Supporting Passive Users in mmWave Networks

Mine Gokce Dogan
University of California, Los Angeles
Los Angeles, CA 90095, USA
minedogan96@g.ucla.edu

Martina Cardone
University of Minnesota
Minneapolis, MN 55455, USA
mcardone@umn.edu

Christina Fragouli
University of California, Los Angeles
Los Angeles, CA 90095, USA
christina.fragouli@ucla.edu

***Abstract*—The interference from active to passive users is a well-recognized challenge in millimeter-wave (mmWave) communications. We propose a method that enables to limit the interference on passive users (whose presence may not be detected since they do not transmit) with a small penalty to the throughput of active users. Our approach abstracts away (in a simple, yet informative way) the physical layer component and it leverages the directivity of mmWave links and the available network path diversity. We provide linear programming formulations, lower bounds on active users rates, numerical evaluations, and we establish a connection with the problem of (information theoretically) secure communication over mmWave networks.**

I. Introduction

The fact that active users can destructively interfere with the operation of passive users is a well-recognized challenge in millimeter-wave (mmWave) communications. MmWave infrastructure is increasingly deployed to support a large variety of active user applications, such as virtual reality communications, wearable devices, vehicular networks, and 5G communication systems [1]–[4]. However, the same spectrum is shared by a number of passive users (i.e., users that do not transmit and can be significantly impacted) such as the Global Positioning System (GPS), passive remote sensing systems, and satellites that study Earth exploration, weather monitoring, and radio-astronomy [5]–[9]. In this paper, we propose and evaluate an approach that aims to provide suitable guidelines on how to support a resilient coexistence between passive and active users over mmWave networks.

Supporting the coexistence of passive and active users is a challenging task, for good reasons: by definition, passive users do not transmit and hence, their presence may not be detected. Moreover, they may be mobile and intermittent, changing their location and their time periods of operation. The question we ask in this paper is, can we guarantee a certain amount of interference-free operation to passive users, while not significantly impacting the performance (communication rates) of active users?

Our main observation is that, perhaps this is possible over mmWave networks that provide sufficient path diversity. In particular, we propose to constrain each active user to only transmit for up to a desired fraction of time θ over each link. Due to the directivity of mmWave communications, this translates to that, with very high probability, each passive user will enjoy interference-free operation for a $(1-\theta)$ time fraction. It is not difficult to see that if the capacity of a mmWave network is C, then we can certainly achieve the rate $\theta\mathsf{C}$ with this operation. The interesting part is that, provided that there exists sufficient path diversity over the network, it may be possible to achieve much higher rates by appropriately designing scheduling and routing schemes. For instance, our numerical evaluations indicate that for $\theta = 0.2$ over randomly generated networks, we can almost always achieve 85% of the unrestricted (oblivious to passive users) network capacity.

Technically, we build on the 1-2-1 network model that offers a simple yet informative model for mmWave networks [10]–[12]. The model abstracts away the physical layer component and it focuses on capturing an inherent and dominant characteristic of mmWave communications, that is, directivity: mmWave requires beamforming with narrow beams to compensate for the high path loss incurred by isotropic transmissions. Thus, both the mmWave transmitter and receiver use antenna arrays to electronically steer and direct their beams towards each other. This activates the communication link between them, which is termed as a 1-2-1 link [10]. In particular, [10] proved that the capacity of a Gaussian noise 1-2-1 network can be approximated to within a constant (i.e., only depends on the number of network nodes) additive gap and its optimal beam schedule can be computed in polynomial time. We leverage the results in [10] to develop efficient transmission and scheduling mechanisms that offer suitable guidelines on supporting the coexistence with passive users in mmWave networks. We analyze the impact of passive users on the approximate network capacity and provide guarantees on the achieved rate. Our main contributions are as follows:

- For arbitrary mmWave networks, we formulate a Linear Program (LP) to find the maximum rate that can be achieved while limiting the interference at every node. We show that the LP efficiently (i.e., in polynomial time in the network size) finds a beam schedule that supports passive users to desired thresholds.
- For arbitrary mmWave networks, we derive lower bounds on the active user rates. We also derive lower bounds on the necessary and sufficient number of paths that achieve a target rate while supporting passive users in arbitrary

The research carried out at UCLA was supported in part by the U.S. National Science Foundation (NSF) under grant no. ECCS-2229560. The work of M. Cardone was supported in part by the NSF under grant no. CCF-2045237. This material is also based upon work supported by the NSF under grant no. CNS-2146838 and is supported in part by funds from federal agency and industry partners as specified in the Resilient & Intelligent NextG Systems (RINGS) program.

mmWave networks with unit capacity links. We provide numerical evaluations over randomly generated networks for unequal link capacities.
- We identify a connection between the passive user problem and the (information theoretically) secure communication problem. For arbitrary mmWave networks with unit capacity links, we prove a reduction between these two problems and provide guarantees on the achieved rates in both problems.

Related Work. A multitude of works in the literature study scheduling and routing in wireless networks by exploring multi-path diversity [13]–[16]. However, these works do not consider passive users and thus, their proposed approaches do not provide interference mitigation between passive and active users. Several works study passive users in passive remote sensing systems and for satellites that study Earth exploration and radio-astronomy [17]–[20]. They study the characterization of these wireless systems and propose routing algorithms or interference mitigation techniques to support passive users. However, these works focus on traditional wireless networks and they do not consider the scheduling constraints of mmWave communications. There exist studies that focus on scheduling and routing in multi-hop mmWave networks [21]–[27]. However, these works do not consider passive users. Closer to our work, there exist studies that focus on passive users in directional communication networks, such as mmWave and Terahertz (THz) networks. These works study possible interference scenarios and propose interference mitigation techniques such as employing highly directive and electrically steerable antennas [5], using spread spectrum techniques [8], or sharing the spectrum between active and passive users [6], [7], [9]. However, these works do not propose routing algorithms for path selection and rate allocation, and they do not provide information-theoretical guarantees on the active user rates. Differently, in our work we leverage the directivity of mmWave links and path diversity to develop efficient scheduling mechanisms that support passive users, and derive theoretical guarantees on the active user rates.

Paper Organization. Section II provides background on the 1-2-1 network model. Section III presents the proposed scheduling mechanisms that support passive users, and it provides lower bounds on the active user rates and numerical evaluations. Section IV introduces a connection between the passive user problem and the (information theoretically) secure communication problem. Section V concludes the paper.

II. System Model and Background

Notation. $[a:b]$ is the set of integers from a to $b>a$; $|\cdot|$ denotes the cardinality for sets and the absolute value for scalars; $\mathbb{1}_P$ is the indicator function.

We consider an N-relay Gaussian noise Full-Duplex (FD) 1-2-1 network where N relays assist the communication between the source node (node 0) and the destination node (node $N+1$). At any particular time, each relay can simultaneously transmit and receive by using a single transmit beam and a single receive beam. Thus, at any particular instance, a relay node can transmit to at most one node and it can receive from at most one node. The source (respectively, destination) can transmit to (respectively, receive from) M other nodes i.e., on M outgoing links (respectively, on M incoming links) simultaneously. Formally, in a Gaussian FD 1-2-1 network, the received signal at node $j\in[1:N+1]$ can be written as,

$$Y_j = \sum_{i\in[0:N]\setminus\{j\}} h_{ji}\mathbb{1}_{\{i\in S_{j,r},j\in S_{i,t}\}}X_i + Z_j, \tag{1}$$

where: (i) X_i is the channel input at node $i\in[0:N]$ with power constraint $\mathbb{E}\left[|X_i|^2\right]\le P$; (ii) $h_{ji}\in\mathbb{C}$ is the complex channel coefficient[1] from node i to node j; (iii) $S_{i,t}$ and $S_{j,r}$ represent the node(s) towards which node i is beamforming its transmissions and the node(s) towards which node j is pointing its receive beam(s); and (iv) Z_j indicates the additive white Gaussian noise at node j; noises across the network are independent and identically distributed as $\mathcal{CN}(0,1)$.

Remark 1: Although 1-2-1 networks capture the essence of mmWave communications and enable to derive useful insights on near-optimal information flow algorithms, the model makes a number of simplifying assumptions that include: 1) not considering the overhead of channel knowledge and of beam-steering[2], and 2) assuming no interference among communication links (a reasonable assumption for relays spaced further apart than the beam width). However, in [29] the authors relaxed this last assumption and considered networks where nodes are equipped with imperfect beams that have side-lobe leakage. They showed that even with imperfect side-lobe attenuation, the 1-2-1 model is a viable approximation when certain operational conditions on the beamforming pattern are satisfied. Thus, for networks satisfying the conditions introduced in [29], the results naturally extend.

We next discuss some known capacity results for Gaussian FD 1-2-1 networks for the case $M=1$.

Capacity of Gaussian FD 1-2-1 networks. In [10], it was shown that the capacity of a Gaussian FD 1-2-1 network in (1) can be approximated to within an additive gap that only depends on the number of nodes in the network. In particular, the following LP was proposed to compute the unicast approximate capacity and its optimal schedule,

$$\begin{aligned}
&\mathrm{P1}: \bar{\mathsf{C}} = \max_{x_p, p\in\mathcal{P}} \sum_{p\in\mathcal{P}} x_p \mathsf{C}_p \\
&(\mathrm{P1}a)\ x_p \ge 0, && \forall p\in\mathcal{P},\\
&(\mathrm{P1}b)\ \sum_{p\in\mathcal{P}_i} x_p f^p_{p.nx(i),i} \le 1, && \forall i\in[0:N],\\
&(\mathrm{P1}c)\ \sum_{p\in\mathcal{P}_i} x_p f^p_{i,p.pr(i)} \le 1, && \forall i\in[1:N+1],
\end{aligned} \tag{2}$$

where: (i) $\bar{\mathsf{C}}$ is the approximate capacity; (ii) $\mathcal{P}$ is the collection of all paths connecting the source to the destination; (iii) C_p is the capacity of path p; (iv) $\mathcal{P}_i\subseteq\mathcal{P}$ is the set of paths that pass

[1]The channel coefficients are assumed to be constant for the whole transmission duration and known by the network.

[2]Following beam alignment, the channel time variations are reduced significantly [28] and hence, the channel state changes much slower than the rate of communication.

through node i where $i \in [0\!:\!N\!+\!1]$; (v) $p.nx(i)$ (respectively, $p.pr(i)$) is the node that follows (respectively, precedes) node i in path p; (vi) x_p is the fraction of time that path p is used; and (vii) $f^p_{j,i}$ is the optimal activation time for the link of capacity ℓ_{ji} when path p is operated, i.e., $f^p_{j,i} = \mathsf{C}_p/\ell_{ji}$. Here, ℓ_{ji} denotes the capacity of the link going from node i to node j where $(i,j) \in [0\!:\!N] \times [1\!:\!N\!+\!1]$.

Although the number of variables in the LP P1 (particularly, the number of paths) can be exponential in the number of nodes, this LP can indeed be solved in polynomial time through the following equivalent LP as proved in [10]. We refer readers to [10] for a more detailed description.

$$\begin{aligned}
&\mathrm{P2}: \bar{\mathsf{C}} = \max_{\lambda,F} \sum_{j=0}^{N} F_{(N+1)j},\\
&(\mathrm{P2}a)\ 0 \le F_{ji} \le \lambda_{ji}\ell_{ji}, \qquad \forall (i,j)\in[0\!:\!N]\times[1\!:\!N\!+\!1],\\
&(\mathrm{P2}b)\ \sum_{j\in[1:N+1]\setminus\{i\}} F_{ji} = \sum_{k\in[0:N]\setminus\{i\}} F_{ik}, \qquad \forall i \in [1\!:\!N],\\
&(\mathrm{P2}c)\ \sum_{j\in[1:N+1]\setminus\{i\}} \lambda_{ji} \le 1, \qquad \forall i \in [0\!:\!N],\\
&(\mathrm{P2}d)\ \sum_{i\in[0:N]\setminus\{j\}} \lambda_{ji} \le 1, \qquad \forall j \in [1\!:\!N+1],\\
&(\mathrm{P2}e)\ \lambda_{ji} \ge 0, \qquad \forall (i,j)\in[0\!:\!N]\times[1\!:\!N\!+\!1],
\end{aligned} \tag{3}$$

where: (i) F_{ji} denotes the amount of information flowing from node i to node j; and (ii) λ_{ji} denotes the fraction of time for which the link from node i to node j is active, which determines the schedule used to align the antenna beams.

Remark 2: In the LP P1 (equivalently, in the LP P2), the beam scheduling allows to share traffic across multiple paths, both over space and time without considering the interference on passive users. Our goal is to identify which paths to use and how to schedule them so as to limit passive user interference with a small penalty on the throughput of the active users.

III. Scheduling Mechanisms for Passive Users

In this section, we aim to build scheduling mechanisms that support the coexistence of active and passive users over arbitrary mmWave networks.

We assume that every node $i \in [0:N]$ in the network is allowed to actively transmit over each network link (i,j) for at most $0 \le \theta_{ji} \le 1$ fraction of time where $j \in [1: N\!+\!1]$. That is, each link can be used for at most a certain fraction of time. These thresholds on the link activation times can be selected depending on the application of interest, side knowledge on passive users and their requirements, or they can be selected subject to the constraint that the active user rates are not significantly affected (by using our analysis over a specific network). To account for these thresholds, we add the constraint in (4) to the LP P2 in (3). This ensures that the activation time of each link is below a certain threshold, i.e., the optimal beam schedule can limit the interference on the passive users.

$$\lambda_{ji} \le \theta_{ji}, \quad \forall (i,j)\in[0\!:\!N]\times[1\!:\!N\!+\!1], \tag{4}$$

where θ_{ji} denotes the threshold on the activation time λ_{ji} of the link going from node i to node j.

Remark 3: The LP P2 in (3) with the constraint in (4) has a polynomial number of variables and constraints; hence, an off-the-shelf LP solver can solve it in polynomial time. By taking the same steps as in [10], we can show that there is a polynomial-time mapping between the optimal solution of the LP P2 in (3) with the additional constraint in (4) and a feasible beam schedule. Thus, the LP P2 in (3) with the constraint in (4) efficiently finds a feasible beam schedule that supports passive users while maximizing the rate of active users.

A. Lower Bounds on the Passive Capacity

Although the LP P2 in (3) with the constraint in (4) can be solved efficiently, it does not provide a closed-form expression for the 1-2-1 passive capacity C, i.e., the supremum of all rates achieved under the passive users constraint in (4). With the goal of further investigating the 1-2-1 passive capacity, we here provide a few closed-form lower bounds on it. We start by noting that a simple lower bound on C is given by

$$\mathsf{C} \ge \hat{\theta}\bar{\mathsf{C}}, \tag{5}$$

where: (i) $\bar{\mathsf{C}}$ denotes the approximate capacity found by solving the LP P2 in (3) without the constraint in (4); and (ii) $\hat{\theta} = \min_{\theta\in\Theta}\theta$, where $\Theta = \{\theta_{ji} \mid (i,j)\in[0\!:\!N]\times[1\!:\!N\!+\!1]\}$ denotes the set of threshold values on the activation times of the network links. Indeed, we can achieve $\hat{\theta}\bar{\mathsf{C}}$ by multiplying every link activation time and link flow in the optimal solution of the LP P2 in (3) (without the constraint in (4)) by $\hat{\theta}$. Since this solution satisfies the constraints in the LP P2 and the passive users constraint in (4), it is a lower bound on C.

We now derive a tighter bound on the 1-2-1 passive capacity C than the one in (5). Let $\{\lambda^\star,\ F^\star\}$ denote an optimal solution of the LP P2 in (3) (without the constraint in (4)). We let $\tilde{\Theta}$ denote the set of threshold values on the activation times of the links that are activated by the optimal solution $\{\lambda^\star,\ F^\star\}$, i.e., $\tilde{\Theta} = \left\{\theta_{ji} \mid \lambda^\star_{ji} > 0,\ (i,j)\in[0\!:\!N]\times[1\!:\!N\!+\!1]\right\}$. We also let Λ denote the set of activation times of the links that are selected by $\{\lambda^\star,\ F^\star\}$, i.e., $\Lambda = \left\{\lambda^\star_{ji} \mid (i,j)\in[0\!:\!N]\times[1\!:\!N\!+\!1]\right\}$. Then, the following lower bound on C holds,

$$\mathsf{C} \ge \frac{\tilde{\theta}}{\tilde{\lambda}}\bar{\mathsf{C}}, \tag{6}$$

where $\tilde{\theta} = \min_{\theta\in\tilde{\Theta}}\theta$ and $\tilde{\lambda} = \max_{\lambda\in\Lambda}\lambda$. We can achieve the bound in (6) by multiplying every element in $\{\lambda^\star,\ F^\star\}$ by $\tilde{\theta}/\tilde{\lambda}$. This solution satisfies the constraints in the LP P2 in (3) and the passive users constraint in (4). Since $\tilde{\lambda} \le 1$ and $\hat{\theta} \le \tilde{\theta}$, it follows that (6) is a tighter lower bound on C than (5). We also note that (6) is a lower bound on C only if $\tilde{\theta} < \tilde{\lambda}$. Otherwise, the passive capacity C is equal to $\bar{\mathsf{C}}$.

Since the LP P1 in (2) and the LP P2 in (3) are equivalent LPs (as proved in [10]), we can use an optimal solution of the LP P1 to derive a tighter bound on C. We let $\mathcal{P}^\star$ denote the set of active paths in the optimal solution of the LP P1 (without considering passive users) and $x^\star_p$ denote the optimal

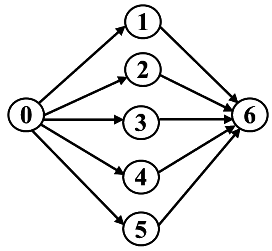

Fig. 1. A network example with $N = 5$ relay nodes.

activation time of the path $p \in \mathcal{P}^\star$. We also let $\mathcal{E}_p$ denote the set of links in path $p \in \mathcal{P}^\star$. The following proposition (proof is delegated to [30, Appendix A]) presents a tighter lower bound on C than (5) and (6) by leveraging the paths in $\mathcal{P}^\star$.

Proposition 1: For an N-relay Gaussian FD 1-2-1 network with an arbitrary topology, the 1-2-1 passive capacity C can be lower bounded as follows,

$$\mathsf{C} \geq \sum_{p \in \mathcal{P}^\star} \min\left(x_p^\star, \frac{\tilde{\theta}_p x_p^\star}{\tilde{\lambda}_p}\right) \mathsf{C}_p, \tag{7}$$

where $\tilde{\theta}_p = \min_{(i,j)\in\mathcal{E}_p} \theta_{ji}$ and $\tilde{\lambda}_p = \max_{(i,j)\in\mathcal{E}_p} \lambda_{ji}^\star$.

Remark 4: By using the definition of $\bar{\mathsf{C}}$ in (2), the lower bound in (6) can be written as,

$$\frac{\tilde{\theta}}{\tilde{\lambda}} \bar{\mathsf{C}} = \sum_{p \in \mathcal{P}^\star} \frac{\tilde{\theta}}{\tilde{\lambda}} x_p^\star \mathsf{C}_p. \tag{8}$$

Since $\tilde{\theta}_p \geq \tilde{\theta}$ and $\tilde{\lambda}_p \leq \tilde{\lambda}$, this readily implies that $\tilde{\theta}/\tilde{\lambda}$ in (6) is smaller than or equal to $\tilde{\theta}_p/\tilde{\lambda}_p$ $\forall p \in \mathcal{P}^\star$. Thus, the bound in (7) is a tighter bound than the one in (6).

Proposition 1 shows that the paths activated by an optimal solution of the LP P1 in (2) can be leveraged to achieve the lower bound in (7). In the example below, we highlight that we can indeed achieve a higher rate than the lower bound in (7) by distributing the traffic across a larger number of paths.

Example 1. Consider the network with $N = 5$ relay nodes in Fig. 1. There exist 5 paths connecting the source (node 0) to the destination (node 6), namely $p_i : 0 \to i \to 6$, $\forall i \in [1:5]$. We consider unit capacity links except for the links in p_1. The link capacities in p_1 are equal to 2. We assume $M = 1$ and $\theta_{ji} = 0.2$ $\forall (i,j) \in [0:N] \times [1:N+1]$. The optimal solution of the LP P1 in (2) (without the constraint in (4)) activates only path p_1 to achieve the approximate capacity $\bar{\mathsf{C}} = 2$. We can reduce the activation time of p_1 to 0.2 in order to satisfy the constraint in (4), and this would achieve the rate 0.4, which is equal to the lower bound in Proposition 1. However, if we perform equal time sharing across all 5 paths, each path is activated for 0.2 fraction of time, and the constraint in (4) is still satisfied. This solution achieves a rate equal to 1.2. □

Example 1 shows that we can leverage the path diversity in a network to achieve a higher rate than the lower bound in Proposition 1. A question that naturally arises is: how many paths would be sufficient to achieve a certain target rate while limiting the interference on the passive users? Or, are there any intrinsic properties of the paths that should be leveraged?

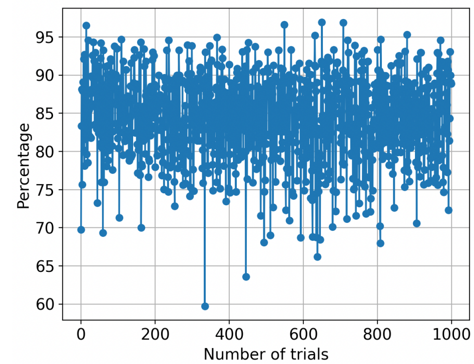

Fig. 2. Achieved percentage of the approximate capacity.

B. Number of Paths for Target Rates

Here, we provide an answer to the aforementioned questions. Towards this end, we let H_e (respectively, H_v) denote the maximum number of edge-disjoint (respectively, vertex-disjoint) paths connecting the source to the destination in the network. Theorem 1 (proof is delegated to [30, Appendix B]) provides lower bounds on H_e and H_v that ensure target rates for the active users.

Theorem 1: Consider an N-relay Gaussian FD 1-2-1 network with an arbitrary topology and unit capacity links, and let θ be the threshold on the activation times of the links in the network. Then, the LP P2 in (3) (without the passive users constraint in (4)) outputs $\bar{\mathsf{C}}$, and the following holds:

- For $M = 1$: The rate $\theta_c \bar{\mathsf{C}}$ can be achieved if and only if

$$H_e \geq \frac{\theta_c}{\theta} \bar{\mathsf{C}}, \tag{9}$$

where $0 \leq \theta_c \leq 1$, and $\bar{\mathsf{C}} = 1$.

- For $M > 1$: The rate $\theta_c \bar{\mathsf{C}}$ can be achieved whenever

$$H_v \geq \frac{\theta_c}{\theta} \bar{\mathsf{C}}, \tag{10}$$

where $0 \leq \theta_c \leq 1$, and $\bar{\mathsf{C}} = \min(M, H_v)$.

Remark 5: Theorem 1 can be directly extended to the case in which there exists a threshold θ_{ji} on the activation time of the link going from node i to node j, $\forall (i,j) \in [0:N] \times [1:N+1]$. To this end, we can simply replace θ in (9) and (10) with the minimum threshold value $\hat{\theta}$ which was defined in (5), and find lower bounds on the number of paths to use for target rates.

The lower bounds in Theorem 1 were derived for networks with unit capacity links. We next numerically evaluate the 1-2-1 passive capacity C and H_e for networks with *unequal* link capacities. Towards this end, we randomly generated a network with $N = 10$ relay nodes and performed 1000 trials over this network. In each trial, we generated a different set of link capacities from the Gaussian distribution with mean 1 and variance 0.1. We assumed that $M = 1$ and we set the threshold on the link activation times equal to $\theta = 0.2$. In Fig. 2, we plotted the achieved percentage of the approximate capacity $\bar{\mathsf{C}}$ over 1000 trials while satisfying the constraint in (4). From Fig. 2, we note that, on average, the passive capacity C is approximately 85% of $\bar{\mathsf{C}}$. This shows that,

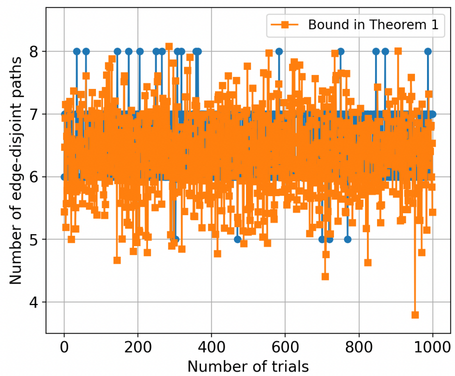

Fig. 3. Maximum number of edge-disjoint paths.

although the activation times of the links in the network can be at most 0.2, our LP formulation finds a schedule that, in every trial, achieves a rate much higher than the naive lower bound in (5) equal to $0.2\overline{\mathsf{C}}$. Thus, we decrease the penalty on the active users throughput. In Fig. 3, we show the maximum number of edge-disjoint paths activated by an optimal solution of the LP P2 in (3) with the constraint in (4). Although we consider unequal link capacities, the maximum number of active edge-disjoint paths varies closely around the bound in (9) for $\theta_c = 1$. Our evaluation shows that if the link capacities have a small variance, the lower bound in (9) still gives a reasonable estimate on the required number of edge-disjoint paths to achieve $\overline{\mathsf{C}}$ (or the target rate $\theta_c\overline{\mathsf{C}}$).

IV. Connection to Secure Communication

In this section, we present a connection between the passive user problem investigated in Section III, and the (information theoretically) secure communication problem. In particular, we show a reduction between these two problems and provide guarantees on the achieved rates.

In the (information theoretically) secure communication problem over 1-2-1 networks [31], an arbitrary 1-2-1 network with unit capacity links is considered, where a passive eavesdropper wiretaps any K links of the network. The authors showed that the source can securely communicate with the destination at high rates by leveraging directivity and multipath diversity in mmWave networks. Particularly, the source can vary which paths it operates over time and this is possible thanks to the fact that we may have several possible choices of paths to achieve the unsecure capacity. Thus, in the secure communication problem over 1-2-1 networks, the traffic is distributed across multiple paths to achieve a high secure rate. This is similar to the passive user problem where we again distribute the traffic across multiple paths to ensure that the activation time of each link in the network is below a certain threshold. Thus, we here aim to perform a reduction between the passive user problem and the secure communication problem. Particularly, we leverage a high-performing (e.g., sometimes capacity achieving) scheme for one problem and see what rate it can guarantee for the other.

In the secure communication problem, we consider the case where a passive eavesdropper can wiretap any K links of the network. In the passive user problem, recall that θ_{ji} is the threshold on the activation time of the link going from node i to node j, $\forall (i,j) \in [0:N] \times [1:N+1]$ (see (4)). We let H_e denote the maximum number of edge-disjoint paths connecting the source to the destination, and we denote the corresponding set of edge-disjoint paths by $p_{[1:H_e]} \subseteq \mathcal{P}$. Similarly, we let H_v be the maximum number of vertex-disjoint paths connecting the source to the destination, and we denote the corresponding set of vertex-disjoint paths by $p_{[1:H_v]} \subseteq \mathcal{P}$. Theorem 2 (proof is delegated to [30, Appendix C]) formally presents our results.

Theorem 2: Consider an N-relay Gaussian FD 1-2-1 network with an arbitrary topology and unit capacity links. Let H_e (respectively, H_v) denote the maximum number of edge-disjoint (respectively, vertex-disjoint) paths connecting the source to the destination. Then, the following holds:

- By using the paths activated by an optimal passive user scheme and the corresponding path activation times, we can guarantee a secure rate R such that,

$$R = \mathsf{C} - \max_{b \in \mathcal{B}} \sum_{(i,j) \in b} \theta_{ji}, \tag{11}$$

where C denotes the 1-2-1 passive capacity and $\mathcal{B}$ is the set of all combinations of K links.

- By leveraging the paths activated by a secure communication scheme and the corresponding path activation times, we can guarantee a rate R in the passive user problem such that,

$$R = \begin{cases} \sum_{p \in p_{[1:H_e]}} \min\left(\frac{1}{H_e}, \theta_p\right) & \text{if } M = 1, \\ \sum_{p \in p_{[1:H_v]}} \min\left(\frac{M}{H_v}, \theta_p\right) & \text{if } M > 1, \end{cases} \tag{12}$$

where $\theta_p = \min_{(i,j) \in \mathcal{E}_p} \theta_{ji}$.

We now show that the connection presented in Theorem 2 is useful as there exist scenarios in which the same set of paths characterize both the passive and secure capacities. Toward this end, we consider the case $M = 1$ and for the passive user problem, we assume that θ is the threshold on the activation times of the links in the network. For $M = 1$, an optimal passive user scheme is found by solving the LP P2 in (3) with the constraint in (4). As we showed in [30, Appendix B], there exists an optimal solution that activates the maximum number of edge-disjoint paths. In [31], an optimal secure scheme that achieves the secure capacity also activates the maximum number of edge-disjoint paths. Thus, the set of edge-disjoint paths $p_{[1:H_e]}$ characterize both the passive capacity and the secure capacity. For example, consider the network in Fig. 1 with unitary link capacities and $\theta = 0.2$. There exist $H_e = 5$ edge-disjoint paths in the network. An optimal solution for the passive user problem activates all five paths such that the activation time of each path is equal to 0.2 and the passive capacity is $\mathsf{C} = 1$. This is equal to the rate R in (12). The optimal secure scheme in [31] also activates all five paths such that the activation time of each path is equal to 0.2 and the secure capacity is equal to $1 - K/H_e = 1 - 0.2K$. This is equal to the rate R in (11). Thus, there exist scenarios where the lower bounds in Theorem 2 are tight and exactly equal to the capacity. In the general case where each link (i,j) has a different threshold θ_{ji}, the set of edge-disjoint paths $p_{[1:H_e]}$ and equal time sharing across these paths with activation time $1/H_e$ characterize both the passive capacity and the secure capacity if $1/H_e \leq \hat{\theta}$, where $\hat{\theta}$ is defined in (5). In the above discussion, we have considered the case $M = 1$; however, it is possible to extend the analysis when $M > 1$, i.e., also for this case there are scenarios in which the same set of paths characterize both the passive and the secure capacities.

V. Conclusions

We have proposed and evaluated an approach to support resilient coexistence of passive and active users in mmWave networks. Our aim was to guarantee a certain amount of interference-free operation to passive users while not significantly impacting the rates of the active users. We formulated an LP to find the maximum rate that can be achieved in arbitrary mmWave networks while limiting the interference at every node. We derived lower bounds on the rates of the active users and on the number of paths that can achieve a target rate, while supporting passive users. We numerically evaluated our results, which showcase the effectiveness of our approach, e.g., 85% of the unrestricted (oblivious to passive users) network capacity can be achieved even when $\theta = 0.2$. Finally, we established a connection between the passive user problem and the problem of (information theoretically) secure communication in mmWave networks. In particular, we performed a reduction between the two problems, and we showed that there are scenarios in which the same set of paths can characterize both the passive and the secure capacities.

We have assumed that the channel coefficients are constant for the whole transmission duration. A research direction worth of further investigation consists of extending the results of this paper to scenarios when the channels experience fading.

References

[1] G. Chittimoju and U. D. Yalavarthi, "A comprehensive review on millimeter waves applications and antennas," *Journal of Physics: Conference Series*, vol. 1804, no. 1, p. 012205, 2021.

[2] X. Wang, L. Kong, F. Kong, F. Qiu, M. Xia, S. Arnon, and G. Chen, "Millimeter wave communication: A comprehensive survey," *IEEE Commun. Surv. Tutor.*, vol. 20, no. 3, pp. 1616–1653, 2018.

[3] A. N. Uwaechia and N. M. Mahyuddin, "A comprehensive survey on millimeter wave communications for fifth-generation wireless networks: Feasibility and challenges," *IEEE Access*, vol. 8, pp. 62 367–62 414, 2020.

[4] S. Rangan, T. Rappaport, and E. Erkip, "Millimeter-wave cellular wireless networks: Potentials and challenges," in *Proceedings of IEEE*, vol. 102, no. 3, 2014, pp. 366–385.

[5] S. Priebe, D. M. Britz, M. Jacob, S. Sarkozy, K. M. K. H. Leong, J. E. Logan, B. S. Gorospe, and T. Kurner, "Interference investigations of active communications and passive Earth exploration services in the THz frequency range," *IEEE Transactions on Terahertz Science and Technology*, vol. 2, no. 5, pp. 525–537, 2012.

[6] M. Polese, X. Cantos-Roman, A. Singh, M. J. Marcus, T. J. Maccarone, T. Melodia, and J. M. Jornet, "Coexistence and spectrum sharing above 100 GHz," *arXiv:2110.15187*, 2021.

[7] M. Polese, V. Ariyarathna, P. Sen, J. V. Siles, F. Restuccia, T. Melodia, and J. M. Jornet, "Dynamic spectrum sharing between active and passive users above 100 GHz," *Communications Engineering*, vol. 1, no. 1, 2022.

[8] C. Bosso, P. Sen, X. Cantos-Roman, C. Parisi, N. Thawdar, and J. M. Jornet, "Ultrabroadband spread spectrum techniques for secure dynamic spectrum sharing above 100 GHz between active and passive users," in *IEEE Int. Symp. Dynamic Spectrum Access Networks*, 2021, pp. 45–52.

[9] E. Eichen, "Real-time geographical spectrum sharing by 5G networks and earth exploration satellite services," in *IEEE International Symposium on Dynamic Spectrum Access Networks*, 2019, pp. 1–2.

[10] Y. H. Ezzeldin, M. Cardone, C. Fragouli, and G. Caire, "Gaussian 1-2-1 networks: Capacity results for mmWave communications," *IEEE Transactions on Information Theory*, vol. 67, no. 2, pp. 961–990, 2021.

[11] Y. H. Ezzeldin, M. Cardone, C. Fragouli, and G. Caire, "Polynomial-time capacity calculation and scheduling for half-duplex 1-2-1 networks," in *IEEE Int. Symp. Information Theory*, 2019, pp. 460–464.

[12] Y. H. Ezzeldin, M. Cardone, C. Fragouli, and G. Caire, "On the multicast capacity of full- duplex 1-2-1 networks," in *IEEE Int. Symp. Information Theory*, 2019, pp. 465–469.

[13] A. Zhou, M. Liu, Z. Li, and E. Dutkiewicz, "Cross-layer design for proportional delay differentiation and network utility maximization in multi-hop wireless networks," *IEEE Transactions on Wireless Communications*, vol. 11, no. 4, pp. 1446–1455, 2012.

[14] J. P. Rohrer, A. Jabbar, and J. P. G. Sterbenz, "Path diversification: A multipath resilience mechanism," in *2009 7th International Workshop on Design of Reliable Communication Networks*, 2009, pp. 343–351.

[15] N. Shillingford, D. C. Salyers, C. Poellabauer, and A. Striegel, "Detour: Delay- and energy-aware multi-path routing in wireless ad hoc networks," in *4th Annual International Conference on Mobile and Ubiquitous Systems: Networking & Services*, 2007, pp. 1–8.

[16] R. W. Yeung, *Information Theory and Network Coding*, 1st ed. Springer Publishing Company, Incorporated, 2008.

[17] L. M. Reindl, "Wireless passive sensors: Basic principles and performances," in *SENSORS, 2008 IEEE*, 2008, pp. 1607–1610.

[18] P. Gamba, E. Goldoni, P. Savazzi, P. G. Arpesi, C. Sopranzi, and J.-F. Dufour, "Wireless passive sensors for remote sensing of temperature on aerospace platforms," in *IEEE International Conference on Wireless for Space and Extreme Environments*, 2013, pp. 1–6.

[19] J. H. Kuypers, S. Tanaka, M. Esashi, D. A. Eisele, and L. M. Reindl, "2.45 GHz passive wireless temperature monitoring system featuring parallel sensor interrogation and resolution evaluation," in *SENSORS, 2006 IEEE*, 2006, pp. 773–776.

[20] F. Alagoz, O. Korcak, and A. Jamalipour, "Exploring the routing strategies in next-generation satellite networks," *IEEE Wireless Communications*, vol. 14, no. 3, pp. 79–88, 2007.

[21] J. García-Rois, F. Gómez-Cuba, M. R. Akdeniz, F. J. González-Castaño, J. C. Burguillo, S. Rangan, and B. Lorenzo, "On the analysis of scheduling in dynamic duplex multihop mmwave cellular systems," *IEEE Trans. Wirel. Commun.*, vol. 14, no. 11, pp. 6028–6042, 2015.

[22] Q. Hu and D. M. Blough, "Relay selection and scheduling for millimeter wave backhaul in urban environments," in *IEEE 14th International Conference on Mobile Ad Hoc and Sensor Systems*, 2017, pp. 206–214.

[23] B. P. S. Sahoo, C.-H. Yao, and H.-Y. Wei, "Millimeter-wave multi-hop wireless backhauling for 5g cellular networks," in *2017 IEEE 85th Vehicular Technology Conference (VTC Spring)*, 2017, pp. 1–5.

[24] Y. Yan, Q. Hu, and D. M. Blough, "Path selection with amplify and forward relays in mmwave backhaul networks," in *IEEE 29th Annu. Int. Symp. Pers. Indoor Mob. Radio Commun.*, 2018, pp. 1–6.

[25] T. K. Vu, M. Bennis, M. Debbah, and M. Latva-Aho, "Joint path selection and rate allocation framework for 5g self-backhauled mm-wave networks," *IEEE Trans. Wirel. Commun.*, vol. 18, no. 4, pp. 2431–2445, 2019.

[26] H. Jung and I. Lee, "Performance analysis of millimeter-wave multi-hop machine-to-machine networks based on hop distance statistics," *Sensors*, vol. 18, no. 1, p. 204, 2018.

[27] S. Saadat, D. Chen, and T. Jiang, "Multipath multihop mmwave backhaul in ultra-dense small-cell network," *Digital Communications and Networks*, vol. 4, no. 2, pp. 111–117, 2018.

[28] X. Song, S. Haghighatshoar, and G. Caire, "A scalable and statistically robust beam alignment technique for millimeter-wave systems," *IEEE Trans. Wirel. Commun.*, vol. 17, no. 7, pp. 4792–4805, 2018.

[29] Y. H. Ezzeldin, M. Cardone, C. Fragouli, and G. Caire, "Gaussian 1-2-1 networks with imperfect beamforming," in *2020 IEEE International Symposium on Information Theory (ISIT)*, 2020, pp. 1599–1604.

[30] M. G. Dogan, M. Cardone, and C. Fragouli, "Supporting passive users in mmwave networks," *arXiv:2308.14071*, 2023.

[31] G. K. Agarwal, Y. H. Ezzeldin, M. Cardone, and C. Fragouli, "Secure communication over 1-2-1 networks," in *IEEE International Symposium on Information Theory*, 2018, pp. 196–200.