A Decomposition Principle for Link and Relay Selection in Dual-hop 60 GHz Networks

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***Abstract*—We investigate the scheduling problem in a centralized dual-hop 60 GHz network with multiple Source-Destination (SD) pairs, relays, and a PicoNet Coordinator (PNC). The objective is to minimize the Maximum Expected Delivery Time (MEDT) among all SD pairs by jointly optimizing relay and link selection, while exploiting reflected mmWave transmissions and considering link blockage dynamics. We develop a Decomposition Principle to transform this problem into two sub-problems, one for link selection and the other for relay assignment when there is enough replays. We prove that the proposed scheme can achieve an optimality gap of just 1 time slot at greatly reduced complexity. We also develop a heuristic scheme to handle the case when there is no enough relays. The proposed schemes are validated with simulations, where their superior performance is observed.**

I. Introduction

60 GHz millimeter wave (mmWave) communications has become a research hot spot recently. There is up to 7 GHz license-free spectrum in this band that is available in many countries, making 60 GHz communications and networks a promising technique to meet the wireless data challenge, as well as a core technology for future 5G Wireless systems [1], [2]. Furthermore, the authors of [3] propose to augment wired hybrid data center networks with highly directional 60 GHz wireless links to provide flexible network connectivity, which demonstrates the great potential of 60 GHz technology. However, to make 60 GHz mmWave networks applicable, many research challenges should be addressed. The wireless signal attenuation in 60 GHz channels is much serious than that in the 5 GHz or 2.5 GHz channels [4], making beamforming indispensable. The authors in [5] show that the highly directional links, especially in the outdoor environment, can be regarded as *pseudo-wired* with negligible collision probabilities. This model has been adopted in several works on 60 GHz networks [2], [6]–[9].

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 a successful transmission. However, in practical networks, an LOS path may not always exist, and it is possible that an LOS path is blocked (e.g., by a pedestrian or a car) from time to time. First, relay nodes should be used to forward data for a distant or blocked receiver [10], by setting up an LOS path between the transmitter and relay, and that between the relay and receiver. Second, the blockage between two nodes may appear or disappear dynamically due to the movement of objects or the nodes themselves [11], [12]. A realistic 60 GHz network protocol should consider the use of relay nodes and model the dynamic blockages of 60 GHz links.

As a unique feature of mmWave communications, network connectivity can be enhanced by exploiting reflections from walls and other surfaces to steer around obstacles [13]. The authors in [14] use static reflectors to maintain the coverage of 60 GHz networks. When the LOS path is blocked, the authors in [15] suggest to switch the beam path from an LOS link to a Non-Line-Of-Sight (NLOS) link. Although using reflections will cause additional power loss and reduce power efficiency, it offers additional choices for increasing network coverage and improving network throughput [1].

In this paper, we investigate the scheduling problem in centralized dual-hop 60 GHz networks. The network consists of one PNC, which is the central coordinator, multiple SD pairs, and multiple relays. When a source and destination are unable to directly communicate with each other (e.g., out of range of each other, or permanently blocked by an obstacle), a relay will be used to forward their traffic. There are multiple links, including both the LOS link and NLOS links (e.g., reflected from a wall), from a source to a relay and a relay to a destination. We adopt a two-state Markov chain model to capture the dynamic blockage behavior of 60 GHz links. At each time slot, the PNC decides the link and relay selection for each SD pair to minimize the Maximum Expected Delivery Time (MEDT) among all SD pairs. We develop a nonlinear integer programming (NIP) formulation of the link and relay selection problem, and then develop effective algorithms that can provide highly competitive solutions.

The main contributions of this paper is summarized as follows.

- Unlike prior works on relay selection in 60 GHz networks [8], [9], [16]–[19], we consider the LOS and multiple reflected NLOS links between source, relay, and destination nodes, as well as link blockage dynamics in problem formulation, and provide a rigorous analysis of the joint link and relay selection problem.
- We develop a Decomposition Principle to break down the formulated NIP problem into a link selection sub-problem and a relay selection sub-problem. We prove that the two sub-problems together provides a sub-optimal solution to the NIP problem with greatly reduced complexity, and more important, the optimality gap is bounded by only 1 time slot, if there is a sufficient number of relays.
- When there is no enough relays, we propose a heuristic

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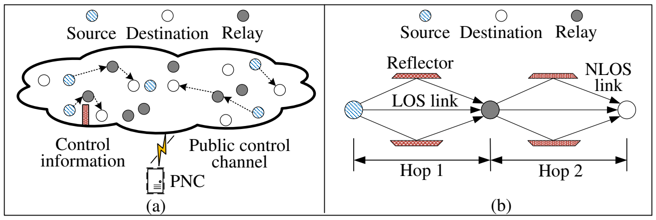

Fig. 1. (a) Network model. (b) Two-hop relay path model.

algorithm that can still achieve highly competitive solutions at a low complexity.

- We validate the proposed algorithms with extensive simulations and comparison with two scheduling algorithms for 60 GHz networks. We find both the proposed Decomposition Principle and heuristic scheme outperform the two benchmarks in all the cases simulated, with respect to delay, MEDT, throughput, and fairness.

In the rest of this paper, we present the system model in Section II and the problem formulation in Section III. We develop the Decomposition Principle and the heuristic algorithm in Section IV and evaluate their performance in Section V. Related work is reviewed in Section VI and Section VII concludes the paper.

II. System Model

As shown in Fig. 1(a), we consider a centralized dual-hop 60 GHz network consisting of multiple nodes and one PNC. Each node can be either a source node (S), a destination node (D), or a potential relay node (R). When the source and destination nodes are unable to directly communicate with each other (e.g., permanently blocked by an obstacle/wall, or out of range), a relay is used to forward their traffic. Due to point-to-point 60 GHz links (unlike traditional broadcast-based relay networks), we assume that each SD pair can choose only one relay at a time. However, a relay may serve multiple SD pairs at different time slots (but not at the same time slot).

To overcome the deafness problem, which makes it highly challenging for coordination of the highly directional links, we assume a lower frequency public control channel (e.g., a WiFi channel) for all nodes and the PNC [20]. Due to the omnidirectional transmissions, better propagation, and larger coverage, the nodes on the control channel actually form a single-hop network. Network state and control information of the dual-hop 60 GHz network can be effectively exchanged among the nodes on the control channel [8], [9], [20], [21], including the following at each time slot.

- The PNC collects network state information, such as traffic requests, link status, etc., from each node
- The PNC broadcasts link transmission schedules to all the nodes if it makes a new schedule at this time slot
- Receiving nodes inform the PNC whether the reception is successful or not, so that the PNC knows the link status.

As shown in Fig. 1(b), there may be multiple links between a pair of nodes within range of each other: there may be one LOS link, as well as other NLOS links formed by exploiting reflections from walls and other surfaces [6]. Due to moving obstacles, the state of a link is either blocked or unblocked at each time slot. We assume the link state follows a discrete-time Markov process [19], [21], while the nodes learn the transition probabilities of their links and inform the PNC these parameters. Note that if the LOS link is more likely to be blocked, an NLOS link may be a better choice. A successful transmission on a link requires the link being unblocked.

Without loss of generality, we assume each node is equipped with an electronically steerable antenna array to beamform in the transmitting or receiving directions; so each node works in the *half-duplex* mode [22]. Both transmission and reception are directional with a very narrow beamwidth. The beamforming weights learned when receiving from a given node can then be used to transmit back to that node, assuming *channel reciprocity*. Some commercial 60 GHz products can have a beamwidth of 1.4° or even as small as 0.6°. A probabilistic analysis is presented in [6] on the interference caused by uncoordinated transmissions in such highly directional 60 GHz networks. The analysis shows that "interference can essentially be ignored in the MAC design" and the links can be regarded as *pseudo-wired* [6]. We adopt such a pseudo-wired link model in this paper, as in prior works [6]–[9].

A relay can be in one of the three states at each time slot: idle, transmitting, or receiving. If a relay is selected for a source, it receive from the source in the first hop. Once finishing the reception, the relay transmit the received packet to the specified destination in the second hop. Until the packet is successfully transmitted to the destination, the relay cannot receive more data from this or other sources due to the half-duplex operation. If a relay is not selected for any source, it stays in the idle state. This model is illustrated in Fig. 1(b), as in prior works [8], [9], [23].

III. Problem Formulation

A. Dynamic Link Blockage Model

For a link l, denote C_l^t as the event that link l is unblocked at time slot t, and $\bar{C}_l^t$ the opposite. Recall that link state follows a discrete-time two-state Markov chain. Let $0 \leq p_l, q_l \leq 1$ be the one-step transition probability from blocked to unblocked, and from unblocked to blocked, respectively. The one-step transition probability matrix of link l is

$$\mathbf{P}_l(1) = \begin{pmatrix} P(\bar{C}_l^{t+1}|\bar{C}_l^t) & P(C_l^{t+1}|\bar{C}_l^t) \\ P(\bar{C}_l^{t+1}|C_l^t) & P(C_l^{t+1}|C_l^t) \end{pmatrix} = \begin{pmatrix} 1-p_l & p_l \\ q_l & 1-q_l \end{pmatrix}.$$

The n-step transition probability matrix of link l is

$$\begin{aligned} \mathbf{P}_l(n) &= \begin{pmatrix} P(\bar{C}_l^{t+n}|\bar{C}_l^t) & P(C_l^{t+n}|\bar{C}_l^t) \\ P(C_l^{t+n}|C_l^t) & P(\bar{C}_l^{t+n}|C_l^t) \end{pmatrix} \\ &= \frac{1}{p_l+q_l}\begin{pmatrix} q_l & p_l \\ q_l & p_l \end{pmatrix} + \frac{(1-p_l-q_l)^n}{p_l+q_l}\begin{pmatrix} p_l & -p_l \\ -q_l & q_l \end{pmatrix} \\ &= \begin{pmatrix} 1-p_l(n) & p_l(n) \\ q_l(n) & 1-q_l(n) \end{pmatrix}, \quad n = 1, 2, \ldots. \end{aligned} \tag{1}$$

B. Expected Delivery Time (EDT)

We consider two types of SD pairs. The first type, denoted as $\mathcal{S}_i$, is that the source and destination are within one-hop distance with each other and are not permanently blocked (e.g., by a wall). Hence the SD pair can either communicate with each other directly, or use a relay if the direct link is poor. The second type, denoted as $\mathcal{S}_j$, is that the SD pair are either out of range or blocked by a permanent obstacle between them. Thus a relay is needed for them to communicate with each other. Define $\mathcal{S}_{i\cup j} = \mathcal{S}_i \cup \mathcal{S}_j$. We next derive the expected delivery time (EDT) for the relay-assisted and direct transmission cases.

1) EDT via Relay : Let s denote a source with destination $d(s)$, and r be a relay that can communicate directly with both s and $d(s)$. Denote a link between s and r as l_{sr}, and the set of all s–r links as $\mathcal{L}_{sr}$. Similarly, we define $l_{rd(s)}$ as a link between r and $d(s)$ and $\mathcal{L}_{rd(s)}$ as the set of these links.

Let $T_{l_{sr}}$ be the delivery time from s to r when link l_{sr} is used in the first hop for a block of data no greater than the channel capacity (normalized to a time slot), and T be the current time slot, $T \geq 1$. The expectation $\mathbb{E}(T_{l_{sr}})$ is the average number of trials until the first successful transmission happens on l_{sr}, which can be expressed as

$$\mathbb{E}(T_{l_{sr}}) = \sum_{t=1}^{\infty} tP(T_{l_{sr}} = t) = 1 \cdot P(C_{l_{sr}}^T) + \sum_{t=2}^{\infty} tP(\bar{C}_{l_{sr}}^T)(1-p_{l_{sr}})^{(t-2)} p_{l_{sr}} = 1 + \frac{1-P(C_{l_{sr}}^T)}{p_{l_{sr}}}, \quad (2)$$

where $P(C_{l_{sr}}^T)$ is the probability that l_{sr} is unblocked at T.

Now let $T_{l_{sr},l_{rd(s)}}$ be the delivery time from r to $d(s)$ when link l_{sr} is chosen in the first hop and link $l_{rd(s)}$ is used in the second hop. To derive $\mathbb{E}(T_{l_{sr},l_{rd(s)}})$, we first note that

$$\mathbb{E}(T_{l_{sr},l_{rd(s)}} | T_{l_{sr}} = t) \quad (3)$$
$$= \sum_{t'=1}^{\infty} t' P(T_{l_{sr},l_{rd(s)}} = t' | T_{l_{sr}} = t) = 1 + \frac{1-P(C_{l_{rd(s)}}^{T+t})}{p_{l_{rd(s)}}}.$$

According to the *law of total expectation*, we have

$$\mathbb{E}(T_{l_{sr},l_{rd(s)}}) = \mathbb{E}(\mathbb{E}(T_{l_{sr},l_{rd(s)}} | T_{l_{sr}} = t))$$
$$= \sum_{t=1}^{\infty} \mathbb{E}(T_{l_{sr},l_{rd(s)}} | T_{l_{sr}} = t) P(T_{l_{sr}} = t)$$
$$= 1 + \frac{1}{p_{l_{rd(s)}}} - \frac{1}{p_{l_{rd(s)}}} \sum_{t=1}^{\infty} P(C_{l_{rd(s)}}^{T+t}) P(T_{l_{sr}} = t). \quad (4)$$

To calculate $\mathbb{E}(T_{l_{sr}})$ in (2) and $\mathbb{E}(T_{l_{sr},l_{rd(s)}})$ in (4), we need to derive $P(C_{l_{sr}}^T)$ and $P(C_{l_{rd(s)}}^{T+t})$. Let t_l be the last time (before the current time T) that PNC knew the state of link l (being either blocked or unblocked). We have

$$P(C_l^T) = P(\bar{C}_l^{t_l}) p_l(T-t_l) + P(C_l^{t_l})(1-q_l(T-t_l))$$
$$= \frac{p_l}{p_l+q_l} + \frac{(1-p_l-q_l)^{T-t_l}}{p_l+q_l} \left(q_l + P(C_l^{t_l})(p_l+q_l)\right). \quad (5)$$

Furthermore, we derive the summation term in (4), which is given at the top of next page. Substituting (5) and (6) into (2) and (4), we thus derive the closed-form expression for the EDT when link l_{sr} and link $l_{rd(s)}$ are chosen for the two-hop relay path, denoted as $\mathbb{E}(T_{srd(s)})$, which is given by

$$\mathbb{E}(T_{srd(s)}) = \mathbb{E}(T_{l_{sr}}) + \mathbb{E}(T_{l_{sr},l_{rd(s)}}). \quad (7)$$

2) EDT via Direct link : Consider the case when s and $d(s)$ use a direct link $l_{sd(s)}$ between them to communicate without using a relay. The EDT from s to $d(s)$ via link $l_{sd(s)}$, denoted as $\mathbb{E}(T_{sd(s)})$, can be derived as $\mathbb{E}(T_{sd(s)}) = 1 + \frac{1-P(C_{l_{sd(s)}}^T)}{p_{l_{sd(s)}}}$.

C. Problem Formulation

Let $\mathcal{R}(s)$ be the set of relays that can communicate directly with both source s and its destination $d(s)$, and $\mathcal{S}(r)$ be the set of sources that can communicate directly with relay r. Denote all the relays and sources as $\mathcal{R}$ and $\mathcal{S}_{i\cup j}$, respectively. Let $\mathcal{L}_{sd(s)}$ be the set of all s-$d(s)$ links. We then define the following decision variables.

$$x_{l_{sr}} = \begin{cases} 1, & \text{source } s \text{ transmits on link } l_{sr} \text{ in hop 1} \\ 0, & \text{otherwise,} \end{cases}$$
$$\forall\, s \in \mathcal{S}_{i\cup j}, r \in \mathcal{R}(s), l_{sr} \in \mathcal{L}_{sr} \quad (8)$$

$$x_{l_{rd(s)}} = \begin{cases} 1, & \text{relay } r \text{ transmits on link } l_{rd(s)} \text{ in hop 2} \\ 0, & \text{otherwise} \end{cases}$$
$$\forall\, s \in \mathcal{S}_{i\cup j}, r \in \mathcal{R}(s), l_{rd(s)} \in \mathcal{L}_{rd(s)} \quad (9)$$

$$x_{l_{sd(s)}} = \begin{cases} 1, & \text{source } s \text{ transmits to its destination } d(s) \\ & \text{via direct link } l_{sd(s)} \\ 0, & \text{otherwise} \end{cases}$$
$$\forall\, s \in \mathcal{S}_{i\cup j}, l_{sd(s)} \in \mathcal{L}_{sd(s)}. \quad (10)$$

Since each relay r can be selected by at most 1 SD pair and only one link can be selected at each hop, we have

$$\sum_{s\in\mathcal{S}(r)} \sum_{l_{sr}\in\mathcal{L}_{sr}} x_{l_{sr}} \leq 1, \forall r \in \mathcal{R}. \quad (11)$$

Note that if relay r is selected by s in the hop 1, then r must also be selected by $d(s)$ in hop 2, i.e.,

$$\sum_{l_{sr}\in\mathcal{L}_{sr}} x_{l_{sr}} = \sum_{l_{rd(s)}\in\mathcal{L}_{rd(s)}} x_{l_{rd(s)}}, \forall s \in \mathcal{S}_{i\cup j}, r \in \mathcal{R}(s). \quad (12)$$

An SD pair can use either a relay or a direct link to communicate directly. So we have the following constraint.

$$\sum_{r\in\mathcal{R}(s)} \sum_{l_{sr}\in\mathcal{L}_{sr}} x_{l_{sr}} + \sum_{l_{sd(s)}\in\mathcal{L}_{sd(s)}} x_{l_{sd(s)}} = 1, \forall\, s \in \mathcal{S}_{i\cup j}. \quad (13)$$

Furthermore, a type $\mathcal{S}_j$ SD pair has to use a relay, i.e.,

$$\sum_{r\in\mathcal{R}(s)} \sum_{l_{sr}\in\mathcal{L}_{sr}} x_{l_{sr}} = 1, \forall\, s \in \mathcal{S}_j. \quad (14)$$

$$\sum_{t=1}^{\infty} P\left(C_{l_{rd(s)}}^{T+t}\right) P(T_{l_{sr}}=t) = \sum_{t=1}^{\infty}\left(P\left(\bar{C}_{l_{rd(s)}}^{T_{l_{rd(s)}}}\right) p_{l_{rd(s)}}(T+t-T_{l_{rd(s)}}) + P\left(C_{l_{rd(s)}}^{T_{l_{rd(s)}}}\right)(1-q_{l_{rd(s)}}(T+t-T_{l_{rd(s)}}))\right) P(T_{l_{sr}}=t)$$

$$= \frac{P(\bar{C}_{l_{sr}}^{T})}{p_{l_{rd}}+q_{l_{rd(s)}}} + \frac{P(\bar{C}_{l_{sr}}^{T})(p_{l_{rd(s)}}+q_{l_{rd(s)}})p_{l_{sr}}}{p_{l_{rd(s)}}+q_{l_{rd(s)}}} \cdot \frac{(1-p_{l_{sr}}-q_{l_{rd(s)}})^{T-T_{l_{rd(s)}}+2}}{(1-(1-p_{l_{rd(s)}}-q_{l_{rd(s)}})(1-p_{l_{sr}}))}. \quad (6)$$

If a relay is selected for an SD pair with source s and destination $d(s)$, the EDT from s to $d(s)$, denoted as g_s, is

$$g_s = \sum_{r\in\mathcal{R}(s)}\left(\sum_{l_{sr}\in\mathcal{L}_{sr}} \mathbb{E}(T_{l_{sr}}) + \left(\sum_{l_{rd(s)}\in\mathcal{L}_{rd(s)}} \mathbb{E}(T_{l_{sr},l_{rd(s)}})x_{l_{rd(s)}}\right)x_{l_{sr}}\right) \quad (15)$$
$$= \sum_{r\in\mathcal{R}(s)}\sum_{l_{sr}\in\mathcal{L}_{sr}} \mathbb{E}(T_{l_{sr}})x_{l_{sr}} + \sum_{r\in\mathcal{R}(s)}\sum_{l_{sr}\in\mathcal{L}_{sr}} x_{l_{sr}} \sum_{l_{rd(s)}\in\mathcal{L}_{rd(s)}} \mathbb{E}(T_{l_{sr},l_{rd(s)}})x_{l_{rd(s)}}.$$

If a relay is not selected, the EDT from s to $d(s)$, denoted as u_s, is

$$u_s = \sum_{l_{sd(s)}\in\mathcal{L}_{sd(s)}} \mathbb{E}(T_{l_{sd(s)}})x_{l_{sd(s)}}. \quad (16)$$

1) Determine If There Is Enough Relays : Before our problem formulation, we first need to determine whether each SD pair in $\mathcal{S}_j$ can have a relay. Let index variable $y_{rs}=1$ denote that relay r is assigned to SD pair s, and $y_{rs}=0$ otherwise. This problem can be formulated as follows.

$$\textbf{P0}:\ \max: \sum_{s\in\mathcal{S}_j}\sum_{r\in\mathcal{R}(s)} y_{rs} \quad (17)$$
$$\text{s.t.} \sum_{s\in\mathcal{S}(r)} y_{rs} \le 1,\ \forall\, r\in\mathcal{R},$$
$$\sum_{r\in\mathcal{R}(s)} y_{rs} \le 1,\ \forall\, s\in\mathcal{S}_j.$$

The constraints are due to the fact that each source can use up to one relay, and each relay can serve at most one source at a time. Let Y be the Objective Function Value (OFV) of problem **P0**. If $Y \ge \|\mathcal{S}_j\|$, where $\|\cdot\|$ denotes the cardinality of a set, each SD pair in $\mathcal{S}_j$ can be served by a relay; otherwise, there are some SD pairs in $\mathcal{S}_j$ that cannot have a relay. We have the following two cases.

2) When $Y \ge \|\mathcal{S}_j\|$: This is the case when each SD pair in $\mathcal{S}_j$ can have a relay. In this case, our objective is to minimize the **MEDT** among all the SD pairs. We thus have the following problem formulation.

$$\textbf{P1}:\ \text{min: } \max_{s\in\mathcal{S}_{i\cup j}}\{g_s+u_s\} \quad \text{s.t. } (8)-(14). \quad (18)$$

Note that when $Y \ge \|\mathcal{S}_j\|$, problem **P1** must have a solution. Although the constraints are linear, the objective function is not. Therefore problem **P1** is a nonlinear integer programming problem (NIP), which is NP-hard. In the next section, we propose a Decomposition Principle to solve this problem.

3) When $Y < \|\mathcal{S}_j\|$: In this case, problem **P1** is not applicable since a type $\mathcal{S}_j$ SD pair may not have a relay to forward its data, if all relays within range are assigned to other SD pairs. We develop a heuristic algorithm to address this case in Section IV-G.

IV. Problem Decomposition and Solution

In this section, we present the Decomposition Principle for the case when each SD pair in $\mathcal{S}_j$ can have a relay, which breaks down problem **P1** into a subproblem for link selection and another subproblem for relay selection. The basic idea is to determine the link selection for each relay first, and then determine the relay selection based on the result of link selection. Moreover, the link selection sub-problem can be further decomposed into three sub-problems, one for link selection in hop 1, the second for link selection in hop 2, and the third for direct link selection. We develop effective algorithms to solve the decomposed problems, and more important, prove a tight *optimality bound* for the decomposition principle solution. In the case that there is no enough relays for the SD pairs in $\mathcal{S}_j$, we develop a heuristic algorithm that can still produce highly competitive solutions.

A. Optimal Choice and Greedy Choice

We first define an optimal choice, Optimal Choice 1 (OC1), and a greedy choice, Greedy Choice 1 (GC1), as follows.

- **Optimal Choice 1 (OC1)**: Given a link $l_{rd(s)}$ in hop 2, choose the hop 1 link as
$$l_{sr}^{*} = \arg\min_{l_{sr}\in\mathcal{L}_{sr}}\{\mathbb{E}(T_{l_{sr}})+\mathbb{E}(T_{l_{sr},l_{rd(s)}})\}. \quad (19)$$
That is, choose the hop 1 link that minimizes the EDT from s to $d(s)$ for a given hop 2 link.
- **Greedy Choice 1 (GC1)**: Given a link $l_{rd(s)}$ in hop 2, choose the hop 1 link as
$$l_{sr}^{+} = \arg\min_{l_{sr}\in\mathcal{L}_{sr}} \mathbb{E}(T_{l_{sr}}). \quad (20)$$
That is, choose the hop 1 link that minimizes the EDT from s to r for a given hop 2 link.

Obviously, the choice of l_{sr}^{*} depends on $l_{rd(s)}$ but that of l_{sr}^{+} does not. We have the following theorem for OC1 and GC1. The proof is omitted for lack of space.

Theorem 1. *For a given relay r and a hop 2 link, GC1 can achieve an EDT from s to $d(s)$ via r that is at most 1 time slot greater than OC1 does.*

In the following, we show how to use GC1 to reduce problem **P1** into a simpler problem.

B. Link Selection in Hop 1

The problem is to minimize the MEDT among the SD pairs while there are plenty of relays. With GC1, we consider links l_{sr}^{+}, for all $s \in \mathcal{S}_{i\cup j}$, $r \in \mathcal{R}(s)$ in hop 1 of problem **P1**, as

$$x_{l_{sr}^{+}} \in \{0,1\}, x_{l_{sr}} = 0, \forall\, l_{sr} \neq l_{sr}^{+}, l_{sr} \in \mathcal{L}_{sr}, s \in \mathcal{S}_{i\cup j}, \\ r \in \mathcal{R}(s). \tag{21}$$

Substitute constraint (21) into problem **P1** and then we have a reduced problem, termed problem **P2**, as follows.

$$\mathbf{P2}\text{: } \min : \max_{s\in\mathcal{S}_{i\cup j}} \Bigg\{ \sum_{r\in\mathcal{R}(s)} \mathbb{E}(T_{l_{sr}^{+}}) x_{l_{sr}^{+}} + \sum_{r\in\mathcal{R}(s)} x_{l_{sr}^{+}} \times \\ \sum_{l_{rd(s)}\in\mathcal{L}_{rd(s)}} \mathbb{E}(T_{l_{sr}^{+}, l_{rd(s)}}) x_{l_{rd(s)}} + \sum_{l_{sd(s)}\in\mathcal{L}_{sd(s)}} \mathbb{E}(T_{l_{sd(s)}}) x_{l_{sd(s)}} \Bigg\} \tag{22}$$

$$\text{s.t. } \sum_{s\in\mathcal{S}(r)} x_{l_{sr}^{+}} \le 1,\ \forall\, r \in \mathcal{R}, \tag{23}$$

$$x_{l_{sr}^{+}} = \sum_{l_{rd(s)}\in\mathcal{L}_{rd(s)}} x_{l_{rd(s)}},\ \forall\, s \in \mathcal{S}_{i\cup j}, r \in \mathcal{R}(s), \tag{24}$$

$$\sum_{r\in\mathcal{R}(s)} x_{l_{sr}}^{+} + \sum_{l_{sd(s)}\in\mathcal{L}_{sd(s)}} x_{l_{sd(s)}} = 1,\ \forall\, s \in \mathcal{S}_{i\cup j} \tag{25}$$

$$\sum_{r\in\mathcal{R}(s)} x_{l_{sr}}^{+} = 1, \forall\, s \in \mathcal{S}_j \tag{26}$$

$$x_{l_{sr}^{+}} = \{0,1\},\ \forall\, s \in \mathcal{S}_{i\cup j}, r \in \mathcal{R}(s) \tag{27}$$

Constraints (9) and (10).

The number of decision variables of problem **P2** is much less than that of problem **P1**. We will prove below that the difference between the OFV of problem **P2** and that of problem **P1** is at most 1 time slot. We first introduce a lemma as a basis of the proof. For ease of presentation, let $\mathcal{S}_1$ denote the set of sources that are assigned with relays in the optimal solution to problem **P1**, i.e., $z_s = \mathbb{E}(T_{l_{sr}}) + \mathbb{E}(T_{l_{sr}, l_{rd(s)}})$, for all $s \in \mathcal{S}_1$, and $\mathcal{S}_2$ be the set of sources that are not assigned with relays and communicate with their destinations using a direct link, i.e., $z_s = \mathbb{E}(T_{l_{sd(s)}})$, for all $s \in \mathcal{S}_2$. Also denote $\mathcal{S}_{1\cup 2} = \mathcal{S}_1 \cup \mathcal{S}_2$. Note that $\mathcal{S}_1 \cup \mathcal{S}_2 = \mathcal{S}_i \cup \mathcal{S}_j$.

Lemma 1. *Denote $\phi^* = \{x_{l_{sr}^*} = 1, x_{l_{rd(s)}^*} = 1,\ \forall\, s \in \mathcal{S}_1$, and $x_{l_{sd(s)}^*} = 1, \forall\, s \in \mathcal{S}_2\}$ as the optimal solution to problem* **P1**. *For all $s \in \mathcal{S}_1$, set $x_{l_{sr}^{+}} = 1$ and then set $x_{l_{sr}^*} = 0$. Then $\phi = \{x_{l_{sr}^{+}} = 1, x_{l_{rd(s)}^*} = 1,\ \forall\, s \in \mathcal{S}_1$, and $x_{l_{sd(s)}^*} = 1$, $\forall\, s \in \mathcal{S}_2\}$ is a feasible solution to problem* **P2**.

Proof: Comparing ϕ with ϕ^*, only the hop 1 link choice is different. Since for all s, we set $x_{l_{sr}^{+}} = 1$ and then set $x_{l_{sr}^*} = 0$, the link choice of hop 1 still satisfies all the constraints in problem **P2**. Hence ϕ is a feasible solution to problem **P2**. ■

Theorem 2. *The OFV of problem* **P2** *is at most 1 time slot greater than that of problem* **P1**.

The proof is omitted for lack of space.

C. Link Selection in Hop 2

Lemma 1 indicates that $\phi = \{x_{l_{sr}^{+}} = 1, x_{l_{rd(s)}^*} = 1, \forall\, s \in \mathcal{S}_1$, and $x_{l_{sd(s)}^*} = 1, \forall\, s \in \mathcal{S}_2\}$ is a feasible, but not necessary optimal, solution to problem **P2**. Furthermore, $l_{rd(s)}^*, \forall\, s \in \mathcal{S}_1$ is hard to obtain because it requires computing the EDT of all possible links in hops 1 and 2. To obtain the optimal solution to problem **P2**, we first define another greedy choice, termed Greedy Choice 2 (GC2), as follows.

- **Greedy Choice 2 (GC2)**: Given a link l_{sr}^{+} obtained by GC1 in hop 1, choose the hop 2 link $l_{rd(s)}^{+}$ as

$$l_{rd(s)}^{+} = \underset{l_{rd(s)}\in\mathcal{L}_{rd(s)}}{\arg\min}\ \mathbb{E}(T_{l_{sr}^{+}, l_{rd(s)}}). \tag{28}$$

  That is, choose the hop 2 link that minimizes the EDT from r to $d(s)$ for given hop 1 link l_{sr}^{+}.

With GC2, we only consider links $l_{rd(s)}^{+}$, for all $s \in \mathcal{S}_{i\cup j}, r \in \mathcal{R}(s)$ in hop 2 for problem **P2**, which means

$$x_{l_{rd(s)}^{+}} \in \{0,1\}, x_{l_{rd(s)}} = 0,\ \forall\, l_{rd(s)} \neq l_{rd(s)}^{+}, l_{rd(s)} \in \mathcal{L}_{rd(s)}, \\ \forall\, s \in \mathcal{S}_{i\cup j}, r \in \mathcal{R}(s). \tag{29}$$

Then we have the following claims for the optimal solution to problem **P2**.

Lemma 2. *Denote $\hat{\phi}^* = \{x_{l_{sr}^{+}} = 1, x_{l_{rd(s)}^*} = 1,\ \forall\, s \in \mathcal{S}_1$, $x_{l_{sd(s)}^*} = 1,\ \forall\, s \in \mathcal{S}_2\}$ as the optimal solution to problem* **P2**. *For all $s \in \mathcal{S}_1$, set $x_{l_{rd(s)}^{+}} = 1$ and $x_{l_{rd(s)}^*} = 0$. Then $\hat{\phi} = \{x_{l_{sr}^{+}} = 1, x_{l_{rd(s)}^{+}} = 1,\ \forall\, s \in \mathcal{S}_1,\ x_{l_{sd(s)}^*} = 1,\ \forall\, s \in \mathcal{S}_2\}$ is a feasible solution to problem* **P2**.

Proof: Comparing $\hat{\phi}$ with $\hat{\phi}^*$, only the hop 2 link choice is different. Since for all s, we set $x_{l_{rd(s)}^{+}} = 1$ and then set $x_{l_{rd(s)}^*} = 0$, the link choice of hop 2 still satisfies all the constraints in problem **P2**. Hence $\hat{\phi}$ is a feasible solution to problem **P2**. ■

Theorem 3. *In the optimal solution to problem* **P2**, *the link selection in hop 2 is $\{x_{l_{rd(s)}^{+}} \in \{0,1\}$, $x_{l_{rd(s)}} = 0,\ \forall\, l_{rd(s)} \neq l_{rd(s)}^{+}$, $l_{rd(s)} \in \mathcal{L}_{rd(s)}$, $\forall\, s \in \mathcal{S}_1, r \in \mathcal{R}(s)\}$.*

The proof is omitted for lack of space.

D. Link Selection in Direct Path

Link selection when the SD pair communicate directly in the optimal solution to problem **P2** can also be obtained with a greedy approach.

For all $s \in \mathcal{S}_j$, set $E(T_{l_{sd(s)}}), \forall\ l_{sd(s)} \in \mathcal{L}_{sd(s)}$, to an arbitrary constant, because the constraints will ensure that for all $s \in \mathcal{S}_j$, the direct link will not be selected. Define a greedy choice, termed Greedy Choice 3 (GC3), as follows.

- **Greedy Choice 3 (GC3)**: Choose the link in the direct SD path as $l_{sd(s)}^{+} = \arg\min_{l_{sd(s)}\in\mathcal{L}_{sd(s)}} \mathbb{E}(T_{l_{sd(s)}})$. That is, choose the link in the direct SD path that minimizes the EDT from s to $d(s)$.

Theorem 4. *In the optimal solution to problem* **P2***, link selection in the direct path is* $\{x_{l^+_{sd(s)}} \in \{0,1\}, x_{l_{sd(s)}} = 0, \forall\, l_{sd(s)} \neq l^+_{sd(s)},\ l_{sd(s)} \in \mathcal{L}_{sd(s)},\ \forall s \in \mathcal{S}_{i\cup j}\}$.

The proof is omitted for lack of space.

E. Relay Assignment

Now that the hop 1, hop 2, and direct link selection sub-problems having been solve with GC1, GC2, and GC3, respectively, we next solve the remaining problem of relay assignment. Substituting the following into problem **P2**,

$$\begin{aligned}&x_{l^+_{rd(s)}} = x_{l^+_{sr}}, x_{l_{sr}} = 0, x_{l_{rd(s)}} = 0, x_{l_{sd(s)}} = 0, \forall\, l_{sr} \neq l^+_{sr},\\ &\forall\, l_{rd(s)} \neq l^+_{rd(s)}, \forall\, l_{sd(s)} \neq l^+_{sd(s)}, l_{sr} \in \mathcal{L}_{sr}, l_{rd(s)} \in \mathcal{L}_{rd(s)},\\ &l_{sd(s)} \in \mathcal{L}_{sd(s)}, \forall\, s \in \mathcal{S}_{i\cup j}, r \in \mathcal{R}(s), \end{aligned} \tag{30}$$

we obtain a reduced problem, termed **SP2**, as follows.

$$\textbf{SP2}: \min : \max_{s\in\mathcal{S}_{i\cup j}} \left\{ \sum_{r\in\mathcal{R}(s)} \Big(\mathbb{E}(T_{l^+_{sr}}) + \mathbb{E}(T_{l^+_{sr}, l^+_{rd(s)}})\Big) x_{l^+_{sr}} + \sum_{l_{sd(s)}\in\mathcal{L}_{sd(s)}} \mathbb{E}(T_{l^+_{sd(s)}}) x_{l^+_{rd(s)}} \right\}$$

$$\text{s.t.} \sum_{r\in\mathcal{R}(s)} x^+_{l_{sr}} + x_{l^+_{sd(s)}} = 1, \forall s \in \mathcal{S}_{i\cup j} \tag{31}$$

$$x_{l^+_{sd(s)}} = \{0,1\}, \forall s \in \mathcal{S}_{i\cup j} \tag{32}$$

$$\text{Constraints (23), (26), and (27).}$$

Also the OFV of problem **SP2** equals to that of problem **P2**. According to Theorem 2, we have Theorem 5 as follows.

Theorem 5. *The OFV of problem* **SP2** *is at most 1 time slot greater than that of problem* **P1**.

F. Decomposition Principle and Problem Reformulation

With analysis in Sections IV-A to IV-E, we are now able to present the following theorem on the Decomposition Principle.

Theorem 6. *Problem* **P1** *can be solved with the following four-step procedure, and the OFV of the solution is at most 1 time slot larger than that of the optimal solution.*

- *Step 1: Choose the set of links in hop 1, i.e.,* $\{l^+_{sr}\}$*, as* $l^+_{sr} = \arg\min_{l_{sr}\in\mathcal{L}_{sr}} \mathbb{E}(T_{l_{sr}}), \forall\, s \in \mathcal{S}_{i\cup j}, r \in \mathcal{R}(s)$.
- *Step 2: With* $\{l^+_{sr}\}$*, choose the set of links in hop 2, i.e.,* $\{l^+_{rd(s)}\}$*, as* $l^+_{rd(s)} = \arg\min_{l_{rd(s)}\in\mathcal{L}_{rd(s)}} \mathbb{E}(T_{l^+_{sr}, l_{rd(s)}}), \forall\, s \in \mathcal{S}_{i\cup j}, r \in \mathcal{R}(s)$.
- *Step 3: Choose the set of links in the direct path, i.e.,* $\{l^+_{sd(s)}\}$*, as* $l^+_{sd(s)} = \arg\min_{l_{sd(s)}\in\mathcal{L}_{sd(s)}} \mathbb{E}(T_{l_{sd(s)}}), \forall\, s \in \mathcal{S}_{i\cup j}, r \in \mathcal{R}(s)$.
- *Step 4: With (30) derived, solve problem* **SP2**.

Let the problem in Step 1, Step 2, and Step 3 of Theorem 6 be termed **SP1**. Note that problem **SP2** is not in the general Integer Linear Programming (ILP) form. To solve problem **SP2**, we reformulate it into a linear programming (LP) problem.

Algorithm 1: Heuristic Algorithm for Link and Relay Assignment When Some $\mathcal{S}_j$ SD Pairs Do Not Have Relays

```
Solve problem P0 ;
if Y ≥ ||S_j|| then
    Apply the Decomposition Principle to solve problem P1 ;
else
    for ∀s ∈ S_i do
        Choose direct link l+_sd(s) to communicate with d(s) ;
    end
    Assign relays to type S_j SD pairs according to the solution
    to P0 ;
    Denote the set of type S_j SD pairs that have a relay as S'_j ;
    Find l+_sr, l+_rd(s), for all s ∈ S'_j, r ∈ R(s) ;
end
```

Introducing a new variable $w = \max_{s\in\mathcal{S}_{i\cup j}}\{\mathbb{E}(T_{l^+_{sd(s)}})x^+_{l_{sd(s)}} + \sum_{r\in\mathcal{R}(s)}(\mathbb{E}(T_{l^+_{sr}}) + \mathbb{E}(T_{l^+_{sr}, l^+_{rd(s)}}))x_{l^+_{sr}}\}$, we have

$$w \geq \mathbb{E}(T_{l^+_{sd(s)}})x^+_{l_{sd(s)}} + \sum_{r\in\mathcal{R}(s)} (\mathbb{E}(T_{l^+_{sr}}) + \mathbb{E}(T_{l^+_{sr}, l^+_{rd(s)}}))x_{l^+_{sr}},\ \forall\, s \in \mathcal{S}_{i\cup j}. \tag{33}$$

Then **SP2** can be rewritten as

$$\textbf{SP2'}: \min : w$$
$$\text{s.t. Constraints, (23), (26), (27), (31), (32), and (33).}$$

Problem **SP2'** is a mixed integer linear programming problem (MILP) and can be solved with an existing effective solver. Once the relay and link selection are completed, the PNC will inform the nodes to start transmission as scheduled. If and only if at least one of the following events happens, the PNC will reschedule the link selection and relay assignment for all the SD pairs based on feedback.

- Case 1: If a source had no traffic in the previous time slot but has traffic in the current time slot.
- Case 2: Whenever a relay finishes transmission to a destination and thus becomes available for source(s).

G. When $Y < \|\mathcal{S}_j\|$

If a type $\mathcal{S}_j$ SD pair cannot be served by a relay, its EDT cannot be defined as in (15) or (16). Thus we cannot directly employ the Decomposition Principle to solve the link and relay assignment problem in this case. We then propose a heuristic algorithm to solve the problem. The basic idea is to maximize the number of SD pairs that can transmit concurrently by relay assignment. We let each type $\mathcal{S}_i$ SD pair transmit via its direct link, and then assign relays to type $\mathcal{S}_j$ SD pairs to maximize the number of $\mathcal{S}_j$ SD pairs that can transmit concurrently. The more concurrent transmissions, the smaller the MEDT.

The Heuristic algorithm is presented in Algorithm 1.

V. Simulation Validation

A. Simulation Configuration

In this section we validate the performance of the proposed Decomposition Principle by Matlab simulations. Unless otherwise specified, the values of simulation parameters are as given

TABLE I
SIMULATION PARAMETERS

Parameter	*Value*
$\|\mathcal{S}_{i\cup j}\|$	10
$\|\mathcal{R}\|$	10
$\|\mathcal{L}_{sr}\|, \forall s, r$	random $\in [3, 7]$
$\left\|\mathcal{L}_{rd(s)}\right\|, \forall s, r$	random $\in [3, 7]$
$\left\|\mathcal{L}_{sd(s)}\right\|, \forall s$	random $\in [0, 3]$
$\max_{\{l\in(\mathcal{L}_{sr}\cup\mathcal{L}_{rd(s)}\cup\mathcal{L}_{sd(s)}),\forall s,r\}} q_l$	0.9
$p_l, \forall l \in (\mathcal{L}_{sr} \cup \mathcal{L}_{rd(s)} \cup \mathcal{L}_{sd(s)}), \forall s, r$	random $\in [0.3, 0.7]$
Chanel capacity	1 Gbps
Time slot duration	1 s

in Table I. Each simulated point in the figures is obtained by repeating the simulation 50 times with different random seeds, while 95% confidence intervals are computed and plotted as error bars in the figures.

We compare the performance of the proposed algorithm in Theorem (6) (termed *Proposed*) with two existing schemes designed for mmWave networks. The first one (termed *Benchmark 1*) is proposed in [19], where a source tries to maximize its throughput by choosing the optimal Access Points (APs), and the source-AP channels are modeled as Markov chains. A heuristic algorithm is used to solve the formulated NP-hard problem in [19]. The second one (termed *Benchmark 2*) is proposed in [18], where relay paths are determined for multiple SD pairs with a heuristic to maximize the total throughput under static channel conditions. Throughput fairness among multiple SD pairs is not considered in this scheme.

The performance metrics to evaluate the proposed algorithm are delay, MEDT among all SD pairs, and network throughput. The delay of a packet is the time it spends at the source queue plus the packet delivery time from source to destination. The traffic is generated with a Bernoulli process [2]. At each time slot, the source generates a number of packets with a predetermined probability, denoted as P_G, and the total volume of bits of the packets generated at each time slot does not exceed the channel capacity.

B. Simulation Results and Analysis

The performance of the proposed algorithm is demonstrated in Fig. 2 by comparing the OFV of problem **SP2'** with that of problem **P1** (i.e., the *Optimal*) under increasing channel transition probability q_l. Problem **P1** is an NIP whose solution takes a very long time to obtain using exhaustive search even for a moderately-sized network. Therefore we simulate a relative small network with 2 SD pairs, 2 relays, 2 links in hop 1, 2 links in hop 2, and 1 link in the direct path, for each SD pair and relay, to obtain the optimal solution within a reasonable time. From Fig. 2, we fine the difference between the OFV of problem **SP2'** and that of problem **P1** is strictly within 1 time slot over the entire range of q_l. The gap is actually much smaller than 1 time slot, which suggests that 1 time slot is in fact the worst case upper bound. Furthermore, the gap increases as q_l grows, since a sub-optimal schedule may result in a relatively worse performance when channel conditions are bad, which means a greater MEDT.

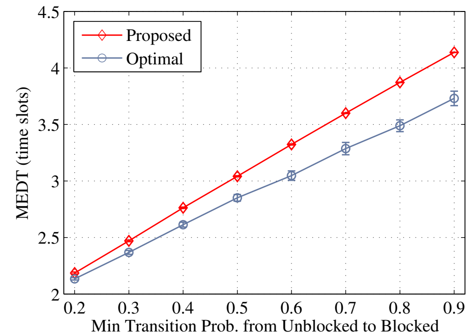

Fig. 2. The OFV of the proposed decomposition principle and that of the optimal solution versus $\min_l\{q_l\}$, while $P_G = 0.8$.

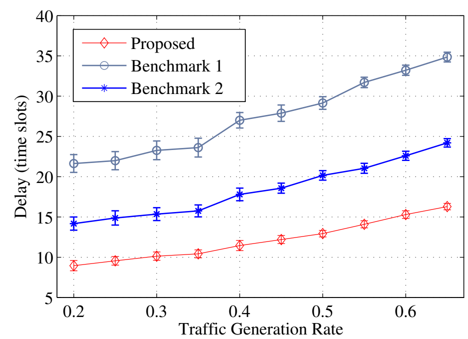

Fig. 3. Delay versus minimum traffic generation probability P_G, while $\min_{\{l\}}\{eq_l\} = 0.2$.

We next compare the delay performance of the proposed scheme with that of the two benchmark schemes in Fig. 3 under various traffic generation rate P_G. As P_G is increased, the average delays of all the three schemes increase due to the increased traffic load, while the average delay of our proposed algorithm is always considerably lower than that of the two benchmark schemes. Benchmark 1 does not consider coordinating the concurrent transmissions among SD pairs. Therefore different SD pairs may select the same relay and thus collision happens, resulting in an increased delivery time. Benchmark 2 does not consider channel dynamics and thus its schedules may be sub-optimal. This comparison also demonstrates that traffic collision has a serious negative effect on delay performance.

Figure 4 shows the MEDT among all SD pairs under changing channel state transition probability q_l. The proposed scheme achieves the lowest MEDT among the three. The confidence interval of Benchmark 1 is greater than that of the other two schemes, indicating Benchmark 1 is less stable in terms of the number of trails until the first successful transmission is achieved. Benchmark 2 considers the channel conditions as static and it lacks adaptation to the channel dynamics, which certainly has an effect on the instantaneous scheduling decision for the current time slot.

The throughput performance achieved by the three schemes is presented in Fig. 5. The network throughput is defined as the total number of bits delivered for all the SD pairs per time slot,

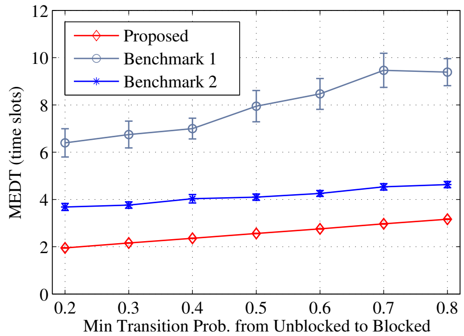

Fig. 4. MEDT versus $\min_{\{l\}}\{q_l\}$, while $P_G = 0.8$.

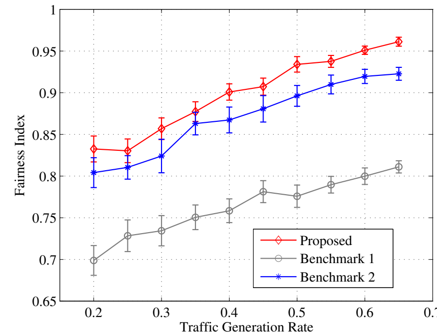

Fig. 6. Fairness performance versus minimum traffic generation probability, for Proposed Scheme, while $\min_{\{l\}}\{q_l\} = 0.2$ and $P_G \leq 0.8$.

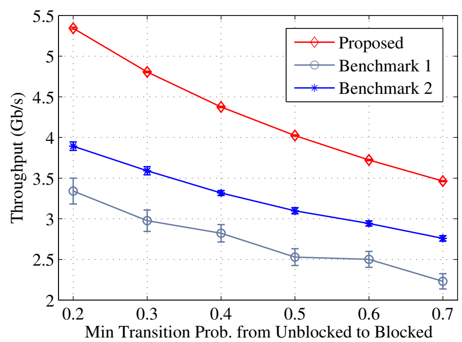

Fig. 5. Throughput versus $\min_{\{l\}}\{q_l\}$, while $P_G = 0.8$.

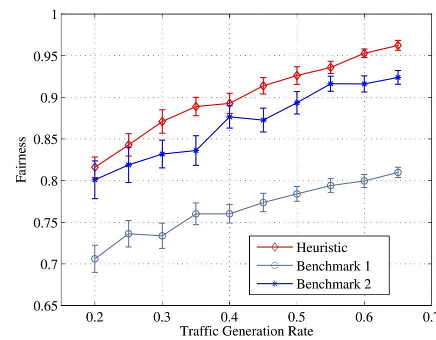

Fig. 7. Fairness performance versus minimum traffic generation probability, for Heuristic Scheme, while $\min_{\{l\}}\{q_l\} = 0.2$ and $P_G \leq 0.8$.

i.e., per second. As channel condition degrades, the number of links available for transmission is decreased at each time slot. So the number of bits that can be delivered at each time slot is reduced. For Benchmark 1, due to the possible collisions, the number of bits successfully delivered per time slot is less than that of the proposed algorithm. For Benchmark 2, due to lack of consideration of channel dynamics, although it tends to maximize the total expected throughput of all SD pairs, it still makes sub-optimal scheduling decisions under dynamic channel conditions, thus achieving a lower throughput.

Finally, we compare the fairness performance of the three schemes, in terms of average delay of the SD pairs. Fig. 6 shows the fairness performance comparison between the proposed scheme and the benchmark schemes. We adopt Jain's fairness index as in [2]: $f(e_1, e_2, \ldots, e_N) = \left(\sum_{n=1}^{N} e_n\right)^2 / \left(N \sum_{n=1}^{N} e_n^2\right)$, where e_n is the average delay of SD pair n, $n = 1, 2, \ldots, N$. The fairness index ranges from 0 (worst) to 1 (best). We can see that our proposed algorithm consistently achieves a higher fairness index than the other two schemes do, due to the *minimax* approach adopted in the problem formulation.

The fairness performance comparison between the heuristic scheme and the benchmark schemes are shown in Fig. 7. We can see that the fairness performance of the heuristic scheme is also consistently better than that of the benchmark schemes.

VI. Related Work

There have been some interesting work on link scheduling in 60 GHz networks. The authors in [21] propose a Partially Observable Markov Decision Process (POMDP) framework to model the link status in 60 GHz networks, and a greedy scheduling strategy that aims to maximize the instant throughput at each time slot. However, this strategy is only applicable for single-hop centralized networks, and the multiple potential links between a node pair is not explored in this paper. A similar problem is studied in [19] with a special scenario of a single-transmitter. To improve network throughput, the authors in [16] propose a fast relay selection algorithm to reduce the overhead of relay selection time, so that there will be more time for data transmission. The basic idea is to determine the sectors where the best relay may be located, and then find the best relays in the selected sector. However, the authors do not consider coordinating concurrent transmissions of multiple transmitters. It is possible that different transmitters may select the same relay and thus collision happens.

In [9], the authors consider the fact that different relays may have different path losses, and thus having different outage probabilities. A relay selection scheme is proposed to minimize the outage probability for a single transmitter. In both indoor and outdoor environments, the obstacles may change over time (e.g., pedestrians move) and thus the blockage of a 60 GHz link is actually not static. Such dynamic channel condition is not considered in [9]. A network throughput maximization problem for a dual-hop network is studied in [8], where different relays may provide different capacities for a SD pair. Relays assignment for multiple SD pairs is optimized to maximize the network throughput. The path loss and blockage model considered in this work are also time-invariant, and thus the proposed algorithm may not be suitable for 60 GHz networks with dynamic link conditions.

In [2], the authors propose a heuristic scheduling scheme for given traffic demands under static channel conditions, aiming to minimize the time needed to clear all the traffic demands. The pseudo-wired 60 GHz channel model is adopted in this work. The authors in [17] study the relationship between the collision probability of two concurrent transmissions on two links and the link distances. It is found that the collision probability is an increasing function of link distance. Based on this finding, the authors propose a hop selection metric based on link distance, to reduce the collision probability of concurrent transmissions. By replacing a single long hop with multiple short hops, the proposed scheme can improve the number of concurrent transmission flows while constraining the harmful interference below an acceptable level. However, the algorithm is heuristic and lacks consideration of multiple coexisting links. The time slot allocation problem in multi-hop 60 GHz networks is investigated in [18], where the direct path shares time slots with the relay path. Different time slot allocation schemes may result in different system throughput, and the effective system throughput is optimized with time slot allocation. A sub-optimal solution is proposed to solve the formulated NP-hard problem.

VII. Conclusion

We developed a Decomposition Principle for the problem of link and relay selection in centralized dual-hop 60 GHz networks. The objective was to minimize the MEDT, and the main idea was to decompose the original problem into a sub-problem for link selection, and the other for relay selection. When there are a sufficient amount of relays, we proved that the two sub-problems together can provide a sub-optimal solution to the original problem with an optimality gap bounded by 1 time slot, with greatly reduced complexity. We also developed a heuristic scheme to handle the case when there is not enough relays to serve the SD pairs. Through simulations, we showed that both proposed schemes outperformed two 60 GHz network scheduling schemes with considerable gains.

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