Millimeter-Wave Meets D2D: A Survey

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Abstract—Device-to-device (D2D) and millimeter-wave (mmW) communications play an important role in the design of future wireless communication systems, since they are mature and resource-efficient technologies. Integrating both technologies while retaining the benefit they offer in isolation is challenging. In this survey, we review the literature on mmW-based D2D proposals to enable network applications and service extensions that span from network-controlled use cases to opportunistic solutions for direct data exchange, caching and relay. The survey unveils that, although a large effort has been devoted to the study of D2D with mmW, we are still far from a full analytical and experimental characterization of the system. More effort is needed in view of 5G and beyond, to consider the integration of network computing elements and to protect mmW-based D2D against security threats.

Index Terms—millimeter wave, D2D, relay.

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1 INTRODUCTION

Millimeter-wave (mmW) and Device-to-device (D2D) are key enablers for future communication systems. Indeed, mmW is part of the 5G technological options [1], whilst D2D is included in 3GPP specifications since Release 12, labelled as Proximity Services (ProSe) [2].

Besides 5G, recent studies have shown that working above 10 GHz is suitable also for connecting vehicles [3] and drones [4]. The availability of ISM and licensed bands for mmW, jointly with the recent advances in field of compact and electronically steerable antennas, makes mmW a suitable technology for smartphones, as recently evaluated via simulation [5]. There are interesting surveys on mmW [6], [7], [8], although a literature review on the advantages offered by mmW to D2D is currently not available. In particular, mmW offers much more flexibility to D2D than any microwave (μWave) band, with much powerful steerable and reconfigurable narrow-beam antennas.

D2D has been designed for direct communication between user devices but also for extending coverage and performance of cellular networks and specific applications, from home automation to social networking, content delivery and caching [9], [10], [11]. D2D has been tested using simulation and software-defined radio platforms [12], [13], and there exist comprehensive surveys, e.g., [14], [15], [16], which describe device pairing techniques, application use-cases, and the integration of D2D within cellular networks. However, there is no comprehensive survey on the use of D2D specifically tailored to mmW characteristics.

Here, we survey the literature on mmW-based D2D—which we refer to as *mmD2D* in the rest of the paper—and show how mmD2D impacts 5G and future generations of cellular technologies. Based on works surveyed here, Figure 1 depicts a scenario of integration between cellular networks, D2D and mmW. It shows that mmD2D embraces planned and unplanned infrastructures, and includes direct communication as well as relaying. Applications that can benefit from mmD2D include real-time and non-real-time data communications, caching and support for IoT and smart environments.

We show that a lot of effort has been devoted into integrating D2D and mmW, especially for spontaneous connectivity. There has been also significant work in designing mmD2D applications under the control of cellular operators, for relay purposes and other 5G applications, from machine-to-machine (M2M) communications to wearable devices. However, more effort should be dedicated to address network modeling and optimization. Moreover, there is still not much experimental evidence of mmD2D pros and feasibility when communication and computation technologies have to converge, e.g., with the introduction of network slicing and edge computing [17].

In the reminder, Section 2 discusses the integration of mmW in ProSe; Section 3 provides an mmD2D taxonomy; Section 4 reviews the work on pure D2D communications using mmW, whilst Section 5 focuses on mmD2D as a relay technique; Section 6 identifies research aspects that require further attention, and Section 7 concludes the survey.

2 MMW IN 5G PROSE

Before diving into the sea of applications and networking solutions identified in the mmD2D literature, this section presents an overview of physical mmW features that can be exploited for D2D and ProSe.

2.1 mmW features applied to D2D

Directionality. mmW devices typically dispose of antenna arrays, which can provide directional transmissions. Still, designing quasi-optical antennas is very challenging and costly. Several antenna models are used for mmD2D:

- The *Sectored antenna model* [18] is the simplest one. It assumes a high constant gain in the half-power beamwidth (HPBW) range, and a lower constant gain in remaining directions. It is used in studies focusing on stochastic geometry [19], [20], [21], [22], [23], [24],

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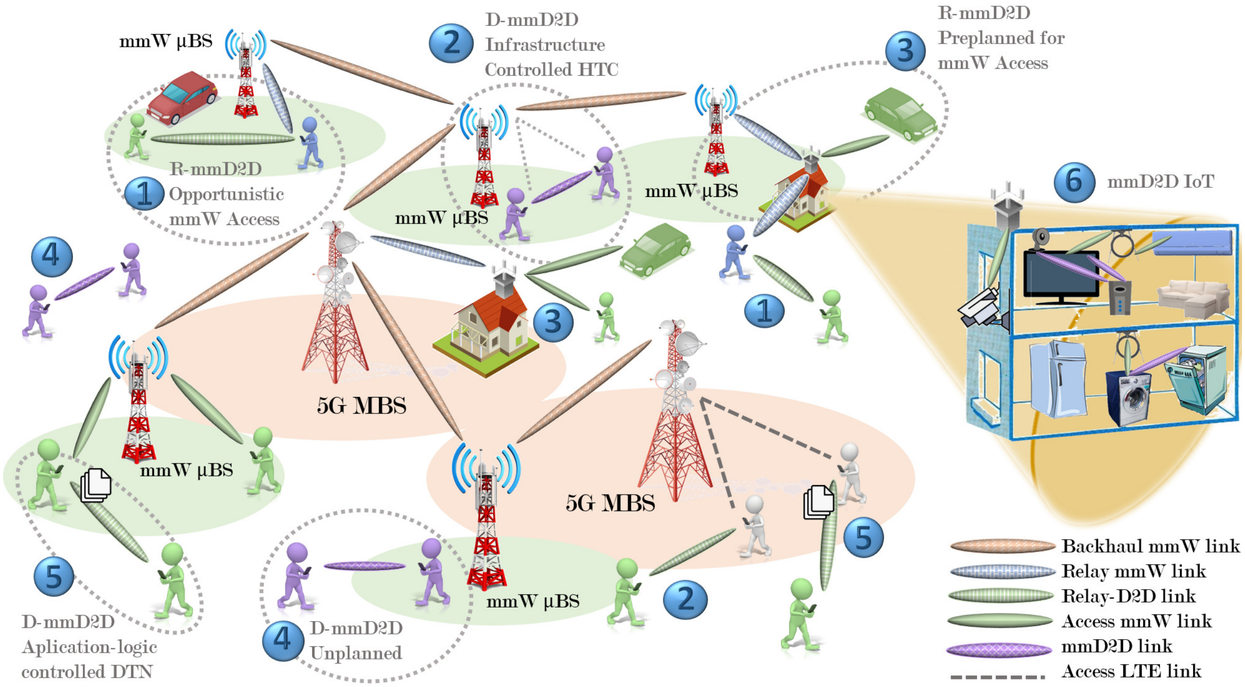

Figure 1. A scenario for the integration of mmD2D into 5G cellular networks

[25], [26], [27], as well as for optimization [28], [29] and caching design [30].

- The *Cosine antenna pattern* [31] is a model that describes the main lobe more realistically, with a cosine function. However, it ignores side lobes. It is used for mathematical tractability in some studies [32], [33].
- The *Toyoda model* [34] presents a variable main lobe gain for directions in between the HPBW, and a non-zero constant gain for the first side lobe. It has been used to study interference [35] and to design cooperative edge caching [36].
- The *Gaussian directional model* [37] is similar to the sectored antenna model, except it accounts for small disturbances and misalignments between transmitters and receivers. It has been adopted to optimize transmission power [38].

Table 1 shows the analytical expression of the antenna gain with respect to the radiating angle θ, namely $G(\theta)$. Here, G_m is the maximum antenna gain, G_s is the average side lobe gain, N is the number of antenna elements spaced by d, λ is the wavelength, and θ_m and θ_h identify center and edge of the HPBW.

Blockage. mmW is very sensitive to obstacles. Indeed, channel attenuation considerably differs when links are in Line-of-Sight (LoS) or Non-LoS (NLoS). Hence, the mmD2D literature considers different blockage models:

- The *LoS Ball model* [18] reflects accurate approximations according to empirical experiments [39] and assumes a constant probability p_L of unblocked signals within a ball of radius R, and null probability elsewhere. Due to its tractability, it has been used in many mmD2D works [21], [23], [24], [25], [26], [27], [32], [33].
- The *Exponential model* [40], [41] assumes that the LoS probability depends on the obstruction size and density. Moreover, the shorter the link, the more likely it is to be in LoS. Tractability makes the exponential model very popular for stochastic geometry works on mmD2D [20], [22], [30], [42], [43], [44].
- The *Boolean model* [45] assumes that obstacle's centroids follow a homogeneous Poisson Point Process (PPP). Any link traversing an obstacle is blocked. It has been used for mmD2D in [46] to model blocking walls with rectangles, and in [19], [47], [48] to model people obstacles with cylinders.
- The *Bernouilli model* [49] assumes that any link can be blocked with a fixed probability.
- Some works like [50] simply rely on *Statistics*.

Transmission bands. Several bands might be used for mmD2D:

- 24 *GHz* is the lowest band employed in the literature. It has been considered in [51] to be compared to the 60 GHz band.
- 28 *GHz* is a licensed band and hence commonly considered for mmD2D controlled by cellular operators [20], [29], [30], [42], [43], [44], [47], [48], [49], [52], [53].
- 38 *GHz* is an unlicensed band that allows for very high mmD2D data-rates at very short ranges, as explored in [42], [44], [54], [55].
- 60 *GHz* is also unlicensed and has been adopted by IEEE 802.11ad and used in several mmD2D studies [28], [36], [38], [42], [51], [56], [57], [58].
- 73 *GHz (E-band)* is the highest band used. It allows for high directionality, as exploited for mmD2D in [26], [42], [50].

2.2 mmW in future ProSe

Although ProSe in 3GPP Release 12 [2] initially referred to cellular LTE devices that may communicate with other

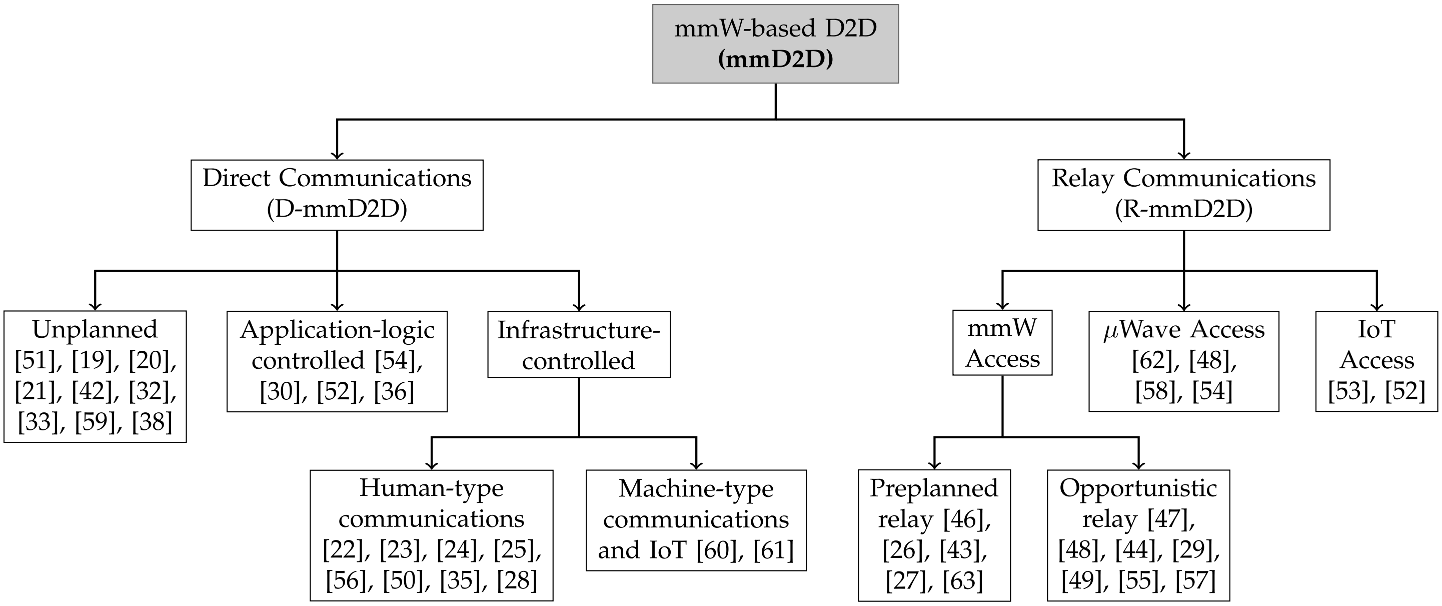

Figure 2. Taxonomy used in this survey for the scientific literature focusing on mmD2D

devices in proximity in a direct manner, it does not restrict D2D to any specific technology. 3GPP Release 13 [64] extends ProSe to relay (*sidelinks*), managed by a centralized controller. The integration of D2D with mmW networks offers a wide amount of possibilities for future networks in which it will be possible to combine legacy μWave technologies (e.g., LTE or WiFi), cellular and mmW-enabled networks with D2D-type communications.

3 A TAXONOMY FOR MMD2D

Figure 2 illustrates a taxonomy for mmD2D, used to categorize the works reviewed in this survey. There are two main categories: works dealing with direct communications between devices—referred to as D-mmD2D—and works focusing on relay—referred to as R-mmD2D.

The **D-mmD2D** category presents research works that use mmD2D to set direct connection sessions between users. We identify three main use-cases:

- *Unplanned mmD2D*. In this case, the works do not rely on network infrastructure and D2D coordination entities. Thereby, direct D2D connections are analyzed as the source for unplanned and uncontrolled data flows. This use-case is relevant for understanding the limits and opportunities offered by mmD2D services developed outside the network control.
- *Application-logic controlled*. Here we consider mmD2D for caching and delay tolerant networks, which lack strict delay constraints although they need to provide robustness and guarantees on content retrieval. Such use-cases mainly rely on unplanned mmD2D, although they require the use of some coordination at application level, which depends on the application's logic.
- *Infrastructure-controlled*. Here, a fixed infrastructure manages D2D discovery, interference, transmission power, antenna configuration, etc. The main uses here regard mobile broadband (MBB) networks and smart environments, which are separately discussed because they involve human-type and machine-type/IoT communications, respectively.

The **R-mmD2D** category focuses on how mmD2D improves and extends access networks performance by means of relays. As mmD2D is very sensitive to blockage and interference, and is robust only over short range links, relay paths are very useful to provide alternative D2D paths that avoid blockage, extend mmW coverage and allow for a better directional spatial reuse. Here, we identify three main use-cases: two are based on the bands used in the access network (*mmW Access* and *μWave Access*), while we keep a separate one for IoT transmissions over mmW paths.

4 DIRECT COMMUNICATIONS (D-MMD2D)

Here we analyze the literature focusing on mmD2D one-hop flows that occur in uncontrolled scenarios, or under the supervision of either the network (infrastructure-controlled case) or a specific application (application-logic controlled case). In the uncontrolled scenario, devices opportunistically share content without the need of a fixed infrastructure, while in supervised cases a network orchestrator is available to coordinate the activity of mmD2D devices, which can include caching and forwarding policies as well as signaling, resource allocation and D2D pairing.

4.1 Unplanned

Here, the main focus is on the characterization of mmD2D channels, stochastic geometry analysis of mmD2D networks performance and simple protocol design and optimization. Table 2 summarizes findings in the unplanned D-mmD2D literature and presents the used analytical tools, application use-cases and evaluation tools of each surveyed work.

The fundamentals for unplanned mmD2D are studied by Al-Hourani *et al.* [51]. They characterize channel attenuation on the 24 GHz and 60 GHz bands for urban environments by means of ray-tracing simulations, based on ITU recommendations. The authors derive path-loss equations for mmD2D links under both LoS and NLoS conditions and hence derive path-loss exponent and shadowing.

For what concerns the use of stochastic geometry, Venugopal *et al.* [19] analyze the performance of D-mmD2D in planar networks and derive closed-form expressions for coverage probability and spectral efficiency. They consider a network of smart devices wore by people. Hence, signals are blocked by people themselves. The authors assume indoor scenarios without leakages nor external influences, and reflections are neglected. The authors consider sectored antennas, boolean blockage accounting for self-blockage, and that interference beyond a predefined range is NLoS. They show that their assumptions are accurate enough and serve for more generic cases; thus, they conclude that blockage and interference are the limiting performance factors. Thornburg *et al.* [20] study D-mmD2D with sectored antennas and boolean blockage, and show that noise and NLoS interference do not substantially affect SINR for a fixed link length, which supports the claim that dense mmD2D networks are mainly interference-limited. To support this idea, authors model the interference-to-noise ratio, whose characterization shows the transition from noise-limited to interference-limited systems as a function of density of users and buildings, beam-patterns and link length. Their work is relevant to motivate more research to mitigate interference coming from LoS transmissions in mmD2D. Deng *et al.* [21] analyze D-mmD2D networks where transmitters follow PPP locations and receivers are at fixed distances. Transmitters know the receivers orientation and use sectored antennas. The authors assume LoS Ball blockage and derive the distribution of SINR and data-rate at the typical receiver. They also derive mean local delay and spatial outage capacity. Their results show that increasing the number of antenna elements improves transmission success probability because it implies the presence of narrower beams and hence reduced interference. However, D-mmD2D is interference-limited. Yi *et al.* [42] analyze coverage performance and area spectral efficiency (ASE) assuming sectored antennas. Users are clustered and distributed according to a Poisson Cluster Process (PCP), and the authors conclude that: pairing closest D2D devices in LoS provides the best performance; there is an optimal cluster size; and higher mmW bands (as 38 GHz) suit high SINR and dense regions, whilst lower bands (as 28 GHz) are best otherwise. Finally, Deng *et al.* [32], [33] study a multi-tier D-mmD2D network in which D2D users form heterogeneous tiers based on transmission power, location distribution, etc. Nodes use the cosine antenna pattern and each transmitter has a dedicated oriented receiver at a fixed distance. The authors derive a mathematical framework based on K-tier Homogeneous Independent PPP (HIP) and use LoS Ball blockage. They find closed-form expressions for mean and variance interference, and SINR and rate distributions. Their simulations prove the importance of considering accurate beam-pattern models, in contrast to other simpler approaches.

Sim *et al.* [59] propose the first decentralized MAC scheduling algorithm that fits both to noise- and interference-limited mmD2D scenarios. The authors show that low dense networks foreground a noise-limited operation regime whilst dense networks are interference-limited. They propose the first one-fits-all scheduling mechanism that adaptively overcomes the challenges of both cases, and that almost converges in finite time, achieving proportional fairness: convergence speed is reasonably low, collision ratio remains lower than 30%, the void slots ratio is around 50% and channel efficiency goes beyond 40%.

Zhang *et al.* [38] propose an optimization scheme for D2D pairing and beamwidth selection so to minimize energy costs. A base station (BS) addresses a non-convex optimization that guarantees Quality-of-Service (QoS) and accounts for possible antenna directions. The authors split the problem into two sequential suboptimal subproblems: device pairing and beamwidth selection. Device pairing is naively performed: users collect transmission power of neighbors and infer the distance. Then, closest pairs are associated. Beamwidth selection is solved with a particle-swarm optimization algorithm using a fitness metric. Their results show that, in comparison to different pairing strategies, their proposal reduces transmit power, mitigates interference and enhances network throughput.

4.2 Application-logic controlled

mmD2D has been recently proposed to address high-reliable delay-tolerant services between devices in proximity. To this end, mmD2D can handle close-in-range and reliable content delivery upon LoS links. In literature, this approach has been compared to different caching strategies and used to ease popular content delivery with high data-rates, improve heavy multimedia content cooperative sharing between smart factory devices or design assisted cooperative edge caching for dense mmW networks.

Ji *et al.* [54] design a delivery algorithm for D2D-assisted outdoor caching networks in which mmD2D is prioritized for short-range links. The authors study the delivery of popular content present on a cache memory. Traffic might follow alternative paths, different from D-mmD2D. However, simulation results show that D-mmD2D especially helps to increase average throughput and serve around 30% of users with good rates. Similarly, Giatsoglou *et al.* [30] design the D2D-aware caching (DAC) policy, that exploits D-mmD2D to facilitate popular content exchange among close devices. DAC splits the mostly popular contents in two groups, and assigns three kinds of cache action probabilities: the cache hit, the D2D transmission to a peer, and the cellular transmission. DAC provides a diverse content spread while improving the offload gain, as numerically shown in the work. Instead, Orsino *et al.* [52] investigates D-mmD2D multimedia caching according to the logic of industrial IoT. Machines produce and collaboratively share heavy multimedia content with a mmW BS. Collaborative D-mmD2D caching is enabled to enhance cell edge performance and the authors study various dissemination policies that are enabled by D-mmD2D. Results highlight that the presence of obstructions is a dominant factor in smart factories. Finally, Wu *et al.* [36] propose a D2D-assisted cooperative edge caching (DCEC) policy in mmW dense networks. Here, users first try to retrieve content from a self-cache memory, second from a D2D peer by means of high-capacity D2D links, and third from a near BS. If the content is miss-cached, users retrieve this content from the internet with longer delay. The results show that DCEC improves backhaul traffic offloading and content retrieval delay.

4.3 Infrastructure-controlled

4.3.1 Human-type communications (HTC)

HTC relies on MBB services like video streaming and gaming, augmented reality, etc. This calls for efficient network architectures relying on different wireless technologies and effective interference management. To this aim, several works exploit mmD2D features to offload the backhaul and speed up communications through multi-gigabit links with high spatial reuse. The analytical techniques mainly employed in this category are stochastic geometry [22], [23], [24], [25] and mathematical optimization [28], [35], [50], [56]. The former allows to study key features as coverage, SINR or outage probabilities and understand the impact of D-mmD2D. The latter enables the use of this knowledge to directly optimize throughput [35], [50] and scheduling efficiency [28], [56]. Table 3 summarizes the findings in the infrastructure-controlled D-mmD2D literature for HTC and presents the used tools and application use-cases in each surveyed work.

For what concerns the analysis with stochastic geometry, Jung *et al.* [22] analyze the connectivity of a mmD2D network under blockage conditions. The authors assume that outages occur when mmD2D links are out of LoS and envision direct and indirect schemes. The former considers direct D2D between close users, while the latter disables D2D and employs two-hop mmW paths through cellular links. In addition, the authors investigate a hybrid scheme. Their results show that as network size and presence of obstructions increases, the probability of achieving a fully connected network and having a high number of reliably connected devices decreases. Still, the hybrid scheme is able to enhance the performance of these metrics up to a 35% in comparison to the direct and indirect schemes. Moreover, Turgut *et al.* propose a stochastic framework to study the uplink performance of mmW cellular networks with non-clustered [23] and clustered D2D users [24], [25]. They assume that D2D users follow either a PPP or a PCP and the spectrum is shared according to either the underlay mode, in which D2D users share resources with uplink cellular users, or the overlay mode, in which users share a reserved portion of the uplink band. Mode selection is based on the link quality, which in turn depends on interference. The authors find out that (i) the underlay mode is limited by intra-cluster and inter-cluster interferences; (ii) the overlay mode is mainly affected by cross-mode interference; and (iii) performance increases with the main lobe gain and decreases with the beamwidth, since these parameters affect cross-link interferences.

For what concerns optimization, Niu *et al.* [56] study access and backhaul with small cells. Flow paths are either direct single-hops between devices, or predetermined backhaul routes between access points. The authors formulate a mixed-integer non-linear program (MINLP) optimization to minimize the number of time slots used for the aggregated flow data delivery. They exploit spatial reuse and schedule as many concurrent transmissions as convenient. Due to high complexity, the authors propose the D2DMAC algorithm, which scales well with traffic load and is close-to-optimal in terms of average transmission delay and total successful transmissions. Focusing on the uplink, Guizani *et al.* [50] derive a scheduling optimization framework for cellular and D2D users. They consider an underlay mode in which D2D pairs are scheduled in parallel if interference is below a threshold. The authors formulate a mixed-integer linear program (MILP) to maximize the aggregate system throughput, and propose a simple heuristic, in which they iteratively assign sets of resource blocks used by some cellular user to D2D pairs, as long as interference constraints are not violated. A simulation study under different system settings, mainly comparing different channel bandwidths, unveils that the power used for transmissions is key to achieve optimal throughput. On a different line, Wang *et al.* [35] propose a time slot allocation scheduling in indoor mmD2D networks aiming to mitigate side lobe interference between D2D flows by means of a combination of TDMA and SDMA techniques so to maximize system throughput. The optimization accounts for QoS and interference, and results in a complex non-convex optimization problem. Hence, the authors formulate an alternative scheduling algorithm and model a conflict matrix that identifies cross-link interference coming from the main lobe of neighbors. The matrix also considers side lobe interference under a threshold. With this, authors propose a modified vertex coloring algorithm and show that side lobe interference has severe negative impact on D-mmD2D if it exceeds an optimal threshold. Finally, Panno *et al.* [28] maximize system throughput, minimize end-to-end delay and improve fairness in a cellular system with D-mmD2D. The formulated problem is an NP-hard MINLP. Consequently, they propose a centralized greedy access control scheme based on graph vertex coloring. Simulations show good performance in terms of concurrent transmissions efficiency, system throughput, end-to-end packet delay and fairness levels.

4.3.2 Machine-type communications (MTC) and IoT

MTC and connected *things* have radically different requirements with respect to HTC, and produce different traffic patterns. They require tight control due to their application to the control of systems and require integration with distributed computing entities. There is still little work in this area of research for mmD2D, although a few papers have recently appeared.

Lv *et al.* [60] study D-mmD2D for M2M communication in dense environments with massive connectivity of MTC devices. Their main contribution is the use of a mmW-NOMA, analyzed with stochastic geometry. The authors consider one central mmW BS with K antennas serving two groups of MTC devices. Transmissions from different groups can be scheduled in parallel, and the authors study D2D pairing schemes within the groups. Hao *et al.* [61] propose the use of mmD2D to build a 5G network of wearable devices that relies on the availability of mobile edge computing (MEC) and network slicing tools in a scenario of ultra-dense cellular networks. The goal of the work is to show how to improve the sharing of resources so as to achieve low latency and energy efficiency.

5 RELAY COMMUNICATIONS (R-MMD2D)

R-mmD2D permits to extend mmW multi-gigabit connectivity to coverage areas similar to the ones of μWave networks, but with much lower interference. We have characterized mmW relay backhauling by considering technological constraints, and shown it allows for concurrent relaying over multiple paths [65]. Other works focus on a fully mmW enabled network, in which cellular and D2D connections are scheduled on the mmW spectrum [26], [27], [29], [43], [44], [46], [47], [48], [49], [55], [57], [63]. A few works focus on legacy infrastructures supported by μWave technologies, as LTE [54], [58], [62], or for IoT in 5G [52], [53].

5.1 mmW Access

There are two kinds of mmW relays: dedicated *preplanned* relays and *opportunistic* D2D relays. Preplanned relays are fixed and strategically positioned relay nodes, usually power-supplied to provide alternative routes. Opportunistic relays are user devices. There exist also hybrid options, in which preplanned and opportunistic mmW relays co-exist. Table 4 reports and summarizes works on R-mmD2D.

5.1.1 Preplanned relay

Lin *et al.* [46] present a stochastic geometry study of multi-hop R-mmD2D to evaluate its feasibility. They assume that relay nodes are used to avoid blockage, without considering interference. Their approach lacks tractability, except it provides an upper bound on the probability of having the D2D pair successfully connected. Still, they show that close-to-optimal connectivity is possible. Biswas *et al.* [26] analyze a similar scenario, but with several source nodes and a single destination, and they consider interference with sectored antennas. Their results show that relay-aided transmissions are able to improve the SNR by 5 dB and enhance coverage and transmission capacity.

Xie *et al.* [43] study the coverage performance of R-mmD2D with several distributions of mmW BSs, users, blockages and preplanned relay nodes used to avoid blockage. By assuming sectored antennas with null side lobes, they study the SNR in low density scenarios and the SINR in ultra dense scenarios. Their results show that although provisioning a mmW network with relays may remarkably improve system performance, there is no need to use many relays. The reason is twofold: performance improvements fade with the number of relays, while the deployment costs becomes soon prohibitive.

Turgut *et al.* [27] analyze the energy efficiency of R-mmD2D. They model two types of users: non-cooperative and cooperative users. Only the latter use relays to avoid NLoS links. They assume sectored antennas and LoS ball blockage. With stochastic geometry analysis, the authors conclude that directional mmW antennas enhance energy efficiency. Indeed, they observe that narrower beams with higher gains result in improved energy efficiency.

Niu *et al.* [63] argue that R-mmD2D enables fog computing. They adopt multi-hop for mobility-aware caching and concurrent transmissions to exploit spatial reuse. With stochastic optimization, they maximize expected cached hits, although they need to resort to a heuristic, due to complexity. Simulation results show that their proposal is able to greatly outperform legacy caching schemes in terms of available cached data.

5.1.2 Opportunistic relay

A few works address opportunistic relay analytically. Wu *et al.* [47] leverage on two-hop D2D relay and derive closed-form expressions for the downlink coverage probability. They use stochastic geometry and assume that mmW BSs serve users through direct links on the downlink spectrum, and over D2D relay in the uplink spectrum when an outage occurs. The authors conclude that R-mmD2D is always beneficial for SINR-based coverage regardless BS density and number of obstacles. Moreover, they identify optimal BS deployment densities and point out that the correlation in blockages between cellular and D2D users plays an important role. Another work by Wu *et al.* [48] provides a wider set of closed-form expressions for several event probabilities in R-mmD2D, when D2D can use mmW or μWave spectrum, depending on which one provides the best channel. The work shows that D2D relay is beneficial for spectral efficiency and for SINR-based coverage. However, using μWave bands provides better spectral efficiency.

Other works focus on optimization. Kim *et al.* [44] minimize the sum-quality of video streams with R-mmD2D, provided that a minimum quality is guaranteed and that flows may follow multi-hop paths that combine preplanned and opportunistic relays. The work neglects interference but involves constraints for devices, relay and flows. The work describes a convex mixed-integer video-routing problem, solvable with Branch&Bound, which is however way too time consuming for video routing. Indeed, this use-case has been tackled also in [29], where the authors introduce interference in the equations but also propose approximations to design an online solution that is near-optimal and results to be 33% better than legacy approaches. Wei *et al.* [49] derive a throughput-optimal relay probing strategy for two-hop cases with Bernoulli blockage. This strategy consists in probing relays until the spectral efficiency of flows is above a threshold. The work shows that there is an optimal threshold and illustrates how to compute it. However, results are derived only for one flow between one mmW BS and one destination user, with many possible preplanned relays placed in between. Moreover, since only one communication flow is considered, interference does not play any role in the system. Eventually, Ma *et al.* [55] optimize R-mmD2D with full-duplex relaying, which causes hard-to-cancel loop interference. They formulate a multi-objective MILP that minimizes the total transmit power of D2D users and maximizes system throughput with the Hungarian method for bipartite graphs. They also propose a suboptimal lightweight distributed algorithm. Compared to a centralized and a distributed relay-selection algorithms, their proposal reduces the total transmit power while improving system throughput.

Sim *et. al.* [57] present the first work involving real mmD2D experiments. They propose symbiosis between mmW and D2D over an adaption of the 802.11ad MAC procedure built on top of ProSe. Applied to picocells, they test it over a simple mmW-based testbed consisting of one BS and two D2D users. The authors build an R-mmD2D framework that is compliant with ProSe specifications. For instance, the mmW link maintenance is guaranteed through user reports to the ProSe Application Server. The authors perform two experiments. First, they compare the legacy mmW-based cellular system and R-mmD2D when an obstacle blocks the cellular link. Second, they test rotary positions for the relays, and show that the system throughput fluctuates mainly depending on the angle of arrival of transmissions, due to limited codebook-based beamforming of commercial 802.11ad devices. Therefore, the authors prove that R-mmD2D is feasible, although still with several limitations on range, interference and mobility.

5.2 μWave Access

Some works focus on legacy 4G. These works mainly rely on signaling to manage relay, supporting cellular services and ProSe, and offloading/caching.

Qiao *et al.* [62] propose a TDMA-based MAC for R-mmD2D supported by reliable 4G signaling. They account for mmW backhaul, mmW access, and D2D relay and formulate a centralized non-convex mixed-integer maximization of transmitted data. Transmissions are scheduled over channel time allocations with non-orthogonal resource sharing, and assume that mmW BSs are *pseudo-wired*, since they neglect interference over distances and steered transmissions. Interference is avoided by means of binary decisions in which only non-crossing beams can be scheduled simultaneously. The problem is unsolvable in efficient time. Hence, the authors resort to a heuristic based on random time slot allocations that avoid cross-links interference. The authors conclude that R-mmD2D in 4G-supported mmW networks reduces outage probabilities drastically. Similarly, Wu *et al.* [48] study the 5G case with μWave- and mmW-based D2D, using stochastic geometry. The authors assume that some cellular flows are rescheduled through two-hop D2D paths opportunistically. They consider sectored antennas and use boolean blockages, and model the presence of people as cylinders. Relay uses μWave or mmD2D, according to channel quality, and derive spectral efficiency and resource utilization. The authors show that when SINR thresholds are high, denser obstacle distributions help to improve the coverage probability over mmD2D relay. Moreover, both relay D2D modes improve the coverage probability and spectral efficiency in general.

Sim *et al.* [58] propose Opp-Relay for ProSe. Opp-Relay supports mobility and includes the discovery of D2D links. The protocol however relies on legacy cellular connectivity. Opp-Relay mainly focuses on choosing the discovery beamwidth *and* the transmission beamwidth that users must employ for relay. The authors propose two techniques: beamwidth disjoint optimization and beamwidth joint optimization. The former optimizes discovery and transmission beamwidths in a sequential manner. Conversely, in the latter the two beamwidths coincide and are optimized using a single function that considers both discovery and transmission performance gains. The work is validated with a simple mmW testbed consisting of two users and one relay. Results show that Opp-Relay operates well in pedestrian-based dynamic scenarios, achieving multi-Gbps physical throughputs. This testbed does not incur interference and the authors conclude that wide beamwidths are convenient. However, with interference due to the presence of multiple users, wide beamwidths may become counter-productive.

Eventually, the work of Ji *et al.* [54] shows that R-mmD2D is a useful alternative to speed up content sharing when it coexists with conventional μWave D2D and LTE cellular communications. Technologies are robustly combined in benefit of cached content delivery efficiency.

5.3 IoT Access

R-mmD2D applied to IoT is also present in the literature. Specifically, it has been envisioned to derive social IoT relationships and to share content among mobile machines.

Kumbhar *et al.* [53] propose Reliable Relay to enable a trustworthy proximity-based communications for IoT. The proposal uses a communication graph and a social graph. The former is composed by devices in proximity while the latter is composed by devices that are autonomously able to develop social relationships. Devices may use trustable relays according to the social graph. This results in increased capacity and data-rate with negligible delay. Moreover, Reliable Relay can be easily integrated into other relay-based existing systems to add flexibility and realistic relay selection schemes. Also the mmD2D-based caching scheme by Orsino *et al.* [52] includes relay aspects. They propose strategies that comply with IoT access services as mmW BSs and machines collaboratively share content while moving. Hence, mmD2D becomes relevant for industrial multimedia content sharing to enable efficient dissemination strategies.

6 OPEN QUESTIONS & FUTURE DIRECTIONS

In this section we identify possible research directions for mmD2D. In general, the number and the technical depth of mmD2D works are still limited in comparison to what available for either D2D or mmW in isolation, so that crucial aspects and potentials of mmD2D are still to be disclosed.

Models and optimization. There has been much effort on studying mmD2D performance through stochastic geometry. However, little is said in terms of comprehensive analytical models and mathematical optimization. Specifically, mmD2D lacks strong models and analysis of optimization frameworks relying on: multi-hop D2D paths; D2D coexistence over multiple technologies (e.g., the mode selection problem); NOMA and interference cancellation; splitting flows over multiple routes; traffic priorities and delay constraints; and mobile optimization of resources. Such scenarios should extend the current work on optimizing throughput-based metrics (e.g., throughput-energy tradeoff) delay bounds or extremely high spatial reuse.

Interference management. Interference cancellation is a key issue of mmW. Most works consider directional spatial reuse to avoid interference and usually rely on theoretical interference models to know in which direction and when it is possible to transmit. However, commercial mmW antennas are quite imperfect (far from quasi-optimal beams). Three interesting directions appear in this regard: (i) investigating the potentials of side lobes and limited interference levels to provide high-capacity mmW links for D2D; (ii) understanding the impact of realistic beam-patterns; (iii) the use of NOMA, which has been proposed for IoT and MTC, yet not properly investigated in the context of mmD2D so far.

Experimental validation. There is a clear lack of research works that have performed experimental studies of mmD2D. The few available experimental works use simple testbeds with a few users and limited mobility. While such works show that mmD2D can maintain stable high-capacity links, further research on more complex architectures is of vital interest. As disposing of ideal experimental testbeds might be costly, we also believe that experimental simulation on well-known simulators as ns-3 is of high interest.

Support for mmD2D in 5G. There is a clear lack of attention on key 5G usage scenarios, including IoT and smart factory scenarios. According to ITU [66], 5G networks are envisioned to support applications beyond the current networks, and recommends to use mmW to comply with such requirements and develop applications for enhanced Mobile Broadband (eMBB), Ultra Reliable and Low Latency Communications (URLLC) and massive MTC (mMTC). Hence, it is crucial to discuss these applications and requirements under the development of mmD2D. Also, other important 5G aspects are network slicing mechanisms and the use of MEC within the communication infrastructure. Slices and MEC make the network smart, flexible and configurable on short time scales for a broad variety of services. However, it is not clear how these 5G components would affect the performance of—and would be affected by—mmD2D.

Artificial intelligence (AI). Related to the use of (edge) computing is the introduction of smart and self-learning algorithms within the network matrix. AI might indeed be used to orchestrate complex mmD2D scenarios, which has not been studied so far. In turn, mmD2D might offer dedicated, efficient and flexible channels for deploying distributed AI engines in the network or on top of the network, under the control of an operator or spontaneously built by end users. It is likely that future research will cover AI-related aspects in the field of D2D, mmW and mmD2D.

Security and privacy. D2D is often criticized because of exposing cellular communications to potential security and privacy attacks. mmW are instead potentially less prone to spoofing, although they are more vulnerable to geometry and obstructions. Thus, mmD2D might stimulate the design of novel kinds of attacks that combine physical aspects of mmW with protocol aspects of D2D. In general, more studies are needed before safely releasing mmD2D protocols in operational networks.

7 CONCLUSIONS

D2D and mmW have paramount importance in 5G and beyond. They are mature technologies that make networks flexible and efficient. Their integration requires the design and deployment of a number of protocols/algorithms and network control mechanisms targeting a broad variety of applications and services. Indeed, this survey shows that there is a growing interest in coordinating the use of D2D in networks that exploit mmW bands for use-cases that span from extending cellular coverage to efficiently enable smart cities. However, there are still many aspects that need to be addressed: from accurate analytical models to a thorough experimental evaluation of the feasibility and security of mmD2D proposals, to their integration with edge computing, AI and network slicing mechanisms meant to provide smart and flexible network and service management.

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Table 1
Antenna models used for mmD2D

Antenna model	Antenna Gain $G(\theta)$	Used in
Sectored [18]	$G(\theta)=\begin{cases} G_m, & \text{if } \lvert\theta\rvert \le \frac{\theta_m}{2}; \\ G_s, & \text{otherwise.} \end{cases}$	[19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30]
Cosine [31]	$G(\theta)=\begin{cases} N\cos^2\left(\frac{\pi N d}{2\lambda}\cos\theta\right), & \text{if } \lvert\frac{d}{\lambda}\cos\theta\rvert \le \frac{1}{N}; \\ 0, & \text{otherwise.} \end{cases}$	[32], [33]
Toyoda [34]	$G(\theta)=\begin{cases} G_m 10^{-c\left(\frac{2\theta}{\theta_h}\right)^2}, & \text{if } \lvert\theta\rvert \le \frac{\theta_m}{2}; \\ G_s, & \text{if } \frac{\theta_m}{2} < \lvert\theta\rvert \le \pi. \end{cases}$	[35], [36]
Gaussian [37]	$G(\theta)=\frac{2\pi}{\int_0^{\theta_h} 10^{\frac{3(\theta_m^2-x^2)}{10\theta_h^2}}dx}10^{\frac{3}{10}\max\left(\frac{\theta_m^2-4\theta^2}{\theta_h^2},0\right)}.$	[38]

Table 2
Summary of the literature proposing unplanned mmD2D

Contribution	Performance Evaluation	Analytical tools	Use-case	Target Environment	Evaluation	Achieved performance & Findings
- mmD2D channel path-loss characterization in LoS/NLoS [51].	- Ray tracing simulation.	- Curve fitting. - Statistical fitting.	- Urban mmD2D channels.		- System level simulation.	- Specific D2D path-loss mean and deviation parameters are derived.
- Stochastic analysis of wearable networks in limited areas with interferers [19].	- Stochastic geometry.	- Binomial theorem. - Multinomial expansion. - BPP. - Orbital model.	- 3D wearable networks.	- Indoor.	- Monte Carlo (MC) simulation.	- Density impacts coverage and data-rate distributions due to high interference and blockage likelihood.
- Stochastic characterization of one- and two-way SINR in ad-hoc networks with ALOHA access [20].	- Stochastic geometry	- PPP. - Binomial theorem. - Laplace transform. - Moment generating function. - FKG inequality. - Taylor expansion.	- Unplanned ad-hoc scenarios: war zones; disaster areas; D2D applications.	- Outdoor.	- MC simulation.	- High density may help to best overall network efficiency with the LoS protocol gain. - Two-way traffic can achieve 75% of the one-way capacity.
- Stochastic characterization of D2D performance metrics with meta distribution [21].	- Stochastic geometry.	- PPP. - Hypergeometric func. - Gil-Peláez theorem. - Moment matching. - Probability generating functional. - Binomial theorem.	- 5G cellular access.		- Numerical simulation.	- Denser antenna elements with narrow beams improves success probability. - Dense mmD2D networks become interference-limited.
- Stochastic analysis of clustered D2D networks with three user association strategies [42].	- Stochastic geometry.	- PPP, PCP, OPP. - Laplace transform.	- D2D networks with clusters of devices.	- Outdoor.	- MC simulation.	- Max ASE with an optimal number of D2D TXs. - 28 GHz is better carrier for low dense areas. - 38 GHz is better carrier for dense regions.
- Stochastic analysis of D-mmD2D with variable main lobe beamwidths [32], [33].	- Stochastic geometry.	- HIP, PPP, Ginibre PP. - Slivnyak's theorem. - Maximum likelihood estimation. - Two moment match. - Campbell's theorem. - Laplace transform.	- 5G cellular access.		- MC simulation.	- Accurate antenna pattern models are relevant. - Large antenna arrays are key for reliability for the 5% worst users.
- Proportional fair decentralized MAC schedule adaptive to interference and dynamics. [59].	- Protocol design	- Graph coloring.	- Heterogeneous wireless networks.		- Numerical simulation.	- Collision prob. is <30%. - <50% of void slots. - Channel efficiency >40%.
- Power optimization scheme for device association and beamwidth choice [38].	- Non-convex optimization.		- Dense 5G cellular access.		- Numerical simulation. - Contrast to Max-SINR, Random matching.	- Reduced power transmission in comparison to other schemes. - Interference mitigation and system rate enhancement.

Table 3
Summary of the literature proposing infrastructure-controlled D-mmD2D for HTC

Contribution	Proposal	Performance Evaluation	Analytical tools	Use-case	Target Environment	Evaluation	Achieved performance & Findings
- Stochastic analysis of full connectivity and reliable connections [22].		- Stochastic geometry.	- Crofron's fixed point theorem. - Combinatorial analysis	- 3GPP Prose. - IEEE 802.15 Peer-Aware Communications.	- Outdoor.	- MC simulation.	- Hybrid scheme (direct+indirect) outperforms connectivity by 35% over non-hybrid schemes.
- Stochastic analysis of SINR outages [23], [24], [25] and ASE [25].		- Stochastic geometry.	- PPP, PCP, Thomas CP. - Rician distribution. - Laplace transform. - Unconstrained optimization.	- Single-tier uplink cellular network.		- Numerical simulation.	- Intra- and inter-cluster interference lead to SINR outages with D2D density. - Higher main lobe gain and narrower beamwidth lead to unlikely SINR outages.
- Access+backhaul schedule optimization with concurrent links [56].	- D2DMAC	- MINLP Optimization	- Reformulation Linearization Technique. - Branch&Bound. - Graph edge coloring.	- 5G access networks.		- Numerical simulation. - Contrast to RPDMAC, ODMAC, FDMAC-E.	- D2DMAC near optimal at low computational cost. - Linear increase of total successful transmissions against early decay of benchmarks.
- Resource allocation scheme to improve rates, fairness and spectral efficiency [50].	- Max-sum rate assignment scheme.	- MINLP Optimization		- Underlay cellular network in the E-band.	- Outdoor	- Numerical simulation.	- Transmission power is relevant for optimal throughput performance.
- Resource allocation TDMA/SDMA scheme with side lobe interference. [35].	- SIRVC	- MINLP Optimization	- Graph vertex coloring. - Combinatorial analysis.	- Network of D2D pairs.	- Indoor.	- Numerical simulation. - Contrast to Traditional VC and TDMA.	- Side lobe interference reduces throughput per time slot. - Suitable thresholds are needed to control side lobe interference.
- Centralized access control scheme for access+blackhaul in MBB systems [28].		- MINLP Optimization	- Graph vertex multi-coloring. - DSATUR graph coloring method.	- High-dense D2D networks: video sharing and gaming.	- Indoor	- Numerical simulation. - Contrast to D3MAC.	- Better concurrent transmissions efficiency, system throughput and end-to-end packet delay than D3MAC.

Table 4
Summary of the literature proposing relay communications for mmW access networks

Contribution	Proposal	Performance Evaluation	Analytical tools	Use-case	Target Environment	Evaluation	Achieved performance & Findings
- Stochastic analysis of multi-hop relay [46].		- Stochastic geometry.	- PPP. - Extreme fluid model. - Boolean blockage.	- Multi-hop mmW relay networks.	- Indoor. - Outdoor.	- Numerical simulation.	- Near-optimal connectivity achieved by setting the relay route window to be the size of obstacles.
- Stochastic analysis of coverage in networks with fixed relays [26], [43].		- Stochastic geometry.	- PPP, MCHPP. - Von-Mises criterion. - Gumbel distribution. - Laplace transform.	- Relay-aided 5G cellular networks.	- Outdoor.	- MC simulation.	- Relay improves SNR 5 dB. - Relays increase coverage prob. and capacity. - No need for lots of relays.
- Stochastic analysis of power consumption and energy efficiency [27].		- Stochastic geometry.	- PPP. - Laplace transform. - Moment generating function.	- 5G downlink access.		- Numerical simulation.	- Better energy efficiency than μWave networks. - Low dense BSs get higher energy efficiency in LoS. - Trade-off between ASE and energy efficiency.
- Cache schedule for mobility-aware TX with multi-hop relaying [63].	- MHRC	- Stochastic MINLP Optimization.	- Dijkstra algorithm. - Graph theory.	- Caching in fog computing edge networks.		- Numerical simulation. - Contrast to Unicast, Cachuni.	- More than 1× higher expected cached data compared to benchmarks.
- Stochastic analysis of downlink mmW coverage with two-hop μWave D2D relay [47], [48].		- Stochastic geometry.	- PPP.	- Downlink 5G cellular networks.	- Indoor. - Outdoor.	- Numerical simulation.	- Relay is better regardless BS density and obstacles. - Optimal BS densities identified. - Obstacles are key to reduce interference.
- Protocol to optimize sum-quality of video streams with multi-hop routing [29], [44].	- DQC.	- MINLP Optimization.	- Quality functions. - S-curve functions.	- Video streaming.		- Numerical simulation. - Contrast to MmF.	- DQC achieves 33% better performance than MmF benchmark.
- Relay choice optimization for two-hop TX paths [49].		- Unconstrained stochastic optimization.	- Threshold stopping rule. - Newton's method.	- 5G cellular access.		- Numerical simulation. - Contrast to myopic, fixed probing.	- Optimal balance between rate gain and better relay search.
- Full-duplex relay optimization to balance power and system rate service [55].		- Multi-objective combinatorial optimization.	- Weighted sum and Hungarian methods. - Pareto optimality. - Bipartite matching. - Interior point.	- Relay-aided 5G access networks.		- MC simulation. - Contrast to ARS, DRS.	- Improved system throughput and transmit power compared to literature.
- Integration of mmW into 3GPP ProSe [57].		- Protocol and architecture implementation.		- 5G access picocells.		- Testbed for experimental validation.	- Stable throughput despite blockages. - mmD2D implementation is feasible.