuation due to randomness in simulation, we observe that as the number of DEVs i.e., N is increased, the overall trend for the scheduling time length is increasing, because of the increase in total traffic demand. For both schemes, the FD case outperforms the HD case, since the FD mode allows more concurrent transmissions. The FD network is expected to achieve a higher throughput than the HD network, which leads to a lower scheduling time for the FD case. The proposed scheme outperforms the benchmark scheme in both FD and HD modes, since it considers the dynamic channel states and always chooses the best set of channels to transmit in each time slot.

Examining Constraints (27) and (30) will also help us to better understand the advantage of FD over HD. It can be seen that if the HD mode is replaced by FD, the right hand side (RHS) value of constraint (30) is increased from 1 to 2.

$$c_{ij}^{m^* z} = \sum_{s_{ij}=0}^{1} \lambda_{s_{ij}}^{m_{ij}^*} \sum_{a=0}^{1} U^{m_{ij}^*}(a|s_{ij}) \left(\sum_{s_{ij}=0}^{1} \lambda_{s_{ij}}^{m_{ij}^*+1} \sum_{a=0}^{1} U^{m_{ij}^*+1}(a|s_{ij}) ... \left(\sum_{s_{ij}=0}^{1} \lambda_{s_{ij}}^{m^*} \sum_{a=0}^{1} U^{m^*}(a|s_{ij}) a r_{ij} \right) \right), \quad \text{for all } ij \in \mathcal{L}(\mathcal{Q}(z)), z \in H(m^*). \tag{31}$$

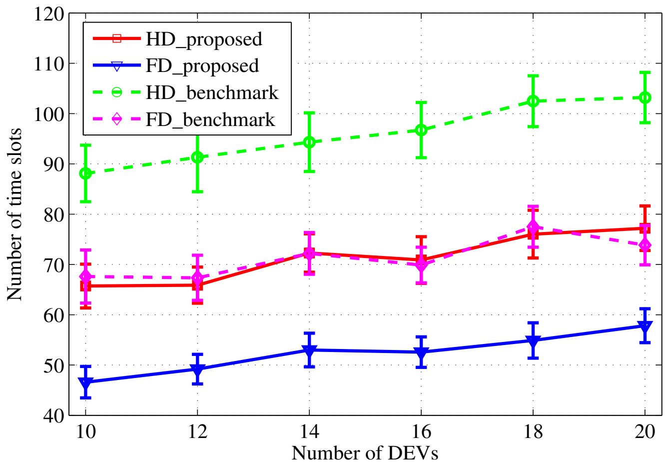

Fig. 2. Number of time slots needed to serve the traffic demands as the number of DEVs is increased ($p_{ij} = q_{ij} \in [0.3, 0.6]$, for all ij, and $\gamma = 0.3$).

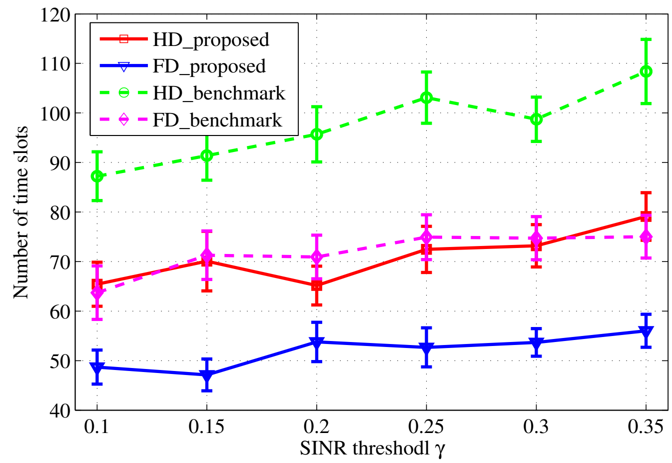

Fig. 3. Number of time slots to serve the traffic demand under various SINR thresholds γ (N=10, $p_{ij} = q_{ij} \in [0.3, 0.6]$, for all ij).

Then the feasible solution region will be larger, thus a better solution may be found and the optimal objective value can be increased, which translates to a higher network throughput.

The effect of the SINR threshold γ on the network performance is shown in Fig. 3. From (18), we can see that as γ is increased for each link, a lower level of interference from the transmission of other links can be tolerated, in order to keep its SINR above γ for a successful transmission. Therefore, fewer concurrent transmissions can be accommodated in the network and thus network throughput is decreased. The transmission delay for a packet may be prolonged since it may spend more time in the queue at the PNC or DEV before it gets transmitted, thereby resulting in an increased scheduling time.

Furthermore, from Constraint (28) we can see that a large γ will allow a larger left hand side (LHS) value. So Constraint (28) will become tighter and the feasible solution space will be narrowed. The optimal objective value will be degraded and network throughput reduced, which is opposite to the case when the network is changed from HD to FD.

The performance gap in scheduling time between our proposed scheme and the benchmark scheme under different minimum link state transition probabilities $\min_{ij}\{\bar{p}_{ij}\}$ is shown in Fig. 4. It can be seen from (8) that as $\min_{ij}\{\bar{p}_{ij}\}$ is increased, the stationary probability of link ij in the good state is increased. Thus more links may have successful concurrent transmissions at each time slot, which improves the network throughput. The PNC may take less time slots to deliver the requested packets to its neighboring DEVs; for the DEVs, the transmission delay between two adjacent DEVs on a path will be shortened due to a greater probability of successful transmissions. These two factors are the main reasons for the shortened scheduling time when $\min_{ij}\{\bar{p}_{ij}\}$ is increased.

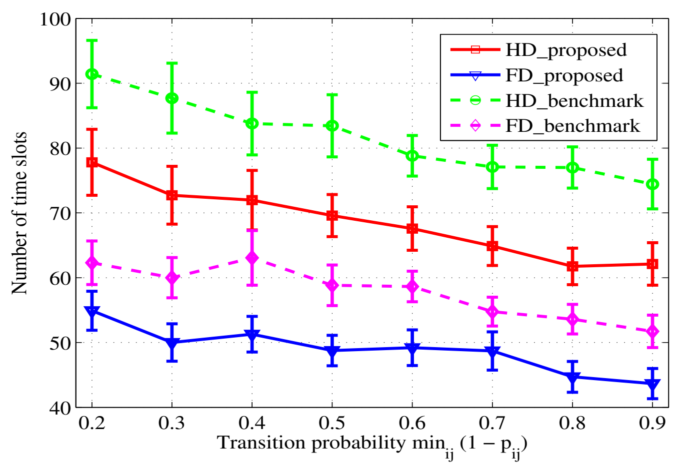

Fig. 4. Number of time slots to serve the traffic demand under various transition probabilities for the 60GHz channels $\bar{p}_{ij}$ ($N = 10$, $p_{ij} \in [0.3, 0.6]$, and $\gamma = 0.3$).

V. Related Work

There has been significant work on mmWave communications recently, mainly on the propagation characteristics of the mmWave channels and MAC protocol design. In [7], the authors quantitatively analyze the vulnerability to blockage and the inherent directivity of mmWave links, pointing out that beam forming and directional antennas are necessary for mmWave communications. In [12], the authors find that the interference between two 60GHz links can be described by their relative geo-locations and the angles between the links, which is named *exclusive regions*, and concurrent transmission pairs can be identified using this concept. Practical and extensive measurement results of urban cellular and peer-to-peer RF wideband channel on 60GHz frequencies are presented in [6], and a significant discovery is that there are very few unique antenna angles for creating a link.

There has also been some interest in developing MAC protocols for 60GHz network recently. In [13], the authors proposed a directional MAC Protocol for mmWave based Wireless Personal Area Networks (WPAN). Directional antennas are used in the proposed protocol, and then rate adaptation is used to coordinate the directional and omni-directional transmissions. Later, the authors develop a channel-time allocation algorithm to leverage the spatial reuse ratio by enabling more coexisting links so that network capacity is enhanced. To deal with the link blockage problem, the authors of [7] propose a multi-hop MAC protocol for mmWave network and show that it improves network connectivity compared with single-hop protocol. A neighbor discovery mechanism is used to build a network topology map, and then polling and path establishing procedures are conducted before data communications. The *deafness* problem (i.e., conventional CSMA/CA protocol does not work well with directional antennas due to impaired carrier sensing at the transmitter) also hinders the feasibility of mmWave network. To deal with this problem, the authors of [14] propose a CSMA/CA protocol that enables the DEV to hear from the PNC at any time by always beam-forming towards the PNC so that the deafness problem is mitigated.

There has not been much work done in the area of link scheduling in 60GHz network so far. In our previous work [15], we propose a link scheduling algorithm to minimize the required time length to serve a given data demand for all the nodes. However, the algorithms can only apply to single-hop 60GHz networks and the problem is easier than the multi-hop network problem addressed in this paper. The authors of [16], [17] propose a Graph Coloring method to optimize the scheduling for given traffic demands, aiming at minimizing the transmission time needed to clear all traffic demands. A "pseudowired" link model is adopted in this paper without considering co-channel interference (CCI) and link blockage.

VI. Conclusion

We investigated the problem of minimum time length scheduling in multi-hop 60GHz networks under both traffic demand and SINR constraints. The problem is formulated as a BIP problem. We developed an effective link scheduling algorithm with significantly reduced computational complexity. The algorithm first finds the optimal routing path for each DEV, and then it tends to maximize the instantaneous network throughput of each time slot by deciding the set of links to activate based on the knowledge of possible channel states and the mutual interference among the channels. Simulation results validated the performance of our proposed algorithm in comparison with a benchmark scheme.

Acknowledgment

This work is supported in part by the US National Science Foundation under Grant CNS-1320664, and through the Wireless Engineering Research and Education Center (WEREC) at Auburn University, Auburn, AL, USA. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the foundation.

References

[1] Z. He and S. Mao "Adaptive multiple description coding and transmission of uncompressed video over 60GHz networks," *ACM Mobile Computing and Communications Review* (MC2R), vol.18, no.1, pp.14–24, Jan. 2014.

[2] IEEE 802.15.3 Working Group, "Part 15.3: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs)," in *IEEE Unapproved Draft STD P802.15.3c/DIO*, June 2009.

[3] S. Mao and T.S. Rappaport, "Millimeter wave wireless networks: A medium access control perspective," in *Wireless Network Performance Enhancement via Directional Antennas: Models, Protocols, and Systems*, F. Hu and S. Kumar (editors). New York, NY: CRC Press, 2015.

[4] R.C. Daniels and R.W. Heath, "60 GHz wireless communications: Emerging requirements and design recommendations," *IEEE Veh. Technol. Mag.*, vol.2, no.3, pp.41–50, Sept. 2007

[5] S. Singh, R. Mudumbai, and U. Madhow. "Interference analysis for highly directional 60-GHz mesh networks: The case for rethinking medium access control," *IEEE/ACM Trans. Netw.*, vol.19, no.5, pp.1513–1527, Oct. 2011.

[6] T.S. Rappaport, E. Ben-Dor, N.N. Murdock, and Y. Qiao, "38 GHz and 60 GHz angle-dependent propagation for cellular and peer-to-peer wireless communications," in *Proc. IEEE ICC'12*, Ottawa, Canada, June 2012, pp.4568–4573.

[7] S. Singh, F. Ziliotto, U. Madhow, E. M. Belding, and M. Rodwell, "Blockage and directivity in 60 GHz wireless personal area networks: From cross-layer model to multihop MAC design," *IEEE J. Sel. Areas Commun.*, vol.27, no.8, pp.14001413, Oct. 2009.

[8] T,. Bai, R. Vaze, and R.W. Heath, "Using random shape theory to model blockage in random cellular networks," in *Proc. IEEE SPCOM'12*, Bangalore, India, July 2012, pp.1–5.

[9] C.R. Anderson and T.S. Rappaport, "In-building wideband partition loss measurements at 2.5 and 60 Ghz," *IEEE Trans. Wireless Commun.*, vol.3, no.3, pp.922–928, Mar. 2004.

[10] M.S. Bazaraa, J.J. Jarvis, and H.D. Sherali, *Linear Programming and Network Flows*, John Wiley & Sons: Hoboken, NJ, 2009.

[11] S. Kompella, J. Wieselthier, A. Ephremides, H. Sherali, and G. Nguyen, "On optimal SINR-based scheduling in multihop wireless networks," *IEEE/ACM Trans. Netw.*, vol.18, no.6, pp.1713–1724, Nov. 2010.

[12] L.X. Cai, L. Cai, X. Shen, and N.W. Mark, "REX: A Randomized EXclusive region based scheduling scheme for mmWave WPANs with directional antenna," *IEEE Trans. Wireless Commun.*, vol.9, no.1, pp.113–121, Jan. 2010.

[13] X. An and R. Hekmat, "Directional MAC protocol for millimeter wave based wireless personal area networks," in *Proc. IEEE VTC-Spring 2008*, Singapore, Singapore, May 2008, pp.1636–1640.

[14] M.X. Gong, Stacey, R. Stacey, D. Akhmetov and S. Mao, "A Directional CSMACA protocol for mmWave wireless PANs," in *Proc. IEEE WCNC 2010*, Sydney, Australia, Apr. 2010, pp.1–6.

[15] Z. He, S. Mao, and T.S. Rappaport "Minimum time length link scheduling under blockage and interference in 60GHz networks," in *Proc. IEEE WCNC 2015*, New Orleans, US, Mar. 2015, pp.837–842.

[16] I.K. Son, S. Mao, M. Gong, and Y. Li, "On frame-based scheduling for directional mmWave WPANs," in *Proc. IEEE INFOCOM'12*, Orlando, FL, Mar. 2012, pp.2149–2157.

[17] I.-K. Son, S. Mao, Y. Li, M. Chen, M.X. Gong, and T.S. Rappaport, "Frame-based medium access control for 5G wireless networks," *Springer MONET Journal*, to appear. DOI: 10.1007/s11036-014-0565-0.

[18] L. Li, K. Josiam, and R. Taori, "Feasibility study on full-duplex wireless millimeter-wave systems," in *Proc. IEEE ICASSP 2014*, Florence, Italy, May. 2014, pp.2769 –2773.