IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received July 25, 2019, accepted September 4, 2019, date of publication September 11, 2019, date of current version September 24, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2940595

Video Transmission Using Device-to-Device Communications: A Survey

IBTIHAL AHMED[1], MAHMOUD H. ISMAIL[1,2], (Senior Member, IEEE), AND MOHAMED S. HASSAN[1]

[1]Department of Electrical Engineering, American University of Sharjah, Sharjah 26666, UAE
[2]Department of Electronics and Communications Engineering, Faculty of Engineering, Cairo University, Giza 12613, Egypt

Corresponding author: Mahmoud H. Ismail (mhibrahim@aus.edu)

ABSTRACT In recent years, the growing interest in video-based applications has resulted in a rapid increase in wireless data traffic and meeting the stringent quality-of-experience (QoE) requirements for such type of traffic poses a great challenge given the scarce spectrum. As a consequence, new approaches have been investigated to tackle this problem and one promising solution proposed by researchers is to exploit device-to-device (D2D) communication in video transmission. D2D communication has been presented as an innovation that can improve the cellular network performance by exploiting the proximity-based service between closely-located devices. It enhances the spectral and energy efficiencies, improves the capacity of the network and reduces the communication delay as well. Despite the above-mentioned advantages, there are some challenges in video transmission over D2D networks that need to be addressed. These issues include proposing methods for improving the quality of video streaming, management of the possible resulting interference between the D2D links and regular cellular links, resource allocation as well as appropriate selection of the mode of operation. Besides, issues related to D2D-based video caching such as clustering, energy consumption and the use of incentive-based schemes have also been discussed. In this paper, we examine the challenges of video streaming over D2D networks and comprehensively review the available solutions proposed in the literature.

INDEX TERMS D2D communication, video caching, multicasting, mode selection, reuse mode, interference management, public safety.

I. INTRODUCTION

Recently, the tremendous increase in the number of portable devices and mobile applications have prompted exponential growth in wireless traffic. Accordingly, new paradigms have been investigated to improve the performance of the traditional cellular architecture [1]. Conventional solutions like increasing the dedicated spectrum, reducing the cell coverage (through the use of femtocells) and using multiple antennas either cost much, as they usually involve deployment of new infrastructure, or are already reaching their limits [2]. device-to-device (D2D) communication is a novel approach that has been receiving much attention during the last few years as a promising solution to offload the base station (BS) or e-Node B (eNB) and relieve future network congestion [3]–[5]. D2D communications enables two devices to communicate directly without traversing the core network. The benefits of incorporating D2D communication into a traditional network include offloading wireless traffic, enhancing spectral and energy efficiencies, decreasing communication delay and boosting the system throughput [6]. Besides, D2D communication is considered as a technique to extend the cellular network coverage and improve the performance of edge users who usually encounter poor services [7].

D2D communication has already been investigated in 3GPP standardization as a proximity service (ProSe) that allows direct transmission between devices located in close vicinity. In particular, the feasibility of D2D communication within the Long Term Evolution network (LTE) and the different use cases are discussed in [8]. Moreover, the architectural enhancements required to integrate D2D communication into the available cellular network are investigated in [9]. The authors in [10] provided an overview of D2D fundamentals and standardization in 3GPP,

The associate editor coordinating the review of this manuscript and approving it for publication was Danping He.

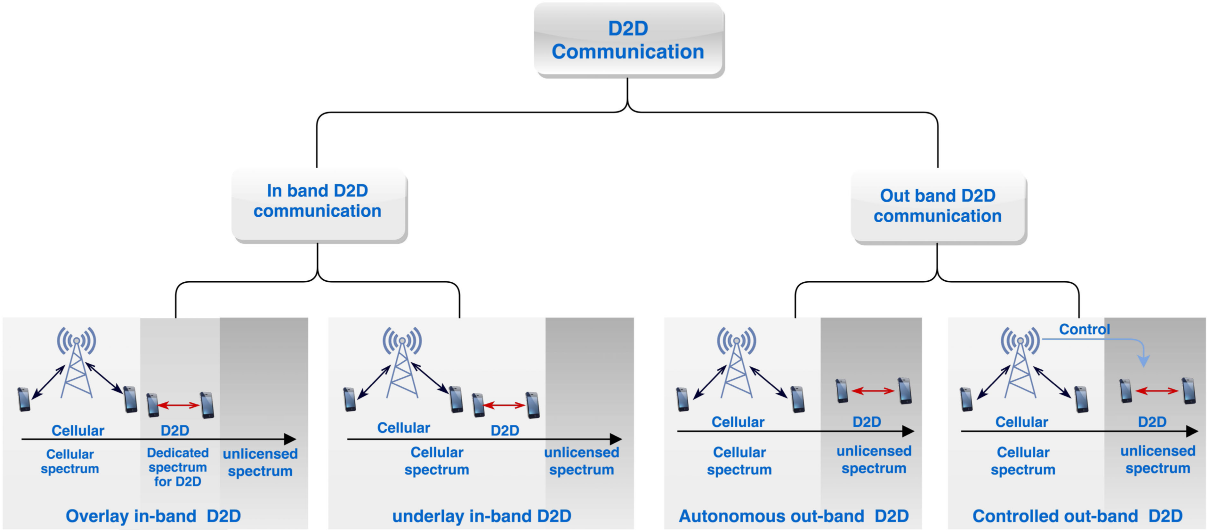

FIGURE 1. Classification of D2D communications.

including device discovery, resource allocation, channels and signaling.

Generally, based on how spectrum sharing between the D2D link and the traditional cellular user equipment (UEs) is managed, D2D communication can be classified into two modes of operation, namely, inband and outband D2D as shown in Fig. 1. Inband D2D communication occurs over the cellular spectrum, while the outband one utilizes the unlicensed frequency bands. Inband D2D is further categorized into underlay and overlay D2D communication [6]. In underlay communication, D2D pairs share the same resources with active UEs, whereas in overlay D2D, a portion of cellular resources is dedicated for D2D communication. Clearly, underlay D2D improves the spectral efficiency, however, it could introduce interference to UEs [6]. A significant amount of literature studied inband D2D communication and the majority of research efforts focused on the issue of mitigating the interference between D2D links and the UEs [11], [12]. On the other hand, overlay D2D obviously mitigates interference [13], however, its major drawback is its inefficient resource utilization. As a consequence, many works proposed the idea of outband D2D communication where D2D operation is moved to the unlicensed spectrum to completely eliminate the interference and enhance the spectral efficiency [14]–[16]. Wi-Fi Direct technology can indeed be considered as some sort of outband D2D communication. Outband D2D communication can be divided into two subcategories, controlled and autonomous. Controlled D2D is proposed to improve the reliability of outband communication by using the BS as a central control device. Managing the communication between the two different bands is an essential issue of outband D2D [7]. Moreover, based on the level of involvement of the BS (whether partial or full), controlled outband D2D communication can be categorized into four types: device relaying with a BS-assisted controlled link, direct communication between devices with a BS-assisted controlled link, relaying device with a device-assisted controlled link and direct D2D with a device-assisted controlled link [17].

A few years ago, most of mobile data traffic was due to low-rate data services and web-browsing applications. Recently, video-based applications (e.g., Netflix, YouTube, online gaming and social apps) have driven an explosive growth in data traffic [2]. According to the recent Global Internet Phenomena Report released by the networking company Sandvine in 2018, a video service like Netflix is actually responsible for 15% of the total downstream volume of traffic across the entire Internet [18]. This growing demand for video streaming puts a serious strain on wireless networks due to the scarcity of the available radio spectrum, which makes it hard to provide the users with the high throughput necessary for the expected quality of experience (QoE). Also, video streaming is very sensitive to delay since the video content should be delivered before a certain deadline. Hence, fluctuations in data rate may lead to stalling events, which greatly degrade the QoE. New techniques have thus been continuously researched in order to improve the video streaming experience. Many works in the literature suggested employing D2D communication for video transmission to offload the traditional network and enhance the quality of video streaming. D2D-based video transmission still encounters several challenges that are currently being investigated such as an extra energy overhead for D2D transmitters, complex network architecture and how to accommodate different video playback qualities for each user.

Lots of surveys on D2D communication are readily available in the literature. For example, in [6], the authors classified the existing D2D works based on spectrum sharing and provided an overview of the literature on inband and outband D2D communication. For each category, they discussed

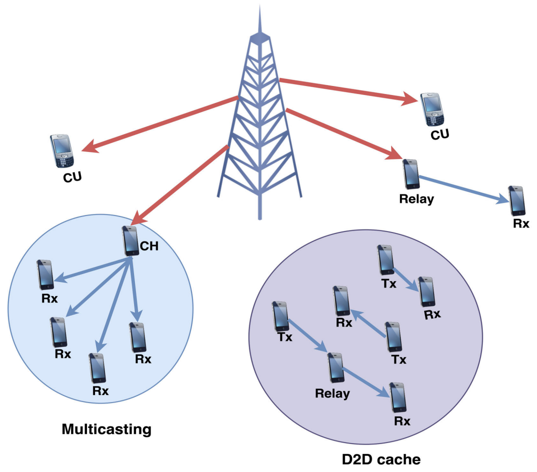

FIGURE 2. System model for video streaming over D2D networks.

the research papers in terms of energy efficiency, spectrum efficiency, cellular coverage and fairness. Also, the authors in [19] provided a comprehensive survey on interference management algorithms in D2D communication. Challenges facing D2D communication including interference mitigation, relay selection and power consumption are surveyed in [20]. In [21], the authors reviewed the existing works on D2D communication underlaying an LTE network; they focused on aspects such as D2D discovery, link establishment and D2D implementation. Finally, they highlighted the open research issues that require further investigation. On another related front, available works on D2D communication from the perspective of security and privacy are reviewed in [17] and [22]. Also, a recent survey [7] focused on different D2D communication issues including mode selection, resource management, security and mobility management.

Despite the fact that there are many survey papers in the literature that discuss different aspects of D2D communications, clearly, none of them have focused on the problem of video streaming in D2D networks. That is why in this paper, we provide a comprehensive review of the available literature on video transmission using D2D communications and this will represent our main contribution in this work.

II. D2D VIDEO STREAMING NETWORKS

A. SYSTEM MODEL AND LITERATURE CLASSIFICATION

Video streaming can generally be classified into live (real-time) video or video on demand (VOD) where video files are cached in an entity and sent to the requesters when needed. Streaming can also be classified as being either uni- or multicast where in the former the video is received by a single recipient while in the latter, it is concurrently received by multiple ones. Based on the above, D2D video streaming can be achieved through multiple different transmission scenarios and a general system model is shown in Fig. 2 where a single cell is depicted. Irrespective of the scenario considered, the concept of clustering naturally arises where a number of users are grouped together based on some criteria. If caching is used, one cluster member (called a cluster head (CH)) or more may cache popular video files for later dissemination to the rest of the members when needed. Another possible scenario is that a CH is selected and will be responsible for receiving a live video stream from the BS via a cellular link and forwarding it to the intended user(s) depending on whether uni- or multicasting is used. D2D relay-based video streaming in which a mobile device acts as a relay for one-hop transmission is also a possibility for both live and cached video. This mode can be used when the distance between the two D2D terminals is greater than a specific predefined threshold as shown in Fig. 2.

As will be discussed later in details, in cache-enabled D2D networks, the caching decision can be taken independently by each device, which is known as probabilistic (random) caching or centrally by the BS in a deterministic fashion. In either case, several performance metrics can be considered to quantify the caching gain. This might include outage probability (OP), offloading gain, network delay and energy efficiency. Also, caching decisions can be affected by multiple factors such as preferences of the clustered users, quality of service (QoS) and QoE of the target users, total energy consumed by the cluster, incentives given to terminals participating in establishing D2D connections, among many others. This will be discussed in detail in the sequel as well.

It is important to note that, generally, the algorithms proposed in the literature to tackle different practical issues in D2D networks might not be directly applicable to the case of video streaming applications and further aspects should be considered. For example, video characteristics and QoS/QoE should be targeted when resource allocation, power control or mode selection algorithms are designed. Mode selection algorithms are used to identify which mode of operation; cellular, dedicated and reuse should be chosen for a particular transmission. In the cellular mode, the BS is considered as a relay while in dedicated and reuse modes, a direct transmission link is established between devices using dedicated resources (overlay) or reusing the cellular resources (underlay). Finally, the usage of scalable video coding (SVC) or layered video in conjunction with D2D streaming whether for real-time or cached videos is a decision that can indeed affect both the design and performance of the network.

Another important aspect that needs to be tackled in D2D networks in general is interference management where interference inevitably arises in such networks due to the reuse of cellular resources. However, it is possible to devise interference management algorithms that are specifically designed while taking the nature of the video data into account.

In summary, D2D video streaming turns out to be a very rich topic and encompasses intersections between various ideas that are not limited to only what has been discussed above in this subsection. In Fig. 3, we show a Venn diagram that summarizes the most significant works in the D2D video streaming literature and the areas covered by each paper. All these works will be discussed in the following sections

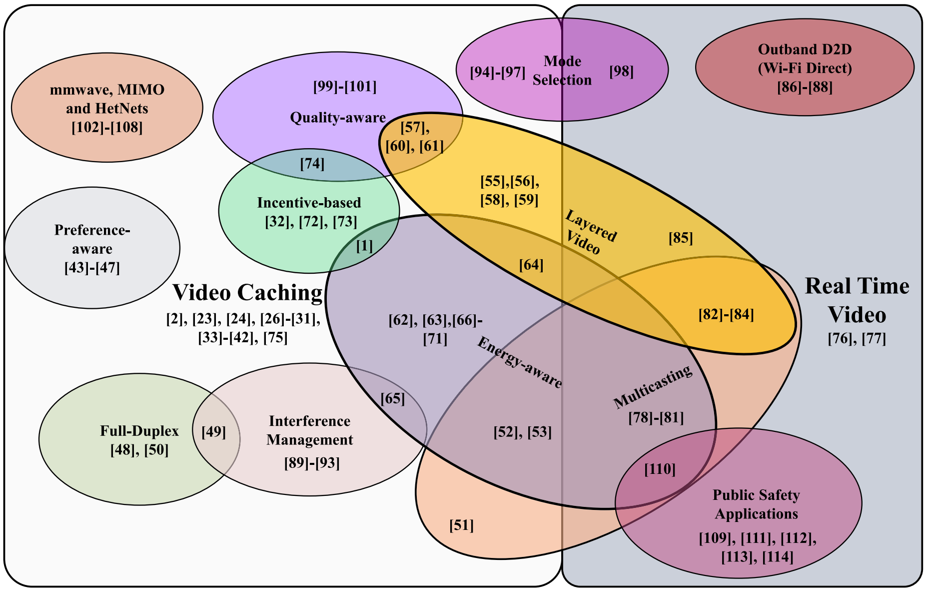

FIGURE 3. Classification of the literature on video streaming over D2D networks.

of the survey highlighting their differences and contributions according to the arrangement described in the next subsection.

B. SURVEY ARRANGEMENT

First, in Section III, we survey an area that has been extensively studied in the literature; namely combining caching video content on mobile devices with D2D communication. In this section, video caching placement and various delivery strategies are discussed followed by a review of layered video and energy-aware caching schemes in D2D networks. Following that, incentive-based D2D video streaming techniques and challenges in cache-based D2D networks are considered. In Section IV, we then present the papers discussing the dissemination of real-time video over D2D networks. Section V details the state of the art in interference management within the context of D2D-based video streaming while works related to mode selection and the effect of D2D communication on the perceived video quality are then discussed in Sections VI and VII, respectively. After that, the integration of D2D video streaming with new enabling technologies is presented in Section VIII. Finally, the use of D2D communication in public safety networks where video streaming might be needed is surveyed in Section IX before the paper is finally concluded in Section X.

III. VIDEO CACHING FOR D2D VIDEO STREAMING

It has been observed that the significant increase in global data traffic is partly a result of duplicate downloads of popular video files [23]. Therefore, the majority of existing works on video transmission over D2D links propose the idea of caching popular video files in smartphones and sharing them with other users via D2D communication to reduce backhaul traffic. D2D video caching thus exploits the large memory of smartphones and benefits from the redundancy in requested video content [2], [24]. Caching-based D2D schemes assume that mobile devices create virtual caches in which popular video files are stored according to a specific probability distribution that reflects the popularity of the file. Zipf distribution is commonly used to model file popularity. When a user requests a cached video file, it can be received directly from nearby devices without passing through the BS [25].

Video caching has thus been extensively studied in the literature [1], [2], [23]–[75]. Researchers discussed different caching strategies considering two aspects, cache placement as well as content delivery. The cache placement phase refers to the decision as of which files to be cached in which BS or UEs. In the content delivery phase, the network decides how to send the file and set various transmission parameters, for example, transmission power and channel allocation.

Most of the available D2D caching schemes are based on virtual clustering where the cell is divided into square or hexagonal virtual clusters with equal sizes, each having a cluster head and cluster members as shown in Fig. 4. Users within the same cluster can communicate and exchange file with each other via D2D links. When a user requests a specific video file from the network and the BS finds that it has been cached by one of the requester's cluster members and the distance between them is less than a specific collaboration distance r, the file is transmitted using a direct D2D link. This transmission mode is labeled as direct D2D transmission as shown in Fig. 4 and the collaboration distance is usually determined according to the transmission power. When a user within the same cluster caches the file but the distance between the pair is larger than r, a relay could be selected to transmit data between the pair. To avoid interference,

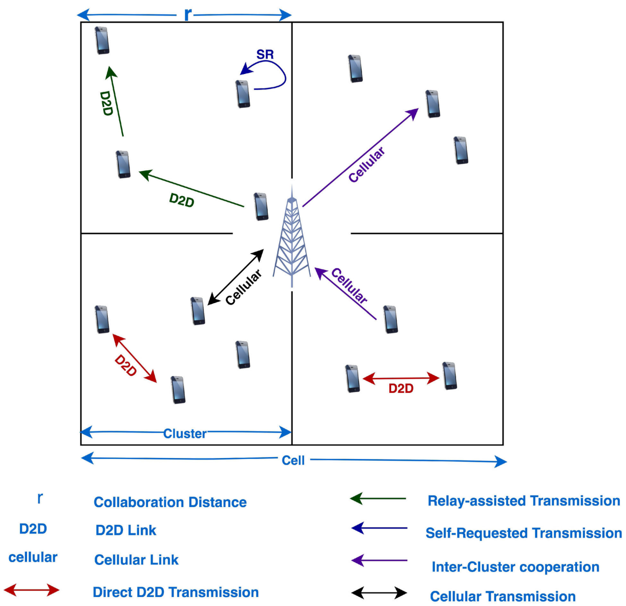

FIGURE 4. Various options for video dissemination in D2D caching systems.

researchers usually assume that only one D2D pair can be active within each cluster. If a cluster contains at least one D2D link, the cluster is considered active. If a requested file is not available in the neighborhood of the requesting device, an outage event is declared [24], [26], [28]–[31] and the BS could get the file from another cluster and forward it to the requester, this is denoted as inter-cluster cooperation. Finally, if the requester caches the file, this is called a self-requested transmission. Clearly, as the cluster size increases, the OP decreases. On the other hand, a small cluster size means a large number of simultaneously active clusters. Therefore, the cluster size is a tradeoff between spatial reuse and content reuse.

Caching schemes in the literature can be classified to being either probabilistic and is thus distributed or deterministic and is thus centralized depending on where the caching decisions are taken. In deterministic caching, the caching decision is made by a central entity (usually, the BS), while in probabilistic caching, each UE decides the file to be cached independently. Clearly, deterministic caching can be considered to provide the optimal cache placement for the network. Having said that, a possible downside of deterministic centralized caching is that it requires the knowledge of all users' locations and their channel state information (CSI) by the BS, which increases the signaling overhead [24]. In probabilistic caching, on the other hand, each user decides independently on which files to be cached [26]–[28]. This caching scheme is suitable for users with high mobility and it reduces the signaling overhead, however, it could lower the caching efficiency and leads to overlap and duplication of cache contents [30]–[32]. In the following subsection, we discuss and compare both probabilistic and deterministic caching schemes.

A. CACHE PLACEMENT AND DELIVERY STRATEGIES

1) PROBABILISTIC CACHING

Most of the works in the literature consider probabilistic caching as the strategy of choice since it is more well-suited to the characteristics of a D2D network where devices can leave and join the network at any time [33]. It is crucial to note that the decision whether to go with probabilistic or deterministic caching is completely independent from D2D scheduling, resource allocation and power control, which is mostly handled in a centralized way by the BS as one would expect. Decentralized caching scheme is proposed in [34], [35] to design a placement and delivery strategy to reduce the traffic congestion during peak hours. The authors considered local gain (when the request is served from the local memory) and global gain, which depends on cumulative memory of all users. Using information theory, they introduced a caching scheme that exploits local and global gains to maximize the rate during peak hours. The performance of a wireless probabilistic caching clustering-based network with D2D communication is discussed in the works of Ji *et al.* [26], [27]. In both works, the authors employed a grid-based clustering model where the network is divided into small clusters of equal size. To avoid interference, the authors assumed that only one potential link is allowed within a cluster and interference between clusters is mitigated using TDMA with spatial reuse. They also proposed a probabilistic caching policy with the objective of maximizing the minimum average user throughput under OP constraint. In [28], the clustering idea is still adopted but with the cell divided into hexagonal instead of square clusters to improve the spectral efficiency. Moreover, relay-assisted transmission as denoted in Fig. 4 is introduced when the separation between the members of the D2D pair is greater than r. Experimental results show that the relay-assisted approach improves the spectral efficiency with a small reduction in system throughput compared to non-relay approaches because relay transmission occupies two-time slots. Also, a D2D-enabled cache system is analyzed in [30] where the focus is on the dependency of scaling law on the cache content. The authors provided an expression for the collaboration distance r as a function of cache content parameters. They also illustrated that throughput-scaling behavior depends on the popularity of the cached video files.

Probabilistic caching is also used in [36] where jointly-optimized cache placement and delivery policies are proposed with the objective of maximizing the offloading gain. The offloading gain is defined as the probability that a user can retrieve the desired video file cached by nearby devices with a throughput greater than a predefined threshold. As for the content delivery strategy, the authors assumed that only helpers (wireless devices that accept to participate in video distribution) with distances less than the collaborative distance from the requester can serve as a transmitter. Random scheduling is also adopted where transmission occurs over time slots and each transmitter independently selects a time slot to transmit through and mutes the transmission during the remaining period. The results illustrate that the offloading gain can be maximized by optimal joint cache placement and delivery strategy. Similarly, an optimal cache placement methodology to maximize the density of successful receptions (DSR) in the presence of noise and interference is proposed in [37]. DSR is a metric related to OP and the number of receivers per unit area. In this work, stochastic geometry, in the form of the Poisson point process (PPP) model, is adopted instead of cluster-based caching to allow simultaneous transmissions. Stochastic geometry is also used in [38] where probabilistic cache placement with the goal of maximizing the throughput and hit probability is discussed. The authors defined the hit probability as the probability that the user finds the required video content in its local cache or inside a certain area. After evaluation, the authors concluded that, reliability of transmission needs to be considered to improve the throughput.

In [39], probabilistic cooperative caching where both BS and D2D caching coexist is discussed. The authors formulated a closed-form expression for the successful transmission probability, which represents the probability that video contents are transmitted successfully within a certain period. The requester can obtain the file through one hop D2D communication or from the BS. They concluded that cooperative caching can improve transmission probability by reducing redundancy between the BS and devices.

Furthermore, the authors in [40] formulated a joint D2D link scheduling and power control problem to maximize the total system throughput. They studied a one-hop D2D-assisted wireless random caching system in which a user can obtain the files from its own memory, from its neighbor through D2D links or directly from the BS. The problem is decomposed into two subproblems, a D2D links scheduling problem and a power allocation one. A D2D scheduling algorithm to maximize the number of scheduled D2D pairs under signal-to-interference-plus-noise ratio (SINR) and transmission power constraints was proposed and a power allocation algorithm is developed to maximize the minimum throughput of scheduled D2D users.

2) DETERMINISTIC CACHING

For deterministic caching, it is assumed that the users' locations and CSI are perfectly known to the BS and hence, caching decisions can be made centrally at the BS. In [31], cluster-based caching with a new inter-cluster cooperation D2D architecture is introduced with the goal of minimizing the network delay. As before, the cell is divided into smaller clusters with equal size and the users within the cluster are able to communicate directly via dedicated links. When the requested video content is not available within a specific cluster, inter-cluster cooperation is allowed thanks to the nature of deterministic caching. The BS thus gets the file from another cluster and sends it to the requester as shown in Fig. 4. Simulation results reveal that the proposed algorithm decreases the network average delay by about 45% to 80%.

Similar to [39], cooperative caching is studied in [41], however, deterministic caching is adopted where each BS takes a decision on what file to be cached based on its popularity. To achieve efficient caching, the BSs exchange their caching information through specific interfaces. In [39], only single-tier caching is considered, for more efficient caching, the authors of [41] discussed multi-tier caching where three types of caching cooperation coexist including inter-BS, inter-device and cross-tier. They formulated an optimal cooperative cache placement to reduce delivery delay and improve the hit probability (probability of being served by a D2D link). Clustering is also implemented in [42], where D2D users are divided into clusters and different frequency bands are assigned to cooperative and non-cooperative D2D links to avoid interference. The authors jointly optimized the cluster size and the bandwidth allocated to cooperative and non-cooperative D2D links with the goal of maximizing the system throughput constrained to a minimum rate requirement.

3) PROBABILISTIC VS. DETERMINISTIC CACHING

Some papers considered both probabilistic- and deterministic-based caching. The work in [24], for example, studied the performance of both schemes and analyzed the collaboration distance in each case. Also, in [2] and [29], Golrezaei *et al.* proposed splitting the cell into smaller square clusters and they compared the performance of deterministic and probabilistic caching in terms of the average number of active clusters. As expected, deterministic caching was found to provide better performance due to the fact that video files do not overlap. Furthermore, the authors formulated an expression for the scaling law of active D2D links with the number of UEs per cell in [2].

4) PREFERENCE-AWARE CACHING POLICIES

As already indicated, improving video content caching has been explored widely in the literature, however, the proposed caching policies assumed the knowledge of content popularity and adopted a homogeneous popularity model. This assumption is not intuitive because different users might have different preferences. Hence, some approaches suggested optimizing the caching policy by learning the users' preferences. In [43], for example, the authors assumed that the network does not have prior knowledge regarding the popularity of the video contents and proposed a learning-based caching algorithm to estimate the intensity function of the file requests using a kernel estimator. The algorithm aims at deciding the best (file, user) cache combination to minimize the network delay. At the initial phase of the caching algorithm, all caches are assumed to be empty and all users communicate with the BS. During the next time slot, the learning algorithm is performed to find the best (file, user) pair that minimizes the average delay and each user's cache is updated every cycle based on the final cache state. Likewise, a cache policy aiming at maximizing the offloading probability given specific users' preferences is introduced in [44]. Users' preferences are assumed to be unknown and need to be learned using

accumulated user requests. A user request is modeled by probabilistic latent semantic analysis (PLSA) where expectation maximization (EM) was used to predict the probability of request and users' preferences. Also, an approach exploiting individual preferences for caching is introduced in [45] where the hierarchical structure is used to build a statistical user preference model based on real data. The probability of requesting a file by a user is modeled as a probability that a user requests a certain genre, then a conditional probability that a file within a genre is requested. Also, a caching policy with the aim of minimizing energy consumption using users' preferences is also proposed in [46]. The authors considered two scenarios; when the users do not collaborate, i.e., a user has no knowledge about other users' preferences and when users collaborate. Results illustrated that the coordinated cache with the knowledge of users' preferences provides the best performance. Similarly, Guo *et al.* in [47] classified the UEs according to their preferences and investigated three cases; full cooperation, partial cooperation and no cooperation users' behaviors. They designed a caching strategy with the aim of maximizing the probability of finding the file in the neighboring devices. Their results provided insights into the effects of selfish caching
behavior.

5) CACHE DELIVERY WITH FULL-DUPLEX CAPABILITIES

Most of the existing literature focused on the performance analysis of cache placement and delivery when UEs have half-duplex (HD) capabilities, which may not be efficient enough to deliver video content. Consequently, cache-enabled D2D communication with full-duplex (FD) capabilities to improve the spectrum efficiency and reduce the network delay is considered in [48]. With FD capabilities, various modes of operation may occur and HD is a special case of them. Specifically, six scenarios are investigated in [48]; self-request, self-request and HD transmission, full-duplex transceiver, half-duplex receiver, half-duplex transmitter and finally, hitting outage when the file is not available in the vicinity or in the user's cache. The authors derived closed-form expressions for the successful probabilities in various modes that depend on signal-to-interference ratio (SIR) distribution and video content availability. Similarly, simulation results in [49] showed that enabling FD transmission for the D2D terminals improves the achievable throughput and video quality via decreasing the download time. Interference from D2D pairs to cellular users (CUs) is mitigated by a D2D transmitter power control algorithm. Considering FD communications, power allocation for relay-assisted D2D communication is also discussed in [50]. The objective is to maximize the D2D users' data rate while satisfying rate requirements for the UEs as well. The relay operates in FD mode, hence, it can simultaneously transmit to a D2D user and receive and forward to a UE using the same frequency band and thus achieves higher spectrum and energy efficiencies.

6) MULTICAST CACHE DELIVERY STRATEGIES

Lots of works in the literature adopted multicast transmission as a delivery strategy in cache-enabled D2D networks. Multicasting allows serving multiple users simultaneously by one transmitter when they are interested in the same content. The basic idea of D2D multicasting is dividing the users in the cell into a number of clusters based on their common interest in receiving a specific video file. Then, each CH, who has previously received the required video from the BS, simultaneously transmits it to the multiple users in the cluster through D2D links. In the deterministic-caching scheme proposed in [51], it has been reported that combining traditional video multicasting and D2D communication improved the overall data rate of the cell and, in particular, enhanced the performance of cell-edge users.

How and which UEs are to be clustered together for video multicasting has also been studied in the literature. Different metrics are adopted for optimizing the cache placement and cluster formation in multicast transmission including energy efficiency, spectral efficiency, users locations, social characteristics and hitting probability. Considering social behavior, [52] proposed a mechanism for cluster formation and CH selection using social characteristics of the users with the aim of increasing spectrum and energy efficiencies. Clustering operation is performed in three steps: cluster formation, head selection and resource allocation. The CH is selected based on two characteristics, first, it caches most of the files required by cluster members. Second, it should have the closet relationship to other UEs in the cluster. An iterative algorithm is used for cluster formation and finally, the bandwidth is allocated to CHs. In [53], the authors proposed two caching models to determine the optimal number of video files M to be cached by the CHs. In the first approach, they optimized the value of M in order to maximize the hitting probability, while in the second model they tried to find the value of M that minimizes the energy consumption. The optimal number of video files to be cached was then compared between the two strategies.

B. PARTIAL/LAYERED VIDEO CACHING IN D2D NETWORKS

Considering users' requirements for video streaming, different users may be able to enjoy different levels of QoE due to different channel conditions and allocated bandwidth. This can be achieved by using SVC where a video sequence is encoded into a base and multiple enhancement layers. The base layer contains the information required to decode the video at an acceptable quality level, while the enhancement layers are used to improve the video quality [54].

Some authors investigated the joint caching and scheduling problem for SVC. Considering SVC makes the cache placement problem more complicated and various issues should be addressed. In addition to the question of which video files to be cached, the number of layers to be cached by each user and how to transmit video content and satisfy QoS requirements of users need to also be investigated [55]. Therefore, caching policies need to be adjusted to support layered video caching as the caching decision should be taken per layer instead of per video file [56]. The work in [55] considered joint caching and SVC streaming over D2D networks. The authors assumed that the eNB caches the entire video (all layers) and due to capacity limitations, each user may partially cache the video contents. Each requester can get the video from nearby devices using D2D links or directly from the eNB if the video is not cached. The authors proposed a two-stage heuristic algorithm with the objective of minimizing the average download time for users. The first stage is the cache placement algorithm to decide the video files and the number of layers to be cached based on users' demand. Based on the caching decision, the transmission strategy is determined, constrained to the bandwidth allocated to each user. Similarly, deterministic D2D caching with different quality level video files is investigated in [57]. The authors assumed that the BS decides which files of which quality to be cached. After a requester finds the neighboring devices caching the required video file, the helper devices should be selected carefully. Therefore, the authors proposed a dynamic algorithm for node association with the goal of maximizing the average quality constrained to some playback delay. Another problem considered in the paper is request collision, which happens when multiple devices request video files from the same user. Two techniques are proposed to solve this issue; either serve only one user assuming that the others may find other helpers caching their requested file or serve users simultaneously at the cost of rate reduction. Furthermore, scheduling and admission control algorithms for a sequence of video chunks are formulated in [58]. Each chunk is encoded at various quality levels and the objective is to select the quality mode, source coding rate and the channel coding rate for each chunk for all the users. The quality of the chunk and the source coding rates selection is performed during the admission control phase, while the channel coding rates assigned by each helper are selected during the transmission scheduling phase.

Continuing along the same lines, cached and segmented video download (CSVD) has been presented in [59] where the BS splits the cell into small clusters and the UEs are assigned to each cluster based on their locations. Next, for each cluster, deterministic caching is used and the BS selects the central users as storage members (SMs) to cache popular video files. Instead of caching the complete video content in one node, the BS subdivides the video into segments and stores them in multiple SMs so that the video can be simultaneously received from multiple nodes. When a user requests a video file, there are three transmission scenarios: if the file is available in the SMs, it is transmitted directly to the requester via a D2D link. If the requester is one of the SMs in one cluster, the BS sends the video through a cellular link and asks the SMs in the target cluster to save the file. Otherwise, the BS forwards the file to the user through a regular cellular transmission. The authors extended their work and introduced a new architecture to improve the QoE of video transmission in [60] and [61]. They combined the algorithm proposed in [59] with dynamic adaptive streaming over HTTP (DASH) and evaluated the performance of the new architecture. The metrics used to evaluate the QoE were video stalling, continuity index, initial delay and the bit rate. The proposed scheme accomplishes significant improvements in QoE as captured by the above-mentioned metrics.

C. ENERGY-AWARE CACHING IN D2D NETWORKS

Clearly, energy consumption is a critical issue especially for the UEs due to their limited batteries. A D2D helper may terminate the D2D link when its battery has a little energy and this will affect the offloading gain and hit probability. This makes the energy consumed by helpers a big concern in D2D-enabled caching systems and that is why many studies focused on the energy consumed by mobile devices to deliver a particular video file to a specific requester.

The authors in [62] studied the effect of battery consumption on offloading gain. First, the caching policy is optimized with the objective of maximizing the offloading gain according to a distance-dependent caching distribution. Then, the transmission power of the helpers is optimized to minimize the energy consumption. Finally, the relation between energy cost and offloading is investigated. Results illustrated that maximum offloading gain with low energy consumption can be achieved by proper optimization of the collaboration distance, the transmission power as well as the caching policy. Also, in [63], an expression for the total energy consumed and the total hit probability for video streaming in a D2D caching system is derived. The authors considered the energy consumed by the D2D transmitter and the BS when the file is not cached and the energy consumed to access video content in storage. Their target was to obtain a relationship between energy consumption and the content distribution mechanism. In addition to the above works, the energy consumed by a helper is studied in [64]. The authors mainly considered SVC where forward error correction (FEC) and multiple description coding (MDC) are applied. In MDC, the video stream is divided into sub-streams referred to as descriptions. The authors proposed an energy-aware rate- and description-allocation technique for video transmission in which the optimal number of descriptions to be assigned to each helper is optimized with the goal of maximizing the energy savings. This is done taking into account the channel gains, distances and interference to the BS. Considering the D2D CSI and energy of the helpers, the rate of each video segment and the number of descriptions for each helper are determined. Comparing the proposed scheme to two non-optimal strategies, the results illustrate that the proposed approach conserves up to 300 Joules and enhances the QoE. Later in [65], the same authors considered the effect of co-channel interference on cellular UEs for further system performance enhancement. In particular, the aim was to achieve high energy efficiency while considering the interference between

D2D links and UEs. In [66], a caching strategy to maximize the cellular network offloading with an energy consumption constraint is investigated. Two parameters are optimized; the transmission power to minimize the energy consumption at helper devices and the caching distribution strategy to maximize the BS offloading. Also, the authors in [67] defined an optimization problem trying to satisfy energy and spectral efficiency requirements for video transmission using D2D communication. They formulated a problem with the goal of minimizing the energy consumption while meeting the rate requirements using transmission power adjustment, resource allocation and relay selection. Moreover, to avoid D2D links interruption during video dissemination due to battery outage at the helpers, a joint route scheduling and video traffic workloads algorithm based on a predefined energy budget for each device is presented in [68]. The total energy consumed in D2D cooperative video dissemination must be below a budget threshold. To avoid battery outage, the authors maximized the minimum cooperative period of all devices. The proposed framework improves the performance of D2D-based cooperative video dissemination and results in a three-fold extension in its lifetime.

On another related front, optimal caching and cooperative distance design considering throughput, energy efficiency (EE) perspectives and their tradeoff are studied in [69]. The authors considered the effect of self-caching, D2D caching and BS transmission. First, the caching policy and cooperative distance design are analyzed for the goal of throughput optimization considering two architectures; random-push and prioritized-push networks. Following that, optimizing EE, which is defined as the ratio of the total average throughput to the total average power consumption is discussed. By comparing throughput-based and EE-based cooperative distance design, it was observed that optimizing throughput is different from optimizing EE and a tradeoff exists. In [70], the authors formulated an optimization problem to jointly determine the optimal transmission and caching policies with the goal of minimizing the energy of the BS. They considered two scenarios; first when the video contents are cached at the BS and the second when caching is performed at user devices and D2D links are used to share video contents. They compared the performance of the deterministic and probabilistic caching and assessed the impacts on local caching gain and pre-download gain in the two scenarios. Results revealed that centralized caching provides better performance than D2D caching and leads to more energy saving.

Along with energy considerations, the economic aspects of D2D communication are discussed in [71]. The goal is to offload cellular traffic into multi-hop D2D video distribution links since providers charge for cellular transmission and not for D2D links. A video dissemination algorithm with the objective of cellular traffic cost minimization taking into account the energy consumed by individual devices is formulated.

D. INCENTIVE-BASED CACHING IN D2D NETWORKS

Recently, an intuitive question has emerged; why should any user cache a video file, transmit it using D2D communication and drain its battery to provide high data rate for another user. Previously, researchers assumed that users are willing to collaborate and relay data to others using a direct D2D link just out of good will. However, this is an impractical assumption. Practically, users will not help in distributing video files without getting benefits, so the providers have to pay incentives to encourage such behavior. To address the aforementioned issue, recent research directions investigated how users should be rewarded. For example, the work in [72] proposed motivating the users using a token-based strategy in which the requester purchases the service electronically from the helper and pays a token. A token acts like credit for the user so they can get relay service in the future. Likewise, an incentive mechanism to prompt users to participate in video distribution is introduced in [73]. Users are categorized into multicast and core users based on their social and mobility characteristics. Core users assist the BS in transmitting video to multicast users. A pricing-based scheme using Stackelberg game theory is proposed to reward core users. In that game, the BS is considered as a game leader that sets the initial price. After that, the followers (core users) show their strategies to the leader. A similar theory is employed in [74] for a pricing problem formulation. However, the UEs are set as leaders and the BS as a follower. Similarly, the authors in [1] proposed a contract algorithm by which the BS decides which user can be selected as a relay and determines the price to be paid for users who accept to work as sellers. They also proposed two algorithms to match between sellers and buyers with the objective of reducing the energy consumption at the BS. Incentive-based distributed cache in which users are rewarded for caching and helping in video distribution is also presented in [32] where users can elect to cache video files that increase their incentives. A major difference from the incentive-based mechanisms mentioned earlier is that the effect of interference is also considered. For each UE, the net utility is calculated as the rewards paid by the BS after subtracting the interference the D2D link introduces to the system.

E. CHALLENGES IN CACHE-BASED D2D NETWORKS

There are still some challenges in D2D-based video caching schemes that may open new research directions and need to be addressed. For example, secure communication represents a challenge in caching systems because it is difficult to cache encrypted video content. Also, the limited storage of user devices should be considered [25]. Other issues include whether a user will still accept, in spite of the incentives, to participate in video distribution or not, the effect of mobility, the need for regular updates of cache contents, the reliability of the transmission and finally, the need for efficient interference management and scheduling for D2D communication. These limitations may result in an increase in the OP. As a result, some authors, as in [23] proposed a technique to reduce the OP via proposing multiple devices to a single device algorithm, where a reference user in dense areas requests a video file and receives it from multiple serving nodes at the same time thus effectively achieving diversity in reception. They derived an expression for the OP as a function of the UE memory size, the popularity of the requested videos as well as the SINR. The effect of different degrees of mobility on the performance of D2D caching has also been studied in [75].

A brief summary of the works proposed on D2D video caching is presented in Table 1 showing the objective of each work, the analytical tools used as well as the performance metric(s) reported.

This section focused on works that studied caching techniques in D2D networks using either information theoretic or algorithmic approaches to unleash the potential of cache-enabled D2D systems. The existing works focused on reducing backhaul traffic, maximizing throughput per user or minimizing average delay and energy consumption. Future works should tackle some challenges that need further investigation. For example, the design of mobility-aware caching since the mobility of users affects the performance of caching. Also, caching techniques need to adapt to the change of popularity of content in the design of cache placement and delivery strategies. Other challenges to be considered could be interference between the users, which is usually ignored especially in grid-based caching as well as their social characteristics.

IV. REAL-TIME VIDEO STREAMING IN D2D NETWORKS

Unlike pre-coded video contents, which are well suited to D2D video caching, live video streaming has a main distinct characteristic, which is its hard deadline. That is, each packet must be received and decoded on time to be usable, otherwise, it is considered lost. Recently, many studies considered live video streaming, which is sensitive to stability and delay, over D2D communication. Real-time video dissemination (e.g., for breaking news or sports events) to a group of UEs using two transmission phases is discussed in [76]. The authors presented an approach that aims at minimizing the mean video distortion using instantly decodable network coding (IDNC) and real-time video attributes. Firstly, the BS broadcasts video packets to all UEs, but due to the network conditions, some packets might be lost. Hence, in the next transmission phase, the devices cooperate using D2D communication to retrieve the missing packets. It is claimed that the proposed scheme enhances the quality of the received video. Also, the problem of real-time streaming when multiple devices are interested in receiving the same live video has been studied in [77]. This work divided the live video stream into blocks, which are further split into smaller chunks. Each device was allowed to receive chunks via cellular and D2D interfaces, simultaneously. The authors also proposed an algorithm to minimize the transmission through the cellular interface to save cost while considering the QoE, which was defined in terms of the average number of received blocks.

A. CLUSTER FORMATION STRATEGIES IN REAL-TIME VIDEO MULTICAST D2D NETWORKS

There are some related works considering D2D cluster-assisted cellular communication in real time video stream multicasting. The real-time video streaming multicast and broadcast multimedia services (MBMS) over LTE is investigated in [78] to study the effect of integrating D2D communication for improving the QoS. The authors also proposed an approach to reduce the energy consumed by the BS and mobile devices in multicasting by forming coalitions. The energy-based cluster formation mechanism consists of two stages; first, in the initialization phase, all users communicate directly with the BS (so a cluster effectively consists of only one user) and no D2D links exist. The following step is to find the user (or cluster) C_i that consumes the highest energy per node. To reduce the overall energy consumption, the BS searches for another user C_j that when merged with C_i, the total energy consumption is reduced. This can be achieved by transmitting data to user C_j directly from the BS, then this user forwards it to C_i using a D2D link so that the total energy consumed by the newly formed cluster is lower than the energy consumed by cluster members individually communicating directly with the BS, i.e., $E_{Ci\cup Cj} \leq E_{C_i}+E_{C_j}$. This process is repeated until no further enhancement (more energy saving) can be achieved. Similarly, Shen *et al.* [79] proposed an energy-based clustering technique using the merge and split algorithm to form D2D coalitions to save the energy consumed at the BS assuming real-time video streaming from either the BS or the CH. To control the total energy per coalition, the coalition head is chosen to reduce the energy consumption and a relaxation factor is introduced to determine the acceptable level of energy consumption per coalition. On the other hand, in [80], cluster formation based on users' locations is proposed. Users close to the base station are selected as CHs that receive the video directly from the BS then relay it to other users. Comparing [80] to previous work, rather than transmitting the full video from the BS to the CH, the video is divided into segments and each CH receives a portion of the segments. Following that, each CH forwards the segments to its neighboring CHs. Finally, the complete video is transmitted to the devices within the cluster using Wi-Fi. The proposed algorithm is shown to provide better performance in terms of energy efficiency and battery lifetime.

B. REAL-TIME SVC MULTICAST D2D NETWORKS

Similar to caching, SVC multicast has been considered as an effective way for real-time video transmission. Some authors proposed multicasting real-time SVC over cellular-D2D communication to improve the users' experience as in [81] and [82]. Specifically, in [81], the authors proposed multicasting SVC over the D2D network underlaying LTE where joint resource allocation, mode selection and power

TABLE 1. Brief summary of the literature on video caching for D2D video streaming.

Problem	Reference	Objective	Proposal	Analytical tool(s)	Performance Metric(s)
Caching Scheme	[2]	Analyze throughput characteristics with the number of users per cell	Derive an expression of the number of active D2D links as a function of caching statistics, requests statistics and collaboration distance	Zipf distribution, Chen-Stein Method	Average number of active clusters
	[23]	Enhance the OP for video delivery	Propose multiple device to single device video content delivery scheme and derive an expression for OP	Zipf distribution	Outage probability
	[24]	Improving throughput of video transmission	Analyze the optimal collaboration distance for both deterministic and probabilistic caching	Zipf distributions	Average number of active D2D links
	[26], [27]	Maximize the average user throughput constrained to OP	Design optimal probabilistic caching strategy and interference mitigation transmission with spatial reuse	Information theory	Throughput, OP
	[28]	Improve spectral efficiency and system throughput	Propose a relay-assisted caching scheme	Zipf distribution	Average number of active clusters
	[31]	Minimizing the network average delay	New inter-cluster cooperation caching architecture	Zipf distribution, N-P hard	Average delay
	[34], [35]	Maximize the throughput during the peak hours	Design placement and delivery caching scheme	Information theory	Throughput
	[36]	Maximize the offloading gain	Jointly optimize cache placement and scheduling policies	Zipf distribution, Poisson point process (PPP)	Offloading gain
	[37]	Maximize the Density of Successful Receptions (DSR)	Develop an optimal cache delivery in the presence of interference and noise	Stochastic geometry	DSR
	[38]	Maximize throughput and hit probability	Formulate a closed-form of throughput and consider the reliability of transmission (content delivery)	Stochastic geometry tools	Throughput
	[39]	Maximize the successful transmission probability in cooperative cache placement	Derive a closed form expression for successful transmission probability and reduce the redundancy between the BS and devices	Stochastic geometry	successful transmission probability
	[41]	Minimize delivery delay and improve the hit probability for multi-tier cooperative cache	Jointly optimize cluster size and bandwidth to be allocated to each user to achieve the objective	————	Delay, hit rate
	[42]	Maximize the system throughput taking into account the minimum rate required by each user	Jointly optimize cluster size and bandwidth to be allocated to each user to achieve the objective	————	Throughput
	[43]–[47]	Design user preference learning-based caching algorithms considering different metrics: delay, energy consumption, hit probability	Find the best (file, user) pair	Kernel estimator, Expectation maximization	Delay, energy consumption
	[53]	Determine the optimal number of video files to be cached	Analyze caching hitting probability and energy consumption	Stochastic geometry	Hitting probability, ratio of energy consumption
	[55]	Jointly optimize the caching and scheduling strategies for SVC streaming	Proposed a two-stage heuristic algorithm to determine files to be cached, the number of layers each user cache and scheduling strategy for each layer to minimize the average download time	NP-hard and a heuristic solution	Average download delay
	[57]	Maximize the average quality constrained to playback delay, investigate request collision problem	Proposed a dynamic algorithm for node association problem and develop two techniques to serve multiple users	————	Playback delay, PSNR
	[59]	Improve the average and aggregate throughput of video streaming	Introduce a new algorithm Cached and Segmented Video Download (CSVD) which subdivides video into segments then caches them in UEs	Discrete EVent System Specification (DEVS)	Average and aggregate data rate
	[60], [61]	Enhance the QoE of video streaming	Combine proposed algorithm CSVD with DASH technique	Discrete EVent System Specification (DEVS)	Video stalling, Video continuity index, Initial delay, Video bit rate
	[75]	Study the influences of mobility and file size on the network performance	————	Stochastic geometry analysis	Throughput, PSNR
	[88]	Enhance the system throughput and video quality	Propose a D2D assisted architecture in which video is transmitted using D2D and cellular link concurrently	————	Throughput, PSNR
Energy Consumption	[62]	Study the effect of battery consumption in offloading gain	Propose cache policy to maximize the offloading gain and then optimize to minimize energy consumption, find the relation between energy cost and offloading	Convex optimization	Outage probability
	[63]	Obtain the relationship between energy consumption and content distribution	Formulate expressions of the average energy consumption and hitting probability to deliver a requested video file	Stochastic geometry	Total hit radio and average energy consumption

control are addressed with the goal of maximizing the total network throughput. Each video stream is encoded into L layers and the user can receive at least the base layer when a certain SINR threshold is met. Each D2D pair shares the resources with one cellular user and introduces interference. To mitigate interference, the authors fixed the transmission power of UEs and adjusted the power of the D2D transmitter. The problem is then decomposed into two subproblems; first selecting the D2D pairs to access the network, then assigning resources. Simulation results showed that the proposed model improves the overall system throughput while providing better video quality. Also, a D2D cooperative-assisted algorithm is introduced in [82] to achieve the required QoE for each UE where communication occurs in two steps; multicast and cooperative. Firstly, the BS multicasts the video content to a group of UEs via cellular links. Afterwards, in the cooperation stage, the users who successfully decoded all video layers (referred to as the responsible UEs) assist other UEs (the target UEs) to meet their QoE by transmitting the needed data using D2D communication. Similar to [52], in [83], clusters are formed based on user preference, social attributes and location information. First, the BS multicasts the video base layer to all users using minimum transmission rate and the highest-rate link is then selected for enhancement layers transmission. Clearly, some users with bad channel quality might be unable to correctly decode all enhancement packets, hence users multicast enhancement layers to each other to improve their QoE.

Even though most of the available work in the literature employs SVC as a video coding technique, experimental results conducted in [84] to compare different coding techniques revealed that MDC is the best encoding scheme for real-time D2D video streaming from the QoE point of view.

C. Wi-Fi DIRECT D2D NETWORKS

Wi-Fi direct is a technique that allows users to communicate directly with each other without having to traverse the cellular network. Consequently, Wi-Fi direct can be thought of as a form of D2D communications. A Wi-Fi direct group consists of a group owner (GO), which acts as a Wi-Fi access point (AP) and group members connected to the GO. In [85], a technique to offload cellular networks and reduce the number of resources needed for video streaming by using different radio access technologies such as Wi-Fi Direct and LTE Direct was proposed. By comparing different paths, the best air interface is selected and when the video is transmitted using Wi-Fi Direct, the number of used LTE resource blocks (RBs) is minimized. Simulation results showed that there is a 16% reduction in the number of used RBs that can be used to serve other users.

Although D2D communication can indeed relieve the congestion in cellular networks by offloading data traffic, this congestion can actually be inherited or passed on to the D2D links themselves. This congestion may result in wireless access issues due to simultaneous connections from multiple D2D pairs. In addition, users could still be receiving data from the eNB via cellular links while forwarding it to other UEs using outband D2D communication. The existence of two types of connections may thus lead to cross-network interactions and eventual degradation in the performance of D2D transmission. To overcome these problems, powerful medium access control (MAC) techniques are needed for efficient coordination of D2D transmissions. Using Network Coding (NC), the work in [86] presented an adaptive cooperative NC-based MAC (ACNC-MAC) approach for Wi-Fi direct D2D communications.

Not only can Wi-Fi direct be used to offload a cellular network but it can also offload Wi-Fi APs in dense areas. For example, in [87], the authors considered an area with high-density traffic where multiple users are interested in downloading the same video file from a Wi-Fi AP. When all users try to download the file simultaneously, this increases the interference level and results in rate degradation. Hence, the authors suggested using Wi-Fi direct as a solution to offload the AP. Clustering and scheduling algorithms are used to divide users into groups and organize files transmission where clustering is based on the position of users; users close to each other form a cluster. The user located at the center of the cluster is selected as a GO, which receives the file of interest from the Wi-Fi AP and forwards it to the group members. In order to further reduce the interference between clusters, power control techniques are applied as well.

In summary, the works in this section discussed real-time video streaming where multicasting was proposed as an efficient way to stream video to a group of UEs. Most of the presented papers studied cluster formation techniques from the perspective of energy consumption. Within this context, further study on energy harvesting for cluster heads could be a useful research direction as a way to decrease their energy consumption. Also, Wi-Fi direct was proposed as a technique to improve the performance of D2D by using the soft-AP technique to enhance connectivity. In the future, if Wi-Fi direct becomes widely spread, a deeper investigation will be required to improve the coexistence with and reduce the interference introduced to other devices occupying the unlicensed spectrum.

V. INTERFERENCE MANAGEMENT IN D2D VIDEO STREAMING

As mentioned earlier, introducing D2D communication imposes various challenges including mode selection, interference management as well as device discovery and security. An important issue that needs to be addressed in D2D communication underlaying cellular networks is the mutual interference between cellular and D2D links in order to maintain an appropriate level of QoS. Clearly, integrating D2D communication into cellular networks introduces two kinds of interference, namely, co-tier and cross-tier interference. The former is the interference between D2D pairs when multiple pairs share the same resources while the latter occurs between D2D and UEs when D2D pairs reuse the same resources allocated to UEs. These two types of interference can occur between users within the cell; intra-cell interference, or between users from adjacent cells; inter-cell interference [7]. Fig. 5 depicts different types of interference in D2D underlaying cellular networks. Several interference management mechanisms have thus been presented in the literature. These mechanisms target allocating radio resources

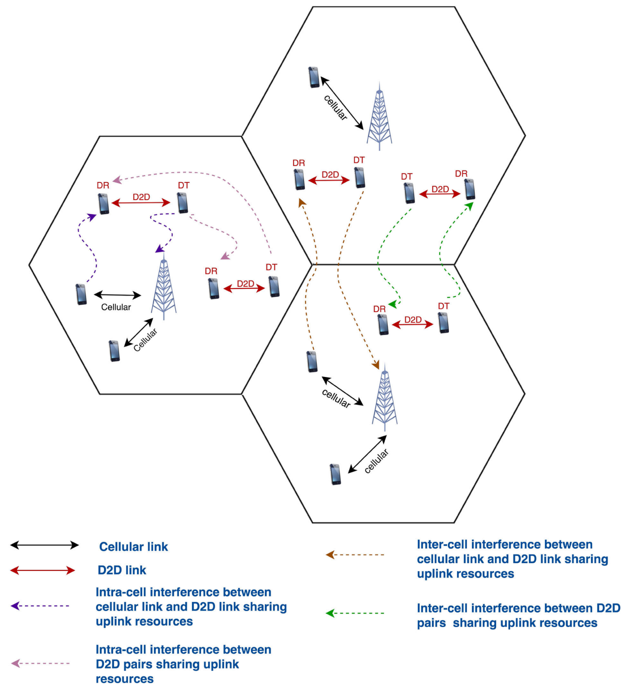

FIGURE 5. Types of interference in D2D-underlaid cellular networks.

(power and bandwidth) to cellular and D2D users in an efficient way so as to decrease the level of interference. This, in turn, maximizes the system throughput as well as preserves power [7]. Usually, resource allocation is jointly discussed with mode selection but in this subsection we will focus on works that have discussed interference management schemes only. It is also important to note that the interference management problem is clearly not exclusive to video streaming over D2D and that is why the amount of literature available on this topic is simply huge. That is why in this subsection, we focus only on works that addressed the effect of interference within the context of video streaming over the D2D links and ways to mitigate this.

To mitigate intra-cell interference between D2D pairs, some researchers allowed only one D2D transmission to be active per cluster in each time slot [24], [29], [31]. Others have adopted outband D2D communication in the form of Wi-Fi Direct to completely avoid interference to the UEs as previously discussed in Section IV-C. A third group completely ignored the existence of inter-cell interference between cellular and D2D links. For example, Golrezaei *et al.* assumed that inter-cell interference is small and can be neglected [24], [30]. Also, in [28], inter-cell interference is ignored via adjusting the transmission power such that the cluster coverage is bounded by a radius r.

Acknowledging the existence of inter-cell interference, many works have proposed the use of power control to limit its level. For example, the authors in [88] proposed a new algorithm to simultaneously send video using cellular and D2D links. When the transmitter and receiver are closely located, D2D transmission is enabled and the BS assigns a reuse uplink frequency for the D2D link while keeping the cellular transmission. A power control algorithm is then employed to limit the interference between the cellular and D2D links to a specific threshold.

A different approach for handling interference has been proposed in [89] where the main idea is to control the interference level between the D2D and cellular links based on the importance of the video frames being transmitted. Specifically, based on whether the data belongs to an I-, P- or B-frames. The authors considered a network model consisting of an LTE UE that is uploading a video file to the network and a D2D user who is simultaneously transmitting data traffic to its neighbor. The D2D transmitter adjusts the probability of transmission depending on the type of frame being uploaded by the UE assuming that any damage in the I-frame affects the whole group of pictures (GOP). The authors formulated an optimization problem using the Markov process to maximize the throughput of the D2D link constrained to achieving a minimum peak signal-to-noise ratio (PSNR) for the video being uploaded to the network by the LTE UE. A very similar idea has been investigated in [90] where a city monitoring application is presented in which video streams from surveillance cameras are first processed for object detection purposes by real-time resources then uploaded to the network. The objective is to control the interference at the BS from D2D links that reuse the uplink spectrum. Based on the frame type and D2D transmission probability, a D2D transmitter decides whether to transmit data and interfere with the uplink video transmission or not. When an I-frame is being transmitted, the D2D transmitter chooses not to communicate with its neighbor and the interference at the eNodeB is reduced. Otherwise, if B or P frames are transmitted, the D2D link is established and interference will be introduced to the BS.

The problem of resource allocation in video streaming D2D communications is tightly coupled to interference management and they both could actually be jointly tackled as we stated earlier. Wu *et al.* investigated this issue in [91] and [92]. In [91], a sub-carriers and transmission power allocation algorithm for each D2D is designed with the goal of minimizing the video mean square error (MSE) for simultaneous k D2D pairs. The allocation is based on the channel state and video rate distortion. Similarly, a joint sub-carriers assignment and transmission power allocation algorithm with the goal of maximizing the overall video quality is proposed in [92] where k D2D pairs and N sub-carriers are assumed. Initially, randomly chosen N D2D pairs are assigned to N sub-carriers. Then using iterations, the remaining D2D pairs are assigned to sub-carriers while considering co-channel interference to the pre-assigned D2D pairs so that the overall video MSE decreases.

In summary, although many of the interference mitigation methods discussed here are similar to conventional interference management techniques, new techniques have also been proposed to reduce the interference based on video characteristics such as the frame type being transmitted. Also, virtually all of the discussed works focus on omnidirectional antennas. However, interference management schemes for directional interference in next generation mmWave-based cellular systems could be a future research direction that needs to be considered.

VI. MODE SELECTION SCHEMES IN D2D VIDEO STREAMING

As mentioned earlier, there are three modes of operation for D2D communications; dedicated, reuse and cellular. Mode selection determines whether to use dedicated or reuse resources [93]. This topic has got considerable research interest and is usually jointly studied with power control, resource allocation or channel assignment. It is also important to note that it is not exclusive to D2D video streaming but is presented in the literature within different contexts. In this section, we will focus only on the works that consider mode selection in the context of D2D video streaming. We start with [94] where a joint mode selection and video coding algorithm for video streaming is discussed to maximize the video quality in consideration of maximum energy consumption. After selecting the coding scheme for each frame (I, P or B), it is forwarded using one of the possible transmission modes. Similarly, mode selection is jointly considered with power control for variable bit rate (VBR) video streaming in [95] aiming at maximizing the overall data rate while considering buffer utilization (buffer underflow and overflow events). Transmission power in each of the three possible modes is determined then the optimal mode that achieves the best data rate is selected. Simulation results showed that the proposed strategy performs better than using one mode for transmission. Mode selection is also studied in [96] and the mode is chosen based on the channel quality index (CQI). However, only cellular and dedicated modes are considered to avoid interference to UEs in the reuse mode. In a similar way, using outband D2D, the transmission mode is chosen to maximize the throughput under a packet delay constraint in [97]. Based on channel quality, the packet is transmitted directly from BS or through a relay via a D2D link.

As a future direction of research, it is important to realize that the frequency of execution of the mode selection algorithm depends on the devices distribution as well as their mobility. Therefore, how often mode selection should be done has to be considered. Furthermore, reducing mode selection overhead is another possible problem that can be tackled in order to improve the performance of the network.

VII. QUALITY-AWARE STREAMING FOR D2D VIDEO DELIVERY

As mentioned in Section I, video-based applications have become the dominant traffic in wireless networks and in this type of applications, minimum requirements on the QoE of the end user need to be met. QoE is generally linked to two main factors: video quality and continuity of streaming, both of which are greatly influenced by channel quality and the employed resource allocation scheme. In this section, we focus on works that took into account the end-user QoE while designing the video delivery algorithms used by the D2D links rather than the typical data rate or throughput as their performance metric. Among the works discussed earlier, [57], [60], [61] and [82] fall under this category. In what follows, we discuss other similar related works.

For a high-quality video with low-latency constraints, the authors in [74] proposed a joint source selection and power control mechanism to select the best source device. The power of the selected device is then allocated to enhance the video quality by calculating the Stackelberg equilibrium that considers the benefits of both the BS and the source. Similarly, to improve the QoE, the work in [98] introduced a QoE-aware resource allocation algorithm for adaptive D2D video streaming. In adaptive video transmission, there is a tradeoff between video quality and the number of stall events. Transmitting video with high data rate results in high quality but this may lead to stall events under bad radio conditions. The proposed scheme aims to maximize the quality of video while taking into account the number of stall events. The video is encoded at multiple quality levels and the optimal number of layers for each user should be determined. After calculating the rate for each user, a high-quality level will be selected when the buffer queue is long and low quality when the buffer is empty. The proposed scheme performs better than QoE-oblivious resource allocation schemes in terms of quality and number of stall events. Also, a QoE-aware power allocation algorithm for video transmission is presented in [99] to improve the user experience. The approach was to formulate an optimization problem that maximizes the video quality for all D2D users subject to the minimum data rate needed by each user, a maximum transmission power and a specific level of interference that can be tolerated. Similar to [60] and [61], DASH is adopted for video streaming in [100]. Using the max weighted independent set (MWIS) and FlashLinQ link methods, scheduling and streaming algorithms are designed to maximize the quality of video transmission. First, scheduling is performed to decide which D2D pairs will transmit at each time slot by considering the interference threshold. Each video file is then split into chunks and each chunk is encoded at different quality levels so that in the next transmission step, each scheduled transmitter determines the quality level of each chunk.

It can be seen that all the papers discussed in this section considered adaptive video streaming by dividing the video into sequential chunks with multiple quality levels to match the bandwidth availability. Possible future work can also consider energy consumption, which is a factor that heavily affects the user experience. Additionally, all papers considered only a single cell model. Another possible direction is thus to design low complexity QoE-aware resource allocation schemes for multiple cells.

VIII. D2D COMMUNICATION WITH NEW ENABLING TECHNOLOGIES

Recent generation network technologies (4G and 5G) incorporate many new techniques that have been integrated to improve the performance. This includes the use of millimeter wave (mmWave) spectrum, massive multiple-input multiple-output (MIMO), heterogeneous networks (HetNets) and cognitive radio capabilities (CRN) [101]. Integrating these technologies into D2D proximity service provides benefits such as mitigating the interference and supporting high throughput. In this section, we shed some light on works that have tackled these issues, again within the context of video streaming.

The use of mmWave spectrum is one of the new enabling technologies for next generation cellular systems. Due to the abundantly available bandwidth over this band, it is expected that this technology will have a very positive impact on video transmission. By exploiting mmWave, D2D multi-hop transmission is introduced in [102] to maximize the quality of video transmission via selecting the optimal route. A similar problem is addressed in [103] where a routing selection algorithm for multi-hop D2D communication was proposed while taking into account the effect of interference that exists in high-directional millimeter-wave propagation.

D2D-underlaying cellular networks with MIMO-enabled devices can significantly enhance system capacity. Scaling laws of throughput for MIMO systems are considered in [104], [105]. The work in [104] investigated a cache-induced MIMO hierarchical cooperation approach where the network is split into clusters and one transmission is active per cluster with more than one cluster allowed to be active simultaneously. The proposed scheme consists of two phases: the hierarchical caching placement, which is the cache initiation phase to decide how to distribute the video contents into caches of different nodes and the tree-graph-based content delivery phase. The content delivery scheme consists of four layers: source determination layer, routing layer, cooperation layer and physical layer. The authors analyzed the throughput performance of the proposed approach and they claimed that the proposed scheme provides significant throughput gain compared to cache-assisted multihop approach. Finally, the throughput scaling law with the size of caches of the proposed scheme was derived. Similarly, the caching network based on hierarchical cooperation is discussed in [105]. Different from [104], here the authors investigate the throughput scaling with the number of users. Their analytical results revealed that the average aggregate throughput is almost linear with the number of users. Also, the authors in [106] proposed optimal as well as heuristic algorithms for precoding and power allocation in multicasting D2D networks employing massive MIMO at the BS. Simulation results show that the proposed solutions are superior to the conventional precoding and power allocation schemes. Full as well as partial CSI were considered in this work.

On another related front, the use of HetNets is expected to dominate in the near future. HetNets promise advantages such as offloading the cellular network, improving the data rates and expanding the coverage areas. This is achieved through the use of smaller cells including pico- and femtocells. However, the main issue in using this technology is that the picocell edge users (PEUEs) suffer from low video quality due to interference from the much stronger microcell eNBs. The work in [107] aims at improving the video quality of PEUEs by using two transmission paths; a direct path from the picocell eNB and a relay-assisted path from the picocell eNB to a selected relay then to PEUEs via D2D links. The second path is used only to recover frame losses if required as the relay sends the lost packets to the user until the frame is recovered. Comparing the proposed mechanism to the conventional scheme when there is only one transmission path from the picocell eNB to PEUEs and frame freeze is used as a frame recovery technique shows that the proposed approach enhances the video quality due to frames recovery using the extra added path.

IX. D2D VIDEO STREAMING APPLICATIONS

D2D video streaming can generally be used in local services (e.g., social video sharing and local advertising), emergency communications and Internet-of-Things (IoT) improvement. D2D is also considered as a technique that can significantly improve the performance of a cellular network when natural disasters such as earthquakes and hurricanes happen because the conventional network may be severely damaged [108].

Current public safety networks mainly depend on voice and messaging services, which should be evolved to support broadband services such as video streaming, image transfer and database access. Transmitting videos and images might help in solving some challenges related to public safety such as giving situation awareness to first responders and provide powerful evidence. For this reason, D2D communication has been exploited in public safety networks to transmit and receive real-time video, images and critical information to/from disaster sites in [109]. In this work, a cooperative cluster formation approach with the target of minimizing the energy consumption of UEs using a merge algorithm is suggested. The proposed approach conserves the energy in both uplink and downlink directions. Another example is given in [110] where a video with a high resolution is transmitted by a helicopter from a disaster location to a command center. After that, the data center multicasts the information to first responders. Moreover, Yaacoub studied the performance of D2D communications in public safety networks in [111] where a coalitions formation algorithm is proposed to maximize the minimum throughput. The considered system consists of a BS and multiple users forming clusters where only one device (a CH) communicates with the BS, receives video directly and then forwards the data to other UEs. In the beginning, all UEs are connected to the BS, next, the UEs are sorted in an ascending order according to their achievable throughput

TABLE 2. Brief summary of the literature on interference management, mode selection, video quality-centric schemes as well as the use of D2D video streaming in public safety networks.

Problem	Reference	Objective	Proposal	Analytical tool(s)	Performance Metric(s)
Energy Consumption	[64]	Enhance the QoE and conserve the energy consumed by helpers	Propose Energy-Aware Rate and Description Allocation strategy	Genetic algorithms	Energy consumption, PSNR
	[66]	Maximize the cellular network offloading taking into account energy consumed by helpers	Optimize two parameters: caching policy and transmission power	Convex optimization, Zipf distribution	Energy cost ratio
	[67]	Minimize the total energy consumption subject to rate requirement	Define an optimization problem considering relay assignment, resource allocation and power control	Mixed-integer linear programming	Total energy consumption
	[68]	Battery outage avoidance during video transmission	Efficient routes and video traffic workloads scheduling constrained to predefined energy budget for each UE	Convex optimization, Alternative Direction Method of Multipliers	PSNR, cache hit, D2D link throughput, cooperation duration
	[69]	Investigate the optimal cache policy from throughput and energy efficiency perspectives	Optimize caching strategy and cooperation distance in term of throughput and energy efficiency, then characterize the trade-off between them	Concave and quasi-concave programs	Throughput, energy efficiency
Real-time video streaming	[76]	Improving real-time video quality	Drive a mean video distortion minimization problem	Backward induction algorithm	Average PSNR
	[78]	Minimizing energy consumption and improving QoS	Coalitions formulation to save energy	Merge split algorithm	PSNR, percentage of energy saved at the BS
	[79]	Energy-saving model for video sharing	Using merge-split algorithm to form coalitions constraints to total energy consumption per cluster	Merge split algorithm	Normalized energy consumption
	[81]	Multicasting real-time SVC over D2D network	Jointly optimized resource allocation, mode selection and power control with the goal of maximizing the overall throughput	Greedy and heuristic algorithms	PSNR
	[82]	Efficient video multicast to satisfy QoE for UEs	Propose a model that combines three techniques: D2D communication, Hierarchical Modulation and Fountain Coding	Stochastic geometry	Average PSNR
Incentive-based D2D	[1]	Utilize D2D link to offload cellular network and reduce BS energy consumption	Define a price-based approach to ensure users will accept to act as a relay and propose two optimal matching techniques between buyer and seller to minimize the BS energy consumption	Matching theory	Total rewards paid by BS
	[32]	Distributed cache placement that maximizes the BS offloading	Propose an incentive-based distributed cache placement that rewards users for caching and relaying content subject to the interference it introduces to BS	Stackelberg game	Average total interference to the Base station
	[72]	Motivate selfish users to collaborate and help other devices to achieve their rate requirements	Propose token-based scheme that inspires user to act as relays and model their decision as Markov decision process	Markov decision process, learning algorithm	Outbound relay demand rate, Inbound relay demand rate, Throughput gain relative to direct transmission
	[73]	Inspire users to participate in video distribution to help to offload cellular network	Propose price-based incentive mechanism	Stackelberg game theory	Offloading rate, Price for core users
Interference Management	[24], [29], [31]	Interference avoidance between D2D pairs	Allow only one active D2D link per cluster	———	———
	[49]	Interference management for full-duplex D2D system	Applying power control and limited-area algorithm to reduce the interference	———	Throughput
	[88]	Eliminate the interference between UEs and D2D users	Adopting power control algorithm	———	Throughput, PSNR
	[89]	Interference management between cellular user and D2D pair	Formulate a content-based interference management problem that maximize the D2D link data rate constrained to PSNR of video being uploaded by cellular user	Markov process, Linear programming	PSNR, D2D throughput
	[91]	Minimize the video MSE for D2D pairs	Efficient resource allocation (sub-carriers and power control)	Heuristic algorithm	SER, PSNR
Mode selection	[94]	Maximize video quality	Propose an optimal code mode and mode selection algorithm	———	Video quality
	[95]	Maximize the total data rate while avoiding buffer underflow and overflow events	Formulate joint power and mode selection strategy	———	throughput, buffer utilization
	[96]	Study the effect of mode selection on resource efficiency	Propose a channel state based mode selection algorithm that maximize the resource efficiency by finding the proper mode	Heuristic algorithm	Resource Efficiency
Quality-aware streaming for D2D video delivery	[74]	Improve video quality	Introduce a joint source selection and power control algorithm	Stackelberg game theory	Distortion reduction
	[98]	Improve the quality of experience of video streaming subject to a number of stall events	Propose a QoE-aware resource allocation algorithm for adaptive video streaming	Lyapunov drift-plus-penalty method	Quality level, PSNR, number of stall events

so that the first device is the one with the worst channel conditions. Starting from the first UE, the D2D link that maximizes the rate is selected. If this UE is a CH, then the link to the BS is disconnected and the CH and group members are connected to the device that maximizes their rates using D2D links. Furthermore, a relay selection algorithm is introduced

TABLE 3. Brief summary of the literature on interference management, mode selection, video quality-centric schemes as well as the use of D2D video streaming in public safety networks.

Problem	Reference	Objective	Proposal	Analytical tool(s)	Performance Metric(s)
Quality-aware streaming for D2D video delivery	[99]	Maximize the video quality	Formulate a QoE-aware power allocation optimization problem	Convex optimization	Data rate
D2D communication with new enabled technologies	[102]	Maximize the video quality	Propose a multihop routing scheme using mm-wave and D2D communication	————	Throughput, Video quality
	[104], [105]	Combine caching policy with hierarchical cooperation to improve the throughput performance	Analyze the throughput performance and obtain the scaling law of throughput of proposed scheme	integer optimization	Throughput
	[107]	Improve video quality for pico-cell edge users	Introduce a second transmission path BS-relay for frame recovery using D2D link between relay and receiver	Heuristic algorithm	PSNR
D2D video streaming in public safety networks	[111]	Maximize the minimum data rate of UEs in public safety network	Propose an efficient clustering approach	Max-min optimization	Minimum effective rate, PSNR
	[112]	Improve the data rate of users when the disaster site is far from the BS	Proposed a relay selection scheme based on the path throughput	————	Throughput
	[113]	Enhance the aggregate data rate of a public safety network	Proposed a resource allocation and scheduling approach considering the interference level	————	Throughput

in [112] to expand the coverage and improve the throughput of UEs when the disaster location is far from the BS. The data is transmitted to the selected relay using D2D communication then a direct link is used to forward this data to the BS. A relay is selected based on the relay-path throughput; a UE with the highest-path throughput is chosen as a relay. Finally, a resource allocation algorithm for D2D communication to improve the aggregate throughput of a public safety network is considered in [113]. Multiple D2D pairs are allowed to share the same resources when the interference level is below a specific threshold. Two scheduling algorithms are studied for that purpose; round robin and proportional fair.

Clearly, the papers that considered the usage of D2D communications for video streaming in public safety networks focused on coalition-formation strategies for the purpose of minimizing energy consumption and improving the system throughput. Interesting topics for future work include investigating the scenario with multiple cells where inter-cell interference should be considered. Another interesting direction is to consider both throughput maximization and energy consumption in cluster-head selection and coalitions formation and also include energy constraints for each device in addition to minimizing the energy consumption of the coalition.

Tables 2 and 3 summarize the proposed approaches in interference management, mode selection, quality-aware streaming schemes and the use of D2D in public safety networks in terms of problems tackled, proposed solutions, analytical tools as well as performance metrics.

X. CONCLUSION

D2D communication is presented as a key solution to enhance the performance of traditional cellular networks. Over the last decade, multimedia applications have constituted the main drive of the growing demands of cellular data traffic and D2D is proposed as a technique to offload wireless networks and can indeed be exploited to achieve high-quality video transmission. In this survey, we have provided a comprehensive review of the available literature that discussed video transmission using D2D communications. Several techniques were discussed related to combining caching of video files with D2D communications, resource management, interference management, mode selection and video quality-aware streaming schemes. Lastly, this survey also highlights the possibility of using D2D communication in the area of public safety networks.

REFERENCES

[1] L. Xu, C. Jiang, Y. Shen, T. Q. S. Quek, Z. Han, and Y. Ren, "Energy efficient D2D communications: A perspective of mechanism design," *IEEE Trans. Wireless Commun.*, vol. 15, no. 11, pp. 7272–7285, Nov. 2016.

[2] N. Golrezaei, A. G. Dimakis, and A. F. Molisch, "Device-to-device collaboration through distributed storage," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2012, pp. 2397–2402.

[3] L. Aymen, B. Ye, and T. M. T. Nguyen, "Offloading performance evaluation for network coding-based cooperative mobile video streaming," in *Proc. 7th Int. Conf. Netw. Future (NOF)*, Nov. 2016, pp. 1–5.

[4] M. Sun, Y. Zou, M. Qian, J. Zhu, and Q. Wang, "Exploiting multi-radio cooperation in heterogeneous wireless networks for absolute security against eavesdropping," in *Proc. ITU Kaleidoscope, Challenges Data-Driven Soc. (ITU K)*, Nov. 2017, pp. 1–6.

[5] Q. Zhao, Y. Mao, S. Leng, and H. Wang, "Multimedia traffic placement under 5G radio access techniques in indoor environments," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2015, pp. 3891–3896.

[6] A. Asadi, Q. Wang, and V. Mancuso, "A survey on device-to-device communication in cellular networks," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 1801–1819, 4th Quart., 2014.

[7] F. Jameel, Z. Hamid, F. Jabeen, S. Zeadally, and M. A. Javed, "A survey of device-to-device communications: Research issues and challenges," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 2133–2168, 3rd Quart., 2018.

[8] *Feasibility Study for Proximity Services (ProSe) (Release 12)*, document TR 22.803 v. 12.2.0, 3GPP, Jun. 2012.

[9] *Study on Architecture Enhancements to Support Proximity Services (ProSe) (Release 12)*, document 3GPP TR 23.703 v. 1.0.0, Dec. 2013.

[10] X. Lin, J. Andrews, A. Ghosh, and R. Ratasuk, "An overview of 3GPP device-to-device proximity services," *IEEE Commun. Mag.*, vol. 52, no. 4, pp. 40–48, Apr. 2014.

[11] T. Peng, Q. Lu, H. Wang, S. Xu, and W. Wang, "Interference avoidance mechanisms in the hybrid cellular and device-to-device systems," in *Proc. IEEE 20th Int. Symp. Pers., Indoor Mobile Radio Commun.*, Sep. 2009, pp. 617–621.

[12] S. Xu, H. Wang, T. Chen, Q. Huang, and T. Peng, "Effective interference cancellation scheme for device-to-device communication underlaying cellular networks," in *Proc. IEEE 72nd Veh. Technol. Conf.-Fall*, Sep. 2010, pp. 1–5.

[13] X. Lin, J. G. Andrews, and A. Ghosh, "Spectrum sharing for device-to-device communication in cellular networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 12, pp. 6727–6740, Dec. 2014.

[14] A. Asadi and V. Mancuso, "Network-assisted outband D2D-clustering in 5G cellular networks: Theory and practice," *IEEE Trans. Mobile Comput.*, vol. 16, no. 8, pp. 2246–2259, Aug. 2017.

[15] A. Asadi, P. Jacko, and V. Mancuso, "Modeling D2D communications with LTE and WiFi," *ACM SIGMETRICS Perform. Eval. Rev.*, vol. 42, no. 2, pp. 55–57, Sep. 2014.

[16] S. Andreev, O. Galinina, A. Pyattaev, K. Johnsson, and Y. Koucheryavy, "Analyzing assisted offloading of cellular user sessions onto D2D links in unlicensed bands," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 1, pp. 67–80, Jan. 2015.

[17] P. Gandotra, R. J. Jha, and S. Jain, "A survey on device-to-device (D2D) communication: Architecture and security issues," *J. Netw. Comput. Appl.*, vol. 78, pp. 9–29, Jan. 2017.

[18] C. Cullen, "1H2018 global Internet phenomena report," Sandvine, Waterloo, ON, Canada, Tech. Rep., Oct. 2018.

[19] M. Noura and R. Nordin, "A survey on interference management for device-to-device (D2D) communication and its challenges in 5G networks," *J. Netw. Comput. Appl.*, vol. 71, pp. 130–150, Aug. 2016.

[20] R. Alkurd, R. M. Shubair, and I. Abualhaol, "Survey on device-to-device communications: Challenges and design issues," in *Proc. IEEE 12th Int. New Circuits Syst. Conf. (NEWCAS)*, Jun. 2014, pp. 361–364.

[21] J. Liu, N. Kato, J. Ma, and N. Kadowaki, "Device-to-device communication in LTE-advanced networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 1923–1940, 4th Quart., 2015.

[22] M. Haus, M. Waqas, A. Y. Ding, Y. Li, S. Tarkoma, and J. Ott, "Security and privacy in device-to-device (D2D) communication: A review," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 2, pp. 1054–1079, 2nd Quart., 2017.

[23] A. S. Daghal and Q. Z. Ahmed, "Video content delivery using multiple devices to single device communications," in *Proc. IEEE 83rd Veh. Technol. Conf. (VTC Spring)*, May 2016, pp. 1–5.

[24] N. Golrezaei, P. Mansourifard, A. F. Molisch, and A. G. Dimakis, "Base-station assisted device-to-device communications for high-throughput wireless video networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 7, pp. 3665–3676, Jul. 2014.

[25] L. Li, G. Zhao, and R. S. Blum, "A survey of caching techniques in cellular networks: Research issues and challenges in content placement and delivery strategies," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 1710–1732, 3rd Quart., 2018.

[26] M. Ji, G. Caire, and A. F. Molisch, "The throughput-outage tradeoff of wireless one-hop caching networks," *IEEE Trans. Inf. Theory*, vol. 61, no. 12, pp. 6833–6859, Dec. 2015.

[27] M. Ji, G. Caire, and A. F. Molisch, "Wireless device-to-device caching networks: Basic principles and system performance," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 1, pp. 176–189, Jan. 2016.

[28] H. Xu, Y. Pan, N. Huang, Z. Yang, and M. Chen, "Relay-assisted device-to-device communications for video transmission in cellular networks," in *Proc. 11th Int. Conf. Mobile Ad-Hoc Sensor Netw. (MSN)*, Dec. 2015, pp. 144–149.

[29] N. Golrezaei, M. Ji, A. F. Molisch, A. G. Dimakis, and G. Caire, "Device-to-device communications for wireless video delivery," in *Proc. Conf. Rec. 46th Asilomar Conf. Signals, Syst. Comput. (ASILOMAR)*, Nov. 2012, pp. 930–933.

[30] N. Golrezaei, A. G. Dimakis, and A. F. Molisch, "Scaling behavior for device-to-device communications with distributed caching," *IEEE Trans. Inf. Theory*, vol. 60, no. 7, pp. 4286–4298, Jul. 2014.

[31] R. Amer, M. M. Butt, M. Bennis, and N. Marchetti, "Delay analysis for wireless D2D caching with inter-cluster cooperation," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2017, pp. 1–7.

[32] A. C. Kazez and T. Girici, "Interference-aware distributed device-to-device caching," in *Proc. IEEE Int. Black Sea Conf. Commun. Netw. (BlackSeaCom)*, Jun. 2017, pp. 1–5.

[33] A. Tebbi and C. W. Sung, "Coded caching in partially cooperative D2D communication networks," in *Proc. 9th Int. Congr. Ultra Mod. Telecommun. Control Syst. Workshops (ICUMT)*, Nov. 2017, pp. 148–153.

[34] M. A. Maddah-Ali and U. Niesen, "Fundamental limits of caching," *IEEE Trans. Inf. Theory*, vol. 60, no. 5, pp. 2856–2867, May 2014.

[35] M. Ji, G. Caire, and A. F. Molisch, "Fundamental limits of caching in wireless D2D networks," *IEEE Trans. Inf. Theory*, vol. 62, no. 2, pp. 849–869, Feb. 2016.

[36] B. Chen, C. Yang, and Z. Xiong, "Optimal caching and scheduling for cache-enabled D2D communications," *IEEE Commun. Lett.*, vol. 21, no. 5, pp. 1155–1158, 2017.

[37] D. Malak, M. Al-Shalash, and J. G. Andrews, "Optimizing content caching to maximize the density of successful receptions in device-to-device networking," *IEEE Trans. Commun.*, vol. 64, no. 10, pp. 4365–4380, Oct. 2016.

[38] Z. Chen, N. Pappas, and M. Kountouris, "Probabilistic caching in wireless D2D networks: Cache hit optimal versus throughput optimal," *IEEE Commun. Lett.*, vol. 21, no. 3, pp. 584–587, Mar. 2017.

[39] Y. Wang, X. Tao, X. Zhang, and Y. Gu, "Cooperative caching placement in cache-enabled D2D underlaid cellular network," *IEEE Commun. Lett.*, vol. 21, no. 5, pp. 1151–1154, May 2017.

[40] L. Zhang, M. Xiao, G. Wu, and S. Li, "Efficient scheduling and power allocation for d2d-assisted wireless caching networks," *IEEE J. Sel. Areas Commun.*, vol. 64, no. 6, pp. 2438–2452, Jun. 2016.

[41] P. Lin, Q. Song, Y. Yu, and A. Jamalipour, "Extensive cooperative caching in D2D integrated cellular networks," *IEEE Commun. Lett.*, vol. 21, no. 9, pp. 2101–2104, Sep. 2017.

[42] B. Chen, C. Yang, and G. Wang, "High-throughput opportunistic cooperative device-to-device communications with caching," *IEEE Trans. Veh. Technol.*, vol. 66, no. 8, pp. 7527–7539, Aug. 2017.

[43] Y. Li, Z. Chen, M. C. Gursoy, and S. Velipasalar, "Learning-based delay-aware caching in wireless D2D caching networks," *IEEE Access*, vol. 6, pp. 77250–77264, 2018.

[44] B. Chen and C. Yang, "Caching policy optimization for D2D communications by learning user preference," in *Proc. IEEE 85th Veh. Technol. Conf. (VTC Spring)*, Jun. 2017, pp. 1–6.

[45] M. Lee, A. F. Molisch, N. Sastry, and A. Raman, "Individual preference probability modeling for video content in wireless caching networks," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2017, pp. 1–7.

[46] M.-C. Lee and A. F. Molisch, "Individual preference aware caching policy design for energy-efficient wireless D2D communications," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2017, pp. 1–7.

[47] Y. Guo, L. Duan, and R. Zhang, "Cooperative local caching under heterogeneous file preferences," *IEEE Trans. Commun.*, vol. 65, no. 1, pp. 444–457, Jan. 2017.

[48] M. Naslcheraghi, M. Afshang, and H. S. Dhillon, "Modeling and performance analysis of full-duplex communications in cache-enabled D2D networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2018, pp. 1–6.

[49] S. Ali, N. Rajatheva, and M. Latva-Aho, "Full duplex device-to-device communication in cellular networks," in *Proc. Eur. Conf. Netw. Commun. (EuCNC)*, Jun. 2014, pp. 1–5.

[50] G. Zhang, K. Yang, P. Liu, and J. Wei, "Power allocation for full-duplex relaying-based D2D communication underlaying cellular networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 10, pp. 4911–4916, Oct. 2015.

[51] L. Militano, M. Condoluci, G. Araniti, A. Molinaro, A. Iera, and G. M. Muntean, "Single frequency-based device-to-device-enhanced video delivery for evolved multimedia broadcast and multicast services," *IEEE Trans. Broadcast.*, vol. 61, no. 2, pp. 263–278, Jun. 2015.

[52] G. Zhang, K. Yang, and H. H. Chen, "Socially aware cluster formation and radio resource allocation in D2D networks," *IEEE Wireless Commun.*, vol. 23, no. 4, pp. 68–73, Aug. 2016.

[53] B. Wenhuan, M. Naslcheraghi, and M. Shikh-Bahaei, "Performance analysis of energy consumption in cache-enabled multicast D2D communications," 2017, *arXiv:1710.04507*. [Online]. Available: https://arxiv.org/abs/1710.04507

[54] H. Schwarz, D. Marpe, and T. Wiegand, "Overview of the scalable video coding extension of the H.264/AVC standard," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 17, no. 9, pp. 1103–1120, Sep. 2007.

[55] C. Zhan and G. Yao, "SVC-based caching and transmission strategy in wireless device-to-device networks," in *Proc. 16th Int. Symp. Modeling Optim. Mobile, Ad Hoc, Wireless Netw. (WiOpt)*, May 2018, pp. 1–6.

[56] K. Poularakis, G. Iosifidis, A. Argyriou, I. Koutsopoulos, and L. Tassiulas, "Caching and operator cooperation policies for layered video content delivery," in *Proc. 35th Annu. IEEE Int. Conf. Comput. Commun. (IEEE INFOCOM)*, Apr. 2016, pp. 1–9.

[57] M. Choi, J. Kim, and J. Moon, "Wireless video caching and dynamic streaming under differentiated quality requirements," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 6, pp. 1245–1257, Jun. 2018.

[58] D. Bethanabhotla, G. Caire, and M. J. Neely, "Joint transmission scheduling and congestion control for adaptive streaming in wireless device-to-device networks," in *Proc. Conf. Rec. 46th Asilomar Conf. Signals, Syst. Comput. (ASILOMAR)*, Nov. 2012, pp. 1179–1183.

[59] A. Al-Habashna, G. Wainer, G. Boudreau, and R. Casselman, "Cached and segmented video download for wireless video transmission," in *Proc. 49th Annu. Simulation Symp.*, 2016, p. 15.

[60] A. Al-Habashna, S. Fernandes, and G. Wainer, "DASH-based peer-to-peer video streaming in cellular networks," in *Proc. Int. Symp. Perform. Eval. Comput. Telecommun. Syst. (SPECTS)*, Jul. 2016, pp. 1–8.

[61] A. Al-Habashna, G. Wainer, and S. Fernandes, "Improving video streaming over cellular networks with DASH-based device-to-device streaming," in *Proc. Int. Symp. Perform. Eval. Comput. Telecommun. Syst. (SPECTS)*, Jul. 2017, pp. 1–8.

[62] B. Chen, C. Yang, and A. F. Molisch, "Cache-enabled device-to-device communications: Offloading gain and energy cost," *IEEE Trans. Wireless Commun.*, vol. 16, no. 7, pp. 4519–4536, Jul. 2016.

[63] F. Guo, H. Zhang, H. Ji, and X. Li, "Energy-aware content placement for D2D communication with caching in cellular network," in *Proc. Int. Conf. Frontier Comput. Sci. Technol. (FCST)*, Nov. 2016.

[64] T. Q. Duong, N.-S. Vo, T.-H. Nguyen, M. Guizani, and L. Shu, "Energy-aware rate and description allocation optimized video streaming for mobile D2D communications," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2015, pp. 6791–6796.

[65] N.-S. Vo, T. Q. Duong, H. D. Tuan, and A. Kortun, "Optimal video streaming in dense 5G networks with D2D communications," *IEEE Access*, vol. 6, pp. 209–223, 2018.

[66] B. Chen and C. Yang, "Energy costs for traffic offloading by cache-enabled D2D communications," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Apr. 2016, pp. 1–6.

[67] P. Li, S. Guo, and J. Hu, "Energy-efficient cooperative communications for multimedia applications in multi-channel wireless networks," *IEEE Trans. Comput.*, vol. 64, no. 6, pp. 1670–1679, Jun. 2015.

[68] B. Liu, Y. Cao, W. Wang, and T. Jiang, "Energy budget aware device-to-device cooperation for mobile videos," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2015, pp. 1–7.

[69] M.-C. Lee and A. F. Molisch, "Caching policy and cooperation distance design for base station-assisted wireless D2D caching networks: Throughput and energy efficiency optimization and tradeoff," *IEEE Trans. Wireless Commun.*, vol. 17, no. 11, pp. 7500–7514, Nov. 2018.

[70] M. Gregori, J. Gómez-Vilardebó, J. Matamoros, and D. Gündüz, "Wireless content caching for small cell and D2D networks," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 5, pp. 1222–1234, May 2016.

[71] Z. Qu, B. Ye, B. Tang, S. Lu, and S. Guo, "Energy-aware cost-effective cooperative mobile streaming on smartphones over hybrid wireless networks," in *Proc. 44th Int. Conf. Parallel Process.*, Sep. 2015, pp. 240–249.

[72] N. Mastronarde, V. Patel, J. Xu, and M. van der Schaar, "Learning relaying strategies in cellular D2D networks with token-based incentives," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2013, pp. 163–169.

[73] D. Wu, J. Yan, H. Wang, D. Wu, and R. Wang, "Social attribute aware incentive mechanism for device-to-device video distribution," *IEEE Trans. Multimedia*, vol. 19, no. 8, pp. 1908–1920, Aug. 2017.

[74] Q. Wang, W. Wang, S. Jin, H. Zhu, and N. T. Zhang, "Quality-optimized joint source selection and power control for wireless multimedia D2D communication using Stackelberg game," *IEEE Trans. Veh. Technol.*, vol. 64, no. 8, pp. 3755–3769, Aug. 2015.

[75] C. Jarray and A. Giovanidis, "The effects of mobility on the hit performance of cached D2D networks," in *Proc. 14th Int. Symp. Modeling Optim. Mobile, Ad Hoc, Wireless Netw. (WiOpt)*, May 2016, pp. 1–8.

[76] M. S. Karim, S. Sorour, and P. Sadeghi, "Network coding for video distortion reduction in device-to-device communications," *IEEE Trans. Veh. Technol.*, vol. 66, no. 6, pp. 4898–4913, Jun. 2017.

[77] N. Abedini, S. Sampath, R. Bhattacharyya, S. Paul, and S. Shakkottai, "Realtime streaming with guaranteed QoS over wireless D2D networks," in *Proc. 14th ACM Int. Symp. Mobile Ad Hoc Netw. Comput.*, 2013, pp. 197–206.

[78] E. Yaacoub and A. Abu-Dayya, "Enhancing the QoS of real-time video streaming over LTE MBMS using D2D communications," in *Proc. 8th ACM Symp. QoS Secur. Wireless Mobile Netw.*, 2012, pp. 41–46.

[79] Y. Shen, C. Jiang, T. Q. S. Quek, H. Zhang, and Y. Ren, "Device-to-device cluster assisted downlink video sharing—A base station energy saving approach," in *Proc. IEEE Global Conf. Signal Inf. Process. (GlobalSIP)*, Dec. 2014, pp. 108–112.

[80] D. Ma, J. Peng, H. Li, W. Liu, Z. Huang, and X. Zhang, "Energy efficient video streaming over wireless networks with mobile-to-mobile cooperation," in *Proc. IEEE Pacific Rim Conf. Commun., Comput. Signal Process. (PACRIM)*, Aug. 2015, pp. 286–291.

[81] J. Li, R. Feng, W. Sun, L. Chen, X. Xu, and Q. Li, "Joint mode selection and resource allocation for scalable video multicast in hybrid cellular and D2D network," *IEEE Access*, vol. 6, pp. 64350–64358, 2018.

[82] Y. Cao and A. Maaref, "Device cooperation-assisted scalable video multicast with heterogeneous QoE guarantees," in *Proc. 11th Int. Symp. Wireless Commun. Syst. (ISWCS)*, Aug. 2014, pp. 733–738.

[83] D. Wu, Q. Liu, H. Wang, D. Wu, and R. Wang, "Socially aware energy-efficient mobile edge collaboration for video distribution," *IEEE Trans. Multimedia*, vol. 19, no. 10, pp. 2197–2209, Oct. 2017.

[84] X. Zhang, J. Chen, F. Tian, and Z. Yuan, "The role of video coding in D2D communications," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2017, pp. 1–6.

[85] T.-C. Chiu, Y.-J. Yu, S.-F. Chou, Y.-T. Tsai, and A.-C. Pang, "Efficient multi-radio selections for device-to-device in wireless cellular networks," in *Proc. Int. Comput. Symp. (ICS)*, Dec. 2016, pp. 142–147.

[86] E. Datsika, A. Antonopoulos, N. Zorba, and C. Verikoukis, "Cross-network performance analysis of network coding aided cooperative out-band D2D communications," *IEEE Trans. Wireless Commun.*, vol. 16, no. 5, pp. 3176–3188, May 2017.

[87] S. Iskounen, T.-M.-T. Nguyen, S. Monnet, and L. Hamidouche, "Device-to-device communications using Wi-Fi direct for dense wireless networks," in *Proc. 7th Int. Conf. Netw. Future (NOF)*, Nov. 2016, pp. 1–3.

[88] Y. Shen, W. Zhou, P. Wu, L. Toni, P. C. Cosman, and L. B. Milstein, "Device-to-device assisted video transmission," in *Proc. 20th Int. Packet Video Workshop*, Dec. 2013, pp. 1–8.

[89] S. Baidya and M. Levorato, "Content-based interference management for video transmission in D2D communications underlaying LTE," in *Proc. Int. Conf. Comput., Netw. Commun. (ICNC)*, Jan. 2017, pp. 144–149.

[90] S. Baidya and M. Levorato, "Content-based cognitive interference control for city monitoring applications in the urban IoT," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2016, pp. 1–6.

[91] P. Wu, P. C. Cosman, and L. B. Milstein, "Resource allocation for multicarrier D2D video transmission based on exact symbol error rate," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2016, pp. 1–7.

[92] P. Wu, P. C. Cosman, and L. B. Milstein, "Subcarrier assignment and power allocation for device-to-device video transmission in Rayleigh fading channels," *IEEE Trans. Wireless Commun.*, vol. 16, no. 9, pp. 5967–5981, Sep. 2017.

[93] G. Yu, L. Xu, D. Feng, R. Yin, G. Y. Li, and Y. Jiang, "Joint mode selection and resource allocation for device-to-device communications," *IEEE Trans. Commun.*, vol. 62, no. 11, pp. 3814–3824, Nov. 2014.

[94] Q. Wang, W. Wang, S. Jin, H. Zhu, and N. T. Zhang, "Joint coding mode and multi-path selection for video transmission in d2d-underlaid cellular network with shared relays," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2015, pp. 1–6.

[95] C. Ye, M. C. Gursoy, and S. Velipasalar, "Power control and mode selection for VBR video streaming in D2D networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2018, pp. 1–6.

[96] M. Klugel and W. Kellerer, "Leveraging the D2D-gain: Resource efficiency based mode selection for device-to-device communication," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2016, pp. 1–7.

[97] A. Asadi, V. Mancuso, and R. Gupta, "An SDR-based experimental study of outband D2D communications," in *Proc. 35th Annu. IEEE Int. Conf. Comput. Commun. (IEEE INFOCOM)*, Apr. 2016, pp. 1–9.

[98] H. Zhu, Y. Cao, W. Wang, B. Liu, and T. Jiang, "QoE-aware resource allocation for adaptive device-to-device video streaming," *IEEE Netw.*, vol. 29, no. 6, pp. 6–12, Nov./Dec. 2015.

[99] N. Eshraghi, V. Shah-Mansouri, and B. Maham, "QoE-aware power allocation for device-to-device video transmissions," in *Proc. IEEE 27th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Sep. 2016, pp. 1–5.

[100] J. Kim, G. Caire, and A. F. Molisch, "Quality-aware streaming and scheduling for device-to-device video delivery," *IEEE/ACM Trans. Netw.*, vol. 24, no. 4, pp. 2319–2331, Apr. 2016.

[101] U. N. Kar and D. K. Sanyal, "An overview of device-to-device communication in cellular networks," *ICT Express*, vol. 4, no. 4, pp. 203–208, 2017.

[102] N. Eshraghi, B. Maham, and V. Shah-Mansouri, "Millimeter-wave device-to-device multi-hop routing for multimedia applications," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2016, pp. 1–6.

[103] J. Kim and A. F. Molisch, "Quality-aware millimeter-wave device-to-device multi-hop routing for 5G cellular networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2014, pp. 5251–5256.
[104] A. Liu, V. K. N. Lau, and G. Caire, "Cache-induced hierarchical cooperation in wireless device-to-device caching networks," *IEEE Trans. Inf. Theory*, vol. 64, no. 6, pp. 4629–4652, Jun. 2018.
[105] J. Guo, J. Yuan, and J. Zhang, "An achievable throughput scaling law of wireless device-to-device caching networks with distributed MIMO and hierarchical cooperations," *IEEE Trans. Wireless Commun.*, vol. 17, no. 1, pp. 492–505, Jan. 2018.
[106] B. S. Amin, A. S. Ibrahim, M. H. Ismail, and H.-A. M. Mourad, "Precoding and power allocation algorithms for device-to-device communication in massive MIMO networks," *Wireless Netw.*, vol. 24, no. 3, pp. 925–942, Apr. 2018.
[107] Z. Liu, M. Dong, H. Zhou, X. Wang, Y. Ji, and Y. Tanaka, "Device-to-device assisted video frame recovery for picocell edge users in heterogeneous networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2016, pp. 1–6.
[108] W. Shuanshuan, "Application of D2D in 5G networks," ZTE Technol., Shenzhen, China, Tech. Rep. 3, 2015, vol. 17.
[109] E. Yaacoub and O. Kubbar, "Energy-efficient device-to-device communications in LTE public safety networks," in *Proc. IEEE Globecom Workshops*, Dec. 2012, pp. 391–395.
[110] *Barricaded Suspect Incident Analysis: Enhancing Critical Incident Response With Public Safety LTE*, Motorola, Chicago, IL, USA, 2011.
[111] E. Yaacoub, "On the use of device-to-device communications for QoS and data rate enhancement in LTE public safety networks," in *Proc. IEEE Wireless Commun. Netw. Conf. Workshops (WCNCW)*, Apr. 2014, pp. 236–241.
[112] T. Ohtsuji, K. Muraoka, H. Aminaka, D. Kanetomo, and Y. Matsunaga, "Device-to-device relay selection based on effective path throughput to fill coverage hole in public safety LTE," in *Proc. Int. Conf. Inf. Commun. Technol. Converg. (ICTC)*, Oct. 2016, pp. 613–618.
[113] K. Muraoka, T. Ohtsuji, H. Aminaka, G. Motoyoshi, and Y. Matsunaga, "Scheduling for device-to-device communication considering spatial reuse and user fairness in public safety LTE," in *Proc. IEEE 84th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2016, pp. 1–5.

IBTIHAL AHMED received the B.Sc. degree in electrical and electronics engineering from the University of Khartoum, Sudan, in 2014, and the M.Sc. degree in electrical engineering from the American University of Sharjah, UAE, in 2019. In 2015, she was a Teaching Assistant with the University of Khartoum. From 2016 to 2017, she was a Post Processing Engineer with Sabal Telecom Solutions Company Ltd.

MAHMOUD H. ISMAIL (S'00–M'07–SM'15) received the B.Sc. degree (Hons.) in electronics and electrical communications engineering and the M.Sc. degree in communications engineering from Cairo University, Egypt, in 2000 and 2002, respectively, and the Ph.D. degree in electrical engineering from The University of Mississippi, MS, USA, in 2006. From August 2000 to August 2002, he was a Research and Teaching Assistant with the Department of Electronics and Electrical Communications Engineering, Cairo University, where he is currently a Full Professor (on leave) with the Department of Electronics and Electrical Communications Engineering. He is also an Associate Professor with the American University of Sharjah, Sharjah, UAE. From 2004 to 2006, he was a Research Assistant with the Center for Wireless Communications (CWC), The University of Mississippi. He was also a Systems Engineering Consultant with the Egypt Design Center (now part of Microchip), Newport Media Inc., Cairo, from 2006 to 2014. His research interests include the general areas of wireless communications with emphasis on performance evaluation of next-generation wireless systems and communications over fading channels. He is a member of the Sigma Xi and Phi Kappa Phi. He was a recipient of the Best Paper Award from the Tenth IEEE Symposium on Computers and Communications (ISCC 2005) Spain, The University of Mississippi Summer Assistantship Award, in 2004 and 2005, The University of Mississippi Dissertation Fellowship Award, in 2006, and The University of Mississippi Graduate Achievement Award in Electrical Engineering, in 2006. He has served as a Reviewer for several refereed journals and conferences.

MOHAMED S. HASSAN received the M.Sc. degree in electrical engineering from the University of Pennsylvania, PA, USA, in 2000, and the Ph.D. degree in electrical and computer engineering from the University of Arizona, AZ, USA, in 2005. He is currently a Full Professor of electrical engineering with the American University of Sharjah. He was involved in multiple projects related to free space optical communications, electromagnetic shielding, demand response & smart grids, anti-static flooring, and fiber optic sensors for infrastructure health monitoring applications. His research interests include multimedia communications and networking, wireless communications, cognitive radios, resource allocation and performance evaluation of wired and wireless networks, and next generation wireless systems.