Opp-Relay: Managing Directionality and Mobility Issues of Millimeter-Wave via D2D Communication

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***Abstract*—The directionality of millimeter-Wave (mm-Wave) communication results in challenging network dynamics and thus complex system design. A key problem with such networks is human blockage, which is highly detrimental since absorption at mm-Wave frequencies is extremely high. This poses a significant challenge for the state-of-the-art technologies in 5G networks such as Device-to-Device (D2D) communication. Essentially, the aforementioned dynamics hinder direct communication between devices. Existing protocols in the mm-Wave band such as IEEE 802.11ad address this problem using relays. However, the complexity relay discovery in these protocols grows linearly with the number of users, Hence, these approaches are infeasible for crowded areas such as malls or busy pedestrian streets. In this paper, we present a lightweight relaying mechanism called *Opp-Relay* that builds on the existing D2D features of the 3GPP standard to opportunistically discover an mm-Wave enabled relay. Specifically, we provide an algorithm to compute the optimal beamwidth for opportunistic discovery of a relay in dense and dynamic network environments. We validate our approach in practice using our experimental testbed operating in the 60 GHz band. Our experiments demonstrate that choosing a suitable beamwidth to discover and communicate with a relay node is crucial. Moreover, we show that our relaying mechanism significantly reduces the complexity of relay discovery.**

I. Introduction

Researchers have resorted to millimeter-Wave (mm-Wave) bands in the pursuit of the multi-gigabit throughput promised for 5G networks. However, the high throughput comes at the price of high attenuation and directional communication. Thus, millimeter-wave networks are susceptible to high risk of blockage caused by the human body or other objects obstructing the communication link. Moreover, the limited available space for antenna on a compact mobile phone is an additional constraint limiting the angles at which a user can transmit [1]. This is a critical limitation in crowded areas/event such as malls, busy pedestrian streets, sport matches, or concerts.

To prevent such outages, we can leverage relays whenever the line-of-sight path is blocked or unavailable. In fact, the existing 802.11ad standard includes relaying solutions. However, these solutions resort to costly trial-and-error approach to find relays. In particular, the Access Point (AP) should keep track of *all* potential relays so that it can provide a list of relays to the users who request for a relay in their vicinity. The key problem is that the communication pair should find a suitable relay by trying to establish a link to each potential relay *one by one* [2]. Note that in a crowded area, most of these potential relays are likely unreachable due to blockage.

While the above approach is suitable for small to medium-sized networks, it becomes infeasible in crowded areas. As an intuitive example, an area where people can still move freely such as a mall has a density of 0.5 people per square meter [3]. Since mm-Wave links up to 20 meters are feasible [4], an AP can easily receive client associations within a mall area of $1000\ \mathrm{m}^2$. If all users are capable of relaying, that translates into 500 potential relays. Thus, a user (based on 802.11ad) tries on average 250 relays until finding one. For each trial, the users transmit a beacon on all their sectors. To this end, existing hardware uses 32 sectors [4], which takes roughly 0.5 ms [5]. Hence, finding a relay would require 125 ms. Since 802.11ad hardware uses beacon intervals of 100 ms, and users in a mall move continuously, users would not be able to transmit any data at all. A solution to the above issue is allowing users to discover relays in a distributed manner. Users would perform a sector sweep requesting a relay, and potential relays would reply. Still, such an approach would break in a crowded environment due to interference—the potentially large number of replies would inevitably result in collisions.

In this paper, we propose *Opp-Relay*, a lightweight solution which does not incur the aforementioned relay discovery overhead, and which is based on the existing 3GPP standard features for Proximity-Based Services (ProSe), a.k.a. Device-to-Device (D2D) communications [6], [7]. Indeed, the synergy of D2D and mm-Wave is highly interesting since the directional nature of mm-Wave communication strongly limits interference [8]–[11]. In particular, *Opp-Relay* substitutes the blind sector sweeping approach with beacon transmissions in a pre-defined direction such that it maximizes the probability of finding a relay while reducing collisions significantly. Next, the potential relays inform the network that they have received the beacon. At this step, the network assists the D2D users by evaluating the potential relays based on their corresponding Signal-to-Noise Ratios (SNRs). This allows *Opp-Relay* to choose the best relay without further beaconing and to start transmitting quicker. Since users are already aware of the direction in which the relay is located, no further beam training is needed. We call such an opportunistic relay an *Opp-Relay*.

Our scheme poses a fundamental question: What beamwidth shall D2D users use, such that they minimize interference in a crowded environment, but still maximize the probability of finding a relay? In this work, we study and answer this question. In particular, our contributions are as follows:

- Building on existing work, we formulate the optimal beamwidth for two users to discover a mutual relay based on the user density within an area.
- To achieve the maximum throughput, we independently derive the optimal beamwidth for data transmission *after* discovering the best common relay.
- While the above angle computation involves precise location information, we also provide a scheme that does not require any location information, but still finds a sub-optimal beamwidth for both discovery and transmission.
- To be standard compliant, we design a protocol that implements *Opp-Relay* in the framework of 3GPP ProSe.
- Finally, we perform experiments involving over 1500 measurements to validate the feasibility of *Opp-Relay*.

The remainder of this paper is organized as follows. We first present related work in Section II. We then introduce our system model for both joint and disjoint beamwidth optimization in Section III. Section IV describes the protocol that puts our system into practice. Finally, we explain the experimental setup and results in Section V and discuss the system limitation and future work in Section VI.

II. Related Work

The characteristics of mm-Wave such as directionality make it an ideal choice for D2D communication. This relaxes the critical interference issue that D2D communication faces in the 2.4 GHz, 5 GHz and cellular frequency ranges. As a result, interest in mm-Wave D2D is increasing [8], [10]–[13].

In [11], Qiao *et al.* improve the concurrent transmission between non-interfering mm-Wave D2D links using an effective resource management scheme controlled by a central entity. Niu *et al.* [10] propose D2DMAC to consider direct transmission between proximate user through 60 GHz links on top of the legacy cellular communication. They further extend the idea to support multihop mm-Wave D2D with an optimal path selection algorithm in [9]. Both works appear promising for concurrent mm-Wave D2D communication. In [12], Ji *et al.* propose a more complex scheme that opportunistically combines the robust D2D and high capacity mm-Wave D2D links for performance improvement. Both [8] and [13] propose a method to discover a relay path using D2D mechanism when the direct path is blocked. In [13], Wei *et al.* proposed a throughput-optimal relay probing strategy to select the best relay while the authors of [8] compliments the work of Wei *et al.* by detailing a protocol design enabling D2D mm-Wave relay as well as the experimental evaluation.

Unlike this manuscript, the majority of the aforementioned work focuses on static scenarios which are validated using simulation or analytical evaluation. Indeed the experimental studies on mm-Wave [4], [8], [14]–[16] are rare in the literature due to implementation challenges. The author of [8] validates their proposal with a simple experimental framework for D2D mm-Wave using off-the-shelf mm-Wave Dell docking stations. Many research groups perform extensive measurement campaign to characterize mm-Wave communication. In mm-Wave community, Rappaport *et al.* [14] conduct one of the first measurement for 60 GHz links for peer-to-peer communication. Later [15] and [16] perform similar, but more intensive 60 GHz link characterization under higher diversity environment. [4] investigates the beamforming, interference, and frame level operation of commercially available 60 GHz device based on the WiHD and WiGig standards.

While the above work contributes to understanding the behavior of mm-Wave networks, we take a step further to study how D2D can mitigate blockage in mm-Wave networks.

III. System Model

We consider a mobile scenario where users are randomly distributed and moving at random direction with pedestrian speed [17]. Each UE is equipped with two interfaces: one cellular interface (e.g., LTE-A) and one mm-Wave interface (e.g., 802.11ad). The transmission mode for 802.11ad communication is full duplex as specified in the 802.11ad standard.

Our system consists a set of $\mathcal{N}$ UEs indexed by $n = 1, ..., |\mathcal{N}|$ and an eNodeB (eNB). At any time instant, a D2D pair $(u, v) \in \mathcal{N}$ can communicate either directly using 802.11ad or through an intermediary user when direct line of sight path is unavailable. This intermediary user is called a *relay* and denoted by b. A relay is essentially an ordinary cellular user who has subscribed to a ProSe service allowing the user to: (i) become the relay for a D2D pair that is incapable of communicating directly; and (ii) leverage other UEs to be the relay when it can not communicate with the desired D2D user via a direct link. Since a D2D pair is expected to be in proximity, we assume that they have the same set of neighbors $\mathcal{M} \subseteq \mathcal{N}$ with a total number of $\mathbf{m} = |\mathcal{M}|$ neighbors. In this scenario, the cellular interface is mainly used for D2D signaling messages sent via the ProSe framework.

To enable the use of relays in the above described system, we should solve two major challenges that stem from the directionality of mm-Wave communication. Firstly, the D2D users should decide on the beamwidth used to *discover the suitable relay*. There exists a trade-off here. On one hand side, if the beamwidth is too narrow, the possibility of finding a relay who is within the boresight of both D2D users reduces. On the other hand side, a wide beamwidth results in a shorter communication range and a lower SNR. The second problem is selecting a suitable *transmission beamwidth* (i.e., the beamwidth used for data transmission). In this case, a narrower beamwidth provides higher data rate, but it also increases the chance of the users walking out of each other's boresight quickly. If a wider beamwidth is used, the SNR weakens, and the communicating users may be out of coverage. In the following, we proposed two schemes. In the first scheme, we solve the above mentioned problems independently where the angle of discovery and transmission may differ. In the second scheme, we jointly formulate the optimal angle that is best for both discovery and data transmission.

A. Disjoint optimization

Here, we first find the optimal angle for user discovery and then the optimal angle for data transmission.

Optimization of discovery beamwidth. In this section, we determine the probability that a D2D pair, formed by user (u, v), is able to find a mutual relay $b \in \mathcal{M}$ within t time slots. We build upon the user discovery approach in [18] and use it to optimize the discovery beamwidth. This probability is a function of both the discovery beamwidth β_{tx} and the total number of neighboring users $\mathbf{m}$. The estimation of the number of neighbors will be detailed in Section IV. As the directional transmission in 60 GHz band is likely to be overheard by only a small subset of users, we assume that the transmission events of each user are independent. Thus, the probability that both UEs discover a mutual relay in a time slot is given by:

$$p_{u,v}^{b}(\mathbf{m}, \beta_{tx}) = \left(2\frac{\beta_{tx}}{2\pi}p_{\text{tx}}^{d}\frac{\beta_{rx}}{2\pi}p_{rx}\left(1-\frac{\beta_{rx}}{2\pi}p_{rx}\right)^{\mathbf{m}-2}\right)^{2} \quad (1)$$

where the transmission and reception of the users happen with equal probability, i.e., $p_{tx} = p_{rx} = 1/2$, when users are not in discovery mode. The probability of transmitting and receiving using an angle is denoted as $\frac{\beta_{tx}}{2\pi}$ and $\frac{\beta_{rx}}{2\pi}$. Note that idle users stay in listening mode and receiving any incoming message with the widest angle, i.e., 2π. A node that is currently discovering a relay has a transmit probability $p_{tx}^{d} = 1$. The objective function is to maximize $p_{u,v}^{b}(\beta_{tx})$ by optimizing β_{tx}

$$p_{u,v}^{*b} = \max_{0<\beta_{tx}<2\pi}\left(p_{u,v}^{b}(\mathbf{m}, \beta_{tx})\right). \quad (2)$$

Optimization of transmission beamwidth. The optimal transmission beamwidth θ_{tx} should maximize the amount of transmitted data bits during the contact time between a D2D user n and a relay b. For simplicity, we referred this as the *capacity* $c_{n,b}$ of the link. The link SNR between n and b is $\gamma_{n,b}$ and it depends on the distances between them $d_{n,b}$ as well as the transmission beamwidth θ_{tx}. The rate of corresponding link $R_g(\gamma_{n,b})$ depends on the selected Modulation and Coding Scheme (MCS) $g \in \mathcal{G}$, where $\mathcal{G}$ is set of available the MCSs. To maxmimize $c_{n,b}$, the transmission beamwidth must take into account the transmission rate $R_g(\gamma_{n,b})$, the UE's velocity $V_{n,b}$, and its distance from the relay $d_{n,b}$. Here, the distance $d_{n,b}$ is obtained from ProSe.

The expression of the achievable capacity between a user and a relay for a given θ_{tx} can be formulated as:

$$c_{n,b}(\theta_{tx}) = \frac{R_g(\gamma_{n,b})l_c}{\overrightarrow{V}_{n,b}}, \quad (3)$$

where $\overrightarrow{V}_{n,b} = |V_n - V_b|$ is the relative velocity between n and b and $l_c = d_{n,b}\tan(\frac{\theta_{tx}}{2})$ is the contact distance.

Although ProSe is aware of the coordinate of the users (refer to Section IV for further details), the contact distance (denoted by l_c in Fig. 1) requires knowledge on the exact direction of the antenna, the antenna pattern, and the contact angle θ_{tx}. Hence, we assume that, on average, a user is in contact with the relay for half of the contact distance, i.e., l_c. Note that if this technological obstacle is overcome, whereby location and complete beam information is available at a low cost, our formulation can provide an even more accurate capacity estimation.

With the above assumption, the optimal capacity between a D2D user and the relay is $c_{n,b}^{*} = \max(c_{n,b}(\theta_{tx}))$. Since the communication path between u and v (i.e., the D2D pair) consists of two communication links, the optimal transmission beamwidth should account for both links, thus $C = c_{u,b}^{*} + c_{v,b}^{*}$. The higher is the difference between the link capacities, the higher is the probability of congestion and packet drops at the relay. Therefore, we optimize the overall transmission beamwidth to minimize this difference as follows:

$$\theta_{tx}^{*} = \underset{0\leq\theta_{tx}\leq2\pi}{\operatorname{argmin}}\left(\left(c_{u,b}(\theta_{tx}) - c_{u,b}^{*}\right)^{2} + \left(c_{v,b}(\theta_{tx}) - c_{v,b}^{*}\right)^{2}\right). \quad (4)$$

The total capacity is thus $C^{*} = c_{u,b}(\theta_{tx}^{*}) + c_{v,b}(\theta_{tx}^{*})$.

B. Joint optimization

Note that the optimization for discovery beamwidth in Eq. 2 is designed to maximize the probability of finding a mutual relay, hence, a wider beamwidth is better. In contrast, the transmission beamwidth optimization in Eq. 4 aims for higher capacity. Thus, transmission beamwidth is optimized towards narrower beams to achieve a higher SNR and better data rate. While disjoint optimization for the discovery and transmission angles yields optimal values for both angles, it requires high fidelity user location information at the ProSe. Therefore, we further propose a joint optimization scheme which is less susceptible to localization error. This optimization provides one angle that is best for both discovery β_{tx} and transmission θ_{tx} phases.

To achieve the joint optimization between β_{tx} and θ_{tx}, we utilize a commonly used squared distance minimization technique, which minimizes the ratio of the sub-optimal value with respect to their corresponding optimal value:

$$\theta^{*} = \underset{0<\theta<2\pi}{\operatorname{argmin}}\left(\left(\frac{C(\theta)-C^{*}}{C^{*}}\right)^{2} + \left(\frac{p_{u,v}^{b}(\mathbf{m},\theta)-p_{u,v}^{*b}}{p_{u,v}^{*b}}\right)^{2}\right), \quad (5)$$

condition over $p_{u,v}^{*b} \leq p_{u,v}^{b}(\mathbf{m}, \theta)$ and $C^{*} \geq C(\theta)$. Here β_{tx} is computed the same as disjoint optimization using Eq. 2. In contrast to the transmission angle obtained in Eq. 8, here, θ_{tx} is calculated based on the expected statistical values of rate $\overline{R_g}$ and distance $\overline{d_n}$ instead of feedback measurements obtained in the discovery phase in Section III-A. Note that here, any neighboring user is a potential relay so we use the location information provide by ProSe to compute the expected values as follows. The expected rate is obtained by

$$\overline{R_g} = \sum_{g,g\in\mathcal{G}} p_g R_g, \quad (6)$$

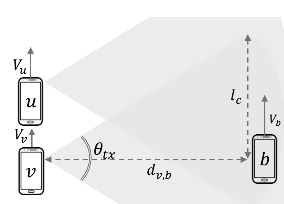


Fig. 1: An example of an *Opp-Relay* communication.

where p_g is the probability of using an MCS g. The estimated distance between a user n and all neighbors $\mathbf{m}$, since all neighbors are a potential relay, is

$$\overline{d_n} = \frac{1}{\mathbf{m}} \sum_{b \in \mathcal{M}} d_{n,b}. \tag{7}$$

As a result, the expected capacity is written as

$$\overline{c(\theta_{tx})} = \frac{\overline{R_g d_n} \tan(\frac{\theta_{tx}}{2})}{\overrightarrow{V}}. \tag{8}$$

The joint optimization is sub-optimal for the independent case (i.e., the optimal discovery and transmission angles) in comparison to the individual approach, but it has the benefit of low implementation complexity and high practicability, which are important features for most use-cases.

IV. Protocol Design

The 3GPP has recently defined a framework to support D2D communication in cellular network. This framework consists of three main elements, namely, ProSe Application, ProSe Function, and ProSe Server. The ProSe application is at the user equipment (UE). While ProSe Function is in the Evolved Packet Core (EPC) and ProSe Server can be located inside or outside the operators' infrastructure. We design our protocol with reference to this framework to maintain maximum standard compliance. Moreover, our protocol design takes into consideration the existing and forthcoming features of IEEE 802.11ad, 3GPP's 4G standard, and 5G standard drafts. This protocol is meant to enable reliable and fast communication for devices with limited beamsteering capabilities (c.f. Section I). In the following, we explain the procedure for: (i) the discovery between a D2D pair, (ii) the discovery of a relay by the D2D pair, (iii) the selection of a relay by the network, (iv) data transmission, and (v) connection termination.

A. User Discovery

3GPP ProSe architecture has put in place the necessary means for D2D users to search for the desired contents/services in their proximity [8]. However, a user should subscribe to the ProSe Server for the desired service before gaining network support for D2D communication. In our protocol, D2D users first send a subscription request to the network to use the *Opp-Relay* service. Once subscribed, the ProSe Function takes care of tracking the UEs' location and their desired services. ProSe Function can also use the location information to obtain the number of neighbors $\mathbf{m}$ that is needed for optimizing the discovery beamwidth in Section III-A. In addition, ProSe Function notifies the users whenever they are in proximity of their desired service using a *proximity alert* message.

B. Direct Communication

The ProSe can only help the D2D users for service discovery but it does not have any knowledge of the antenna direction and beam pattern the is used by the UE. In our protocol, each user sends a discovery beacon tagged with ProSe ID and service ID which is provided by the ProSe Function in the notification message. If the D2D pair receives these beacons from each other, they can immediately start the communication phase. Otherwise, they send an *out of sight* message to the ProSe Function to activate the relay discovery procedure.

C. Relay Discovery

The *out of sight* message triggers ProSe to compute the proper discovery beamwidth based on the density of the relays in the area. As discussed in Section III-B, one may choose to compute the discovery and the transmission beamwidth separately or jointly. We elaborate on both approaches here. ProSe function sends a *discovery beamwidth configuration* message to the D2D pair. This message contains either the discovery beamwidth computed based on Eq. 2 or the joint beamwidth calculated using Eq. 5. After receiving the configuration message, the D2D pair retransmits the beacons with the optimal discovery beamwidth. Any relay that receives the

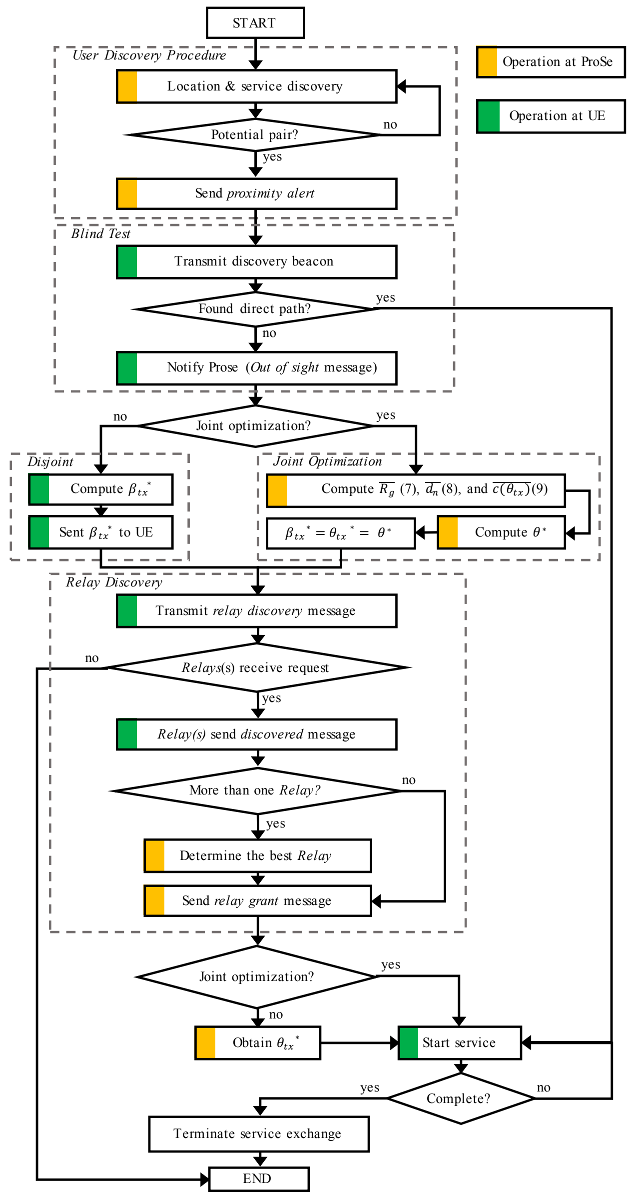


Fig. 2: A flow chart for users subscribed to *Opp-Relay*.

matching beacons sends a *discovered* message to the ProSe Function indicating the SNR of the received beacon, and the tagged ProSe ID and service ID of the beacon. If multiple relays are discovered, the ProSe Function determines the best relay based on the received SNRs from the D2D pair. Finally, the selected relay is notified to assist the D2D pair using *relay grant* message.

D. Communication

If the joint discovery and transmission beamwidth approach is implemented (see Section III-B), the ProSe Function sends a *link ready* message to the D2D pair to initiate the communication. Otherwise, the ProSe Function calculates the transmission beamwidth using Eq. 4 and sends a *transmission beamwidth configuration* message to the D2D pair before sending the *link ready* message.

E. Termination

After the communication is over, the D2D pair informs the relay and the ProSe that they no longer need the relay service via a *termination* message.

V. Evaluation

In the following, we present our experimental results that validate the feasibility of our proposed *Opp-Relay* mechanism (c.f. Section IV). Specifically, we consider an indoor scenario with two UEs who wish to exchange data using D2D but whose antenna configuration prevents direct communication, and a third user that acts as a relay between them.

A. Experiment Scenario

Our experiment scenario is depicted in Fig. 3. We place all nodes in the entrance hall of the IMDEA Networks Institute, which is roughly 16 meters long and 5 meters wide. The room features a diversity of materials such as foliage, a wooden front desk, metal doors, concrete wall, and glass walls. Hence, it represents a typical indoor scenario in a conference hall or a shopping mall. Since some of the above materials may act as reflectors, we expect to observe their impact in the results.

We place the nodes on the intersections of the virtual grid shown in Fig. 3. This allows us to obtain the achievable physical layer data rate at a set of well-defined locations. We also consider nodes moving continuously on the grid. The specific scenario of each experiment is defined in Section V-C.

B. Hardware Setup

To obtain the physical layer rate via the relay, we measure the SNR on both links using the experimental setup as shown in Fig. 4. We keep the minimum of both since the worst link defines the overall performance. Then the achievable rate is computed based on the 802.11ad standard [2]. To obtain the SNRs in the testbed, we generate a narrowband signal on each of the UEs using GNU Radio and a Universal Software Radio Peripheral (USRP) X310. As a result, we obtain the signal at an intermediate frequency of ~ 1 GHz. We then upconvert the signal to the 60 GHz band at each UE using a SiversIMA FC1005V/00 V-band converter and transmit it using different horn antennas. This allows us to study the impact of different beamwidths and thus validate our analysis in Section III.

We include an offset of 100 MHz between the signal of UE1 and UE2. As a result, we can receive and distinguish both signals simultaneously at the relay. This is not a limitation of our system, but a measurement technique to ease experimentation. At the relay, we use an omnidirectional antenna connected to the receiver unit of a Pasternack VubIQ 60 GHz Development System to receive the signals of both UEs. Note that this is also in line with 802.11ad protocol where idle nodes stay in quasi-omnidirectional mode. Finally, we record the resulting baseband signals on an Agilent EXA N9010A Signal Analyzer.

C. Results

Next, we describe each of our experiment settings and results. While experiments V-C1 to V-C3 analyze the static case, the remainder focuses on mobile scenarios.

1) Beamwidth Impact on Balanced and Imbalanced Relay: In our first experiment, we place the antenna of the UEs facing as in Fig. 3, that is, along the y-axis of our grid. For each measurement, we place both UEs on the same value of the y-axis to emulate two users standing next to each other but whose devices cannot communicate due to the orientation of their antennas. Still, for each user location value on the y-axis, we measure all possible combinations of x-axis values. In other words, we analyze the impact of increasing or decreasing the distance between the two people on the x-axis. For instance, Fig. 3 shows the case where they are located at a distance of two meters. Moreover, different y-axis values translate into different distances to the relay. The relay is always at $y = 5$, but we vary its location along the x-axis. The relay is *balanced*, if it is located at the x-axis midpoint of the UEs. Otherwise, the relay is *imbalanced* (c.f. Fig. 3). We expect better performance

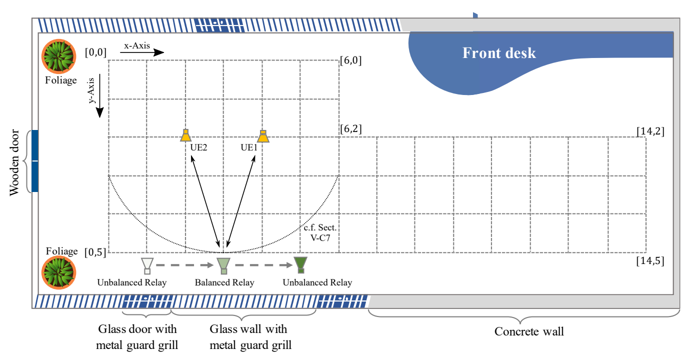


Fig. 3: Experiment scenario.

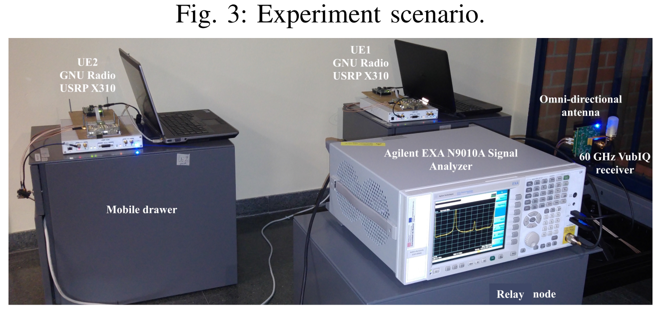


Fig. 4: Experiment setup.

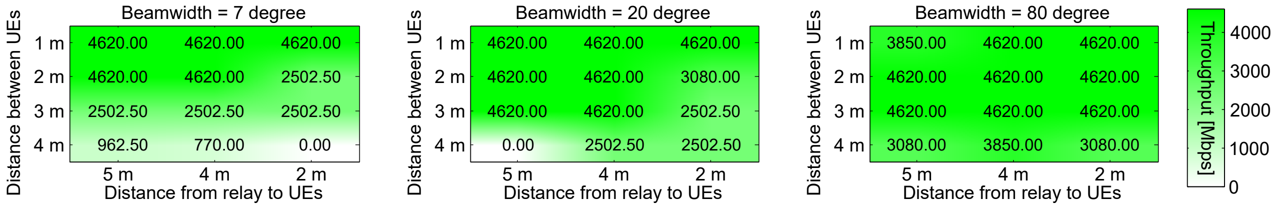


Fig. 5: Impact of different antenna beamwidth on the physical rate for a *balanced* relay.

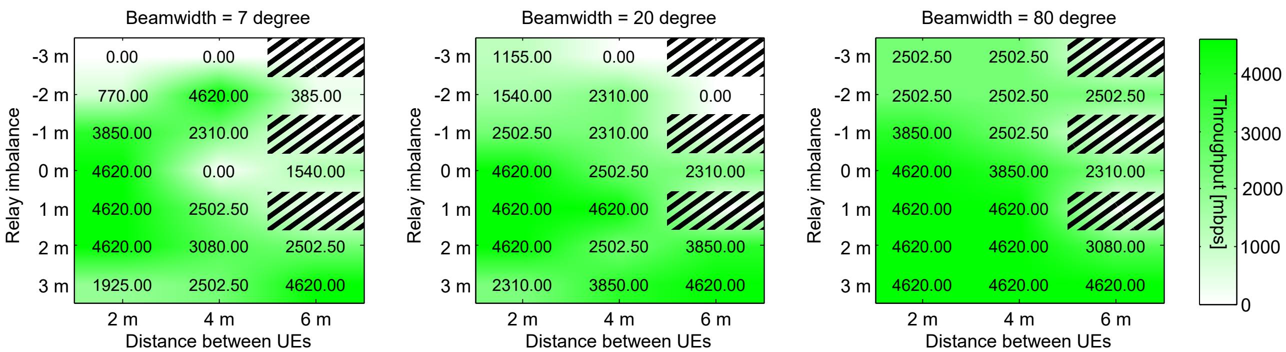


Fig. 6: Impact of different antenna beamwidth on the physical rate for an *imbalanced* relay. Hatched areas were not measured.

in the balanced case, since both links are similar in terms of length and thus none of them should become a bottleneck.

Balanced Relay. Fig. 5 depicts the impact of different antenna beamwidths on the performance of our system for a balanced relay. If both UEs use narrow $7°$ antennas, the physical layer rate drops as soon as we increase the distance between the UEs. This is expected, since the relay quickly gets out of the boresight of both UEs. When the UEs and relay are further apart, this effect is milder since the increased distance allows the beams to fan out wider. Fig. 5 shows that this limitation vanishes for wider beamwidths. While we still observe some impact for $20°$ antennas, for $80°$ the link via the relay supports more than three gigabits per second at all locations. However, for $20°$ antennas, we obtain zero rate for a distance of four meters among UEs and five meters distance to the relay. This unexpected behavior is likely due to a destructive reflection. We conclude that narrow beamwidths are only suitable if the UEs are less than two meters apart. Otherwise, wider beamwidths are needed at the cost of more interference on neighboring links. Further, wider beamwidths are more likely to cause reflections which may be harmful, as shown above.

Imbalanced Relay. In this experiment, we analyze a similar scenario but focus on the impact of an imbalanced relay. In this case, we place the UEs at $y = 1$ and vary the distance among them as well as the location of the relay on the $y = 5$ line. Fig. 6 depicts our results. Some values are hatched because our measurement campaign did not include those specific distance combinations. As expected, relay imbalance tends to have a higher impact on narrower beamwidths and larger distances among UEs. Still, we observe that the imbalance has a different effect depending on the location of the relay. If the relay is to the right of the midpoint of the UEs in Fig. 3, we define the imbalance as negative in Fig. 6. If the relay is to the left, the imbalance is positive. Surprisingly, in the positive case the imbalance has a much smaller impact than that in the negative case for all beamwidths. This shows that reflections in indoor environments play a significant role. In the positive case, the signal reflects off the glass wall with metal guard grill twice, that is, both at the bottom and at the top of Fig. 3, eventually reaching the relay. In contrast, in the negative case the wooden front desk absorbs most of the signal. We conclude that relay imbalances of two meters and above can become harmful. In line with Eq. 4, we observe that a balanced relay yields a higher throughput, unless in the presence of reflections.

2) Extreme Beam Misalignment: Our third experiment studies the case of high beam misalignment for both balanced and imbalanced relays. In this case, we place the relay at location $(8, 5)$ and the UEs on the y-Axis line $y = 3$ at a symmetric location with respect to the relay. Moreover, we repeat the experiment for multiple such symmetric locations of the UEs on $y = 3$ to study the impact of increasing distance to the relay. If this distance increases beyond 4m, Fig. 7b shows that even $80°$ antennas cannot establish a connection. In the imbalanced case in Section V-C1, such antennas achieved connectivity up to a distance of 5m. The key difference is the distance among the UEs. In Fig. 7a, the UEs are very close to each other, and thus can use the same reflection to reach the relay. In contrast, in Fig. 7b the UEs are far apart. The probability of both of them having a reflective path to the relay is thus much lower than in Fig. 7a. These experiments show that the distance between UEs and relay is key to find the optimal beamwidth, as studied in Eq. 8.

3) Tilting Impact: Next, we investigate the impact of UE tilting. In particular, we measure performance when UE1 and UE2 deviate from the y-Axis orientation in Fig. 3. That is, a deviation of $-90°$ or $+90°$ means that the UEs point towards the wooden door or the front desk, respectively. This emulates the potential tilting of a hand-held device. We place the UEs at a distance of 6m from each other, and keep the relay balanced. As in Section V-C2, in Fig. 7c we obtain zero rate if both

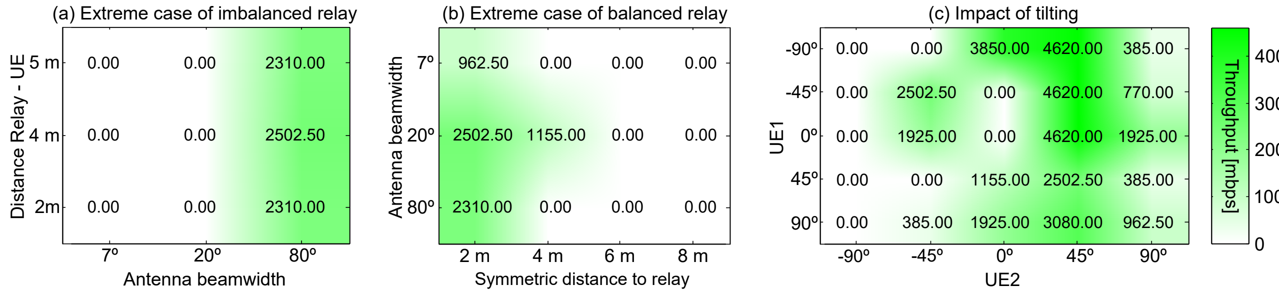


Fig. 7: Results (a) and (b) refer to extreme link misalignment (Section V-C2), while result (c) refers to UE tilting (Section V-C3).

devices are tilted $0°$. Still, when tilting UE1 to negative values and UE2 to positive values, both UEs point towards the relay and as a result we obtain up to four gigabit per second. For the opposite case (UE1 at $45°$ and UE2 at $-45°$), the rate drops to zero since both devices are pointing away from the relay.

4) Single Node Deviation: In the following experiments, we focus on mobile scenarios. As a first step, we consider a static relay at location $(5, 5)$ and two mobile UEs moving at constant pedestrian speed past the relay along $y = 3$. After passing the relay, UE2 deviates from the straight line to the right while UE2 continues along $y = 3$. This allows us to assess the impact of a node suddenly moving away during an on-going communication. Both UEs start close to the front desk in Fig. 3 and move from right to left towards the wooden door. Fig. 8a shows our results. We fit the depicted curves on the measurement points shown in the figure using the smoothing spline method. For a beamwidth of $7°$, we observe that the achievable rate peaks at a traveled distance of about 1.5m. Before, the relay is not yet in the boresight of the UE traveling behind, thus resulting in low rates. However, the rate immediately decreases after the peak since the UE traveling in front diverts from the straight path. While this also happens for $20°$ and $80°$ antennas, the impact is much less since the relay is within the beam of both UEs for a longer time. This confirms our intuition in Section III-A where a wider beamwidth provides a longer contact distance and time between the UE and relay, which leads to a higher throughput.

5) Both Node Deviation: Building on our previous experiment, we now consider a case where both UEs deviate from $y = 3$. Initially, UE1 is off track while UE2 moves along $y = 3$. After a few meters, UE1 aligns with UE2. At the end, UE2 deviates similarly to Section V-C4 while UE1 continues on $y = 3$. Figure 8b shows that such a behavior is highly harmful for the case of narrow beamwidths since the relay is out of the boresight of the UEs most of the time. In contrast, our $80°$ antenna achieves high data rates with less fluctuation.

6) Relay Mobility: Finally, we study a case with a mobile relay and static UEs. Specifically, the UEs are located at a distance of six meters from each other at $y = 0$, and the relay moves along the parabolic path depicted as a dotted line in Fig. 3. In Fig. 8c, we observe that for both $7°$ and $20°$ antennas performance has a clear minimum at about three meters of traveled distance. This minimum matches the location $(3, 5)$, that is, the location at which the relay points at the midpoint of both UEs. Similarly to Section V-C2, the minimum is due to both UEs being too far apart and using a narrow beamwidth. As soon as the relay enters the beam of one of the UEs and tilts towards the other, communication becomes feasible again.

VI. Discussion

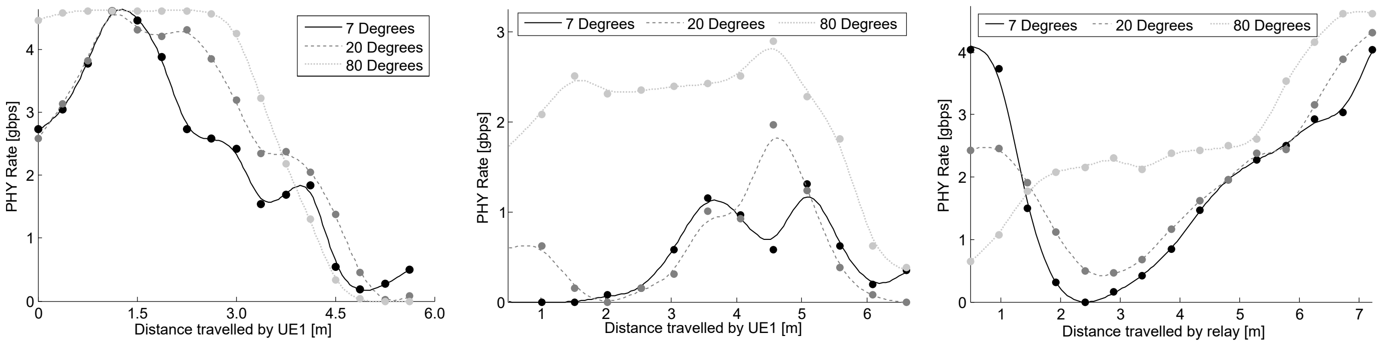
Our experiments in Section V show that *Opp-Relay* is able to establish two-hop relay links in a real-world scenario. Although our evaluation is limited to a three user scenario due to hardware limitations, we could obtain crucial insights on the pros and cons of such a system. In the following, we elaborate on some of our assumptions and evaluation choices, and discuss other alternatives and their implications.

Node orientation. In the evaluation, the node orientations were in line with a shopping mall scenario. Movement in a mall is typically not random but mostly linear along corridors, see Fig. 1. Our setup in Fig. 3 mimics such a movement. This setup is neither particularly benign nor adverse for *Opp-Relay*, since the UEs are neither pointing always to the relay nor directly facing walls or other obstacles. This results in a broad scenario, for which we obtain encouraging results. While in some cases communication is not feasible, *Opp-Relay* frequently achieves high throughput, even via reflections. On average, we expect a similar behavior for other node orientations, since both more benign and more adverse cases are possible. Note, node orientation becomes less relevant in dense cases since the probability of finding a relay increases.

Alternative scenarios. The linear movement model is not confined to shopping malls. Another interesting scenario is mm-Wave based vehicular communication where cars move along the lanes [19]. In such a scenario, the direct communication between two vehicles can be blocked by another vehicle. With *Opp-Relay*, a third vehicle driving on a parallel lane may act as a relay to bypass the obstacle.

Beamforming at the relay. The relay node in our experiments uses an omnidirectional antenna. Our results show that this allows for high data rates despite high attenuation in the mm-Wave band. Most importantly, this simplifies the operation of the relay by eliminating the need for beamtraining during discovery phase and individual beamforming for the D2D UEs.

Probability of finding a relay. Our evaluation suggests that the probability of finding a relay is reasonably high for our scenario. Deriving the generic formula for this probability is left for future work. Such an analysis requires taking into account complex issues such as detailed mobility models, the impact of a user holding a device, and the specific steering



(a) Single node deviation

(b) Both node deviation

(c) Relay mobility

Fig. 8: Mobility experiments for different beamwidths.

capabilities of a device. Moreover, the analysis requires more advanced optimization approaches, which are beyond the technique used in this paper.

Signaling overhead. The high signaling overhead of existing mm-Wave protocols in dense scenarios motivates our work. In contrast to such protocols, *Opp-Relay* achieves high performance with minimal overhead. The key feature of *Opp-Relay* is to avoid probing each potential relay individually. Most importantly, most of the signaling messages are exchanged via the legacy cellular interface, thus avoiding inefficient use of the mm-Wave interface. Moreover, the signaling overhead does not necessarily increase with the size of the network—while larger networks result in more potential relays, a large number of them does not have a line-of-sight link to both UEs. In contrast to existing mm-Wave protocol, *Opp-Relay* naturally discards such nodes without incurring overhead.

VII. Conclusions

Directional communication in the mm-Wave band is prone to severe blockage. To address this issue, IEEE 802.11ad resorts to relaying techniques. However, it incurs high relay discovery overhead. We propose *Opp-Relay*, which is a standard compliant approach that enables efficient and lightweight relay operation using D2D communication. Additionally, we design an analytical model that allows *Opp-Relay* to obtain optimal discovery and transmission beamwidths. Our model features both joint and disjoint beamwidth optimization to suit different levels of network information. As a result, *Opp-Relay* avoids the large relay discovery overhead of current solutions such as the IEEE 802.11ad standard. Finally, we validate the practicality of *Opp-Relay* based on over 1500 measurements using a 60 GHz testbed. Our results show that beamwidth selection is critical to maximize the probability of finding a relay while minimizing interference on nearby nodes.

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