Performance Analysis for Millimeter Wave Device-to-Device Communication Networks: A Review

Filbert Onkundi Ombongi, Absaloms Heywood Ouma, Philip Langat Kibet

Abstract—The mobile broadband access is expanding rapidly in the recent times due to advancement in technical specifications of the Fourth Generation (4G) mobile cellular system. The resulting higher traffic demand which continues to increase as more devices are coming up to provide broadband services might not be supported by the current 4G network at the required user experience and quality. These services need a wide range of requirements that can be offered only by the Fifth Generation (5G) cellular networks. The millimeter-wave (mmwave) Device-to-Device (D2D) communication has emerged as an enabling technology to offer high capacity network connectivity, traffic offloading and high energy efficiency. The mmwave D2D communication can support bandwidth-intensive applications due the large bandwidth available in the mmwave band. However, at the mmwave frequency range the transmitted signal suffers from high path and blockage losses. Therefore, this calls for solution approaches which can mitigate these losses and increase performance of mmwave D2D communication with reduced complexity in terms of achievable rate, energy consumption, energy efficiency and sum rate. The paper gives an overview of the studies that have been done in the area of mmwave D2D communication in terms of beamforming, caching, cooperative communication, scheduling schemesand their solution approaches. In addition, it discusses the challenges of the proposed solutions and gives open research directions for further study.

Keywords**:** 5G, Beamforming, Caching, D2D, mmWave, Relaying, Scheduling

I. INTRODUCTION

The Device-to-Device communication allows two users who are in close proximity to exchange information over a direct link without going through the base station. This can reduce the traffic load on the base stations which improves coverage for the cell-edge users. Since the microwave spectrum (sub-6GHz) is almost getting depleted, the mmwave communication has emerged as a key enabler for the future 5G wireless technology. The large amount of bandwidth in the mmwave band allows the implementation of bandwidth-intensive applications such as video streaming. In addition, the radio energy of the signal in the mmwave frequency can be concentrated with the help of directional antennas in a given direction which can reduce interference between different mmwave links. The main shortcoming in the mmwave communication, is the high path and blockage losses which makes it a short range communication technology. In addition, the short wavelength of the transmission signals at mmwave frequencies makes them to be easily shadowed and blocked by objects such as concrete buildings, terrains, trees, human body and vehicles [1, 2]. The channel measurements that have been done using directional antennas for mmwave communication in [3, 4] have shown that blockage causes significant differences between the LOS and NLOS path loss characteristics due to negligible diffraction effects, small angle of spread and a few scattering clusters. The D2D communication can be integrated with mmwave communication to offer proximity based services and traffic offloading from the current 4G networks. The D2D communication can be implemented in the mmwave band to support multi-Gbps wireless requirements due to large bandwidth to improve network throughput. The benefits associated with D2D communication include; traffic offloading, maximization of throughput, energy efficiency and spectrum efficiency. This paper gives an overview of the studies that have been carried out in mmwave D2D communication by looking at the solution approaches, challenges and open research issues for further study. The performance analysis of mmwave D2D communication is discussed based on beamforming, caching, cooperative communication or relaying, scheduling together with their solution approaches

II. INTRODUCTION TO D2D COMMUNICATION

The D2D communication technology enables two D2D users to exchange information over a direct link by sharing radio resource with cellular users in the microwave band or in the unlicensed mmwave band. The D2D communication can offload traffic from the base stations, reduce energy consumption and improve coverage especially for the cell edge users. The D2D communication can be implemented either for inband communication (in sub-6GHz band) or outband communication (in ISM band and mmwave band).The frequency spectrum allocations for inband and outband D2D communication is as shown in Figure 1.

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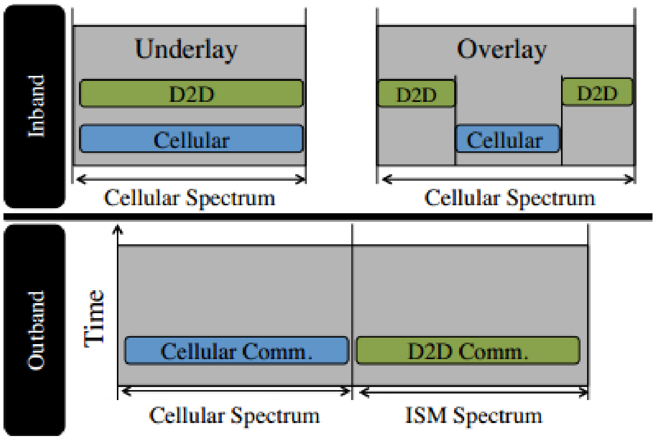

Figure 1: D2D Communication scenarios[5]

A. *In-band D2D Communication*

In this type of communication, the cellular users (CUs) and the D2D users utilize the same licensed spectrum which is referred to as the sub-6GHz band. The inband D2D communication can further be subdivided into underlay and overlay.

In underlay inband, the licensed spectrum is used by the D2D users to share resources with the cellular users where the D2D users opportunistically access the resources that have been allocated to the cellular users which in turn improves the spectrum efficiency (SE). The underlay D2D communication is as shown in Figure 2.The resource blocks (RBs) are assigned to the cellular users which are then reused by the D2D users to offer proximity based services[6]. The underlay inband D2D communication can enhance the performance of the cellular users in terms of spectrum efficiency. However, this type of communication increases the interference between the cellular users and the D2D users which needs the development of complex resource allocation schemes which leads to high computation overhead at the base station.

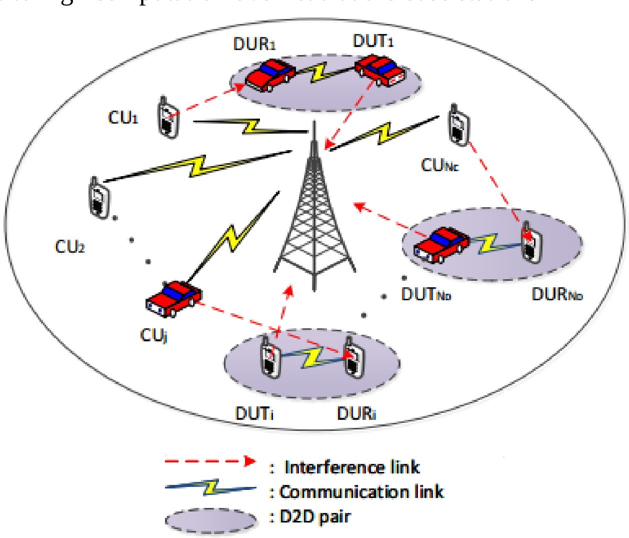

Fig. 2: Underlay inband D2D Communication [7]

In overlay inband D2D communication, a fraction of the licensed spectrum is dedicated for D2D communication. This ensures that the interference problem experienced in underlay inband is mitigated as the cellular and D2D communication occupy different bands. The overlay inband communication is as shown in Figure 3 where the solid lines denote D2D communication and the dotted line is used for control information exchange between the base station and the D2D user device. This type has the merit of enhancing scheduling and power control for D2D direct communication and it can provide an enhanced spectrum efficiency and signal strength for relay-assisted D2D networks[8]. The main challenge of the overlay inband communication is the inefficiency in spectrum utilization dedicated to D2D users which leads to poor resource utilization and a reduced system throughput.

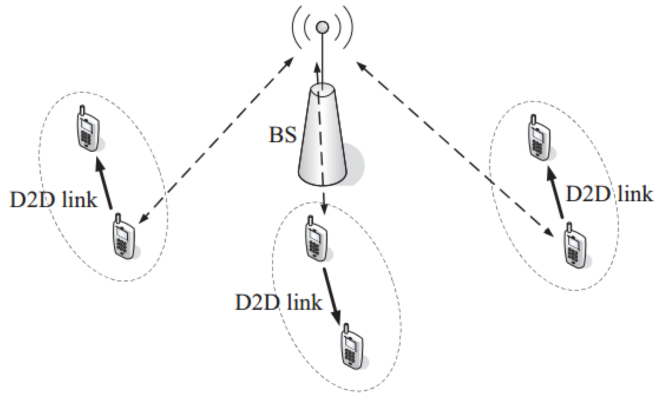

Fig. 3: Overlay inband D2D Communication [9]

B. *Out-Band D2D Communication*

In outband D2D communication, the D2D users utilizes the unlicensed spectrum i.e. the (Industrial, Scientific and Medical (ISM) band and millimeter wave (mmwave) band in a network scenario shown in Figure 4.

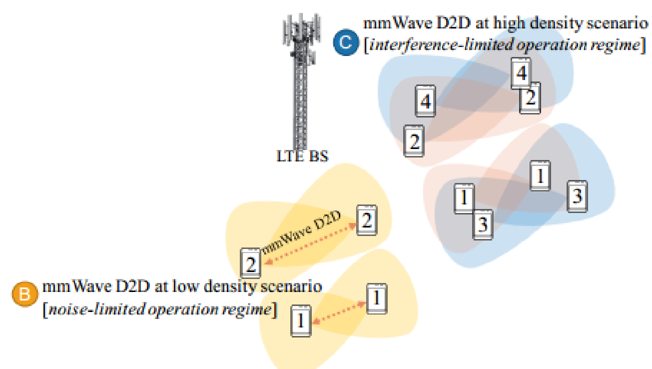

Fig. 4: mmwave D2D communication[10]

III. SOLUTION APPROACHES IN MMWAVE D2D COMMUNICATION

A. *Beamforming*

The mmwave D2D communication can easily be implemented with the support of directional beamforming. The use of directional antennas and beamforming scheme offers a way of concentrating the mmwave signals in a desired direction to minimize the interference among the various mmwave links. Beamforming can be applied in mmwave D2D communication to reduce interference among D2D user equipment and the base stations or cellular users' equipment to increase spectrum efficiency. In addition, the mmwave communication can be combined with D2D communication for traffic offloading and extension of coverage for cell-edge user equipment. However, in mmwave D2D communication there will be blockage due to the narrow beamwidth of mmwave signals and relatively low antenna height of the D2D users devices compared to the base station. This makes D2D device discovery and beam alignment a challenging task.

Some studies have tried to develop beamforming solutions for beam alignment and interference reduction in mmwave D2D communication. In [11], a hybrid communication model in a heterogeneous multicell system was developed that can switch between the mmwave line-of-sight (LOS) transmission at 28GHz and the microwave transmission mode in case there is blockage of the mmwave signals with the capability of exchanging signaling information for efficient beam alignment. The scheme was implemented by developing protocols between the base stations and the D2D users. The coverage probability and area spectral efficiency were evaluated using stochastic geometry for the hybrid mode closed form expressions. The results indicated some improvement in performance compared to microwave and millimeter wave communication done separately. However, this study did not consider relaying as a technique which can solve the blockage issue in mmwave D2D communication instead of switching back to microwave band where the interference scenario between cellular users and D2D users is complex.

In[12], the mmWave wearable communications network performance was characterized by determining the coverage and rate in a finite region such as inside a train. The study considered the effect of antenna parameters such as beamwidth and antenna array gain on the coverage and spectral efficiency of the system by modelling people as blockages of mmwave signals instead of buildings. The interferer positions were considered as fixed and random to develop closed form expressions for spatially averaged coverage probability for mmwave wearable communications network for users located in the center of a dense crowd and are finite. It was shown that the interference and blockage probability of the interfering signals increases with increase of the crowd density for a lower rate of decreasing SINR coverage probability for this higher density. In addition, it was noted that the antenna main lobe directivity and array gain are critical for obtaining a giga-bits-per second performance for the mmwave wearable networks.

The sectorial model of mmwave communications in clustered D2D networks was analyzed by considering beamforming with the locations of D2D transceivers modelled as Poisson cluster process in [13] using stochastic geometry. The study considered three models which include; uniformly distributed, nearest and closest LOS D2D transmitter models with each cluster having multiple antennas and an active D2D user to communicate with another D2D user in close proximity. It was shown that the intra-cluster interference with LOS links affects the coverage probability and an optimal number of D2D users in each cluster can be found to maximize the area spectral efficiency. The closest LOS model outperformed the uniformly distributed and the nearest D2D user transmitter models despite the closest LOS model showing an additional system overhead. The comparison of carrier frequencies showed that the 28GHz frequency is suitable for a low SINR region whereas the 38GHz is for high SINR region. However, this study did not consider the interference of the LOS links from the D2D users in the neighboring clusters which accounts for inter-cluster LOS interference. Furthermore, the interference between D2D user transmitters within a cluster was not considered for the LOS and non-line-of-sight (NLOS) links cases.

The beam alignment problem for wearable D2D communications was optimized through formulation of noncooperative and quantum game models in[14]. The noncooperative game model was used for wearable devices that were acting as transmitters to select their directions autonomously to maximize user data rate for the D2D receivers. The quantum game model was applied in D2D communications at the mmwave band to improve the beamforming and assist the D2D devices utilize new quantum directions during the beam alignment process to further improve their achievable data rate. The games were solved by an algorithm based on best response dynamics to enable the transmitters determine their Nash equilibrium strategies in a distributed way. The performance results indicated that there was a 75% improvement compared to the uniform beam alignment scheme.

The framework to perform performance evaluation of D2D-enabled mmwave cellular communication networks was developed in [15]. The SINR outage probabilities for the cellular users and D2D users were derived by applying stochastic geometry. The study considered directional beamforming with different path loss for expressions for LOS and NLOS links for outage analysis. In addition, the effect of beam alignment errors on the outage probability was studied for a single tier uplink network. It was shown that the outage probability worsens for the cellular and the D2D links when the alignment error standard deviation was increased. Though the interference from the interfering nodes was unaltered, its effect on the system was found to increase with the increase of the beam alignment error of the main link. This showed the need for proper beam alignment to achieve an improved performance. However, the correlation between the locations of potential D2D users, beam steering errors and the area spectral efficiency was not taken into consideration. This study was extended in [16] by incorporating clustering of D2D users with the location of cellular users modeled by Poisson point process and those of the D2D users modeled by Poisson cluster process. The area spectral efficiency for the whole network was determined for underlay and overlay modes of communication. The results showed that an optimal value exists for the average number of simultaneously active D2D links that maximizes the area spectral efficiency which was found to be independent of the cluster center density. The study can be extended further by incorporating different Poisson point cluster processes and the impact of using various types of mode selection schemes.

The success probability (SINR) distribution for a general and realistic case where devices are equipped with heterogeneous antenna arrays for concurrent transmission of beam of varying width was considered at a typical receiver for D2D communication in the mmwave band in [17]. The interactions between various beams of different widths and their sensitivities to the antenna model developed were considered. The cosine antenna pattern was applied in the determination of the success probability expressions together with their tight bounds for exact results simplification. The results indicated that large antenna arrays can improve the performance in terms of success probability which not only improved the required signal but also minimized the interference. The study can be extended to incorporate scheduling and resource allocation mechanisms for enhancing the performance of D2D communication in mmwave band in terms of energy efficiency and achievable D2D data rate.

An analogue beam splitting approach was developed in [18] for attaining a better coverage and throughput trade-off in mmwave D2D multicast communication network. The objective was to maximize the capacity of mmwave D2D multicast channel by considering antenna element grouping and adaptive phase shifting to account for inter-beam interference. The analogue beam splitting approach showed that the effect of inter-beam interference was very small when the receivers were randomly distributed on a circle that was centered on the transmitter with a uniform distribution. In addition, the proposed approach showed better results in terms of coverage and throughput compared to the time division duplex beam steering approach. The study can be extended to incorporate the effect of dense number of users of the performance in terms of energy efficiency.

B. Caching

The implementation of caching in D2D communications can offer a suitable method of delivering content by caching the popular content at the helper nodes or D2D user devices. The concept of caching can reduce data traffic in the backhaul links, improve user experience when D2D-enabled caching is used in video streaming services [19, 20]. The device caching offers more benefits when compared to small-cell caching. For example, in device caching the average cache capacity increases when the number of connected devices increases which in turn increases also the caching efficiency. In addition, the device caching can enhance D2D communications either directly or through the BS which can result in a reduction of the BS load. There are a few studies which have tried to implement caching on the D2D devices for mmwave communication networks. In[21], a D2D caching policy was proposed that supported popular content exchange for mmwave D2D communication network at 28GHz. The policy allowed splitting of the cacheable content into two groups which were randomly distributed to the user devices as a guarantee of D2D connections. The network topology was modelled by applying stochastic geometry and offloading gain was derived to obtain the caching policy and content retrieval delay distribution for D2D communication in the half or full duplex modes. The proposed device-aware caching policy showed a higher offloading gain and lower content retrieval delay compared to the most popular policy. It was also shown that the full duplex mode had a better performance in terms of delay than the half duplex mode since the probability of bidirectional content exchange was low for full duplex mode. This study can be extended to incorporate other performance metrics such as cache hit ratio, power consumption and energy efficiency.

The D2D caching was also studied in [22] where mobility pattern of the user was taken into consideration. A mobility-aware caching placement scheme was proposed to maximize the offloading ratio. Due to the complexity of the nonlinear programming problem formulated, a dynamic programming algorithm was applied with much lower complexity than the exhaustive search technique. The results showed that the mobile users with a very low or very high speed cached many popular files whereas for moderate speed there was less caching of popular files for duplication avoidance. The study can be extended by exploring the effect of caching at both the base station and the D2D devices using distributed algorithms for densified networks.

C. Cooperative Relaying

Millimeter-wave communication involves the use of directional antennas which presents a challenging issue in network dynamics leading to complex system design. For example, the mmwave signal can be blocked by humans or any other obstacle. Therefore, different relaying techniques can be applied to solve the problem of signal blockage in mmwave communication and improve the coverage. Some studies have tried to develop relaying and beamforming solutions to curb this problem either jointly or separate analysis. In [23], a light weight relaying mechanism based on the 3GPP standard that can opportunistically discover a relay in mmwave communication was developed. The algorithm that can compute the optimal joint and disjoin beamwidth optimization for opportunistic relay discovery in a dense and dynamic network environment was considered. The results which were validated by an experimental test bed operating at 60GHz showed that suitable choice of the beamwidth to perform relay discovery and communication can maximize the probability of finding a relay and reduce complexity of relay discovery. However, the study did not consider a dense indoor environment without user mobility at 60GHz or other mmwave carrier frequencies.

Channel inversion to adapt transmission power relative to the link distance, path loss exponent and signal to noise ration to analyze SINR and energy efficiency (EE) of an outband D2D links equipped with directional mmwave antennaswas studied in [24] at 28GHz.In addition, the sectored antenna models using analog beamforming were considered for uniform linear antenna arrays (ULA) which were probabilistically incorporated in the system model to determine spectrum efficiency and EE for different types of ULA elements (i.e. 1, 3, 5 elements) using their relative radiation pattern. The results indicated that the EE can be greatly enhanced by applying multiple element directional antennas which was found to increase by a factor of 23 in a dense urban network with antenna elements of 5 compared to omnidirectional antennas. However, this study did not consider how the linear array directional antenna parameters under consideration affects the outband D2D user data rate. In addition, there is no consideration of the outband D2D transmit power or energy consumption optimization and their relationship with the parameters that were considered in this study.

The coverage probability model was developed by applying stochastic geometry for downlink D2D two-hop relay-assisted mmwave cellular networks with dominant interferer analysis taken into account for both beamforming gains and blockages in [25] for urban macro and indoor office environments. The assumption was D2D communication reuses the uplink mmwave spectrum of the cellular network. The scenario under consideration ensured that the D2D communication can switch between direct D2D and D2D relaying modes with the D2D relaying mode being selected whenever there is an outage on the direct D2D link. The study was extended in [26] by considering the spectral efficiency and coverage probability in the downlink D2D communication and impact of D2D transmissions on the cellular uplink communication. The coverage probability was derived for LOS and NLOS propagation scenarios. The results showed that the two-hop D2D relaying improved the downlink coverage probability and spectral efficiency. In addition, as the density of interferers becomes large, there is an improved coverage since the blockages are removed from the NLOS interferers by the D2D relays. These studies should have considered the energy efficiency and the attainable data rate for the achieved coverage probability.

A hybrid network scenario consisting of two-hop downlink D2D relaying was proposed in [27] by integrating the mmwave and the sub-6GHz band as a way of avoiding blockage and coverage extension in an urban outdoor scenarios with different site deployment densities. The relay and beam selection was combined with a coordinated resource allocation mechanism over the two subcarriers to improve user data rates for the cell edge users and ensuring consistent user experience. The sub-6GHz band was responsible for the network control and communication reliability while the mmwave communication provided high throughput improvement. The multi-objective problem of relay selection, resource allocation and interference coordination was formulated and solved by graph theory. The graph coloring addressed the channel allocation and interference coordination problems by modeling the interaction of the neighboring links as an interference graph which ensured relay and beam selection, resource allocation and interference coordination were done in a simplified manner. The results showed some consistent user experience with high throughput can be obtained. However, a significant percentage of users missed two-hop mmwave connectivity when the inter-site distance is above 400m. The other challenge was difficulty in finding the proper incentive for UEs for them to be used as relays.The results showed some consistent user experience with high throughput can be obtained. However, a significant percentage of users missed two-hop mmwave connectivity when the inter-site distance is above 400m. The other challenge was difficulty in finding the proper incentive for UEs for them to be used as relays. The study can also be extended to consider a multicell scenario for energy efficiency improvement in mmwave D2D networks where relaying is applied.

The work of [28] proposed a relay assisted D2D communications in mmwave 5G network to address limited battery capacity of mobile devices and a high data rate requirement in emerging applications with an objective of maximizing system throughput and minimizing the total transmit power. A multi-objective combinatorial optimization problem was formulated for joint relay selection and power allocation with D2D minimum data rate and total transmit power of D2D devices and relays constraints. The optimization problem was solved by a one-to-one matching weighted bipartite graph construction to provide tractable solutions for the combinatorial resource allocation problem. The results of the proposed centralized relay selection and power allocation algorithm showed some improvement in performance compared to the augmented random search (ARS) and distributed relay selection algorithms.

D. Scheduling

The mobile communications has seen an exponential growth on the number of smartphones, data traffic from the mobile applications such as multimedia file sharing through the social networks and video streaming. This has brought the challenge of meeting the user requirements in the provision of the mobile services. The D2D communication can be used to mitigate some of these challenges for an improved network capacity, information transfer latency user throughput and energy efficiency. Therefore, there is need to develop access control of scheduling algorithms that can help to meet the user requirements in mmwave D2D communication networks. The application of scheduling algorithms for mmwave D2D networks can help in allocating limited channel resources to multiple number of users (e.g. densified networks) by taking into consideration the system performance requirements such as packet delay for delay sensitive applications. The scheduling of resources can also be used for D2D communication to perform mode selection channel allocation and power control to reduce latency, energy consumption and maximize energy efficiency and throughput[29]. Some studies have been carried out on scheduling in mmwave communication to enhance link connectivity ratio, supported traffic flows, D2D ratio and energy ratio, energy consumed and packet delay.

A study in [30]proposed a new centralized radio access control and efficient multiobjective scheduling algorithm based on greedy graph vertex coloring technique to maximize resource allocation efficiency for multiple simultaneous transmissions in mmwave network scenario with high user density for a wide indoor environment scenario. Furthermore, it investigated the symbiosis between D2D communications, 60GHz unlicensed mmwave band transmissions and adaptive beamforming. The scheduling algorithm took into consideration the concept of concurrent transmissions, source rate and delay requirement to improve the transmission efficiency, maximize throughput and minimize end-to-end delay with a low computational load. The results showed that the proposed scheduling algorithm provided a better performance compared to the reference scheme in [31] in terms of throughput and end-to-end delay. However, the proposed centralized scheduling scheme did not consider the energy efficiency performance metric for the studied D2D communication in a wide indoor network scenario. The energy efficiency would have ensured that the battery life was improved. The study will have also considered the energy consumed in the transmission of data packets from the transmitter to the receiver.

In [32], a mmwave and 4G system architecture with a Time Division Multiple Access (TDMA) based Medium Access Control (MAC) structure was developed for 5G networks. Then, an effective resource sharing scheme was proposed to allow non-interfering D2D links to operate concurrently for sharing of network resources among local and global D2D communications for improvement of network capacity. The directional interference in mmwave 5G cellular networks was considered to enable multiple D2D communications. In addition, the resource sharing scheme considered was determined by the base station by considering the mutual interference between a device and the base station and local D2D communication. However, this study did not consider the energy consumed for transferring data from the source to destination for the resource sharing scheme developed. The study can also be extended to incorporate other 5G performance parameters such as average transmission delay and throughput per time slot for the TDMA scheme.

An energy-efficient multicast scheduling scheme which integrated D2D communications and concurrent transmissions was proposed [33]. The scheduling scheme comprised of the D2D path planning algorithm which identified the D2D transmission paths and a concurrent scheduling algorithm that allocated the links to the established D2D paths with diverse pairings whereas the power control algorithm allocates power to the links to reduce the energy consumed for maximum throughput. The results of the energy efficient multicast scheduling scheme showed an improved performance in terms of energy consumption compared to ordinary directional MAC, random path directional MAC and extended frame-based scheduling directional MAC protocols.

A similar study was done in [31]by proposing a joint transmission scheduling scheme denoted as D2DMAC for radio access and backhaul for mmwave small cells for path selection and enabling of D2D communication. It also incorporated concurrent transmission scheduling for spatial reuse exploitation in the mmwave network. The joint scheduling problem was formulated as a mixed integer linear program (MILP)for minimization of time slots for traffic data demand. The results showed the improvement in performance in terms of throughput and delay compared to ordinary directional MAC, random path directional MAC and extended frame-based scheduling directional MAC protocols. However, this study did not incorporate energy consumption to analyze fully its effectiveness in terms of energy efficiency. The study was extended by modifying the scheduling scheme to come up with a directional D2D MAC (D3MAC) to perform path selection and enable D2D communication in [34]. The scheduling scheme was formulated as a mixed integer nonlinear programming (MINLP) problem to minimize the number of time slots which can accommodate the data traffic demand. The impact of user behavior was also considered by factoring in the device mobility and distribution, traffic demand and traffic mode for static and dynamic network environments. The proposed scheduling method achieved near-optimal performance in terms of throughput and delay compared to other protocols. In addition, it was shown that there was some performance improvement for low speed compared to static case and a poor performance realized for high device mobility due to frequent variations of D2D pairings. The study can be extended by developing a distributed scheduling scheme that incorporates blockage channel modelling and fading channels to analyze their effect on performance for the proposed protocols.

In [10], a centralized MAC scheduling scheme that adjusts according to the interference conditions and network dynamics to support the noise limited and interference limited scenario for mmwave D2D communications. The scheme was found to converge to a collision free operation in a finite time no matter the interference conditions or the network densities. The results showed that the algorithm achieved a proportional fair TDMA schedule with a better performance in terms of number of schedules, collision probability, number of unused slots and channel efficiency. However, the study can be extended to consider transmission delay, energy consumption and energy efficiency for the mmwave D2D communication network.

The time and space division for scheduling was introduced in [35] for mmwave D2D communication networks that takes into account the effect of side lobe interference. The study formulated a time-slot allocation problem for network throughput maximization per time slot. The algorithm based on vertex coloring resource allocation was used to redefine concurrent transmission conditions and power decision level for side lobe interference reduction. The results showed that the proposed scheduling scheme achieved better performance which had a 12.5% improvement compared to TDMA and traditional vertex coloring algorithm. In addition, it performed well when the number of flows and beamwidth increased. The study can be extended to incorporate transmission delay and then compared to the developed protocols in [31, 33, 34]

IV. EXTENT OF MMWAVE D2D STUDIES

The extent to which the mmwave D2D studies have been carried out based on mmwave D2D enabling technologies such as beamforming, caching, cooperative relaying and scheduling can be summarized in Figure 5.The summary shows that very few studies have been done in the area of D2D caching. This area has the potential of enabling cloud radio access networks (CRANs) and software defined networking which can easily integrate the social features.

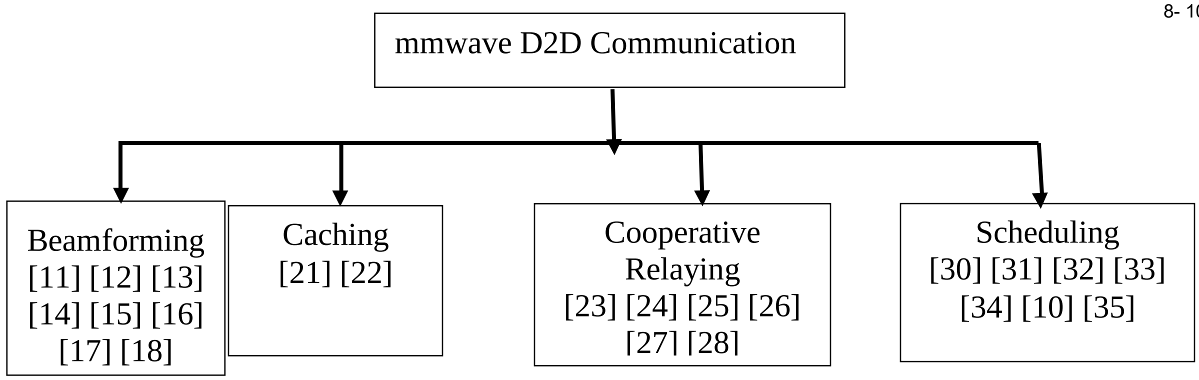

Fig. 5: Summary on extent of studies on mwave D2D enabling technologies

V. CHALLENGES IN MMWAVE D2D COMMUNICATION

A. *Blockage Modelling*

The millimeter wave communication has a weak diffraction ability and suffers from severe penetration loss due to short wavelengths. The mmwave communication is characterized with narrow beamwidth and a relatively low antenna height when compared with that of the base station. This makes communication in the mmwave band highly prone to blockages which make mmwave transmission to rely majorly of the line of sight (LOS) paths only resulting in dead zones.

In addition, the mmwave communication is hindered by two challenges namely deafness and single link scheduling [36]. The deafness problem is a situation where the antenna beams of the transmitter and receiver are not properly aligned which makes the beam searching operation time consuming. The single link scheduling allows the mmwave standards to schedule a link for every time slot to hinder the mmwave communication from achieving its full potential by allowing multiple concurrent transmission. Therefore, there is need to develop efficient hybrid scheduling and resource allocation mechanisms that incorporates beamwidth selection and allows multiple concurrent transmissions in mmwave D2D communication.

B. *Densification and Heterogeneous Networks*

The 5G mmwave D2D communication scenario consists of high device density, densified networks co-sharing resources in the mmwave band. In this scenario, the main challenge will be the complex interference which needs a concurrent transmission of maximum flows with minimal interference to improve network throughput per time slot. In addition, some of the developed scheduling algorithms for mmwave networks which can enable D2D communication have shown some weaknesses. The scheduling mechanism developed in [31] can deliver all packets for a frametime whether the delivery is through access points or D2D direct links. However, when one or more transmission paths are available, the packet delivery for a single frame time can increase the frame length by a high margin which makes the next delivery cycle taking several milliseconds. This results in a high delay for new transmission requests which might be too long for delay-sensitive applications. In addition, this scheme cannot exploit the concurrent transmission benefits. Therefore, new scheduling mechanisms should be developed that allows concurrent transmissions with minimal computation load time and incorporates non-line-of-sight transmission and retransmissions. This can also consider the impact of multipath fading on heterogeneous network performance

C. *User Mobility in D2D Cache Networks*

This is the main issue in mobile edge networks which has a great impact on caching and computation offloading decisions. The frequent mobility of D2D users will result in frequent hand overs among the D2D edge users. This requires mobility management schemes which can perform both horizontal and vertical mobility which can allow users to reach the edge servers seamlessly.

VI. FUTURE RESEARCH DIRECTIONS

A. *mmWave Channel Modelling*

There is need to develop efficient channel modelling that covers a wide range of frequencies upto the Terahertz spectrum and the visible light spectrum. This can be done by considering underground, under water and even human body network scenarios[37]. The study can be extended to develop visible light communication (VLC) model applicable to mmwave D2D communication since it has minimal interference, high energy efficient and highly secure compared to other wireless communication technologies. In addition, channel modelling can be integrated with big data theories such as data mining and machine learning to simplify the modelling process and increase the modelling accuracy.

B. *Scheduling and Resource Allocation*

Many existing studies have considered scheduling and resource allocation schemes for device-to-device communications in single cell network scenario in a static environment. However, the scheduling and resource allocation scheme is much complicated for a multicell network scenario due to the requirement of proper coordination among neighboring BSs for better channel feedback, mobility management and hand over functions. Therefore, this multicell network scenario should be considered as it has the merit of reducing energy consumption especially for the cell-edge users. The study can also be extended to incorporate intelligent machine learning resource management tools to perform network functions such as cell association, radio access technology (RAT), spectrum allocation and management, power control and adaptive beamforming. This will be beneficial for the future 5G wireless networks especially those that will need real time and low latency operation. Furthermore, there is need to develop hybrid scheduling mechanism which is integrated with TDMA/FDMA/SDMA frame structure. The directional antenna beams can be designed in a manner that there is side lobe noise removal when resource allocation algorithms are applied.

C. mmWaveD2D Caching

A further study on caching can involves the integration of caching at the edge with D2D communication and applying social interactions between the users in the cell to further push caching from the edge to the users. In addition, the application of computing and storage resources on large number of smart devices can be a beneficial area to be considered. Computation offloading and content sharing problems that occur through the D2D communication networks can also be considered in the future mmwave D2D communication network.

Furthermore, there is need to develop online caching strategies form mmwave D2D networks that takes in to account the effect of user mobility in video streaming applications. There is also need to develop resource allocation and rate adaptation schemes for better user selection during the content delivery phase that is applicable to mmwave device-to-device communication networks.

There should also be a caching scheme that divides the cacheable content into a number of groups and then consider their impact on the network performance. It should also incorporate machine learning techniques in the solution of device caching problems such as the one used applied in [38] for 5G networks.

The caching policies can also be developed in a way that pricing and resource allocation techniques are integrated for mmwave D2D video caching communication systems from the perspective of game theory for device caching instead of edge caching proposed in [39]. The resource allocation in mmwave D2D video caching system ca also be extended to incorporate social networking.

Another interesting research direction for D2D caching policies is the incorporation of socially-aware features to further improve the quality of experience in mmwave D2D networks. In addition, the network security issues for D2D caching policies form the network operator perspective should be considered.

D. D2D Relaying

The device-to device communication can be combined with relays to offer the benefits of spatial diversity of the D2D devices, multiuser shadow diversity and extend the coverage range of mmwave communication where there are signal blockages. The mode and relay selection mechanisms needs to be optimized to have an intelligent resource allocation coordination strategy between the licensed and unlicensed band. In addition, the D2D relay assisted communications should be investigated further on the uplink of mmwave cellular networks. This will be necessary as since the D2D links that reuse the uplink spectrum makes the interference for the cellular and D2D links to have correlation between them. This correlation in blockages between the cellular and D2D links in mmwave D2D communication should be taken into consideration for spectrum efficiency maximization. The impact of the underlay mmwave D2D relaying on the performance of the cellular users' uplink communication should be studied.

VII. CONCLUSION

The implementation of D2D communication in the millimeter-wave and will offer many benefits compared to the current 4G cellular networks. The paper has given an overview of the solution approaches and the challenges related to the implementation of mmwave D2D communications based on beamforming, caching, scheduling and cooperative communication (relaying). It has also been shown how these technologies can be integrated to improve the performance of D2D communication networks. In this paper, it has been demonstrated to what extend the D2D communication has been studied by utilizing this technologies to improve performance. The comparison has shown that D2D caching is the area that has been least studied. Therefore, this area needs to be exploited as it is very crucial in the realization of software defined or cloud radio access networks which are D2D-enabled with incorporation of the social features and some mobility. The paper has concluded by giving the areas to be explored further to realize the full potential of D2D communication networks operating in the mmwave band.

REFERENCES

[1] J. G. Andrews, T. Bai, M. N. Kulkarni, A. Alkhateeb, A. K. Gupta and R. W. Heath, "Modelling and Analyzing Millimeter Wave Cellular Systems," *IEEE Transactions on Communications*, vol. 65, pp. 403-430, 2017.

[2] Y. Niu, Y. Liu, D. Jin, L. Su and A. V. Vasilakos, "A Survey of Millimeter Wave Communications for 5G: Opportunities and Challenges," *Wireless Networks*, vol. 21, pp. 2657-2676, 2015.

[3] T. S. Rapapport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi and F. Gutierrez, "Millimeter Wave Mobile Communications for 5G: It will Work," *IEEE Access*, vol. 1, pp. 335-349, 2013.

[4] T. S. Rappaport, F. Gutierrez, E. Ben-Dor, J. N. Murdock, Y. Qiao and J. I. Tamir, "Broadband Millimeter Wave Propagation Measurements and Models using Adaptive Antennas for Outdoor Urban Cellular Communications," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 4, pp. 1850-1859, 2013.

[5] A. Asadi, Q. Wang and V. Mancuso, "A Survey on Device-to-Device Communication in Cellular Networks," *IEEE Communications Surveys and Tutorials*, vol. 16, no. 4, pp. 1801-1809, 2014.

[6] C. Vitale, V. Mancuso and G. Rizzo, "Modelling D2D Communications in Cellular Access Networks via Coupled Processors," in *7th International Conference on Communication Systems and Networks*, Bengaluru, 2015.

[7] X. Li, R. Shankaran, M. Orgun, G. Fang and Y. Xu, "Resource Allocation for Underlay D2D Communication with Proportional Fairness," *IEEE Transactions on*

Vehicular Technology, vol. 67, no. 7, pp. 6244-6258, 2018.

[8] B. Zhou, H. Hu, S. Q. Huang and H. H. Chen, "Inter-Cluster Device-to-Device Relay Algorithm with Optimal Resource Utilization," *IEEE Transactions on Vehicular Technology,* vol. 62, no. 5, pp. 2315-2326, 2013.

[9] J. Lyu, Y. H. Chew and W. C. Wong, "A Stackelberg Game Model for Overlay D2D Transmission with Heterogeneous Rate Requirements," *IEEE Transactions for Vehicular Technology,* vol. 65, no. 10, pp. 8461-8475, 2016.

[10] G. H. Sim and C. Cano, "Proportional Fair Decentralized Scheduling for mmWave D2D Communications," in *IEEE 19th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, Chania, Greece, 2018.

[11] F. Wang, H. Wang, H. Feng and X. Xu, "A Hybrid Communication Model of Millimeter Wave and Microwave in D2D Network," in *IEEE 83rd Vehicular Technology Conference* , Nanjing, China, 2016.

[12] K. Venugoal, M. C. Valenti and R. W. Heath, "Device-to-Device Millimeter Wave Topologies: Interference, Coverarge, Rate and Finite Topologies," *IEEE Transactions on Wireless Communications,* vol. 15, no. 9, pp. 6175-6188, 2016.

[13] W. Yi, Y. Liu and A. Nalanathan, "Modeling and Analysis of D2D Millimeter-Wave Networks with Poisson Cluster Processes," *IEEE Transactions on Communications,* vol. 65, no. 12, pp. 5574-5588, 2017.

[14] Q. Zhang, W. Saad, M. Bennis and M. Debbah, "Quantum Game Theory for Beam Alignment in Millimeter Wave Device-to-Device Communications," in *IEEE Global Communications Conference*, Washington, 2016.

[15] E. Turgut and M. C. Gursoy, "Uplink Performance Analysis in D2D-enabled mmwave Cellular Networks," in *86th IEEE Vehicular technology Conference (VTC-Fall)*, Toronto, 2017.

[16] E. Turgut and M. C. Gursoy, "Uplink Performance Analysis in D2D-Enabled mmWave Cellular Networks with Clustered Users," *IEEE Transactions on Wireless Communications,* 2019.

[17] N. Deng, Y. Sun and M. Haenggi, "Success Probability of Millimeter-Wave D2D networks with Heterogeneous Antenna Arrays," in *IEEE Wireless Communications and Networking Conference*, Barcelona, 2018.

[18] L. Liu, Y. Ma, N. Yi and R. Tafazolli, "An Analogue-Beam Splitting Approach for MmWave D2D Multicast Channel," in *IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Bologna, 2018.

[19] X. Peng, J. C. Shen, J. Zhang and K. B. Letaief, "Backhaul-Aware Caching Placement for Wireless Networks," in *IEEE Global Communication Conference*, San Diego, 2015.

[20] M. Ji, G. Caire and A. F. Molisch, "Wireless Device-to-Device Caching Networks: Basic Principles and System Performance," *IEEE Journal on Selected Areas of Communications*, vol. 34, no. 99, pp. 176-189, 2015.

[21] N. Giatsoglou, K. Ntontin, E. Kartsakli, A. Antonopoulos and C. Verikoukis, "D2D-Aware Device Caching in mmWave-Cellular Networks," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 9, pp. 2025-2037, 2017.

[22] R. Wang, J. Zhang, S. H. Song and K. B. Letaief, "Mobility-Aware Caching in D2D Networks," *IEEE Transactions on Wireless Communications*, vol. 16, no. 8, pp. 5001-5015, 2017.

[23] G. H. Sim, A. Asadi, A. Loch, M. Hollick and J. Widmer, "Opp-Relay: Managing Directionality and Mobility Issues of Millimeter-Wave via D2D Communication," in *9th International Conference on Communication Systems and Networks (COMSNETS)*, Bangaluru, 2017.

[24] R. Chevillon, G. Andrieux, R. Negrier and J. F. Djouris, "Spectral and Energy Efficiency Analysis of mmWave Communications with Channel Inversion in Outband D2D Network," *IEEE Access,* vol. 6, pp. 72104-72116, 2018.

[25] S. Wu, R. Atat, N. Mastronarde and L. Liu, "Coverage Analysis of D2D Relay-Assisted Millimeter-Wave Cellular Networks," in *2017 IEEE Wireless Communications and Networking Conference*, San Francisco, 2017.

[26] S. Wu, R. Atat, N. Mastronarde and L. Liu, "Improving the Coverage and Spectral Efficiency of Millimeter-Wave Cellular Networks using Device-to-Device Relays," *IEEE Transactions on Communications,* vol. 66, no. 5, pp. 2251-2265, 2018.

[27] J. Deng, O. Tirkkonen, R. Freij-Hollanti, T. Chen and N. Nikaein, "Resource Allocation for Opportunistic Relaying in Integrated mmwave/Sub-6 GHz 5G Networks," *IEEE Communications Magazine,* vol. 55, no. 6, pp. 94-101, 2017.

[28] B. Ma, H. Shah-Mansouri and V. Wong, "Full Duplex Relaying for D2D Communication in mmwave Based 5G Networks," *IEEE Transactions on Communications,* vol. 17, no. 7, pp. 4417- 4431, 2018.

[29] Y. Li, M. C. Gursoy and S. Velipasalar, "Scheduling in D2D underlaid Cellular Networks with Deadline Constraints," in *IEEE 84th Vehicular Technology Conference*, Nanjing, 2016.

[30] S. Riolo, D. Panno and A. Di Maria, "A New Centralized Access Conrol for mmWave D2D Communications," in *IEEE 13th International Conference on Wireless and Mobile Computing, Networking and Communications*, Rome, 2017.

[31] Y. Niu, C. Gao, Y. Li, L. Su, D. Jin and A. U. Vasilakos, "Exploiting Device-to-Device Communications in Joint Sceduling of Access and Backhaul for mmwave Small Cells," *IEEE Journal of Selected Areas in Communications*, vol. 33, no. 10, pp. 2052-2069, 2015.

[32] J. Qiao, X. S. Shen, M. J. W., Q. Shen, Y. He and L. Lei,

"Enabling Device-to-Device Communications in Millimeter-Wave 5G Cellular Networks," *IEEE Communications Magazine*, vol. 53, no. 1, pp. 209-215, 2015.

[33] Y. Niu, Y. Liu, Y. Li, X. Chen, Z. Zhong and Z. Han, "Device-to-Device Communications Enabled Energy Efficient Multicast Scheduling in mmWave Small Cells," *IEEE Transactions on Communications*, vol. 66, no. 3, pp. 1093-1109, 2018.

[34] C. Gao, Y. Li, H. Fu, Y. Niu, D. Jin, S. Chen and H. Zhu, "Evaluating the Impact of User Behavior on D2D Communications in Millimeter-Wave Small Cells," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 7, pp. 6362-6377, 2017.

[35] L. Wang, S. Liu, M. Chen, G. Gui and H. Sari, "Sidelobe Interference Reduced Scheduling Algorithm for mmWave Device-to-Device Communication," *Peer-to-Peer Networking and Applications*, pp. 1-13, 2018.

[36] H. Shokri-Ghadikolaei, L. Gkatzikis and C. Fischione, "Beam-Searching and Transmission Scheduling in Millimeter Wave Communications," in *IEEE International Conference on Communications*, London, 2015.

[37] P. H. Pathak, X. Feng, P. Hu and P. Mohapatra, "Visible Light Communication, Networking and Sensing: A Survey, Potential and Challenges," *IEEE Communication Surveys*, vol. 17, no. 4, pp. 2047-2077, 2015.

[38] H. Pang, J. Liu, X. Fan and L. Sun, "Toward Smart and Cooperative Edge Caching for 5G Networks: A Deep Learning Based Approach," in *IEEE/ACM International Symposium on Quality of Service*, Banff, Alberta, 2018.

[39] J. Li, Y. Chen, Z. Lin, B. Vucetic and L. Hanzo, "Pricing and Resource Allocation via Game Theory for a Small-Cell Video Caching Systems," *IEEE Journal on Selected Areas of Communication*, vol. 34, no. 8, pp. 2115-2129, 2016.