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Review Article

Resource Allocation in Millimeter-Wave Device-to-Device Networks

Filbert Onkundi Ombongi,[1] **Heywood Ouma Absaloms**,[2] **and Philip Langat Kibet**[3]

[1]*Pan African University Institute for Basic Sciences, Technology and Innovation, Juja, Kenya*
[2]*Department of Electrical and Information Engineering, University of Nairobi, Nairobi, Kenya*
[3]*Department of Telecommunication and Information Engineering, Jomo Kenyatta University of Agriculture and Technology, Juja, Kenya*

Correspondence should be addressed to Filbert Onkundi Ombongi; onkundifilo12@gmail.com

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Recently, the mobile wireless communication has seen explosive growth in data traffic which might not be supported by the current Fourth Generation (4G) networks. The Fifth Generation (5G) networks will overcome this challenge by exploiting a higher spectrum available in millimeter-wave (mmwave) band to improve network throughput. The integration of the millimeter-wave communication with device-to-device communication can be an enabling 5G scheme in providing bandwidth-intensive proximity-based services such as video sharing, live streaming of data, and socially aware networking. Furthermore, the current cellular network traffic can also be offloaded by the D2D user devices thereby reducing loading at Base Stations (BSs), which would then increase the system capacity. However, the mmwave D2D communication is associated with numerous challenges, which include signal blockages, user mobility, high-computational complexity resource allocation algorithms, and increase in interuser interference for dense D2D user scenario. The paper presents review of existing channel and power allocation approaches and mathematical resource optimization solution techniques. In addition, the paper discusses the challenges hindering the realization of an effective allocation scheme in mmwave D2D communication and gives open research issues for further study.

1. Introduction

The mmwave D2D communications is a 5G network enabling technology to satisfy multigigabit data demands. The high data rate links and the directional coverage of mmwave networks makes it suitable for the provision of proximity services through D2D communications. The directional characteristics at the mmwave band minimizes the interference between D2D pairs in dense D2D pair network scenario [1].

However, mmwave communication has a challenge of signal blockage which results in more signal losses for the indoor network scenario. In addition, when mobility of users is allowed, then overall network performance is affected due to the need of frequent hand overs from one cell to the other and frequent updating of the base station on D2D user location variations. Therefore, the mmwave D2D will be realized with some modifications on the system and hardware, such as scheduling algorithms and use of directional antennas. The main benefits of integrating mmwave and D2D communications are provision of bandwidth-intensive applications and services, offloading traffic from the current cellular systems, higher throughput or system capacity, higher energy efficiency, and lower energy consumption [2, 3]. However, due to low antenna height compared to the BSs and narrow beamwidth, the mmwave D2D communication is more vulnerable to signal blockages from buildings, trees, walls, and human bodies; this is the major challenge for successful operation of D2D communications in the mmwave band.

The challenges in mmwave D2D communication notwithstanding, the D2D communication in the mmwave band offers more benefits compared to its communication in the sub-6 GHz band. When devices in close proximity communicate directly it results in improved capacity and reduced latency in comparison to BS-enabled communication. In addition, there is minimization of the load on the backhaul network thereby increasing the network capacity. The direct D2D communication is performed at a lower transmit power which results in better energy efficiency. The D2D technology can also improve coverage and throughput for cell edge users who might be experiencing weaker reception of signals by acting as relays.

Most research studies that have been carried out for D2D communications have majorly considered in-band D2D communication. In in-band D2D communication, the D2D user devices reuse spectrum resources of cellular user devices below 6 GHz [4, 5]. The surveys that have been published on D2D communication have dwelt on in-band D2D communication, where there is complexity in modelling interference originating from the D2D users to the cellular user equipment. In [6], a survey on D2D communication involved the concepts such as network discovery, interference management, provision of proximity services, and security in the network. The survey also proposed vehicle-to-vehicle (V2V) communication, mmwave spectrum, social-aware D2D networks, and simultaneous wireless information and power transfer as areas that needed further study for in-band D2D communication. In [7], a comprehensive analysis on in-band D2D challenges and open research issues were discussed based on mode selection, device discovery, radio resource and interference management, mobility management, and privacy and security schemes which were not considered for in-band D2D surveys given in [8–12].

In [13], an overview of in-band D2D communication resource allocation schemes was given by categorizing resource optimization objectives, constraints, and associated mathematical solutions. These studies have shown that the practical D2D communication will be operated in the mmwave band with a switch to the microwave band whenever there are nonline of sight conditions (NLOS). The main goals of this survey are as follows:

(1) Present the issues related to mmwave D2D networks with a comprehensive analysis of the resource allocation mechanisms with a view of proposing techniques which can provide better results
(2) Describe the challenges in relation to resource allocation techniques in mmwave D2D communication
(3) Provide open research directions in the area of mmwave D2D communication

The survey is the first one in the area of mmwave D2D communication which is sometimes referred to as outband D2D communication in terms of resource allocation approaches by looking at the resource optimization objectives, solution approaches, and performance parameters. In [14], an overview of the D2D use cases was given by categorizing D2D network based on commercial and public safety services. The outband D2D considered in this survey is where D2D users coexist with the Wi-Fi Direct as a dominant unlicensed D2D communication network in the industrial, scientific, and medical (ISM) spectrum. In [15], a survey was given by considering the routing problem in D2D communication. It also considered different routing techniques applicable to D2D communications in terms of their relay type and spectrum used.

However, this review covered only the multihop routing protocols which were proposed for mmwave D2D networks in [16–18]. The resource allocation problem in mmwave D2D networks was not considered in this review.

In [19], an overview was given on implementation of a hybrid D2D communication network covering the mmwave band and the conventional cellular band. It also gave the mmwave propagation features and technical issues for D2D communication. However, the resource allocation problem and the associated algorithms were not considered in this review.

The remainder of the paper is organized as follows. Section 2 discusses the applications of mmwave D2D communications, Section 3 gives resource allocation mechanisms, network scenarios, and performance targets, Section 4 discusses the mathematical solution techniques, Section 5 looks at challenges in mmwave D2D communication, Section 6 discusses the merits and demerits of the mathematical solution techniques, Section 7 deals with the future research directions, and Section 8 gives the conclusion.

2. Applications of mmwave D2D Communication

The device-to-device networks can be deployed in the mmwave band to mitigate the complexity of interference modelling in the sub-6 GHz band. The mmwave D2D finds its application in different areas to offer proximity-based services such as public safety communications, offloading traffic from current cellular networks, wearable devices and Internet of Things (IoTs), and social-based networking for content delivery services [20]. These applications have been discussed briefly and summarized in Figure 1.

2.1. Public Safety Communication.

The D2D communication can be used to enhance public safety in case of unexpected disasters such as fire outbreak, earthquake, and flooding by integrating D2D to the conventional network infrastructure [22, 23]. The D2D network can then be activated whenever an emergency occurs to set up communication in a faster way.

2.2. Traffic Offloading.

Due to an increased number of devices which includes tablets, smartphones, wearable devices, and laptops, coupled with an increase in demand for the services offered by them, has brought the challenge of the current 4G network not meeting the required traffic capacity and quality of service. Therefore, the deployment of D2D communication in 5G networks has shown that the current traffic can be offloaded to the D2D devices [24].

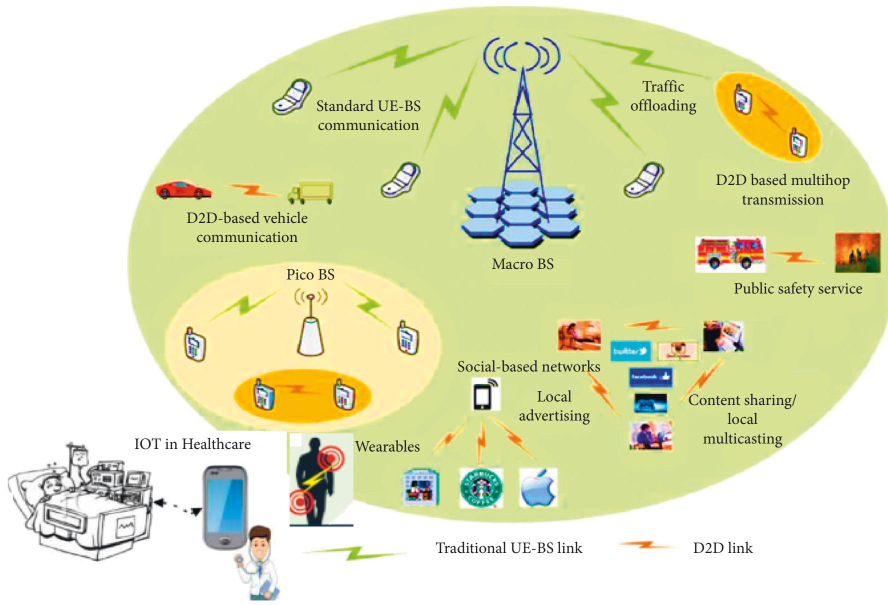

Figure 1: Application areas of D2D Communication [21].

This D2D-based traffic offloading can assist in minimizing end-to-end latency especially for delay tolerant applications.

2.3. Wearable Devices and Internet of Things (IoT). The 5G network has a main goal of providing connectivity to different types of devices. The D2D devices can be deployed as relays in buildings and in areas where there is no coverage of the sensor devices, and then the home appliances are allowed to have D2D communication mode thereby reducing communication through the Base Station (BS).

The smart watches and medical monitoring devices are some of the wearable devices that can save power since they communicate through D2D relays [25]. Since D2D communication is seen to be versatile, it can easily be applied in IoT and wearable devices for provision of low-power short range communications [26].

2.4. Social-Based D2D Networking. The D2D devices can allow direct communication between devices that are close to each other to deliver or share multimedia content. This can be made possible by applying proper device discovery and pairing algorithms to enhance performance targets such as energy efficiency, sum rate, and connection density. Some of the services that can be offered as social-aware D2D services include local advertisements, multimedia content sharing, and playing games [6, 27].

3. Resource Allocation Schemes in Millimeter-Wave D2D Networks

This section gives an overview of the resource allocation approaches that have been carried out in millimeter-wave D2D networks by considering the solution approaches, network scenarios, and performance targets. Table 1 gives a comparison of some of the spectrum and power allocation approaches that have been studied for mmwave D2D networks. The resource allocation solution approaches are covered in detail in Section 4.

Chang and Teng [28] had an objective of maximizing the energy efficiency (EE) and reducing transmit power. The millimeter-wave optimization problem was mathematically formulated as a nonlinear programming power allocation problem, which was solved by an iterative algorithm by considering a full duplex relay. This study proposed a modified bottleneck effect elimination power algorithm to minimize transmit power and further improve energy efficiency while maintaining end-to-end network throughput. The iterative power allocation algorithm and bottleneck effect elimination power algorithm were combined by applying the Gale–Shapley (GS) and Hungarian matching algorithms. The simulated results showed that relay consumed power reduced by 45.9% and that of D2D pairs reduced by 61.6%. In addition, the EE was improved by 32.3% when compared to conventional techniques applied in [45].

Feng et al. [29] considered resource sharing mechanism and mode selection to optimize the sum logarithmic rate in a single cell mmwave cellular network based on time division duplexing (TDD). In this network scenario, multihop D2D relays or multibeam reflections in a TDD mode served the blocked users. The optimization problem was divided into two parts. One part was dealing with the resource-sharing solution while the other was dealing with adaptive mode selection. The resource-sharing solution was developed to a mixed-integer programming (MIP) function which was remodelled as a convex programming function. The optimization function was solved by applying the Lagrangian method for optimal solution. The simulated results showed some performance gain when compared to the conventional allocation techniques.

Table 1: Summary of mmwave D2D communication resource allocation solutions.

Reference	Target/objective	Method	Performance metric
[28]	Maximize energy efficiency and reduce transmission power in a full duplex (FD) relay-aided mmwave D2D communication	Lagrange dual decomposition and Karush–Kuhn–Tucker (KKT) conditions Matching theory for relaying	Energy efficiency(EE) Transmit power Jains' fairness index
[29]	Maximize sum rate in a single-cell mmwave time division duplex cellular network by considering joint adaptive selection for multibeam reflection of NLOS devices and D2D relays	Lagrangian dual-based algorithm	Sum rate Jains' fairness index
[30]	Maximization of throughput in an outdoor mmwave small cell environment with a trade-off between number of admitted devices and interference constraint.	Heuristic algorithm	Throughput Satisfaction ratio
[31]	Joint relay selection and power allocation to maximize system throughput and minimize aggregate transmission power by taking data rate threshold and total transmit power constraints	Matching theory	Transmit power Throughput
[32]	Optimal subchannel allocation for underlay to maximize sum rate and spectrum efficiency for D2D communication in outdoor mmwave scenario	Iterative water filling algorithm	Sum rate Spectrum efficiency Jains' fairness index
[33]	Optimal subchannel allocation for access and D2D links in a densely deployed multiple mmwave small cells to maximize sum rate	Coalition game	Sum rate
[34]	Enhance system throughput and spectrum efficiency in an urban scenario in the E-band by reducing interference from multiple D2D pairs	Heuristic algorithm	Throughput D2D efficiency ratio
[35]	Maximize the network sum rate in D2D-enabled communication in heterogeneous cellular networks by combining mmwave and sub-6 GHz	Coalition formation game	Network sum rate
[36]	Maximize EE of the CUs served by either macrocells or mmwave small cells by considering simultaneous subcarrier and power allocation to satisfying a given QoS level for D2D pairs. The macrocells operate at 2.4 GHz and small cells operate at 28 GHz.	Lagrangian and Hungarian method	Energy efficiency Outage probability of D2D pairs
[37]	Energy efficiency maximization for cellular and D2D user devices. The cellular devices are either served by macrocells or mmwave small cells and the QoS requirements of D2D users are maintained.	Lagrange technique and KKT conditions Hungarian method	Energy efficiency Sum rate Outage probability
[38]	A Stackelberg game-based time-sharing technique proposed for interfering D2D communication paths to maximize throughput at 60 GHz	Stackelberg game	Throughput D2D user density
[39]	Transmit power minimization scheme by considering device association and beamwidth selection in a 60 GHz mmwave D2D network	Particle swarm optimization (PSO)	Transmit power Achievable rate
[40]	Resource allocation, beam selection, and interference coordination in integrated mmwave and sub-6 GHz network scenario with two-hop D2D relaying.	Graph theory	Throughput
[41]	Resource sharing in D2D communication for a mmwave and 4G system architecture with TDMA-based MAC structure	Nonlinear integer programming Heuristic resource sharing scheme	Network capacity

Table 1: Continued.

Reference	Target/objective	Method	Performance metric
[42]	Maximization of mmwave D2D throughput by joint allocation of transmit angle and time slot	Graph theory	Throughput
[43]	Minimize D2D link transmit power and maximize the achievable throughput	Stackelberg game	Transmit power Throughput
[44]	Optimize outage probability for uplink cellular and D2D communicating users for a D2D-enabled mmwave network with clustered D2D pairs	Stochastic geometry and Laplace transform	Outage probability

In [30], an interference mitigation and spectrum resource allocation scheme was proposed in an outdoor mmwave cell having uplink cellular and D2D communication for maximization of the attained sum rate by trading-off between density of admitted user equipment and interference constraint. A mathematical optimization problem was formulated as a nonlinear integer function which was hard to find a solution. This complexity was overcome by proposing a heuristic algorithm for uplink interference alleviation so that the solution of the optimization function can be determined.

Ma et al. [31] proposed a relay-enabled mmwave D2D communication to offer a solution of battery capacity limitation of the user devices with high-data rate requirement in emerging applications with an objective of maximizing system throughput and minimizing the total transmit power. The optimization function was formulated as a multiobjective combinatorial problem to address simultaneous selection of relay and power allocation. The optimization function was to satisfy the constraints of the D2D minimum data rate and aggregate transmission power and relay aggregate transmission power. The optimization problem of this nature can either be solved by branch and bound, outer approximation, or Benders decomposition techniques.

These methods have the challenge of some degree of complexity in determining solution to the polynomial. This was overcome by proposing matching-theory based solutions. The weighted bipartite graph construction was applied as a one-to-one matching game to provide solutions that can be easily tracked for such resource optimization problem. The results of the proposed algorithms showed some performance improvement compared to the augmented random search (ARS) and distributed relay selection algorithms.

In [32], a resource allocation for the outdoor mmwave D2D underlay network was considered to maximize spectrum efficiency by ensuring the resources are distributed fairly within a cell. The sum rate maximization problem was formulated to ensure optimal resource allocation. This study was carried out with an aim of allowing more than one user resource-sharing scheme without reducing the spectrum efficiency to attain an improved system throughput. For complexity reduction, a threshold was imposed on the users per resource block with traffic environment adaptation. The frequency of operation was taken to be 28 GHz with emphasis on network-assisted D2D communication. The power allocation problem for the D2D users in the same cell was solved by an iterative water filling algorithm by considering interference experienced by the resource blocks with suboptimal results being obtained.

In [33], a millimeter-wave network with dense deployment of small cells was considered to optimize D2D links subchannel allocation process. The sum rate of accessing the mmwave network and individual D2D link sum rate was maximized by formulating the channel assignment as a coalitional game. The results showed that the proposed channel assignment algorithms offered an improved performance compared to other channel assignment techniques.

In [34], an E-band D2D undelay millimeter-wave network was considered by proposing an algorithm to optimize the resource allocation process. The study considered an urban area with an aim of improving spectrum efficiency and throughput. In addition, the proposed algorithm was to minimize interference in a dense network, where the D2D pairs reuse same cellular users' resource blocks. The formulated optimization function was solved by a heuristic algorithm in an outdoor realistic path loss model at 73 GHz. The proposed algorithm offered better overall system throughput and reduced interference.

In [35], an uplink resource allocation optimization function was mathematically expressed as a nonlinear optimization function for microwave and mmwave band users, where there were multiple D2D pairs. The sum rate was maximized by applying a coalition formation game. The proposed scheme had a rapid convergence rate and reached Nash equilibrium with suboptimal solution obtained. The proposed game offered improved results than other practical techniques.

In [36], a hybrid D2D-enabled cellular network was developed that operates on the microwave and millimeter-wave band. The macrocells had a number of millimeter small cells within their coverage area. A downlink transmission was considered by proposing a resource-sharing scheme to maximize the energy efficiency of opportunistically served cellular users by macrocells or millimeter-wave small cells with QoS threshold level for the D2D pair's guaranteed. The power control scheme for D2D pairs was formulated that was self-adaptive while maintaining minimum QoS level and cellular users' interference threshold. The problem was decomposed into D2D pairs/CUs' power allocation and subcarrier allocation for the microwave BS associated cellular users. The problem of allocating power to D2D and cellular users was solved by an algorithm based on Lagrangian multiplier technique while the subcarrier allocation was solved by the Hungarian algorithm. The results were suboptimal and showed some improvement in EE maximization compared to the algorithms for sum rate maximization and consumed power minimization. A similar study, in [37], for EE maximization with a trade-off between energy efficiency, outage probability, sum rate at different QoS levels and variation of D2D pairs, and cellular users' density was carried out. The energy-aware radio resource management scheme was formulated for optimization of the achievable rate and energy efficiency of cellular users with minimal QoS requirement and maximum input power constraint. The optimization problems were reformulated to convex subproblems by using the Lagrange multipliers and dual decomposition techniques. Then, the optimal power allocation for a microwave BS and mmwave BS was determined by using the Karush–Kuhn–Tucker conditions. The multilevel water filling algorithm was then applied to determine optimal power allocation between the microwave BS and associated users. The water level depended on the beamwidth for a transmitter and receiver. The Hungarian algorithm was applied to solve the subcarrier allocation problem for suboptimal allocation strategy.

Li et al. [38] developed a time-based resource allocation mechanism for interfering D2D communication links to maximize throughput. The resource optimization problem was modelled as a Stackelberg game with interference causing links paying a higher price compared to those ones which are not causing interference. The interference causing D2D links were scheduled to access mmwave network concurrent transmission. The optimization function was also formulated as a noncooperative Nash game to maximize the D2D rate and at the same time obtain a transmission power control that is distributed between interference causing links. In addition, there was a modification of the pricing strategy by setting an interference limit to guarantee the transmission quality at 60 GHz carrier frequency. The results showed an improvement in the network throughput compared to an algorithm based on vertex colouring proposed in [46].

Zhang et al. [39] proposed a transmit power optimization scheme for a millimeter-wave D2D network by integrating device association and beamwidth selection. The Gaussian directional antenna model's roll-off feature and the reflective nature of the two-ray channel model were both integrated in the network scenario. The formulated optimization problem to minimize the transmission and energy saving in mmwave networks was a nonlinear problem which is complex in determining its solution. This problem was split into two with one dealing with device association and the other for beamwidth selection. The device association problem was solved by a distributed framework while particle swarm optimization (PSO) algorithm was used to optimize beamwidth scheme. The result showed some improvement by reducing transmission power, mitigating interference, and improving the sum rate of the system compared to other interference mitigation schemes which do not consider device transmit power.

A hybrid network scenario consisting of two-hop downlink D2D relaying was proposed in [40] by integrating the mmwave and the sub-6 GHz band as a way of avoiding blockage and coverage extension for an outdoor urban network scenarios with different densities of site deployment. The resource allocation mechanism over two subcarriers was integrated with relay and beam selection to improve data rate for users at the cell edge thereby ensuring consistent user experience. The sub-6 GHz band was responsible for the network control and communication reliability while the mmwave communication provided high throughput improvement. The multiobjective problem was formulated and solved by graph theory that had the capability of selecting a relay, allocating resources, and coordinating interference. The graph colouring method addressed allocation of channel and coordination of interference problems by modelling interaction between neighbouring links as an interference graph which ensured proper selection of the beam and relay, allocation of resources, and coordination of interference. The results showed a higher system throughput with some consistent user experience. However, a substantial number of users missed mmwave two-hop connectivity when the intersite distance was above 400 m. Another challenge was difficulty in determining an appropriate incentive for user equipment (UE) that can be used as relays.

In [42], a dense heterogeneous D2D network was studied by allocating both the transmit angle and time slot for a D2D transmitter in a dense network. This involved modelling interference graphs to show the status of interference in the system at any given time. The transmit angle and time slot allocation optimization problem was solved by graph theory-based iterative algorithm. The results showed a reduction in simulation complexity and improved performance compared to exhaustive search methods. However, the obtained results were suboptimal and the algorithm is not efficient for a higher or smaller number of D2D devices. This is due to minimal adjustment of the transmit angle at such cases since most D2D links have direct communication.

In [43], an interference control scheme supporting full frequency reuse was developed based on the Stackelberg game in a mmwave D2D network. The D2D pairs were sharing the uplink resource blocks with the mmwave small cells. The resource allocation optimization function was aimed at minimizing interference and transmit power while maximizing the achieved D2D throughput. The results showed a faster convergence rate and an improved performance compared to maximum sum rate assignment algorithm used in [34].

A single tier uplink mmwave D2D-enabled cellular network was developed to analyse the outage probability performance for the cellular and clustered D2D users in [44]. The study formulated a mode selection and spectrum-sharing scheme to optimize the outage probability of mmwave cellular and D2D links. The results indicated that a higher outage probability was obtained when the network is densified with cellular and D2D users or when there is concurrent transmission for majority of the D2D user pairs.

3.1. Network Scenarios. This gives a description on how the network modelling was carried out. This entails number of cellular users, number of D2D pairs, single cell or multicell, either uplink or downlink communication or both, number of BSs, and dimensions of the simulation area (which can be either circular, hexagonal, or square). In [28], the network model consisted of a single BS placed at the center of the cell, multiple D2D pairs, and multiple full duplex relays that were uniformly distributed within the coverage area of the cell. The antenna pair had an Orthogonal Frequency-Division Multiple Access (OFDMA) subchannel with a decode-and-forward relaying procedure. The single-cell radius was taken as 300 m with the distance between two ends of the D2D transmitter and receiver varying from 50 m to 200 m.

In [29], a single cell with a BS at the center serving multiple D2D users which acted as relays for data transfer was considered. The network was assumed to operate in Time Division Duplex (TDD) mode for effective channel estimation. The cell coverage was taken as 50 m. In [30], the network model had multiple D2D user pairs and multiple cellular users for single cell having 500 m radius. The minimum range between a cellular user and a D2D user that share resources was taken as 35 m in an outdoor environment. The same network scenario was used in [34]. In [31], the network model considered full duplex multiple relays supporting multiple D2D users for coverage expansion. The study assumed that the BS, multiple relays, and D2D user pairs were controlled by the same network operator. For every relay, there were two sets of antennas for full duplex communication through decode-and-forward procedure. The D2D user pairs were allocated orthogonal nonoverlapping channels and a dedicated band. The study considered a single cell of radius 500 m with sectored directional antenna model for the transmitters.

In [32], a single hexagonal cell of radius 500 m with a BS located at the center was considered for multiple cellular and multiple D2D pair network scenario. The D2D pairs were reusing the cellular user resources whenever the channel state information (CSI) was favourable. The maximum allowable range between D2D devices was taken as 20 m. The cell was subdivided into three sectors with each sector having 100 resource blocks.

In [33], the study considered a network having multiple mmwave small cells with a dense implementation. Each small cell had its own BS serving a number of users. The D2D communication was within a small cell and between small cells. The multiple D2D pairs shared the radio resources of the cellular users in a circular cell of radius 100 m. The maximum range between the D2D devices was taken to be 5 m and the IEEE 802.15.3c antenna model was used for the simulated network scenario.

In [35], a heterogeneous single-cell network was considered which supported communication in the microwave and mmwave band. The D2D user pairs were communicating in a dedicated mmwave band but were also allowed to reuse the microwave band if the link interference level is beyond the set threshold. The network had multiple D2D pairs and multiple cellular users with the D2D pairs sharing the uplink resources of the cellular users. The distance between the D2D user devices was taken as $10\sqrt{2}$ m. A square simulation area was considered with each side being 500 m and the BS located at the center.

In [36], a hybrid heterogeneous cellular network was considered covering the mmwave and microwave band with the dual-band BS located at the center. The multiple cellular users and multiple D2D pairs were randomly distributed within the cell coverage. The network had a number of small cells within the coverage of the macrocell. The macrocell had a radius of 400 m, whereas the one of the small cell was 50 m. This network model was also used in [37] but with some modifications such as defining some multiple virtual reality users from the set of cellular users. In [38], a mmwave pico cell with a piconet controller at the center was considered. The network had multiple wireless user devices which were assumed to communicate in half-duplex.

The communication between different user devices was implemented by applying the super-frame structure consisting of a beacon, data transmission, and contention access. In addition, the network model had randomly distributed multiple D2D pairs that were assumed to interfere with one another. The ideal flat-top antenna array model was used as a directional antenna for all the user devices. The radius of the cell was taken as 50 m and the distance between D2D devices varied from 5–15 m.

It can be seen from this analysis, there is need to implement a dual band hybrid network that incorporates cellular users, D2D pairs, full duplex relays, small cells, and macrocells in an outdoor and indoor environment. The impact of an increase in density of D2D pairs, cellular users, relays, and small cells on the network performance should be studied in detail in terms of energy efficiency and achievable capacity. However, most of these studies have considered single-cell network scenario. Therefore, there is need to extend this study to a multicell network scenario and consider all the interferences present in this kind of network set up. Table 2 shows the comparison of performance evaluation based on the network scenario, direction of communication, evaluation method, and solution techniques and tools.

3.2. Performance Targets. These are the metrics which are supposed to be optimized in a mmwave D2D communication network as shown in Table 2.

These performance targets have been considered in most mmwave D2D communication networks and can be described as follows.

(1) Energy Efficiency (EE). This is the total number of bits transmitted per joule of energy consumed by the signals transmitted and the transmitter and receiver circuitry [47]. The 5G network implementation should achieve an energy efficiency of at least 100 times the energy efficiency of the current cellular networks [48]. The higher the value of this metric the better the performance which in turn results in an extended battery lifetime and energy saving for the given 5G wireless network.

(2) Throughput. This is defined as the maximum data rate achievable by summing the rate of all the links available for

Table 2: Comparison based on performance metrics, network scenario, and solution method and tools.

Performance metric	Reference	Network scenario	Solution method and tools	Direction of communication
Energy efficiency	[28]	Single cell, multiple relays, multiple D2D pairs	Lagrange multiplers, Gale–shapley and Hungarian-based simulation	Uplink
	[36, 37]	Dual band (microwave and mmwave), heterogeneous multicell multiple cellular users, multiple D2D users	Nonlinear optimization, weighted-Tchebycheff technique and matching-theory simulation	Uplink
Transmit power	[28]	Single cell, sectored antenna multiple relays, multiple D2D pairs	Shannon capacity model, Lagrange multipliers, Gale–shapley and Hungarian-based simulation	Uplink
	[31]	Single cell, sectored antenna, full duplex multiple relays, multiple D2D relays, three-sectored antenna	Shannon capacity relation, bipartite graph construction, Hungarian algorithm simulation	Uplink
	[39]	Single cell, clustered into different classes, multiple D2D users	Shannon capacity, particle swarm optimization simulation in MATLAB	Uplink
	[43]	Single cell, multiple D2D users, multiple cellular users	Shannon capacity relation, stackelberg game simulation	Uplink
Jain's fairness Index	[28]	Multiple relays, multiple D2D pairs	Lagrangian multipliers, Gale–shapley and Hungarian-based simulation	Uplink
	[29]	Single cell, sectored antenna, multihop D2D users, multiple cellular users operating in TDD mode	Dijkstra's algorithm and Lagrangian decomposition	Downlink
	[32]	Single cell, sectored antenna, multiple D2D users, multiple cellular users	Rician fade modelling, Monte Carlo simulation	Uplink
User throughput or sum rate or achievable rate	[29]	Single cell, multiple D2D users, multiple cellular users operating in TDD mode	Dijkstra's algorithm and Lagrangian multipliers	Downlink
	[30]	Single cell, multiple D2D users, multiple cellular users	Heuristic MATLAB simulation	Uplink
	[31]	Full duplex multiple relays, multiple D2D relays, three-sectored antenna	Bipartite graph construction Hungarian algorithm simulation	Uplink
	[32]	Single cell, sectored antenna, multiple D2D users, multiple cellular users	Rician fading modelling and Monte Carlo simulation	Uplink
	[33]	Multicell, IEEE 802.15.3c antenna model, multiple D2D pairs, multiple cellular users	Coalition formation game modelling	Uplink
	[34]	Single cell, multiple D2D pairs, multiple cellular users	Heuristic simulation	Uplink
	[35]	Hetnet single cell, dual band, multiple D2D pairs, multiple cellular users	Coalition game modelling	Uplink
Network capacity	[35]	Hetnet single cell, dual band, multiple D2D pairs, multiple cellular users	Shannon capacity relation and coalition game modelling	Uplink
Outage probability	[36, 37]	Dual band (microwave and mmwave), heterogeneous multicell, multiple cellular users, multiple D2D users	Nonlinear optimization and matching theory simulation	Uplink
	[44]	Multiple clustered D2D users, multiple cellular users	SINR modelling for cellular and D2D users	Uplink

all the D2D user pairs or cellular users. It is given in megabits per second (Mbps). It can also be referred to as the sum rate, achievable rate, or the capacity of a network. This is a significant metric for 5G networks as it is projected to have a minimum peak data rate of 20 Gbps and a minimum user data rate of 100 Mps to support bandwidth-intensive applications in mmwave D2D communications [47].

(3) Connection Density. This is the number of devices that are connected per unit area. Since 5G networks will be characterized by densified number of users (cellular users and D2D users) and small cells in an outdoor and indoor environment, it makes connection density to be an important metric in the implementation of mmwave D2D communication networks.

4. Mathematical Optimization Techniques

There are different mathematical solution approaches that have been applied in resource allocation problems in wireless networks with varying levels of complexity and convergence to a solution. The mathematical techniques that have been used in allocating resources for sum rate, network throughput, and energy efficiency maximization, minimize interference, energy consumed, and delay or latency for mmwave D2D communication are discussed in the following sections.

4.1. Nonlinear Optimization Techniques. The optimization of energy efficiency in mmwave D2D communication networks falls in a class of optimization problems referred to as fractional programs. The objective function for the fractional programming problems is a ratio of two real valued functions. If the numerator and denominator are differentiable, then energy efficiency function is pseudoconcave, and its solution can be found by applying nonlinear optimization techniques such as Lagrangian technique or KKT conditions, iterative water filling, and bisection method. The nonlinear solution techniques do not guarantee convergence to optimal point and they tend to have long computation times i.e., slow convergence. The Lagrangian method which is based on KKT conditions is widely applied to solve problems associated with allocation of resources in mobile communication networks.

The Lagrangian technique has been applied to determine solutions in mmwave D2D resource optimization problems for energy efficiency [28, 36, 37], sum rate [29, 37], Jain's fairness index [28, 29], minimization of transmit power [28], outage probability of D2D users [36, 37], and network capacity [41]. However, the computational complexity of the nonlinear optimization techniques will increase due to network densification and mobility which make them unsuitable in future wireless networks which will be characterized by dense users and dense small cells.

4.2. Game Theory. A game can be defined as a mathematical technique which can be used for modelling and analysis of different interactions amongst multiple players. Wireless communication networks have employed game theory in modelling the network interactions as a game. In these wireless networks, the nodes or mobile devices being the decision makers are the players which can compete or cooperate to maximize their payoff. The main objective for game formulation is the interdependence between the strategies of the network nodes or devices in terms of computational, storage, and spectrum resources in the presence of interference in a wireless network. The game has the capability of modelling and analyzing problems associated with resource allocation in D2D-enabled millimeter-wave communication networks.

The games can be categorized into noncooperative or cooperative games. In noncooperative game, the strategic decisions are made from interactions of competing players who choose their strategies or actions independently to enhance its own utility or reduce interference or losses (cost). The noncooperative game has been applied in D2D underlay cellular communication for controlling power [49], spectrum sharing [50], user association [51], protocol design, and resource allocation [52]. The cooperative game studies the behaviour of rational players which can form a coalition or enforce a cooperative behaviour. The players form cooperative groups or clusters in this type of game.

This game has emerged as a promising tool for D2D networks to enhance performance. Despite the benefits of cooperative or coalition game there exists a challenge of adequate modelling, complexity, and user fairness for densified mmwave D2D networks. The cooperative game has been applied in D2D underlay networks for security [53], relay selection and resource allocation [54], power control [55–57], interference management [58], and joint allocation of network resources and interference management [59].

Since there is cellular resource reuse by the D2D users, there has been a challenge of accurate interference modelling in underlay network systems. This has been solved by utilizing the mmwave band to implement D2D networks for bandwidth-intensive applications to mitigate interference caused by multiple D2D users in underlaid communication networks. In mmwave D2D communication, resource allocation and interference management problems have been solved by cooperative game theory. For example, in mmwave D2D networks game theory has been used to solve optimization problems for sum rate maximization [33, 35], network throughput, and D2D user density maximization [38].

However, these game-theoretic resource allocation approaches in mmwave D2D studies have not considered multicell network scenario, where there is need to account for intercell interference, interference between multiple D2D user pairs, and D2D user and mmwave small-cell base station interference. The multicell network scenario is very useful for future networks as it will reduce energy consumption for cell edge users.

4.3. Matching Theory. This is a branch of mathematics that has been applied in wireless networks to analyse the performance based on mutual and dynamic relations among different kinds of rational and selfish users [60]. It has been applied in wireless networks to develop low complexity and high performance decentralized protocols [61]. It has also been applied for resource allocation optimization in microwave and millimeter-wave networks.

In [31], matching theory was applied to solve a relay selection problem for D2D communications in the mmwave band to maximize system throughput and minimize total transmit power. A multiobjective combinatorial optimization function was formulated to perform joint power allocation and relay selection while satisfying minimal D2D data rate, aggregate D2D devices', and relays' transmission power constraints. Due to the complexity of Benders decomposition, outer approximation, and branch and bound techniques, a one-to-one matching with weighted bipartite graph construction was applied to provide tractable solutions for the joint relay and power allocation problem. The results showed some level of improvement compared to the augmented random search (ARS) and distributed relay selection algorithms. However, the centralized resource allocation scheme proposed in this study will not work well where cooperation, self-organization, decentralization, and autonomous networks functions are required. In addition, the study did not consider energy efficiency and energy consumption metrics as a way of solving the challenge of battery lifetime for future wireless devices.

However, matching-theory application to resource allocation problems in wireless networks requires development of network scenarios that properly handle the intrinsic properties which may include interference and delay. Moreover, if there is unstable matching, it can result in a BS swapping, its least preferred mobile user, with another as both resource and user benefit from the swap which leads to unstable network operation.

4.4. Graph Theory. Graph theory is a mathematical tool that can be applied in modelling and analysis of interactions and relationships in wireless networks. It has been applied in wireless networks to formulate algorithms for power control, interference management, and congestion control with low-computational complexity. In addition, graph theory can be applied to model the interference relationships as interference-aware graphs are applied as interference-aware resource allocation algorithm to reduce interference between D2D user devices.

The graph theory techniques that have been applied in wireless networks include graph colouring and graph partition. The graph colouring has been applied in D2D networks to perform interference management, channel assignment, and resource allocation. The graph partition has been applied to perform clustering of network nodes or mobile devices. The graph colouring technique can determine solutions for a wide range of practical wireless network optimization problems.

Graph theory has been applied for downlink resource allocation in the D2D underlaying communication network [62]. The proposed resource allocation algorithm that was based on interference-aware graph gave near optimal results on channel assignment solutions. This helped the BS to obtain local awareness for each communication and interference link in terms of channel gains. However, an interference graph becomes complicated when the number of the D2D users goes up as envisioned in the future 5G wireless networks.

The graph theory has also been applied for mmwave D2D communication in [40] with a challenge of two-hop connectivity for some users when the intersite distance is above 400 m. Therefore, for maximizing the benefits of graph theory, algorithms need to be developed that are based on new clustering mechanisms. This will involve by combining mode selection, QoS requirement, and energy efficiency in the developed resource allocation algorithms.

4.5. Heuristic and Metaheuristic Techniques. The evolutions that have been experienced in the field of computer science have given rise to key technologies and solution complexity increase for wireless communication resource allocation optimization problems which has resulted in the need for specialized software design techniques for large-scale or dense network optimization functions. The mathematical methods such as dynamic programming, Lagrange optimization, heuristic techniques, and metaheuristic approaches, such as PSO and genetic algorithm, have been used for interference management and resource allocation algorithms in wireless communication. The GA and PSO algorithms have the advantage of avoiding premature convergence to a local optima due to their stochastic search mechanism. In addition, they are suitable for large-scale network problems, where there are multiobjective optimization problems with conflicting constraints.

The GA has been applied for D2D communication underlaying cellular communication in [63] to maximize spectrum efficiency and minimize the interference. However, this study considered single-cell network scenario with an assumption of no intercell interference, which however is a possible network scenario in practical D2D wireless communication networks.

The PSO algorithm was applied in [39] for transmission power minimization and achievable data rate maximization by considering device association and beamwidth selection in a 60 GHz mmwave D2D network. These studies can be extended to other performance indicators such as energy efficiency and energy consumption to enhance battery lifetime for future mobile devices.

5. Challenges in mmwave Device-To-Device Communication

This section deals with the issues that may hinder the deployed mmwave D2D communication networks from meeting their performance targets. This involves the mathematical solution algorithms applied, modelling of the channel, and scaling up the network (densification). They are discussed in detail as follows.

5.1. Mathematical Techniques. There are many algorithms that have been considered in the literature which are fast but heuristic in nature which implies that the results obtained can be far from the optimal solution. Therefore, the application of the existing algorithms may not be able to meet the strict performance requirements for fifth generation (5G) D2D networks. The numerical optimization has been used to develop algorithms that are used to find solution in D2D networks giving optimal or suboptimal solutions with the assumption of no mobility for the mobile devices. Therefore, considering the mmwave D2D network scenario with some mobility will lead to more complex optimization functions which possess high complexity. The currently used mathematical tools may not work well in a practical dynamic mmwave D2D network due to long convergence time.

Furthermore, the algorithms that have been applied so far rely on some ideal assumptions to realize a mathematical optimization problem so that the problem can be tractable. However, these assumptions cannot work in a practical D2D network environment. In addition, in densified mmwave D2D network, where there are multiple D2D devices, multiple mmwave pico cells, and mmwave femto cells underlaying a microwave macrocell network management algorithms, can be complex due to computational complexity, increased overhead at the base station in centralized network management, and increased cost of gathering the required information.

5.2. Channel Modelling. Most of the studies in the literature have considered a single cell with all communication links modelled as a single path loss parameter with inadequate precision. There is no precise independence between the path loss exponents and the link distances with the single path model. Thus, there is need to determine accurate path loss models that incorporates densification of mmwave small cells. The densification of these cells leads to some irregularities in the cell patterns and blockage in mmwave communications which brings in interference composition which cannot be modelled as a single path loss exponent.

5.3. Network Densification. Network densification has emerged as a key enabling 5G technology solution for exponential growth of traffic demand. The implementation of future 5G networks will see the deployment of low-cost and small cells which are low-power operating in millimeter-wave spectrum especially in areas with higher traffic demand. This will involve having dense number of small cells and dense number of users supported by each cell. Since the number of small cells goes up, they will come in close proximity to the D2D users operating within their coverage area which reduces the intersite distance. This will generate severe intercell interference among neighbouring cells and between cells and users if they are operating in the same mmwave band. This interference will reduce the capacity of ultradensified networks. Interference cancellation and interference coordination schemes can be effective solutions for curbing this interference. However, since the interference signals come from nodes and devices which are geometrically in close proximity with the intended receivers, the interference becomes less divergent and spatially correlated. This reduces the effectiveness of interference cancellation and coordination schemes in mitigating interference. In addition, the ultradense networks operating in the mmwave band employ directional antennas that produce beams which can be used to mitigate interference between the neighbouring nodes or devices. However, these directional antennas rely on information about the physical locations of the transmitting nodes or devices and their corresponding receivers. These nodes or devices change their positions dynamically due to user mobility which in turn increases the network overhead. Therefore, there is need to consider beamwidth selection and beam alignment techniques jointly together with the resource allocation or scheduling techniques for energy-efficient D2D communication in ultra-dense networks where both are utilizing the mmwave band. The backhauling in a network with dense millimeter-wave small cells can be a challenging issue for developing energy-efficient resource allocation schemes with backhauling constraint [64].

6. Merits and Demerits of the Mathematical Techniques

The mmwave D2D resource optimization techniques are compared in Table 3 by giving the merits and demerits of each technique based on the computational complexity and the ease of converging to a solution.

7. Future Research Directions

7.1. Machine Learning. The mmwave D2D communication networks will be characterized with much variations in the channel conditions and network parameters. The D2D devices and the base stations should have knowledge of these variations so that they can take appropriate action. The interference between the D2D devices, interference between femto cells and D2D devices, and interference between femto cells all working in the mmwave band need to be accurately modelled for improved system performance in terms of throughput, energy efficiency, and latency. Therefore, machine learning tools can be applied to model this complex interference and radio resource allocation optimization problems without explicit programming. Machine learning can overcome some of the challenges that have been noted in the existing algorithms. The existing resource allocation algorithms cannot process or apply some data to solve optimization problems of which some meaningful information or patterns embedded in the data might be lost. This makes them difficult to adapt to the changing network environment resulting in a system performance which deviates much from the optimal results. In addition, most of the current algorithms are developed from the numerical optimization tools which results in either optimal or near optimal solutions for the considered inband or outband D2D network scenarios in a static environment. These developed algorithms are also associated with high complexity and are based on some ideal assumptions to make the formulated mathematical problem tractable. This assumptions might not hold for the practical mmwave D2D wireless networks. With all these challenges, machine learning enables the development of computationally intelligent techniques with less complexity and overhead [65].

Table 3: Merits and demerits of the mathematical solution techniques.

Mathematical technique	Merits	Demerits
Coalitional game	Cooperation in this game can offer better network performance The users are capable of making contracts which are mutually beneficial	Increase in complexity in large-scale communication networks
Stackelberg game	Utility maximization for leaders and best responses for the followers are guaranteed	Need accurate channel state information between the leaders and the followers
One-to-one matching	Can be used to characterize interactions between heterogeneous network nodes or devices with different objectives and information Has capability of defining user preferences in a heterogeneous network and UEs QoS in wireless networks The match theoretic algorithms' solutions converge to a stable state Match theoretic algorithms can be implemented efficiently with a self-organizing feature	It provides multiple stable points which need proper selection of appropriate matching Optimality of a stable solution cannot be guaranteed Dynamic algorithms require additional signaling for exchange of proposals in wireless networks.
Lagrangian dual decomposition and Karush–Kuhn–Tucker conditions	Gradient-based nonlinear optimization techniques have relatively low-computational and set up time	High-dimensional and multimodal problems require infinite running time Global optimality is not guaranteed The continuity and differentiability assumption for the objective function does not hold for practical network systems
Iterative water filling	Operations performed by this algorithm includes only basic arithmetic in addition to the logarithm function which can be implemented as a look up table	Increased complexity for multicell, multiuser, and multiantenna networks
Genetic algorithm	Random mutation offers a wide range of solutions It has a large and wide solution searching space capability Has potential of solving multiobjective optimization problems Use of the fitness function for evaluation offers the capability of extending to continuous and discrete optimization problems	Difficult to develop good heuristic which reflects what the algorithm has carried out Difficult to choose parameters such as number of generations and population size Extremely difficult to fine tune to get enhancement in performance
Particle swarm optimization	It has guidelines for selecting the optimization parameters Has variants for real, integer, and binary domains Provides best solutions due to the capability of escaping from the local optima Converges rapidly	Weak local search ability It has premature convergence
Graph colouring	Has suitable tools for modelling and analyzing wireless networks Low-computational complexity for D2D networks Provides a common formalism for different wireless network problems	Difficult in modelling the user interactions for densified (large scale) networks

Some studies on inband D2D communication networks in sub-6 GHz band have applied machine learning techniques. In [66], a cooperative reinforcement learning algorithm was developed to perform adaptive power allocation in D2D communication to maximize D2D and cellular users' throughput by maintaining a proper interference level. In [67], joint power adaptation and mode selection strategy were developed based on multiagent Q-learning algorithm was considered. The study considered a realistic scenario where the base station had incomplete channel knowledge with the D2D users and cellular users having only private SINR information. The near optimal results were obtained and they showed an improved performance. However, this study did not consider link gains between eNB and D2D pair, between D2D pairs in the formulation of the reward function, which are very useful in the determination of an improved transmission power, and SINR level, and for throughput maximization.

In [68], a power control scheme for D2D users was considered by employing a distributed Q-learning algorithm incorporating a distributed and collaborative update of the Q-values. The resource allocation scheme was maximizing throughput of D2D pairs and cellular user in a single-cell network. The proposed algorithm performed better that the random resource allocation. However, the study did not consider the channel gains associated with the corresponding reward function.

In [69], a transmit power control scheme based on deep learning was considered for weighted D2D sum rate maximization. The D2D users were sharing radio resources with the cellular users in the uplink communication with one resource block considered in the system model. The findings showed that the proposed approach obtained high-weighted sum rate with a lower computation time compared with the numerical iterative optimization methods.

However, all these studies which have been performed on microwave D2D underlaid networks can be extended to mmwave D2D communication in mmwave pico cells to mitigate the interference. The interference between the D2D users and interference between the D2D users and the mmwave pico cells should then be taken into account for energy efficiency and energy consumption maximization which are the key performance indicators in future 5G networks to prolong battery life. In addition, the resource allocation based on reinforcement learning can be extended for a multicell network scenario in the mmwave band where every cell can be modelled as an agent.

7.2. Channel Modelling. The mmwave D2D communication will require some additional analysis and a clear understanding of D2D links in the mmwave band. This will also involve the experimental verification of beam switching methods which includes the practical implementation of the antenna arrays. The improvement of the mmwave D2D channel modelling will involve multiple channel modelling approaches or combination of multiple modelling approaches (hybrid) instead of dealing with one modelling approach. This will overcome the challenges associated with 5G systems' modelling with accuracy of the developed model and complexity trade-off. For example, the multiple slope path loss models provides a better LOS and NLOS links approximation in densified millimeter-wave systems due to irregular cell patterns and blocking features compared to the single path loss exponents. The study can also incorporate machine learning-based beamforming models for multiuser mmwave D2D systems in various LOS and NLOS environments with time-varying scenario [70].

7.3. Clustering of D2D Users. Clustering can be applied in mmwave D2D communication for D2D devices that are close to each other to offer energy saving through common resource sharing. The D2D clustering can help incorporating physical relations and social interactions among the D2D user terminals. The heterogeneous network scenario through radio resource sharing between other devices. The D2D clusters can also help in reducing signaling traffic and offer improved energy performance than the traditional cellular systems [71, 72]. However, most of the studies in D2D clustering, such as in [73], have considered D2D communication forming clusters by using Wi-Fi Direct.

For mmwave D2D communication, clustering has been employed for performance analysis in mmwave D2D communication in terms of SINR outage probability, coverage probability, and area spectral efficiency [74–76] and coverage. Therefore, there is need to extend D2D clustering for mmwave D2D communication by considering the performance metrics such as energy consumption, energy efficiency, packet loss ratio, and delay in a static and dynamic environment.

7.4. Green Communications. The main challenge of 5G mmwave D2D networks will be mobile D2D devices' energy consumption. The key objective is enhancing the energy efficiency by increasing the D2D rate or decreasing the power consumed. Energy harvesting is a promising solution to enable mobile devices user equipment whose battery capacity is limited to harvest energy to prolong battery life. Therefore, the deployed mmwave D2D networks will require an analysis of energy efficiency resource allocation algorithms for an integrated mmwave D2D network by incorporating energy harvesting.

The optimization function for energy harvesting mmwave D2D networks will consider the constraints such as battery capacity and QoS and transmit power threshold. The offline and online resource allocation optimizations problems with causal knowledge should also be taken into consideration. In addition, energy-efficient sleep/wake up eNB mechanism based on Q-learning can be designed and incorporated to D2D communication in mmwave pico cells [77].

7.5. User Mobility. Most of the studies that have been carried on millimeter-wave device-to-device communication have considered static environment for cellular and D2D users. This scenario might work well for indoor users, where there is minimal mobility, but for outdoor network scenario, the assumption might not hold. Therefore, there is need to consider user mobility for the resource allocation optimization mechanisms to maximize the D2D sum rate and energy efficiency and minimize the latency and inter-D2D pairs' interference.

8. Conclusion

The paper has given a review of resource allocation in millimeter-wave D2D networks based on a new classification consisting of six different mathematical techniques as demonstrated in the taxonomy. It was found that most of these techniques can offer better results even though they are based on assumptions to reduce their computational complexity during simulation. In practical systems, some of these assumptions cannot hold for deployment of D2D pairs in the millimeter-wave band. In addition, these studies have majorly dealt with single-cell network scenarios which needs an extension to multicell networks. The multicell scenario can then be analysed by considering energy efficiency, throughput, latency, and connection density performance metrics. The survey has also pointed out the challenges that are hindering attainment of optimal results with all the features of a practical network scenario incorporated in the study. The open research issues that should be explored further by the research community to achieve an improved performance in device-to-device networks in the millimeter-wave band have also been given for a better performance mmwave D2D implementation.

Conflicts of Interest

There are no conflicts of interest for this publication.

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