5G Millimeter-Wave and D2D Symbiosis: 60 GHz for Proximity-based Services

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***Abstract*—The characteristics of two key communication technologies in 5G, namely, Device-to-Device (D2D) and millimeter-wave (mmWave), are complementary. While D2D facilitates the communication of nearby mobile nodes, mmWave provides very high throughput short-range links by using carrier frequencies beyond 30 GHz, and reduces interference by using directional communication. This directly addresses two critical issues in cellular networks, namely, the increasing number of users and the high throughput requirements. In this paper, we explore the above symbiosis of D2D and mmWave. More precisely, we integrate mmWave communications into the 3GPP framework for D2D communication, i.e., Proximity-based Services. To this end, we design the message exchange among entities in the ProSe Architecture to support the discovery, establishment and maintenance of mmWave links. Further, we evaluate the performance of a mmWave D2D system for the case of a picocell operating in the 60 GHz band. We experimentally analyze the benefits of combining D2D and 60 GHz communication. Our results show that this combination improves performance in terms of throughput by up to 2.3 times.**

I. INTRODUCTION

The requirements for a 5G cellular network architecture differ substantially from those of its predecessors, among others due to the support of the Internet of Things (IoT) and the giant leap in the number of connected devices. As a result, 5G cellular networks promise not only an order-of-magnitude increase in bandwidth but also an enhanced network architecture that is tailored to the services expected from today's cellular infrastructure. One of the significant architectural enhancements is Device-to-Device (D2D) communication [1] that allows mobiles to establish a direct connection without traversing the eNodeB. D2D is a key component in the context of IoT, since a substantial fraction of the traffic is generated and consumed locally. Thus, eliminating the eNodeB from the transmission path leads to higher spectral efficiency, lower signaling overhead, and higher energy efficiency. However, these gains can only be achieved if we can overcome several challenges faced by D2D communication.

The main problem in D2D communication, also known as Proximity-based Services (ProSe) in 3GPP's terminology, is interference management. Depending on the spectrum resources used for D2D communication, one faces different flavors of interference related issues. On the one hand, if D2D users communicate over ISM bands using technologies such as WiFi [2], they may have to compete with many other devices for channel access and there is little control over the interference encountered in these bands. Hence, QoS guarantees and transmission reliability may become an issue. On the other hand, using licensed spectrum provides much more control over the radio environment and thus facilitates more reliable communication, but it requires accurate interference management among legacy cellular communications and D2D communications. Prior studies proposed several techniques for addressing the aforementioned concerns. Nevertheless, D2D link capacity is significantly affected by the network density, no matter which of these prior solutions is used. This limitation is due to the fact that the current technologies for D2D communication are not ideal for proximity-based direct communication because they (i) have insufficient bandwidth, and (ii) they cause significant interference due to the omni-directional nature of communication.

In this paper, we elaborate on the symbiosis between two key technologies in 5G: millimeter-wave (mmWave) and D2D communications. We believe that the characteristics of mmWave such as high pathloss [3], which requires directional beamforming for higher channel gain, is a perfect fit for D2D communication. This directional transmission tremendously decreases the interference and enables extreme spatial sharing [3], [4]. Thus, high bandwidth mmWave paves the way for extremely high throughput D2D applications without interfering with existing cellular users. Also, short range directional links make mmWave D2D communication much less susceptible to network density.

Related work studies beamforming for D2D [5], [6] in the context of Multiple-Input-Multiple-Output (MIMO) communication. While some of the benefits in that case also apply to D2D at 60 GHz, the key difference is that 60 GHz communication typically uses codebook-based analog beamforming. That is, instead of using Channel State Information (CSI) to shape their beampattern such that interference is minimized, 60 GHz D2D transmitters must choose out of a predefined set of beampatterns. Although this alleviates constraints on CSI feedback, it also means that avoiding interference becomes more challenging. Several research groups have explored this mmWave D2D spatial reuse in earlier work. Al-Hourani et al. [7] examine this potential by means of simulation based on ray-tracing for the case of ISM bands. In [8], Qiao et al. investigate a resource sharing mechanism which enables non-interfering D2D and multi-hop links to operate concurrently. Further, the gain of mmWave transmission for joint access and backhaul is presented in [9]. Recent work also studies analytically the interference of D2D communication in home networks [10]. The aforementioned works discuss several prominent aspects of integrating mmWave and D2D communications. In this work, we take a further step by (i) integrating mmWave into the 3GPP ProSe framework, and (ii) evaluating the feasibility and performance of this concept by conducting a practical testbed evaluation.

II. MMWAVE AND D2D SYMBIOSIS

Using the mmWave spectrum poses several challenges. In the following, we will show that some of these challenges are in fact desirable features for D2D communication.

A. High pathloss

mmWave transmissions experience very high path loss, which is the reason why this part of the spectrum is starting to be explored for consumer telecommunication only very recently. To counter the high path loss, beamforming techniques are widely used for mmWave transmissions to achieve the desired communication range. Nevertheless, the theoretical range for mmWave is still below 50 meters (for consumer-grade off-the-shelf 60 GHz devices [11]). Interestingly, this shortcoming is an advantage for D2D communication as it helps to limit interference – a key issue in D2D communication. Due to lack of capacity and increased user demand, eNodeBs usually cover a small area. Moreover, small cell deployments are becoming more and more common. In particular, when D2D communication occurs over cellular spectrum, power control and interference management become very complex. As a result, more frequent feedback and control messages are required. In contrast, mmWave does not impose such interference issues and it perfectly matches the envisioned transmission range for D2D communications.

B. Directional Transmissions

mmWave transmissions are highly directional due to the use of beamforming to compensate for the high path loss. This path loss is primarily caused by the carrier frequency dependent attenuation, and secondarily by oxygen absorption. Beamforming in mmWave is typically codebook-based, that is, nodes use a predefined set of possible beam patterns. For high rate communication, the beam patterns of a pair of communicating nodes need to be very well aligned. In scenarios in which a single base station communicates with tens of randomly distributed mobile users, maintaining this alignment is challenging. Also beam-steering to cover all spatial directions, either for neighbor discovery or distribution of common information, induces high overhead. Due to the smaller number of users that communicate directly and the close proximity, the overhead issues caused by directionality are tremendously reduced for D2D communication. In fact, directional transmissions are advantageous for D2D communication as they allow two or more nearby D2D pairs to communicate concurrently in most cases. Thus, mmWave is a perfect candidate for D2D communication in very dense scenarios.

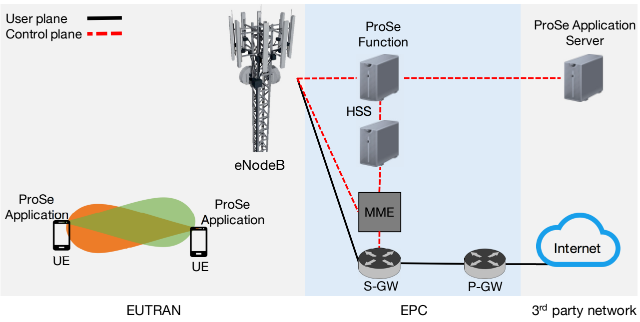

Fig. 1. 3GPP ProSe architecture.

III. MMWAVE D2D FRAMEWORK IN 3GPP

This section describes the framework of mmWave D2D within the 3GPP architecture.

A. ProSe Architecture

The architecture of ProSe is depicted in Fig. 1. There are three main elements for supporting D2D communication, namely ProSe Application, ProSe Application Server, and ProSe Function.

- The **ProSe Application** runs at the UE. This element handles the D2D communications for both control and data messages. For example, a given ProSe Application can send beacons to discover new nodes, or it can report its location information to the Evolved Packet Core (EPC) and ask for network assistance in the discovery phase. In addition, ProSe Application handles the D2D data communication between two UEs after discovery.
- The **ProSe Function** is located inside EPC and acts as a reference point towards the ProSe Application Server, the EPC and the ProSe Application on the UE. The ProSe Function is connected to the Home Subscriber Server (HSS) in the control plane. As a result it can manage operations such as EPC-level discovery, authorization, UE configuration, security, and billing.
- The **ProSe Application Server** is located outside the EPC and provides the necessary functionalities for the D2D specific application which runs on the UE. It also supports application layer functionalities such as the storage of ProSe User and ProSe Function IDs, and the mapping between them.

B. Medium access control for mmWave

Potential medium access for mmWave communication includes contention-based access, dynamic polling, and time division multiple access (TDMA) [12]. Further details on these channel access mechanism are available in [13]. In particular, CBAP and SP channel accesses are designed

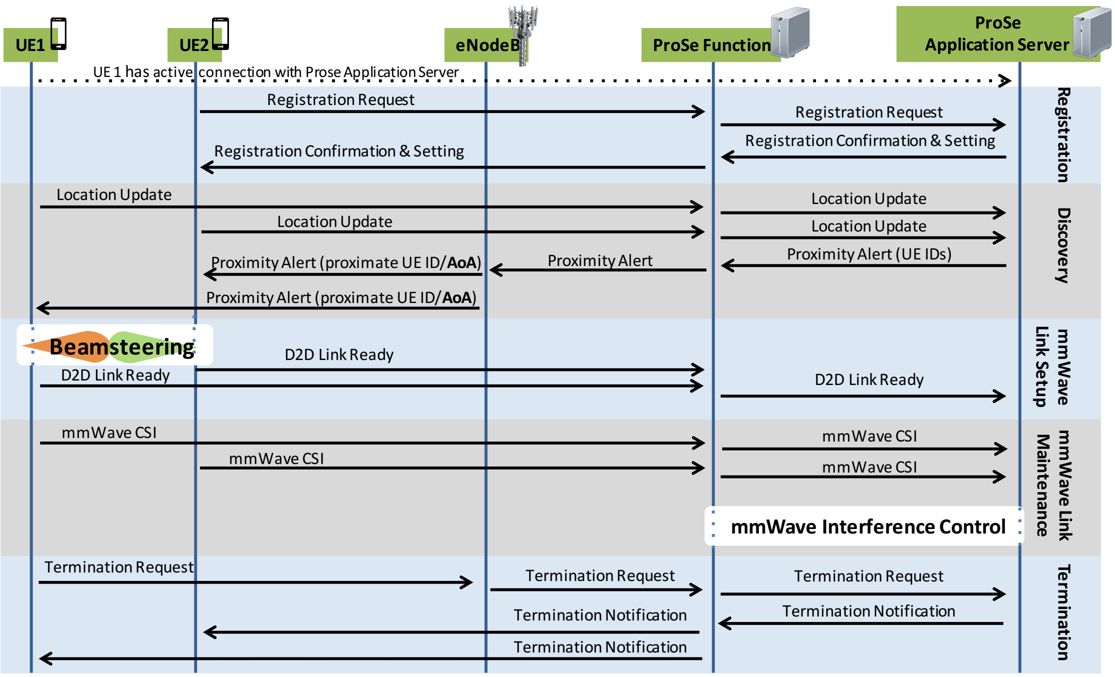

Fig. 2. Our envisioned mmWave ProSe signaling using EPC-level discovery.

such that multiple directional transmissions are allowed to simultaneously transmit/receive. Therefore, we deem these channel access mechanisms the most suitable candidates for D2D communication.

In the current architecture for D2D communication, concurrent channel access is only possible if the D2D transmissions are far from each other in order to avoid interference. As we discuss in the next subsection, directional communication enables concurrent transmission between different D2D pairs in proximity without incurring significant mutual interference. Thus, a high gain is expected by substituting the legacy WiFi/cellular D2D links with mmWave links. As a result, network throughput can be improved substantially.

C. *mmWave D2D in ProSe Architecture*

There are five phases to setup, initiate and complete a mmWave D2D transmission. Fig. 2 illustrates each phase and its associated signaling message exchange and procedures. In the following, we explain these phases.

Registration Phase. D2D users should register for the mmWave D2D service at the ProSe Application Server. This helps speeding up the mmWave connection setup upon successful discovery since the server can provide to each node of a node pair the coarse location of the other node, thus reducing the time required for beam search. Further, registration is necessary for D2D users that exploit EPC-level discovery, as discussed in the next phase.

Discovery Phase. In this phase, a UE discovers another UE in proximity prior to the initiation of communication. 3GPP specifies two options for discovery: direct discovery and EPC-level discovery. In direct discovery, a UE using directional communication transmits beacons sequentially as it sweeps in all directions. This procedure is similar to existing mmWave protocols, such as IEEE 802.11ad. The EPC-level discovery procedure is a centralized approach which allows discovering another UE in proximity based on the location obtained from each UE, which is stored in the ProSe Application Server. For brevity, we only illustrate the discovery phase using EPC-level discovery in Fig. 2.

While direct discovery allows out-of-range UEs to obtain assistance from a UE closer to the BS, the EPC-level discovery reduces energy consumption. Further, it minimizes overhead and interference incurred by periodical control message transmissions. In particular, we propose sending the estimated Angle of Arrival (AoA) along with proximity alerts to the UEs. AoA could be estimated by the ProSe Application Server based on the location information. This AoA information can significantly speed up the beamsteering and the connection setup phase, as mentioned earlier.

mmWave Link Setup Phase. After successful discovery, the pair of D2D nodes can set up a D2D link for data transmission. Prior to any data transmission, the UEs have to perform beamsteering. In this stage, the UEs limit their beam training to the estimated AoA they received from the ProSe Application Server, thus saving valuable connection time. If needed, further beam refinement can be performed. Then the UEs transmit a *D2D Link Ready* message to the ProSe Function. Once acknowledged, the D2D data transmission can be initiated.

mmWave Link Maintenance Phase. Given the dynamic nature of D2D communication, UEs may change position or new D2D UEs may join or leave the system. As a result, a coarse central management is necessary to ensure a consistent system performance. Therefore, we propose two mechanisms. First, we suggest regularly sending coarse average CSI from the UEs to the ProSe Application Server, that is, mmWave link characteristics such as signal-to-noise ratio. The time-scale at which this feedback takes place can be adjusted to system needs. However, the minimum feedback and averaging interval must be at least in the order of the end-to-end delay to the ProSe application server to avoid that outdated CSI arrives at the server. Second, we propose adding local interference control at the ProSe Application Server to monitor the channel quality of the mmWave D2D links in smaller neighborhoods and detect interfering links.

Termination. If either of the D2D UEs wishes to stop the connection, this intention should be reported to the ProSe Application Server via a *Termination Request* message to the eNodeB. If the ProSe Application Server decides that the D2D link has poor performance, it can send a *Termination Request* to ask the UEs to continue the communication through legacy cellular communication.

IV. EVALUATION

In this section, we evaluate the feasibility of mmWave D2D communication in practice. Specifically, we use consumer-grade off-the-shelf half-duplex devices operating in the 60 GHz band, and focus on the impact of 60 GHz propagation characteristics on D2D communication. This shows that mmWave D2D is not limited to experimental hardware only but is beneficial also in real-world scenarios.

A. *Evaluation scenario*

We consider a scenario with two UEs and one eNodeB. In legacy D2D networks, the UEs can communicate with each other using local area network technologies such as 802.11n. Further, they communicate with the eNodeB using, for example, LTE. However, 5G foresees the use of mmWave communications not only for local networking but also for picocell coverage [14]. Hence, in our scenario, both the UEs and the eNodeB use the 60 GHz band to communicate. This matches, for instance, the case of a picocell eNodeB deployed on the facade of a building in a urban environment, and two mobile nodes located along the walkway in its proximity.

In our experiments, we evaluate the potential benefits of mmWave D2D as described in the previous sections. On the one hand, we expect D2D to be beneficial for mmWave picocells because it enables the eNodeB to provide better service to users which are at the cell edge. On the other hand, we expect mmWave to be beneficial for D2D because its directional nature reduces interference among nearby links. Our evaluation scenario allows us to validate this symbiosis by means of two experiments. In the first experiment, we place UE A partially occluded from the eNodeB by an obstacle. UE B has a Line of Sight (LOS) link to both A and the eNodeB. Assuming that the ProSe Application realizes this situation, UE A can establish a D2D connection to UE B, which then relays the traffic to the eNodeB. We compare throughput with and without UE B acting as a D2D relay. In the second experiment, we consider a similar scenario but vary the spatial angle between the two links involved in the communication. This allows us to assess the alleged interference improvement. Note that both the D2D and the cellular link operate in the same mmWave band and thus interfere with each other in both directions. The bidirectionality of the interference is due to the physical layer acknowledgements generated by the hardware.

B. *Off-the-shelf 60 GHz D2D testbed*

While major vendors have announced mmWave *networking* products in the coming months, at the time of writing such devices are not yet available. However, consumer-grade hardware operating in the unlicensed 60 GHz band is widely available. For instance, wireless docking station systems such as the Dell D5000 follow the WiGig standard to connect a laptop wirelessly to external devices such as a monitor, a wired Ethernet connection, and input peripherals. The WiGig standard has led to 802.11ad, which is the 802.11 amendment for mmWave communication. Hence, we exploit this existing hardware to set up a practical D2D 60 GHz testbed. In particular, we use two D5000 docking stations and two Dell Latitude E7440 notebooks. Each of them has a single 2x8 element antenna array. Further, each pair of docking station and notebook establishes a 60 GHz link. As shown in earlier work using this hardware [11], the link follows the standard both at the physical and at the medium access control (MAC) layers. This includes mechanisms such as beamsteering, frame aggregation, and CSMA/CA. That is, it behaves similar to an 802.11ad link with the limitation that it operates point-to-point only.

To use the link, we connect (a) the Dell E7440 laptop via 60 GHz to the docking station, and (b) the docking station via Ethernet to an additional laptop. This additional laptop does not require 60 GHz networking capability but just serves as an end point for the communication. Using a networking tool (iperf[1]), we generate traffic among both laptops and thus on the link. This tool also displays the achieved throughput at the receiver. However, to recreate the D2D scenario described in Section IV-A, we need to establish two 60 GHz links. While the docking system does not allow for such a setup, we circumvent this limitation as shown in Fig. 3. Essentially, we extend the above setup adding an additional 60 GHz link and connecting it to the aforementioned Dell E7440 laptop via Ethernet. This laptop acts as UE B in Section IV-A. To allow UE B to relay data from the first to the second 60 GHz link, we simply bridge its Ethernet and 60 GHz interfaces in the operating system network configuration. As a result, the laptop acting as the eNodeB can transmit data via UE B to UE A, and vice-versa, despite the limited capabilities of the hardware.

C. *Experiment setup*

Fig. 4 shows the lab setup for the two experiments that we describe in Section IV-A. In Experiment 1, we place a metallic obstacle on the LOS path between the UE and the eNodeB. In Experiment 2, we remove the obstacle but move UE A along the dotted circle shown in Fig. 4 to evaluate the interference between the D2D link

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[1] Available at https://iperf.fr/

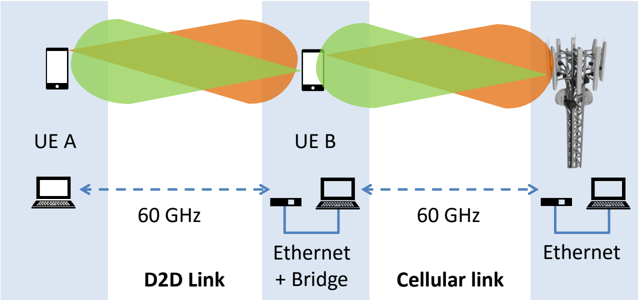

Fig. 3. Realization of the evaluation scenario in the testbed.

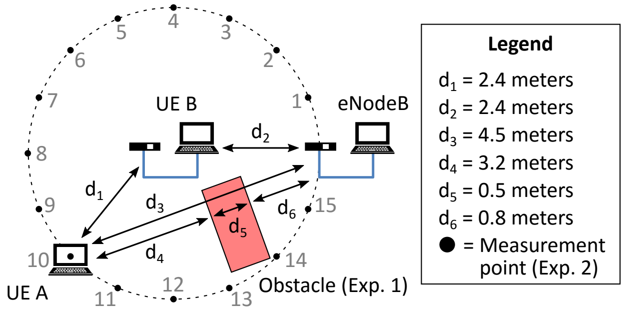

Fig. 4. Experiment setup. The obstacle is only in place in Experiment 1. For that case, UE A is placed as shown in the figure. In Experiment 2, we place it at each of the locations marked with a black dot.

and the cellular link. This allows us to understand how the interference among them changes depending on their relative position and angle. In particular, we place UE A at each of the black dots. For each measurement, we align the Dell D5000 docking stations with their respective Dell Latitude laptop. While both sides support beamsteering, this allows for a fair comparison since the performance of the Dell docking station system is known to become worse when beamforming sideways [11]. Moreover, we also reset the 60 GHz connections prior to each measurement to avoid suboptimal beamsteering as a result of moving UE A to the next measurement point. This limits the uncertainty that the beamsteering algorithm introduces—since the algorithm is implemented in firmware, we cannot influence it.

D. Evaluation results

In the following, we describe and discuss the results of the two experiments presented in Section IV-A.

1) Experiment 1: Fig. 5 shows our results for Experiment 1. The average throughput when using D2D to relay traffic to the eNodeB via UE B is approximately 200 Mbps. In contrast, the average throughput on the direct link is only about 85 Mbps. That is, D2D provides a throughput gain of about 2.3× by avoiding the obstacle shown in Fig. 4. In our case, communication is still possible via the direct link. Still, an obstacle might also prevent mmWave communication entirely. In such a case, D2D relaying is crucial for the operation of the picocell. In Fig. 5 we also observe that the D2D connection is significantly more stable than the direct uplink from UE A to the eNodeB. The large fluctuations in the latter case are a result of UE A continuously trying to improve its link quality by means of rate adaptation and beamsteering. This even leads to outages, as shown in Fig. 5 at seconds 19 and 42. Such large fluctuations significantly hinder the operation of upper-layer protocols. Hence, Experiment 1 clearly shows that D2D is beneficial for mmWave, contributing to the aforementioned symbiosis.

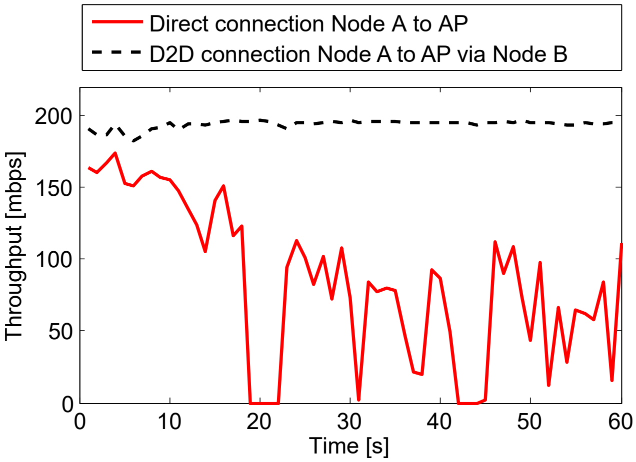

Fig. 5. Experiment 1. Throughput with and without a D2D relay.

2) Experiment 2: In our second experiment, we show how mmWave reduces the interference in D2D. More precisely, Fig. 6 shows a box-plot of our throughput measurements when placing UE A at each of the locations marked in Fig. 4. The horizontal mark on each box is the median of our results for a certain location. We observe that the median is at about 100 Mbps, or even below, for positions 1 to 3, 6 to 9, and 12 to 15. From Fig. 4, we find that these positions correspond to the cases when the concurrent links are roughly parallel or at a moderate angle towards each other. In such cases, either the transmitter or the receiver of one link is approximately aligned with the transmitter or the receiver of the other link. This causes interference and thus reduces the throughput. The more narrow the beamwidths, the less often this should happen. However, the beam patterns of the Dell docking station system are known to be rather wide [11]. Hence, interference occurs often. However, when the links are at roughly 90° towards each other, we expect interference to be low. Indeed, Fig. 6 shows that for Position 4, the median rises to above 200 mbps, resulting in a 2× throughput gain compared to, for instance, Position 3. This shows that mmWave is highly beneficial for D2D as it enables simultaneous operation of nearby links. Fig. 6 shows a second peak at Positions 10 and 11, which corresponds to the same effect when moving UE A to the other side of the circle in Fig. 4. However, we would rather expect this peak at Position 12, which is the symmetric location to Position 4. This asymmetry is a result of the irregular beam patterns of the D5000, which have significant sidelobes [11]. This shows that the actual characteristics of consumer-grade off-the-shelf devices might result in unexpected effects, making it more difficult to predict how devices will behave. If our 60

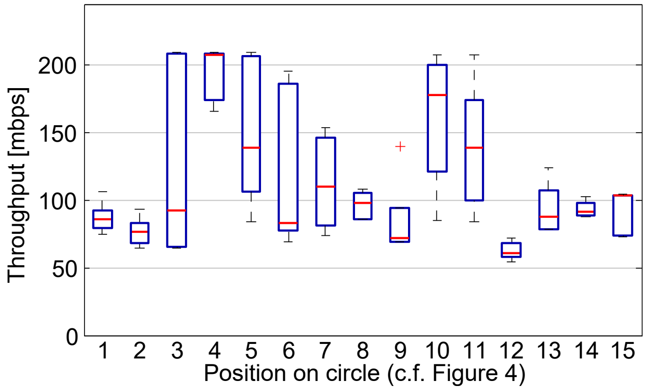

Fig. 6. Experiment 2. Throughput for different link relative angles.

GHz devices would feature ideal pencil-beams, the second peak in Fig. 6 would occur at Position 12.

The whiskers of each box in Fig. 6 show the maximum and minimum throughput measurements at each location. For some cases, such as Positions 3 and 6, we occasionally achieve high data rates but most of the times they are limited by interference, as the median reveals. This occurs at borderline locations, that is, at locations where the links are not parallel to each other anymore but also not perpendicular yet. In such cases, the algorithm that chooses the beampattern at the docking station finds a number of patterns that seem suitable to minimize interference during communication. As a result, the docking station may choose a different beam pattern in each experiment repetition, resulting in different performance. For instance, at Position 3, we sometimes achieve up to 200 Mbps but most often throughput is about 65 Mbps. Unfortunately, we have no influence on beam pattern selection. In other words, the docking station is not able to fully exploit the spatial resources. This highlights the need for more sophisticated beamsteering algorithms in future mmWave D2D hardware.

V. CONCLUSIONS

In this paper we integrate mmWave communication into the 3GPP framework for D2D Proximity-based Services. We identify the benefits of D2D for mmWave, and vice-versa, showing that this symbiosis is highly promising. On the one hand, the directional nature of mmWave communication helps mitigating the interference among nearby D2D node pairs. On the other hand, the D2D ProSe Application Server can, for instance, provide coarse location information which significantly reduces the mmWave link setup time. Further, we perform the first practical evaluation of 60 GHz D2D using commercial off-the-shelf devices. We experimentally validate the aforementioned symbiosis of mmWave and D2D. Our results show that D2D can improve the throughput of a 60 GHz picocell by 2.3 times on average. Conversely, we find that reduced interference in 60 GHz communication can improve D2D throughput performance by two times.

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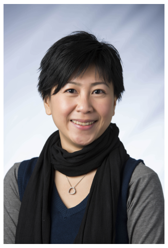

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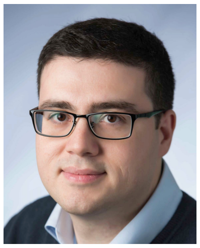

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