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Device-to-Device Communications: A Contemporary Survey

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Abstract Device-to-device (D2D) communication is a new enabling technology for the next generation cellular networks. In D2D communications, two or more user equipments directly communicate with each other with a very restricted involvement of the evolved Node B. The main objective is to realize high data rates, low power consumption, low delays and improve the overall spectral efficiency. In addition to these advantages, D2D communications poses several research challenges in terms of interference and power control, and whether or not D2D communication should be used in a given environment. In order to solve these issues, significant amount of research and development work has been done by both industry and academia, which is comprehensively covered in this survey article. Firstly, we discuss the use case scenarios of D2D communication by classifying its applications into two types: commercial and public safety services. This is followed by an in-depth discussion on the state-of-the-art solutions proposed in various research studies addressing different issues associated with each classification. While discussing a large

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number of previous works, we highlight some of the open research issues and challenges in D2D communications.

Keywords Device-to-device communications · Public safety networks · Resource allocation · Transmit power control · LTE-A

1 Introduction

The demands of ubiquitous communication services have surged significantly over the past few years [1, 2]. According to a Cisco report [3], the number of mobile devices will reach 5.2 billion by 2019. In order to accommodate this massive number of devices, the network operators are exploring different means to manage and effectively operate such a highly dense network. One naive solution is to increase the network infrastructure in order to serve a large number of users. While this idea can improve the overall network capacity, it also increases the deployment and operational cost of the network. Consequently, a more feasible alternative is to offload the traffic from Evolved NodeB (eNB) by exploiting direct device-to-device (D2D) communication between user equipments (UEs) that are in close proximity [4, 5].

Unlike the conventional cellular technology that conveys information between two UEs via eNB, D2D communication allows UE-to-UE data exchange on direct links. Thus, by relieving the eNBs from too much relaying, D2D communication improves the overall system capacity and end user data rates [6]. A simplified example of D2D communications is shown in Fig. 1. Note that the figure shows two kinds of UEs: Cellular UEs (CUEs) and D2D UEs (DUEs). The difference between the two UEs is that DUEs transmit and receive data without eNB relaying, CUEs always communicate via the base station [7]. In certain situations, it may be necessary for the UEs to send their information

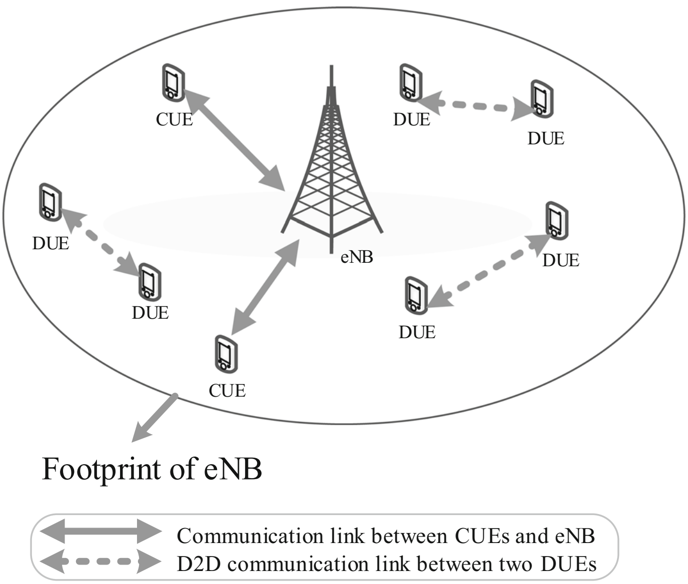


Fig. 1 D2D-enabled network houses CUEs (that use eNB) and DUEs (that communicate on direct links)

via eNB. For instance, if the distance between two UEs is very large, direct D2D communication cannot take place. Thus, CUEs and DUEs are expected to coexist, at least at present.

The applications of direct information exchange between DUEs can be classified into two types: commercial D2D and Public Safety D2D (PS-D2D), as shown in Fig. 2. The commercial D2D communication aims to maximize the reuse of available frequency spectrum (both licensed and unlicensed) so as to increase the overall network capacity. Maintaining a reasonable level of quality of service (QoS) for the end users is also an important objective of the commercial D2D setup. In addition, in terms of the available frequency resource, commercial D2D communication can be classified as out-of-band (unlicensed) and in-band (licensed). The out-of-band D2D communication utilizes the unlicensed industrial, scientific and medical (ISM) band. The in-band (licensed) Commercial D2D communications can be further classified as (1) centralized (controlled by eNB) and (2) distributed (which is purely autonomous). On other hand, the goal of PS-D2D is to provide reliable communication services to the end users who are outside the coverage area of an eNB. The lack of coverage can be observed in a remote area where the network infrastructure does not exist, or in an event of emergency/disaster, which destroys the base stations. The PS based D2D can further be classified into autonomous PS-D2D and eNB controlled PS-D2D. In autonomous PS-D2D communications, the out of coverage UEs autonomously establish communication links without any help of a central entity (such as eNB). On other hand, in eNB controlled PS-D2D, eNB plays a vital role in establishing communication links between itself and out of coverage UEs.

Regardless of the application scenario, the CUEs and DUEs can either use the same or different frequency channels for sending data. D2D communication in general has two operation modes: underlay and overlay. As shown in Fig. 3, in the underlay mode, the CUEs and DUEs "share" the same radio resources. This is often referred to as non-orthogonal resource sharing (NORS). Certain parameters (transmit power, channel allocation, etc) must be controlled in order to avoid or at least reduce the interference between UEs in the underlay mode. On other hand, in the overlay mode, the available frequency band is split into two parts so that CUEs and DUEs have their own dedicated share of the spectrum. This kind of frequency allocation is also called orthogonal resource sharing (ORS). While the overlay mode works best in reducing interference, it results in the under-utilization of the frequency resource [6, 8]. This is because the radio resources for both cellular and D2D communications are dedicated and orthogonal. In other words, both CUEs and DUEs do not share the available radio resources which results in degraded spectrum efficiency.

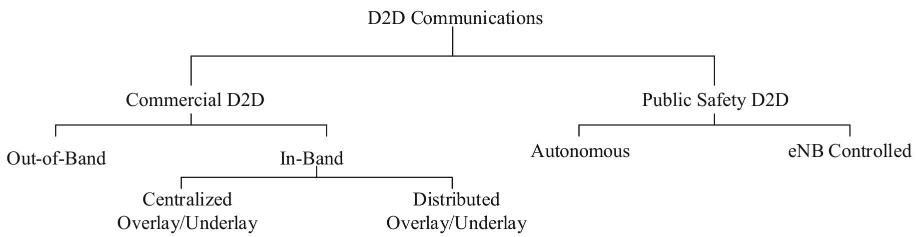


Fig. 2 Classification of D2D communications in terms of application scenarios

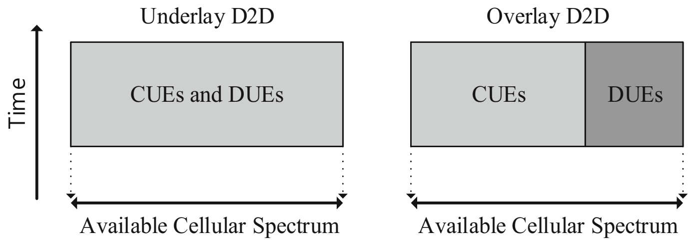


Fig. 3 Spectrum partitioning in underlay and overlay modes

1.1 Contribution

To the best of our knowledge, three major surveys on D2D communications have been published. Liu et al. [9] have discussed a wide range of research topics ranging from D2D link establishment to D2D services and prototypes. The paper also provides details on different performance evaluation techniques used for D2D communications. The authors in [10] have surveyed the papers related to energy efficiency, radio resource management, cellular coverage and other performance targets in in-band D2D communications. The papers dealing with out-of-band D2D and D2D architectures are also briefly reviewed. Finally, the authors summarizes the pros and cons of spectrum selection and the practical implementation of D2D in real world environment.

A survey on interference mitigation and radio resource management in in-band D2D communications has been provided by Mach et al. [11]. They have provided discussion on resource management, mode selection, energy efficiency and coexistence of D2D communications in HetNets.

In our survey we complement the above-mentioned surveys and additionally provide the information on several missing pieces. Our survey primarily focuses on a wide range of issues in out-of-band D2D, in-band D2D and PS-D2D communications. Most of the previous surveys have either only considered in-band D2D communications or have provided very little detail on out-of-band D2D and PS-D2D communications. However, since the current licensed radio spectrum is highly saturated, the use of unlicensed frequency bands (such as ISM) for cellular communication have attracted a significant research interest. In this survey, we have thoroughly covered the research work done in the area of unlicensed D2D, licensed D2D and PS-D2D communications. More precisely, the major contributions of our paper are as follows:

- We provide a taxonomy of D2D communication by classifying it as commercial-D2D and PS-D2D. The proposed classifications are based on D2D applications and their different objective gains.
- Since an enormous amount of research has been conducted in the area of D2D communications, for the better understanding of the readers, we systematically divide the major issues in both commercial- and PS-based D2D communications.
- In case of commercial D2D, a detailed discussion on both out-of-band (unlicensed) and in-band (licensed) D2D communications is provided. Then the major issues in commercial D2D (i.e., efficient resource allocation, dynamic transmit power control, and mode selection) are thoroughly discussed. In addition, several other interesting issues in commercial D2D communications such as load balancing, prototypes, and simulator constructions are also discussed in great detail.

- We also provide deep insight into PS-D2D and discuss its importance. The major issues in PS-D2D (i.e., peer discovery, synchronization, and relay selection) are highlighted and their potential solutions are discussed in great detail. In addition, several other aspects of PS-D2D communications such as resource spectrum, power control, group communication, experiments, and prototyping are also thoroughly discussed.
- At the end, this paper also discusses the unique applications of D2D communications and highlights several open research issues.

The rest of this paper is organized as follows. Section 2 discusses and analyzes the existing state of the art in commercial D2D communications. Several works pertinent to the legacy issues associated with resource allocation, energy efficiency, mode selection, etc are highlighted. This section also describes some of the emerging concerns that are related to load balancing, prototyping, simulation analysis, etc. Section 3 discusses the issues and their proposed potential solutions in the PS-D2D environments. In public safety environments, since the connection between out-of-coverage UEs and eNB is very weak or it does not exist, a lot of previous works have been on peer discovery, synchronization and relay selection which are examined in this section. Some applications that are unique to D2D communication, and several open research issues are highlighted in Sect. 4. This paper is concluded in Sect. 5.

2 Commercial D2D Communications

It has already been mentioned earlier in this paper that D2D communication is concerned with direct data exchange between two (or more) UEs. The term "commercial" refers to the fact that the information sharing is being done on a licensed frequency band for day-to-day communication activities. From the network operators' perspective, the main objective of commercial D2D is to increase the network capacity through optimal reuse of the available licensed spectrum. Frequency reuse is affected by a number for factors. For example, if the two UEs reusing the same frequency are spatially far apart, both can send their data at a higher transmit power. In addition to the transmit power control, optimization of frequency reuse requires careful consideration of the following factors.

2.1 Frequency Bands

In order to increase the spectral efficiency of the cellular networks, it is necessary to reuse the available frequency channels while guaranteeing a certain minimum level of QoS. The most important consideration while allocating frequency resources is concerned with mitigating interference among the neighboring UEs. Therefore, a significant amount of research has been reported, and various interference management techniques have been proposed in the recent years. Before taking up the discussion on how frequency resources should be allocated, let us first examine the available frequency resources and the related research done in this area.

As mentioned earlier in Sect. 1 that in terms of the available frequency resource, D2D communication can be classified as out-of-band (unlicensed) and in-band (licensed) [12]. The out-of-band D2D communication utilizes the unlicensed industrial, scientific and medical (ISM) band. While the ISM band is free, its use in D2D communication may result in increased network capacity. However, the performance of D2D might be affected due to uncontrolled interference from other wireless technologies operating in the same spectrum

(802.15 Bluetooth, 802.11 Wi-Fi, etc) [13]. On the other hand, as shown in Fig. 4 the in-band D2D communication, DUEs use the licensed cellular spectrum in either NORS (underlay) or ORS (overlay) mode. The resource allocation in the in-band D2D communication can be controlled either by a centralized entity (such as eNB) or it can remain distributed where DUEs themselves allocate the available resources. The rest of this section first reviews the research work done in the area of unlicensed D2D communication and then the resource allocation issues in licensed band D2D, which can be realized in centralized as well as distributed manners, are throughly discussed. Also note that in this section the terms unlicensed/out-of-band and licensed/in-band are interchangeably used.

2.1.1 Out-of-Band D2D Communication

Alexander et al. [13] have studied the performance of out-of-band D2D communication using WiFi Direct as a prominent unlicensed D2D communication technology. The authors have demonstrated that offloading legacy cellular traffic onto out-of-band WiFi Direct can bring significant gains in terms of overall network capacity and energy efficiency. It is assumed that the network assists its users to find the potential D2D partner. In other words, the network only helps the DUEs in device discovery. Through system level simulation they demonstrated three different scenarios: (1) LTE-only (baseline), (2) out-of-band D2D with no interfering nodes (3) out-of-band D2D with unmanaged interfering nodes (WiFi APs). Their results show that significant throughput gain can be achieved when 30% of licensed band D2D traffic is offloaded on to unlicensed WiFi Direct. It is demonstrated that compare to baseline case (LTE-only), the proposed out-of-band D2D scheme both with and without interfering nodes achieves significantly higher throughput. Furthermore, it is also shown that in terms of energy efficiency the proposed schemes outperform the baseline scheme. However, the energy efficiency of proposed scheme significantly decreases as the offloaded traffic increases. Alexander et al. [14] have further explained their simulation environment and shown that the user in close proximity can offload their traffic from licensed cellular infrastructure to out-of-band WiFi Direct D2D links to achieve higher user throughputs. Their simulation results show that by just offloading the 30% cellular traffic onto WiFi Direct, the cell throughput becomes nearly double and the energy efficiency is improved up to six times.

In an extended version of [13] and [14], the authors in [15] have further explored the impact of offloading licensed band cellular data onto unlicensed band D2D links. Similar to [13], in this work the authors have assumed that in order to manage the out-of-band D2D

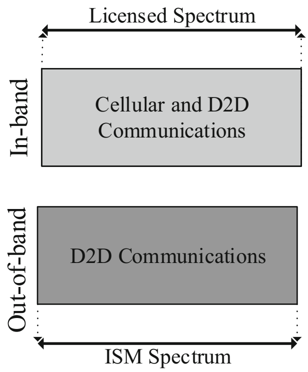


Fig. 4 In-band and out-of-band spectrum utilization in D2D communications

data session, the UEs are assisted by their respective cellular networks. Note that here the network assistance is in terms of D2D admission control, device discovery, and offloading of CUE sessions onto D2D. An out-of-band D2D data session is explained as a real-time data flow from one UE to another UE which follows a Poisson point process (PPP). As a performance metric the authors have evaluated both the energy efficiency and blocking probability of a data session in a dynamically loaded cellular and D2D network. Additionally, they have also analyzed the performance of their proposed network-assisted data session offloading scheme under different network conditions using both analytical models and system level simulations. Their results conclude that offloading cellular traffic onto unlicensed band D2D can reasonably increase the network capacity which in return significantly improves the session blocking probabilities. Additionally such offloading will also result in increased energy efficiency of the D2D transmitter. The results also reveal that the locations of the users and the distance between communicating users also highly impact the resulting system performance. A prototype for offloading 3GPP cellular traffic onto WiFi Direct links has been studied in [16]. Using route injection technique in Linux-based Android system, the authors have tested and shown that the existing UEs can be used to successfully forward the packets from one interface (such as 3GPP cellular) to another interface (such as WiFi Direct).

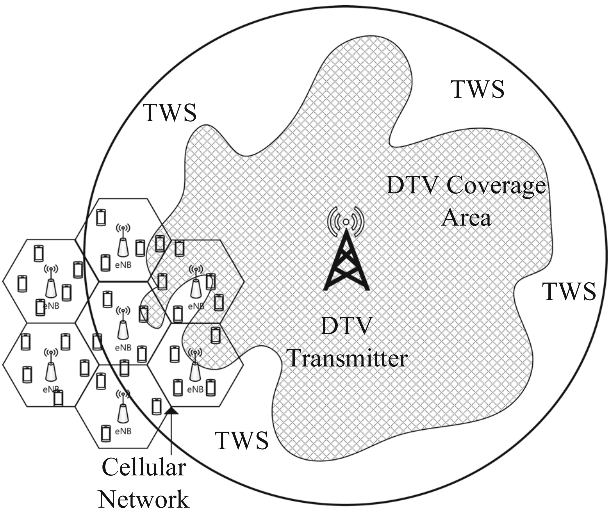
Sergey et al. [17] argue that the implementation of licensed band D2D requires significant changes in both network and physical layer and the 3GPP standardization process in this regard is very slow going, therefore for its quick implementation, the attention of industry has shifted towards D2D over unlicensed bands. Moreover, it is also stated that, since the protocols for unlicensed band D2D are standardized and are already available on current user devices (e.g. IEEE 802.11), therefore, it makes sense to leverage the unlicensed spectrum for D2D. Based on these facts, the authors have provided a detailed technical discussion on the gains of using unlicensed band for D2D communications. They have also highlighted several issues, challenges and their potential solutions for out-of-band D2D. The major issues associated with currently available unlicensed band D2D protocols (such as Wifi Direct) are energy inefficient device discovery, cumbersome connection establishment, inefficient resource management and poor service continuity. To improve these shortcomings, the authors propose that the users should be assisted by their operator networks to manage their out-of-band D2D communications. Two primary steps required to establish such D2D connection are: D2D discovery and connection establishment. For device discovery in network assisted peer-to-peer (P2P) out-of-band D2D communication, the authors have proposed the concept of content tracker (i.e., the third party application server) which will store the locations of all offered P2P contents/services from their registered users and would then use this information to provide alternative download sources to the requesting users. For connection establishment the authors have proposed a new globally visible network entity called D2D server. The D2D server acts as a connection manager for the devices involved in the D2D discovery and communication. It also tracks the user position and manages the active D2D connections.

A system level simulation results are provided to evaluate the performance of unlicensed band D2D communications. The results show that the use of unlicensed band D2D can significantly improve the overall cell throughput. Though the throughput decreases as the number of interfering nodes (uncontrolled WiFi APs) increases, but it still achieves reasonably higher throughput than baseline licensed band. It is also shown that, even during the presence of interfering nodes the out-of-band D2D links achieve significantly better throughput than baseline licensed band. Results with similar trend are also reported by same authors in their previous papers [13–16].

The research work in [13–17] have provided different valuable insights in the area of out-of-band D2D communications. However, their research work only focuses on static users, while it is expected that in near future, a significant portion of mobile data traffic will be generated by moving users. In addition to mobility the authors have also not considered any kind power control, resource management and fairness mechanisms for out-of-band D2D communications. Although their results show that, compared to baseline LTE (uplink) the proposed unlicensed band can achieve significant throughput gains, it would be more interesting if the results are compared with D2D communications underlaying LTE-A networks. Moreover, different scenarios of D2D such as group communication and multi-hop D2D using unlicensed bands are not investigated. Therefore, further research is required to completely understand the pros and cons of using unlicensed band D2D in cooperation with legacy cellular networks.

Another interesting approach for out-of-band D2D communications in cellular networks is the use of unlicensed TV white space. Since the transmission range of a digital TV (DTV) transmitter is up to hundreds of kilometers, its spectrum can be exploited and reused by cellular networks for short range D2D communications. Another advantage of TV spectrum is its superior propagation characteristics compared to 2.4 and 5 GHz unlicensed bands and due to these characteristics it can offer more energy efficient and high transmission range D2D communication link. Guoru et al. [18] have studied this idea of cellular eNB assisted D2D communications in TV white space. The considered network model is shown in Fig. 5. According to their proposed scheme, first a mobile crowd sensing mechanism based geolocation-specific TV white space database is constructed with the help of existing eNBs. The database contains massive DTV spectrum measurements, and it helps to provide lookup table service for a D2D link to select the appropriate DTV spectrum and determine its maximum allowed transmission power. An optimization problem is formulated to maximize this allowed transmission power while keeping the interference from licensed DTV under a defined threshold. Simulation results show that the proposed approach can successfully enable D2D communications in TV white space while satisfying the interference constraint from the licensed DTV services. Although the use of TV white space for D2D communications seems a promising idea, but there are several

Fig. 5 Network model depicting the coexistence of cellular network and DTV Network [18]

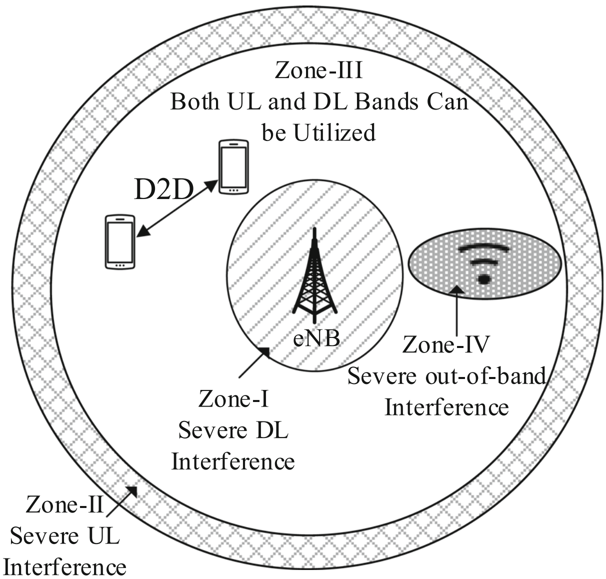


challenges such as multiple D2D pairs using the same TV white space, multiple operators simultaneously exploiting the available TV spectrum and their combined interference effect on a TV receivers needs to be investigated.

To take the full advantage of the underutilized unlicensed spectrum, both academia and industry are investigating its proper use in cellular networks. The term adopted for such type of communication is LTE-Unlicensed (LTE-U). The aim of the LTE-U is to extended legacy LTE transmission into the unlicensed ISM bands [19]. 3GPP has already included LTE-U in its Release 13 standardization process [20]. The authors in [21] have studied D2D communication in conjunction with LTE-U. Three major technical issues are reviewed in the perspective of LTE-U multi-hop D2D: communication band selection, routing path selection, and radio resource management (RRM).

It is shown that for transmission band selection, a performance trade-off between CUEs and D2D exists. The trade-off is that, when UL band is used for D2D communication it results in better D2D performance but significantly affects the CUE communication. On other hand if DL band is used for D2D communications, it favors the reliability of cellular communication over D2D. It has also been identified that the band selection in relation with geometric zone, significantly affects the D2D communication. This relationship is depicted in Fig. 6 which shows that D2D communication in the center of the cell (Zone-I) is highly affected when DL band is used. Likewise, at cell edges (Zone-II) the performance of D2D communication is degraded if UL band is used. Therefore, if it is desirable to use both UL and DL bands, the D2D should only operate in Zone-III. In case of unlicensed band (LTE-U) the D2D should consider two major coexistence requirements: (1) reduced Tx power levels (200 mW–1 W) and (2) interference mitigation using clear channel assessment (CCA) and listen-before-talk (LBT). Furthermore, LTE-U D2D should be avoided in areas where other unlicensed RAT are operating (Zone-IV). In order to select the proper route for LTE-U D2D communication three different distributed routing strategies are proposed. These three routing strategies are: (1) wait for a CCA period, (2) perform localized Interference avoidance routing (IAR), and (3) switch to the licensed

Fig. 6 Restriction on D2D operation in different parts of the cell [21]



cellular band. While waiting for a CCA period the DUEs periodically performs the LBT operation until there is an unlicensed channel available for transmission. Localized IAR mechanism is used in to hop around the local WiFi APs and avoid contention. The third strategy is to switch to the licensed cellular band when the interference on unlicensed band is very significant.

In cellular networks there always exists a trade-off between spectrum efficiency and computational cost [22]. For multi-hop D2D RRM, the authors in [21] have also proposed a two stage joint routing and RRM for LTE-U D2D. In stage one the eNB will allocate resources to DUEs according to the above mentioned band selection strategies and also periodically update their location information. In stage two the DUEs decide their transmit power according to their channel state. If the DUEs are operating on unlicensed bands, they can choose any transmit power which maximizes their throughput. System level simulation results are provided to evaluate the performance of unlicensed D2D communications in an LTE-U enabled network. It is concluded that when WiFi is in light usage, more than 100 % throughput improvement can be achieved on D2D communications. However, on other hand when the traffic load of WiFi is heavy, D2D communications should utilize the licensed cellular band with IAR. Likewise, if a multi-hop D2D route needs to go through a loaded WiFi hotspot, it is better to adopt the third strategy and switch to the licensed cellular band. Though the results in [21] provides different valuable insights and research directions in the area of unlicensed D2D, more detailed studies are still required to completely understand the existence of both out-of-band D2D and other unlicensed RAT in a fully loaded network environment. A joint radio resource optimization of cross-RAT can be one of the interesting issues in this area. Another interesting issue can be the energy efficiency trade-off in a WiFi free setup where DUEs are allowed to use their maximum Tx power.

The authors in [23] have proposed a D2D packet retransmission scheme for a D2D group operating at unlicensed band. The need for packet retransmission arises when few or all UEs of the group fail to receive complete data packets from eNB. The authors propose that instead of requesting retransmission from eNB on licensed band the UEs in the group should broadcast and share their received packets within the group using unlicensed spectrum. The UEs in the group combine all the received packets and try to decode it. If any UE successfully decodes the packet, it will broadcast it to the other group members using unlicensed spectrum. Through link level simulations, the authors have shown that the proposed scheme improves the spectral efficiency of cellular at the cost of extra D2D resources.

2.1.2 In-band Centralized Resource Allocation

In previous subsection we reviewed research work done in the area of out-of-band D2D communications. However, majority of the research studies in the area of D2D communications have considered licensed bands for resource allocation. In licensed band D2D the resources can be allocated in both underlay mode and overlay mode. A detailed discussion on underlay and overlay mode has been provided in Sect. 1 of this paper. This subsection provides a detailed survey of state-of-the art resource allocation mechanisms in in-band D2D communications.

In order to reuse the suitable UL resources, an interference-aware undelay resource allocation scheme is presented in [24]. The DUEs measure UL transmit power of CUEs and update the eNB about these values. The eNB uses this information so not to allocate the same channels to a resource sharing pair. It has been shown in [24] that the proposed scheme can increase the network capacity by 30% in comparison with the random resource allocation.

Shaoyi et al. [25] have addressed a similar underlaying resource allocation approach, where the use of a dedicated common control channel (CCCH) for D2D communication is proposed. The CUEs periodically listen to CCCH and measure the SINR. CUEs advise the eNB if the measured SINR is higher than a predefined threshold. In response, eNB stops scheduling the CUEs on channels that are already occupied by the reported DUEs. Furthermore, eNB broadcasts the information about location of CUEs and their resources. The DUEs avoid using the channels that cause significant interference to the CUEs. The simulation results show that the proposed scheme can yield a 3.74 fold increase in the average system throughput when compared with a case where no interference is avoided. An extension of this work is reported in [26], where an effective priority based interference mitigation mechanism in a multi-cell cellular system has been proposed. According to their proposed scheme, the CUEs monitor the related D2D CCCH and report the information of neighboring DUEs to the eNB. If any of the reported DUEs is not in the same cell, eNB exchanges the necessary information with its adjacent eNBs. If the priority of a DUE is higher than the interfering CUE, eNB may stop scheduling that CUE. On the contrary, if a CUE has higher priority, DUE can still transmit data but with a reduced transmit power. The simulation results show that the proposed scheme can significantly mitigate the interference between CUEs and DUEs, and increase the overall network capacity.

A distance-constrained resource sharing scheme for underlaying D2D communication has been discussed in [27]. The proposed scheme mitigates the interference between CUEs and DUEs by maintaining the optimal minimum distance between resource sharing D2D pair and CUE. Two different power control schemes [24, 28] are used for evaluating the performance of the proposed scheme. The numerical results show that the proposed scheme significantly reduces the outage probability of DUEs. Min et al. [29] have proposed a δD-interference limited area (ILA)-based interference mitigation scheme. $\delta D - ILA$ is defined as the area where the signal to interference ratio (SIR) of a DUE receiver is less than a predefined threshold δD. According to the scheme, a CUE located in $\delta D - ILA$ is not allowed to reuse the UL radio resources of DUE Tx in the same region. The numerical results reveal that the proposed scheme can achieve better D2D gain when $\delta D - ILA$ is larger in size. A similar approach for interference mitigation in D2D communications using DL radio resources is reported in [30]. An ILA-based resource allocation scheme for DUEs using partial frequency reuse (PFR) cellular architecture has been proposed.

A geometrical-based throughput analysis for underlaying D2D communications in different network scenarios is studied by Minming et al. [31] and [32]. In [31], the authors have considered the multi-reuse scenario, where several D2D pairs residing in the same cell are enabled to communicate simultaneously by reusing the same uplink resources. In order to satisfy the minimum SIR requirements of both CUEs and DUEs, a geometrical method is proposed to obtain the guard distance G_B (between a DUE Tx and eNB), G_D (between DUE Rx and the neighboring Tx DUEs), and G_C (between DUE Rx and CUEs Tx). As shown in Fig. 7, the guard distance is the minimum separation a D2D transmitter should maintain between itself and other transmitters operating at the same channel. Furthermore, the maximum throughput bounds for D2D communications operating in a single cell are also derived. In [32], a Power Emission Density (PED) based interference mitigation scheme [33] is proposed for sector-partitioned cells. Like [31], the guard distances and bounds for maximum throughput are derived for several different sector-based D2D resource allocation schemes. The major difference between [32] and [31] is the interference calculation mechanism. In [31] the authors have used the traditional discrete-

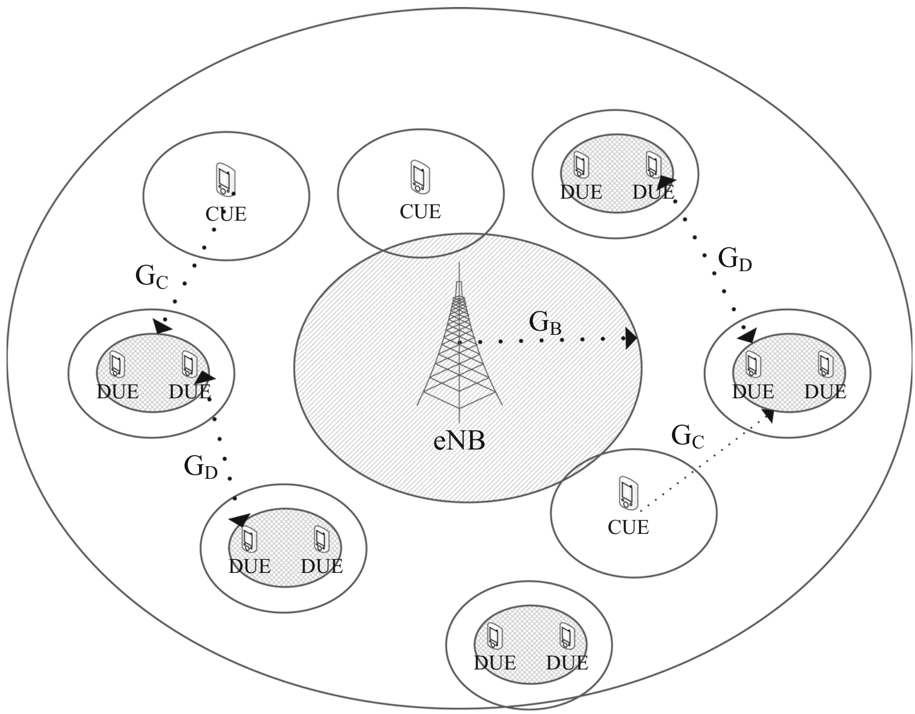


Fig. 7 An illustration of guard-distance based D2D enabled cellular network [31]

style method for interference calculation and analysis, where PED based interference analysis is used in [32].

Pei et al. [34] have proposed a resource allocation scheme in an overlay two way cellular network. The proposed scheme allows the DUEs to (1) communicate bi-directionally with each other and (2) act as a relay between CUE and eNB. The system model considers a single cell scenario which consist of a CUE and a D2D pair. D2D users communicate with each other over a direct link and CUE communicates with eNB by using one of the DUEs as a relay. It is assumed that the cue is far apart from BS and the direct link is not good enough to support any kind of communication. It is also assumed that the relay DUE can communicate bi-directionally with its paired D2D user, as well as assisting the transmission between the CUE and eNB. The transmission time is divided into two distinct periods. During the first period, relay DUE receives data from its paired DUE, CUE and eNB concurrently, and during the second period, the relay DUE sends the data to its paired DUE eNB and CUE. It is shown through numerical analysis that with proper power control at eNB and CUE, the achievable rate for DUEs and CUEs can be increased by up to 60%.

Xu et al. [35, 36] have proposed an auction-based underlaying resource allocation scheme to optimize the sum-rate in an underlayed single-cell D2D setup. The proposed scheme considers radio resources as bidders that compete to obtain business. Likewise, DUEs are considered as services or goods that are waiting to be auctioned. The authors have formulated the valuation of each D2D pair for each resource unit. Based on this value, a cheat-proof non-monotonic descending price iteration mechanism. Using the channel models in [37], the proposed algorithm can increase the sum-rate up to 13%. The proposed scheme is also shown to converge in a finite number of iterations with a comparatively lower complexity.

In [38] the authors have considered an overlay case where a dedicated and orthogonal set of resources (RBs) are available for D2D communication. In order to guarantee the D2D communication QoS with minimum dedicated RBs, the authors first derive a lower bound for DUE interference distance. The derived lower bound is based on two main factors DUEs density and QoS requirement. Based on this interference distance two resource allocation mechanisms namely, dual metric (DM) and the tolerant interference degree (TID) are proposed. To uniformly divide the DUEs for each dedicated RB and identify the interfering sources, the DM mechanism defines two metrics called partner distance and interference distance. Then a graph coloring technique based on saturation degree is designed for DM scheme to allocate the resources uniformly. In TID mechanism a new metric called TID metric is defined which aims to limit the interference at D2D Rx to tolerable threshold level. Then a TID metric based greedy coloring method is defined to reduce the number of allocated resources. Their simulation results show that both of the proposed schemes outperform the random allocation scheme and other reference schemes.

2.1.3 In-band Distributed Resource Allocation

An underlay distributed and low-overhead resource allocation scheme for D2D communication is proposed in [39]. The proposed distributed algorithm can be categorized as a fictional pricing mechanism [40]. The proposed scheme is divided into two stages. In the first stage, eNB transmits a pricing signal to DUEs, where the price depends upon the difference between CUEs tolerable interference limit and total interference caused by the DUEs. Note that price is a variable term used for accessing resource blocks. It increases when the total DUE interference is higher than the CUEs tolerable limit. In second stage, given the pricing signal, each DUE selfishly maximizes its utility. It consists of two components: reward and penalty. Reward is the expected data rate of a DUE and penalty is the interference it generates. The numerical assessment shows that the proposed algorithm effectively protects the cellular transmission with only 12% reduction in the average throughput of the DUEs.

Brett et al. [41] develop a distributed dynamic spectrum sharing protocol for underlay D2D communications in which DUEs can opportunistically access the UL resources of the active CUEs. The DUEs can reuse the UL resources as long as their interference to CUEs does not exceed a margin K. In the proposed scheme, all DUEs first estimate the channel gain between themselves and eNB in a distributed manner, and then set a feasible transmit power to keep the interference within the allowed margin K. Secondly, DUEs utilize CSMA/CA to randomly access the UL CUE channels and Dynamic Source Routing (DSR) protocol [42] for both single and multi-hop D2D link discovery. The simulation results show that a significant improvement in D2D performance can be achieved at the cost of very small loss in CUE performance. Nevertheless, the distributed resource allocation schemes reduce the network signaling overhead, but at the same time, also degrade the overall spectrum efficiency and fairness [43].

Summary It is observed in this subsection that enabling D2D communication in both unlicensed [13–23] and licensed [24–43] bands can significantly improve the overall network capacity. Both of these approaches have different pros and cons. From the perspective of CUEs, the unlicensed band is ideal for D2D communications, since D2D will use the ISM band, it can not cause any interference to cellular communication. Most of the currently available smart phones in the market can operate on multiple RATs and therefore by using unlicensed band the users can simultaneously avail both D2D and cellular communication services. Since the scheduler in out-of-band D2D does not have to consider the time, frequency and geographical location of users into account, the resource allocation is not very complex. However, besides these advantages, the QoS in out-of-band D2D cannot be fully guaranteed because the interference management in such network is beyond the control of eNB. Similarly, the interference that out-of-band D2D will cause to other RATs (e.g. WiFi, BT etc) operating at same ISM band is another drawback of using unlicensed spectrum.

On other hand, the licensed band D2D also has several pros and cons. Since the power control and resource scheduling in in-band D2D is mainly controlled by eNB, improved spectral efficiency and guaranteed QoS can be achieved. Additionally, due to network controlled D2D session, better security can be implied. Alongside these advantages, in underlaying in-band D2D communication mode, the DUEs might cause severe interference to CUEs and interference mitigation in this case is very challenging. Likewise, in overlay mode, since the NOR are used for D2D communication, resource utilization and spectrum efficiency is decreased. Additionally, complex resource scheduling and power control mechanisms need to be adopted to maintain the QoS in the network. Furthermore, note that compare to DL resources, the reuse of UL resources for underlaying D2D communication is extensively studied in literature. It is because in UL reuse case the interference from D2D communication is only observed at eNB and since it has significantly higher computational power compared to a normal UE, it can effectively coordinate interference between CUEs and DUEs. Another advantage for reusing UL resources is that since CUEs has relatively less transmission power compared to eNB, they tends to cause less interference to D2D communication.

It can also be observed from this subsection that, compared to in-band D2D very limited research work has been done in the area of out-of-band D2D. However, based on these initial studies it is safe to claim that the use of unlicensed band for D2D communication can also significantly improve the overall network capacity. A more desirable solution to further improve the network capacity, will be a dynamic approach where based on network environment, the appropriate selection of radio band is made. Nevertheless, to fully explore the long term advantages of unlicensed band D2D in comparison with licensed band underlaying D2D, more detailed studies are required.

2.2 Power Efficiency

The aim of D2D communication is to exploit the cellular infrastructure to achieve better spectrum and energy efficiency. Optimal transmit power control of UEs in combination with proper resource allocation can significantly increase the network performance in terms of both energy and spectrum efficiency. An optimal power control scheme for energy efficient distributed D2D communication is proposed by Yuan et al. [44]. The proposed scheme considers the circuit power consumption of DUEs and aims to maximize their energy efficiency while guaranteeing a minimum throughput requirement for both CUEs and DUEs. The circuit power is defined as the amount of power consumed by the UE circuit. The value of circuit power might vary depending on its mode of operations (e.g., idle mode or active mode), however the authors assume that the mode of operation is already known. Based on DUEs circuit power consumption, three different zones (i.e. low, medium and high) for circuit power consumption are defined and closed form optimal power control strategies are derived for low and high consumption regions. A nonlinear equation for optimal power control in medium consumption region is also derived.

Furthermore, the authors have also proposed a distributive algorithm for the implementation of proposed power control scheme. For performance evaluation, the authors have only considered one CUE and one D2D pair. The numerical analysis shows that the proposed scheme has low complexity and in terms of energy efficiency it has better performance than heuristic best-response scheme.

Gu et al. [45] have proposed a dynamic power control scheme for D2D communications. The DUEs in [45] periodically adjust their transmit power and maintain a threshold received signal strength (RSS) so that eNB and resource sharing CUE do not face massive interference. However, the proposed power control scheme does not consider any threshold SINR for either CUEs or DUEs. It has been shown that the proposed scheme outperforms the conventional power control schemes. A distributed power control and link selection algorithm with temporary removal of DUEs is proposed in [46]. In the proposed scheme, the DUEs have to maintain a certain threshold SINR and are not allowed to increase their transmit power beyond predefined value. The transmit power of the potential DUEs is minimized through link selection, where the link selection decision is made based on the received SINR at eNB and D2D receiver. The temporary removal algorithm sets the transmit power of DUEs to zero when the required power exceeds the predefined maximum power. A single-cell CDMA cellular system is considered for performance evaluation. It has been shown that the proposed algorithm outperforms the GRR-GDCPC algorithm [47] in terms of outage probability and convergence rate.

Gabor et al. have studied the performance of various power control strategies in LTE networks that may be applicable to D2D communication [48]. A utility function based distributed power control scheme has been proposed are compared with the existing methods. The proposed scheme uses dynamic resource allocation and mode selection. The utility function maximization technique balances the total transmit power and the spectral efficiency. The numerical results show that LTE-based power control scheme performs close to utility optimal scheme. In [49], Yu et al. have analyzed different power control schemes for D2D communication in a cellular network with orthogonal and non-orthogonal resource sharing. The study focuses on network sum-rate maximization, and analyzes two different power control mechanisms. In first case, both CUEs and DUEs are treated equally without any priority and a greedy sum-rate maximization is applied with constraint on transmit power. Similarly, in the second case, CUEs are given more priority by guaranteeing a minimum threshold data rate (rate-constrained) under the same transmit power constraint. Moreover, an upper bound has also been defined for the maximum transmission rate of all links. It is concluded that reasonable QoS can be guaranteed with increased sum-rate by using rate-constrained power control mechanism.

Xing et al. [50] have studied four power control schemes for D2D communication. Firstly, they study the case where DUEs use the fixed transmit power without considering any target SNR. On the other hand, in the second case, a target SNR for DUEs is considered. The third and the fourth case study the LTE open loop and closed loop power control schemes, respectively. The authors conclude that the closed loop power control with a dynamic tuning step may be suitable for D2D communication. Here tuning step is defined as a step when power in closed loop power control scheme is tuned (increased or decreased) based on the SINR feedbacks. It has also been noted that power control alone is not an effective method to avoid co-channel interference between CUEs and DUEs. In [51], Zhou et al. have studied the combined energy efficiency and resource allocation in an underlay D2D communication network. The authors have proposed a non-cooperative game-theory based distributed energy efficient resource allocation scheme. The UEs in the proposed scheme try to maximize their energy efficiency while satisfying certain QoS requirements under transmit power constraints. To compare the proposed algorithm, the authors in [51] have also derived a spectrally efficient algorithm. The simulation results show that there is no significant improvement in the spectral efficiency if the transmission power is increased more than the derived optimal energy efficiency. To further analyze the trade-off between energy and spectral efficiency, the authors have derived close-form expressions for energy and spectral efficiency gaps.

In [52], Wang et al. have investigated a joint power control and resource allocation scheme for D2D communication underlaying cellular networks. A reverse iterative combinatorial auction (ICA) game is introduced to solve the optimization problem of energy efficiency. In the proposed ICA game, DUEs with their respective transmit powers are considered as items while CUEs occupying radio resources are viewed as bidders competing for the items. It is shown through simulation results that the proposed algorithm performs near to optimum, and significantly improves the system energy efficiency. In [53], the authors propose an iterative algorithm which jointly optimizes the matching and power control of CUEs and D2D links. The proposed algorithm investigates the reuse of downlink radio resources between multiple D2D links and multiple CUEs, and imposes a QoS target for each CUE link. Each D2D link in the proposed scheme is allowed to reuse the radio resources of multiple CUEs. It has been shown that by proper matching and power coordination, an optimal resource reuse solution can be achieved. Janis et al. propose a power control scheme in [54] and a resource allocation scheme in [55] for CUEs and DUEs working in an underlay cellular network. The scheme reuses CUEs UL and DL resources in D2D communications. In order to satisfy a predefined minimum threshold SINR of CUEs, the transmit power of DUEs are restricted to a certain level. The eNB allocates the radio resources to DUEs in such a manner that it causes least interference to the CUEs. The single-cell based semi-analytical results show that significant gains in terms of sum-rate can be achieved by enabling D2D communications.

A joint power control and resource allocation scheme for D2D communication in an OFDMA based cellular system is proposed by Gu et al. [56]. The resources to CUEs and DUEs are allocated in such a manner that it maximizes the sum-rate of the network. The proposed power control scheme ensures a certain threshold SINR for CUEs and imposes a maximum limit on the SINR of DUEs. The authors in [56] have compared their simulation results with [55]. It has been shown that a better sum-rate can be achieved by using the proposed combined resource allocation and power control scheme. A constrained Single Carrier Frequency Division Multiple Access (SC-FDMA) [57] based joint resource allocation and power control scheme for D2D communication has been proposed in [58]. The proposed scheme uses fractional frequency reuse (FFR)-based architecture to efficiently allocate the resources to both CUEs and DUEs. In the proposed scheme, DUEs are not allowed to reuse the uplink resources of CUEs located in the same sector. Thus, by maintaining a spatial distance between resource sharing UEs, the proposed scheme significantly reduces the overall interference in the network. Moreover, the proposed power control scheme provides equal opportunity to CUEs and DUEs for maintaining reasonable SINR levels at all times. The simulation results also show that the proposed scheme improves the overall network sum-rate and significantly reduces the peak-to-average power ratio (PAPR). The authors in [59] have proposed a joint resource allocation and power control scheme for D2D communication using uplink resources of the CUEs. The proposed scheme uses proportional fair (PF) scheduling algorithm for resource allocation. Moreover, the resources of DUEs are allocated based on their highest PF metric values while their transmit power is controlled to guarantee a minimum threshold SINR of the CUEs. The performance evaluation reveals that the proposed scheme can improve the system capacity and promote overall scheduling fairness.

2.3 Mode Selection

One of the key issues in D2D communication is the mode selection, which decides that which radio resources DUEs in proximity should use. The mode selection in D2D communication is usually classified into three types. The first is the non-orthogonal resource sharing (NORS) mode in which the DUEs reuse the uplink/downlink resources of the CUEs. The second mode is the orthogonal resource sharing (ORS) mode in which DUEs communicate using some dedicated resources. Finally, in the cellular mode (CM), UEs communicate with each other only via the eNB and direct D2D communication is not allowed. Mode selection can be either be statically performed at the time of connection establishment, or dynamically performed at every time slot. The static mode selection reduces the communication overhead and requires less computational power while dynamic mode selection has the advantage to opportunistically capture and utilize the fast fading effect of the wireless channels. Several studies have combined the mode selection issues with frequency resource allocation for effective D2D communications.

Yu et al. [60] have considered a static mode selection method that employs resource allocation and power control mechanisms. An optimization problem has been formulated in which, first the optimal mode is determined. If the optimal mode is NORS, suitable resource selection and DUE transmit power control is performed to guarantee the QoS for both CUEs and DUEs. It is shown that the formulated problem is non-convex and NP-hard. Based on the prevailing network load, two sub-optimal heuristic algorithms have been proposed in [60] for joint mode selection and resource allocation. The numerical results analyze the sub-optimality and computational complexity of the proposed algorithms. It has been shown that their performance in terms of overall system throughput is near to optimal. Dynamic mode selection and spectrum partitioning has been proposed in [61]. In the proposed scheme, a DUE can dynamically adopt any of the three communication modes (NORS, ORS, and CM) based on the cost and performance. The eNB divides the spectrum and reserves dedicated resources in case ORS mode is chosen. A Stackelberg game framework is proposed to address the joint problem of mode selection and optimal division of the spectrum. The optimal division of the spectrum depends on the distribution of UEs adopting different modes. Conversely, the UE distribution is also affected by the spectrum division. Based on this cyclic dependency, eNB assumes the role of a leader and the UEs act as the followers. Thus a leader optimal control problem is proposed to solve the dynamic mode selection problem. The numerical analysis reported in [61] shows that the proposed scheme can be used as an incentive mechanism to drive the UE distribution closer to the optimal solution.

Wang et al. [62] have analyzed the selection of NORS and ORS mode for D2D communications with shared relays. For NORS mode, both UL and DL resources are reused. The shared relays are deployed at the sector edges and their job is to assist the neighboring cellular communication. For both UL/DL NORS and ORS, the overall network sum-rate is analyzed in the presence and absence of the shared relays. The performance evaluation shows that in most cases, NORS mode outperforms all others when shared relays are used. More specifically, the UL NORS mode is more feasible if the CUEs are located closer to the shared relays. An optimized resource allocation and mode selection scheme for D2D communication underlaying cellular network has been proposed in [63]. A D2D transmission graph is built to describe the transmission relationship between DUEs, and a joint max-flow optimization problem is formulated to optimize the network throughput. The simulation results show that for a considerably long time duration , more data is transmitted in the network via D2D communication mode compared to the cellular mode.

Wen et al. [64] have proposed a dynamic QoS aware joint mode selection and resource allocation scheme for D2D communication. Based on the service demands, the proposed scheme provides equal opportunity to both CUEs and DUEs during resource scheduling. The transmission modes (NORS, ORS, and CM) are determined based on the channel state in the beginning, which is then dynamically adjusted according to the service history. The numerical results show that under heavy traffic load, the proposed scheme outperforms the legacy cellular and D2D schemes in terms of system throughput. A semi-static mode selection mechanism for three different routing modes (i.e. D2D, cellular and hybrid) with various resource allocation mechanisms is studied by Lei et al. [65]. For D2D and cellular communications, semi-static mode selection is considered where decision is made on the basis of time scale of connection establishment/release. On the other hand, the dynamic mode selection is applied in hybrid routing mode where decision is made dynamically at each time slot. To achieve the optimal tradeoff between complexity and efficiency, an intelligent mode selection mechanism is proposed. The idea is to determine whether mode selection should be performed semi-statically or dynamically. The simulation results demonstrate that the dynamic mode selection outperforms the semi-static approach. However, note that the signaling overhead generated by dynamic mode selection is not considered in this work.

2.4 Miscellaneous

In addition to energy efficiency, spectrum efficiency, and mode selection there are some other interesting areas of D2D communications where significant research works have been conducted. Some of the well known research contributions on load balancing, prototypes, and simulator construction are discussed in this subsection.

By using low power nodes (e.g. Pico, Femtocells) in LTE-A, heterogeneous networks (HetNets) are aiming to provide enhanced communication services, such as high throughput, better coverage, low latency and enhanced user experience. However, these networks generate random traffic. Therefore, some cells (Macro and Microcells in particular) may end up having a higher amount of traffic. Liu et al. [66] propose a D2D relay based load balancing algorithm. The algorithm consists of four steps that are executed in a sequence. In first step, the macro eNB tries to offload the new user to a neighboring uncongested cell via D2D relay. If there is no uncongested eNB near the new user then the algorithm proceeds to step 2. In step 2, to accommodate the new user, macro eNB tries to release one of its existing user by offloading its ongoing traffic to an adjacent uncongested cell via D2D relay. If the macro eNB fails to offload any of its existing users, the algorithm proceeds to step 3 in which the macro eNB finds a congested eNB in close proximity of the new user. If the macro eNB fails to find even a congested cell adjacent to new user, it proceeds to step 4. In this last step, the macro eNB offloads one of its current users to a nearby congested eNB, which in turn offloads one its current users to its neighboring uncongested eNB. It has been shown that by using this scheme, 21% more users can be accommodated in a single macro cell with 2 femtocells and 2 pico cells.

FlashLinQ is a synchronous and distributed P2P wireless PHY/MAC network architecture developed by QualComm [67, 68]. FlashLinQ is an OFDM-based package for D2D communication that inherits the synchronization from cellular network and offers device discovery, resource allocation and scheduling services with appropriate power control mechanism. Moreover, it also maintains the fairness among users by randomly assigning transmission priorities to all contesting links. The major technical contribution is to make sure the availability of signal and its definite signal strength within each tone, and then based on the OFDM propagation physics and parallel signaling, a tone matrix based analog signaling mechanism is developed. Using the tone matrix, both transmitting and receiving nodes on a direct link can sample the interfering links and estimate the signal-to-interference ratio (SIR) at the receiving node. This allows the system to schedule an appropriate set of links such that each link has SIR greater than the required threshold. The scheduling algorithm is such that random priorities are assigned to different links which are scheduled in a sequential manner. The nodes agree to use a direct link if: (1) their link usage does not cause severe interference (i.e. greater than a predefined threshold) to an already scheduled link and (2) estimated SIR of the link is sufficient for data transmission. QualComm have implemented FlashLinQ over a dedicated licensed spectrum of 5 MHz bandwidth at 2.586 GHz carrier frequency on a TI DSP chipset TMS-C6482 and XiLinX Virtex-4 FPGA. Both experimental and simulation results show that FlashLinQ outperforms 802.11 CSMA/CA system in both outdoor and indoor environment in terms of throughput. For 256 active links, the overall throughput achieved by FlashLinQ in both outdoor and indoor environment is 450% higher than 802.11 CSMA/CA system.

Simulators play a vital role in evaluating the performance of D2D communication under various network architectures and environments. The performance of different proposed schemes has been studied using various performance metrics. Most of the famous network simulators such as OPNET, NS3, OMNET, etc, do not offer any module for D2D communications. Most of the researchers evaluate the performance of their proposed ideas using either by a custom-designed simulator or by modifying Vienna LTE simulator [69]. A system level simulator for D2D communication underlying LTE-A cellular network is developed by Choi et al. [70]. The simulator has considered a network where DUEs operate underlaying LTE-Advance network. The simulator consists of three parts: an event handler, a graphical user interface (GUI) and the main module. The event handler maintains a queue to deal with the incoming events. An event can be the arrival of a new packet/service, resource scheduling request, a possible handover, etc. A GUI is incorporated to make the simulator more user friendly and easy to operate. The main module of simulator further consists of five basic sub-modules:

1. Packet scheduler sub-module, which is responsible for resource allocation and packet transmission. Three widely recognized resource schedulers i.e. round robin, maximum carrier-to-interference ratio and proportional fair have been made available for use.
2. Call admission control sub-module ensures QoS guarantees for the ongoing network services. Based on available resources and maximum allowed packet delays, this sub-module decides the admission or rejection of the new calls.
3. Channel modeling sub-module estimates the RSS at eNB, CUEs and DUEs based on path loss, shadow fading and multipath fading effects.
4. Traffic generator sub-module is designed to evaluate the performance of D2D communication under various traffics types. Both real-time traffic (VoIP and video streaming) and non-real time traffic (FTP and web browsing) generators are incorporated in this sub-module.
5. Finally, the mobility management sub-module controls UE deployment and their mobility patterns.

3 D2D Communications in Public Safety

Recently, a growing interest has been witnessed in applying the commercial cellular technologies to public safety environments. One of such examples is PS-D2D communications. PS-D2D communication relates with the situations where in-coverage UEs (also known as relay UEs (RUEs)) provide reliable communication services to the out-of-coverage UEs (also known as isolated UEs (IUEs)). The out-of-courage zone in PS is assumed to be the area where there is no network coverage available and the infrastructure is completely or partially destroyed due to some disaster, such as flood or earthquake. Figure 8 shows an example of a typical PS-D2D environment. Recognizing the importance and need of the PS communications, the 3GPP has started to study the scenarios, requirements, and technology enablers related to PS-D2D communication [71].

In this section, major issues associated with PS-D2D communications such as peer discovery, synchronization and optimal relay selection are discussed in great detail. For reliable PS-D2D communications, successful peer discovery and synchronization are two very important initial steps to establish a reliable communication link between IUEs and eNB. Since IUEs are isolated and out of eNBs coverage zone, it is necessary for them to discover their neighboring UEs. Similarly, since IUEs are not connected with any centralized network it is essential for them to be synchronized with neighboring IUEs and RUEs for successful data transmission. Similarly, proper relay selection also plays a vital role in providing reliable communication to IUEs. In addition to the above mentioned issues, some other issues related to PS-D2D communication such as communication specifications, group communication, experiments and prototypes are also discussed here in considerable detail.

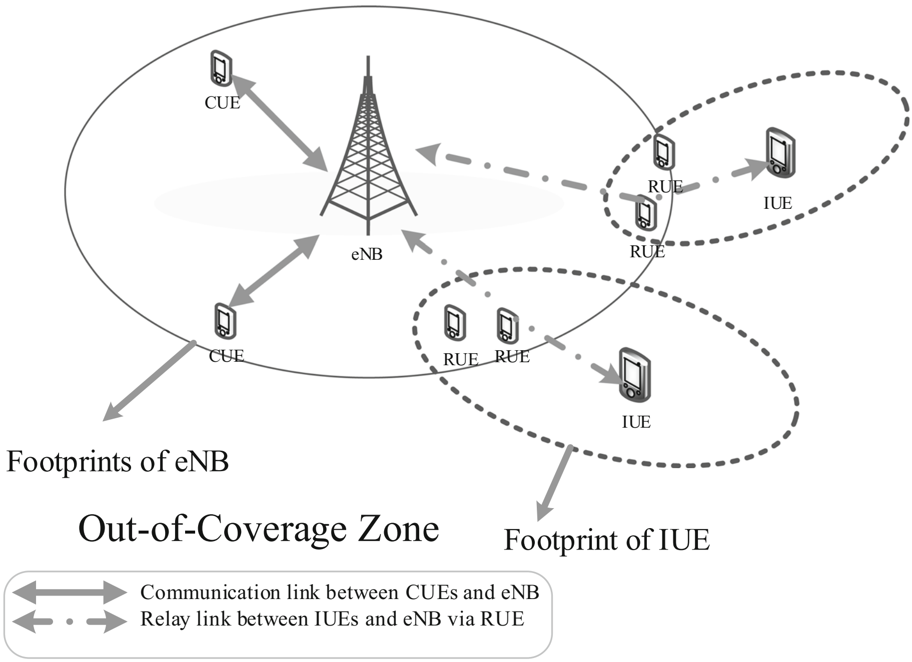


Fig. 8 D2D communication in public safety

3.1 Peer Discovery and Synchronization

Efficient peer discovery and synchronization is one of the most important aspects of D2D communications in LTE-A. The peer discovery becomes more critical in public safety scenarios when there is no centralized eNB to assist the discovery procedure. Moreover, the discovery procedure in public safety should be autonomous, energy efficient (low duty cycle), and scalable to support large number of UEs in different network topologies [72]. In this section we provide a review of the available distributed and autonomous D2D discovery mechanisms.

A bio-inspired distributed D2D discovery and synchronization algorithms have been proposed by Chao et al. [73]. Each device in the basic firefly scheme is equipped with a counter and beacon signal transmitter. The value of the counter keeps rising with time until it reaches a predefined threshold, at which time a beacon signal is transmitted. On other hand, when the neighboring devices receive a beacon signal they increase the counter value at a fixed rate. For example, this can be expressed as a phase function $\phi_i(t)$ which is integrated from zero to a certain threshold ϕ_{th}. Once ϕ_{th} is attained, the UE transmits the beacon and resets the $\phi_i(t)$ to zero. Note that the rate of increment and threshold may vary based on the users groups, services, and applications. The beacon transmission and detection process is repeated until complete synchronization is achieved between all discovered devices. This basic firefly algorithm is not very efficient for large scale networks such as LTE-A. Therefore, a more advanced, topology-adaptive algorithm named firefly-spanning tree has also been proposed. The simulation results show that the proposed algorithm outperforms the other existing algorithms for peer discovery. The DUEs may consume a considerable portion of energy in maintaining the correct counter. The energy efficiency issues have not been explored in [73].

A distributed synchronous device discovery mechanism is proposed by Huang et al. [74]. The proposed scheme first forms a synchronized group of neighboring devices and then all the devices in the group announce their existence one by one. Unlike legacy discovery mechanism where each device periodically transmits a beacon signal, the devices in the proposed scheme only transmit on their turn. The main motivation is to reduce the amount of energy consumed by each node in transmitting discovery messages. The simulation results show that the proposed scheme can reduce the discovery time and that it is highly scalable. Since in a distributed network, all DUEs independently transmit their beacon signals, the probability of collision between these signals is very high. Hong et al. [75] have proposed a neighbor-assisted collision detection scheme. According to the proposed scheme, an assisting UE can detect collision between different DUEs by measuring RSSI and SINR of the received beacon signals. Upon detection of possible collision, the assisting UE notifies the neighboring DUEs that they must not use the same resource simultaneously. After receiving this notice, the colliding DUEs transmit their beacons in another resource block during the next discovery period. The simulation results shows that the proposed scheme discovers more DUEs when compared with the legacy idea of transmitting beacons randomly. Note that the signaling overhead caused by the assisting UE has not been addressed in [75].

Two different D2D discovery models: I am here and who is there?/are you there? are specified by 3GPP in [76]. According to I am here, a UE assumes one of the roles: announcing and monitoring. In the announcing mode, a UE periodically broadcasts its presence via the beacon messages. The beacon messages contain necessary information about the UE (ID, ProSe application code, etc). On the other hand, in the monitoring mode, a UE periodically listens to the announcing UEs. In who is there/are you there model, the UEs discover their neighbors that have the same interest. The discovering UE broadcasts its interests (e.g. discovering a particular group) in beacon messages and upon receiving those beacon messages, the discovered UEs can respond if their interests match. This approach may also give rise to considerable energy inefficiency. Prasad et al. [77] study the energy efficiency of the schemes proposed in [76]. The authors also propose a proximity area (P-Area) based energy efficient D2D discovery mechanism. P-Area is defined as the region where the probability that multiple devices with same interests can meet is high. According to the proposed scheme, the UEs activate their D2D discovery mode only when they are in the P-Area and thus save significant amount of energy. The simulation results show that the proposed scheme can save up to 78% of their battery power in comparison with legacy discovery mechanisms.

3.2 Relay Selection

The appropriate relay selection in PS situation is an important step to provide reliable network coverage to the isolated UEs (the UEs that are out of eNB coverage). Several crucial issues such as meeting QoS requirements, mobility management and energy efficiency, etc, need to be considered while selecting a relay. In this section, we review the available research work as well as 3GPP technical reports pertinent to relay selection in PS environment.

Kim et al. [78] propose three different relay selection mechanisms. (1) Best relay selection, (2) Relay cooperation, and (3) Relay ordering. The first is the best relay selection scheme, in which the UE having the highest relay-to-destination transmission rate is selected as relay UE (RUE). The second method proposed in [78] is relay cooperation. In this scheme, two RUEs are randomly selected that cooperate in forwarding the received signal to an IUE. Finally, in the relay ordering mechanism, IUE broadcasts a signal which is responded to by several candidate RUEs. The RUE with highest SNR is selected as a first hop RUE for a given IUE. The simulation results reported in [78] show that the best relay selection scheme outperforms the other schemes in terms of achievable transmission rates. While [78] provides useful assessment of the relaying mechanisms, it assumes that the UEs remain stationary. Therefore, it fails to provide any insight into the changes brought by the mobility patterns of the RUEs and IUEs.

Munir et al. [79] have proposed a QoS-aware relay selection scheme for public safety environments. Unlike [78], the proposed scheme additionally considers the four QoS classes identified by 3GPP (interactive, background, conversational and streaming) and the radial velocity of UEs. Since each QoS class requires different data rates for reliable data transmission, the proposed scheme uses weighted sum model (WSM) to select the most appropriate RUE. It has been shown that the proposed scheme outperforms the best relay selection scheme of [78]. The extended version of [79] is appeared in [80]. The authors in [80] have described the complete communication process of IUE with evolved packet core (EPC) via RUE in. Their main goal is to provide seamless communication services to IUEs without additional infrastructure while satisfying the QoS requirements of minimum packet delay and high data rates. The QoS parameters along with number of relay reselection are compared with different relay selection schemes and their performance evaluation shows a significant decrease in average communication delay and number of relay reselection. However, there is a minimal degradation of throughput performance as compare to other schemes because a large number of IUEs are sharing the same radio resource.

According to 3GPP [81, 82], Qualcomm and ZTE have proposed several RUE selection mechanisms. The following discusses the schemes put forward by their commercial units. Qualcomm has proposed six relay selection mechanisms based on downlink reference signal received power (DL-RSRP), downlink SINR (DL-SINR) and device-to-device RSRP (D2D-RSRP) [81]. More specifically, the first three scenarios based on DL-RSRP are; (1) only those CUEs whose DL-RSRP from eNB is less than −85 dBM (DL-RSRP < −85) can be selected as RUE, (2) only those CUEs whose DL-RSRP from eNB is greater than −85 dBM (DL-RSRP > −85) can be selected as RUE, and (3) CUE whose DL-RSRP from eNB is highest among all other CUEs is selected as a RUE. Similarly, the remaining three scenarios are; (4) based on DL-SINR between eNB and CUE, the IUE selects the CUE with highest DL-SINR as its RUE, (5) based on D2D-RSRP (i.e. RSRP at IUE from CUE), the IUE selects the CUE with highest D2D-RSRP for relaying its information to eNB, and finally (6) IUE randomly selects a CUE in its proximity as its RUE. Qualcomm evaluated all six schemes in terms of end-to-end packet loss and achievable SINR for both VoIP and video traffics. The simulation-based assessment reveals that D2D-RSRP based relay selection has the best end-to-end performance. It has also been noticed that DL-SINR based selection utilizes minimum radio resources while providing reasonable end-to-end performance. In comparison with DL-SINR scheme, D2D-RSRP increases resource utilization by 24 and 43% for VoIP and video traffic, respectively. More detailed results are summarized in Table 1.

Based on who selects RUEs for the isolated node, ZTE have proposed two main approaches [82]. In the first approach, eNB decides the most appropriate RUE while in the other approach, IUEs themselves select RUEs. The first approach (also called eNB controlled approach) assumes that all potential RUEs and IUEs are within the coverage of the eNB, but the SINR at IUEs is very low and not suitable for data communication. Figure 9 shows the signaling flow of the first approach, where after discovery, the IUE will report the RUE-to-IUE link (sidelink) quality via PUSCH. Based on the received information, eNB can choose the particular RUE for IUE and transmit feedback information which contains at least the ID of the selected RUE.

Table 1 Performance details of different relay schemes proposed in [81]

S. no	Metric	Number of UEs relayed (VoIP)	Resource utilization per packet per access link (VoIP)	Number of UEs relayed (video)	Resource utilization per packet per access link (Video)
1	DL-RSRP > −85 dBm	276 out of 444 (62%)	1.92 RBs (−13.5%)	215 out of 444 (48%)	2.60 RBs (−26.5%)
2	DL-RSRP < −85 dBm	298 out of 444 (67%)	3.03 RBs (+36%)	282 out of 444 (63%)	2.60 RBs (−26.5%)
3	DL-RSRP	354 out of 444 (79%)	2.27 RBs (+2%)	318 out of 444 (71%)	3.60 RBs (+1.5%)
4	DL-SINR	354 out of 444 (79%)	2.22 RBs (Baseline)	318 out of 444 (71%)	3.54 RBs (Baseline)
5	D2D RSRP	354 out of 444 (79%)	2.77 RBs (+24%)	318 out of 444 (71%)	5.08 RBs (+43%)
6	Random	354 out of 444 (79%)	2.72 RBs (+22%)	318 out of 444 (71%)	4.92 RBs (+38%)

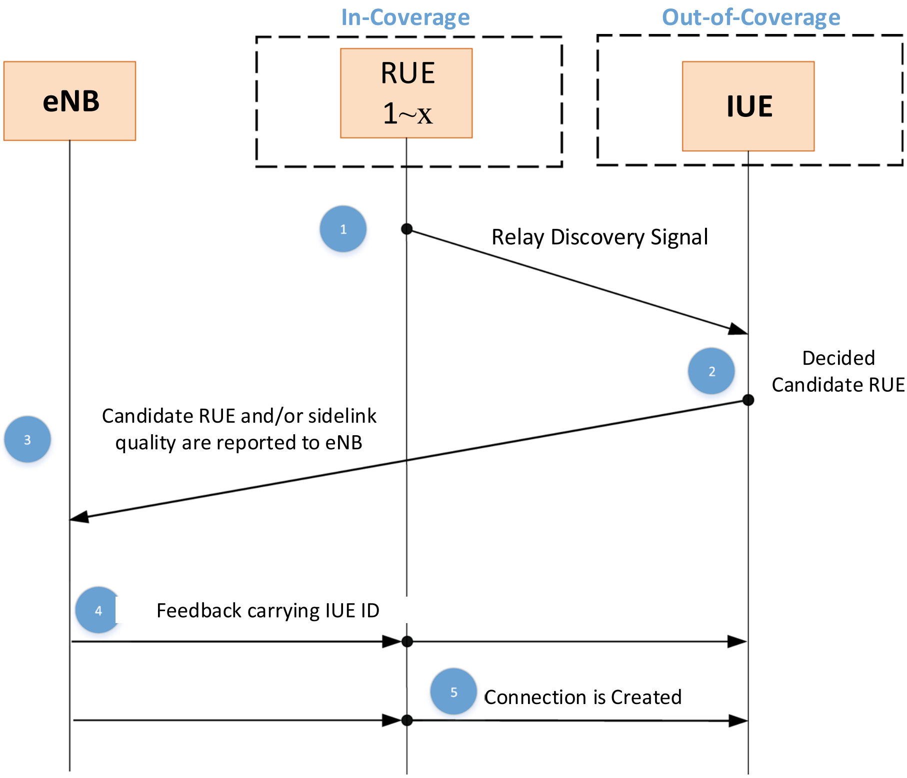


Fig. 9 eNB controlled relay selection [82] (case when IUEs are in-coverage)

The second approach is further classified into three cases. case-1 based on both D2D-RSRP and DL-RSRP values, IUE chooses its RUE; case-2 based on only D2D-RSRP, IUE selects its RUE; and case-3 IUE randomly selects its RUE among the CUEs available in its proximity. It has been shown by using simulation that D2D-RSRP scheme (case-2) outperforms all other schemes in terms of drop packet ratio. It is because the performance of proposed two-hop communications schemes is primarily determined by the bottleneck link. It is shown in [82] that in both case-1 and case-3 the access link (link between RUE and IUE) is significantly weaker than the backhaul link (link between eNB and RUE). Therefore, their drop packet ratio is higher than case-2 where the quality of both access link and backhaul link are close to each other.

3.3 Communication Specifications

The channel bandwidth available for legacy narrow-band emergency service communication is between 12.5 and 50 kHz. This much bandwidth may be sufficient for routine traffic updates and small packet exchange. However, several traffic awareness applications increasingly use services like interactive maps, which require a larger band. Consequently, in the United States, 20 MHz BW at 700 MHz carrier frequency has been dedicated for PS communication [83, 84]. The band was previously used by the digital TV systems in the US. In Europe, 400 and 800 MHz bands are to be dedicated for PS services. Similarly, most of the countries following Asia Pacific Telecommunity (APT) standards are in the process of dedicating spectrum slots for PS in the 400 and 800 MHz bands [85]. Note that the channel sizes for UL/DL may vary depending on the specification of each country. Another important physical consideration is the amount of allowable transmit power in the PS spectrum. In typical PS environments, a UE has to cover a large geographical area while satisfying certain QoS requirements. According to the current LTE standard, the maximum Tx power of UE is 23 dBm which is believed to be insufficient to achieve the desired QoS in PS environment [86]. 3GPP has dedicated a special Work Item to standardize a new UE class for PS services with higher Tx power [87].

3.4 Group Communication

In public safety scenarios, the group communication service (GCS) provides an efficient and controlled mechanism to dispense the contents to multiple users (see Fig. 10). Unlike push to talk (PTT) service of the land mobile radio (LMR) system [88], GCS in LTE supports video, voice, and general data communication [89]. A UE using GCS can be a member of more than one groups and can simultaneously communicate to multiple groups [90]. For public safety applications, 3GPP has been working on different enablers for GCS such as designing open interfaces and modular functions. In order to make GCS more scalable and interpretable, 3GPP is also considering different mechanisms to allow the non-3GPP devices (e.g. wired devices) to connect with the group. The so-called 3GPP Group Communication System Enabler (GCSE) can be enabled on a group member basis. Therefore, several flexible and efficient resource distribution mechanisms are under consideration [90]. The GCS groups and their members will have different priority levels, consequently, different mechanisms for priority resource allocation and their efficient

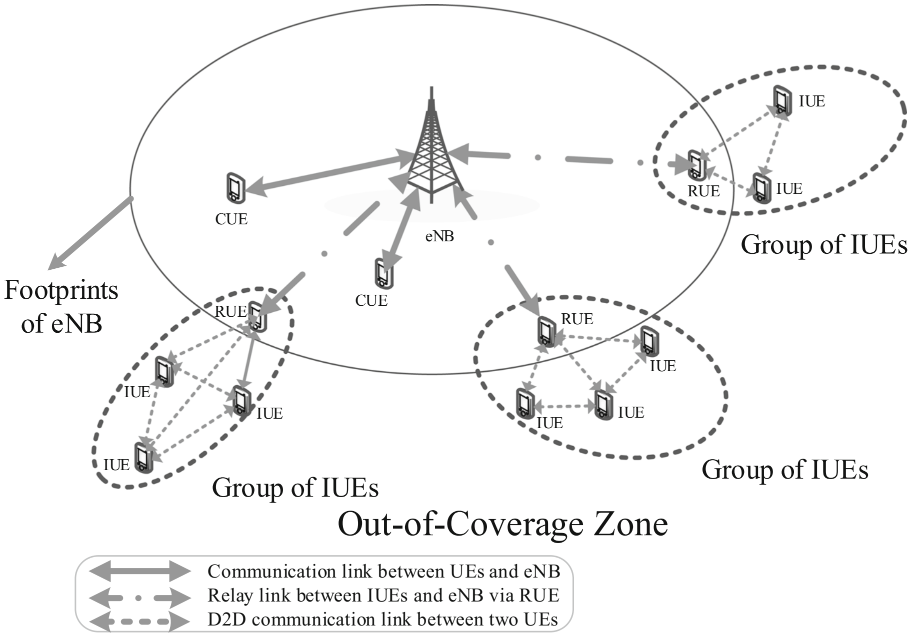


Fig. 10 Group communication in public safety environment

utilization are also being considered. A new cellular network independent entity called the GCS Application Server (GCSAS) has been considered by 3GPP for application signaling and data delivering to the groups [91]. GCSAS can either broadcast data over Multimedia Broadcast Multicast Service (MBMS) bearer services [92] or it can send unicast messages over Evolved Packet System (EPS) bearer [93]. Since GCSAS is not associated with any cellular network and it is a third party application server, in order to extend the mobility aspects to group calls, two different GCSE LTE architectures for roaming and non-roaming scenarios are also proposed by 3GPP [91].

3.5 Experiments and Prototypes

Most of the research work conducted in the area of D2D communications considers the centralized network approach where eNB controls and monitors entire D2D communications. However, in the public safety scenario, a decentralized D2D communication network is of equal importance. In this section, a discussion on some of the experimental prototypes specifically developed for D2D applications in public safety environment, is provided.

Relay-by-smartphone is a decentralized multi-hop D2D communication system developed by Tohoku University [94]. Because PS services are often required in environments where a single networks parameters vary greatly (e.g. frequency spectrum, distance, and required QoS), it is necessary that a UE supports multiple interfaces for always-available communication. The main contribution of [94] is to develop a prototype PS network in which the fusion of two routing techniques, namely mobile ad hoc network (MANET) and delay/disruption tolerant network (DTN) [95, 96], are integrated in all UEs. And UEs can select the optimal routing mechanism depending on the network environment such as, UE mobility and density of UEs in the network. Since both MANET and DTN operate at different OSI layers, it is possible to combine both of them in one UE. MANET is more effective in a network environment where UEs are static and densely deployed and DTN is more suitable in situations where UEs are isolated and have high mobility. Thus, in the relay-by-smartphone system, a UE can switch between two different modes i.e. MANET mode and DTN mode. This switching decision is based on three factors: the number of neighboring UEs, physical acceleration of the UE, and remaining battery power. A threshold value for each of these factors is predefined. If both the number of neighboring UEs and the amount of remaining battery power are greater than the threshold, but the acceleration of UE is less than the threshold, the UEs select the MANET mode. On the other hand, if the number of neighboring UEs and the amount of remaining battery power is less than the threshold, and the acceleration of UE is greater than defined threshold, the UEs switch to the DTN mode.

The authors in [94] also envision that in order to connect an isolated disaster-affected area with an unaffected area, it is necessary that D2D systems should additionally incorporate other networking technologies. Networks like movable and deployable resource units (MDRUs) and unmanned aircraft systems (UASs), etc [97] can be good examples. To study the effectiveness of the relay-by-smartphone prototype, the authors in [94] have conducted several field experiments in Sendai City. A total of 20 moving UEs operating in the ISM band using WiFi ad-hoc mode were deployed along the streets. Using multi-hop D2D communication, messages were successfully transmitted from source to the destination (2.5 km away). Another experiment successfully transmitted a message from source to destination (3 km away) using UAS relay system. It has also been observed in the experiments that the delivery time is directly proportional to the message size.

4 D2D Applications and Open Research Issues

4.1 D2D Applications

This section covers the discussion on potential D2D applications and services. A shorter communication range, improved throughput, low power consumption, and high spectrum efficiency are some of the features of D2D communication that have extended its use case domain. The major applications of D2D communications are as follows:

- *LTE V2x*: The growing deployment of LTE based cellular networks and the potential features of D2D communications have urged 3GPP to actively consider the use of LTE networks to ensure connectivity between vehicles. This connectivity also includes people inside and around the connected vehicle, and the roadside infrastructure [98]. LTE V2x is considering the use of LTE-based broadcast services and proximity services (ProSe) in automotive industry. Three different use cases for LTE V2x are considered by 3GPP i.e., V2V, V2P and V2I [99]. V2V is referred to LTE-based communications between different vehicles. Likewise, V2P is the LTE-based communication between a vehicle and a device carried by an individual user such as a cyclist, pedestrian, driver or passenger. The LTE-based communication between a vehicle and a roadside unit (RSU) is studied under the name of V2I. A typical example of LTE-V2x has been shown in Fig. 11a.
- *Coverage Extension*: In addition to the fact that D2D communication can significantly improve the system capacity and spectral efficiency, it also has the potential to increase the network coverage and capacity. The DUEs with better network coverage can serve as a relay to support the UEs with poor network coverage. The authors in [100] have studied a D2D coverage extension scenario where DUEs relay the data from eNB to the out-of-coverage UEs. The relay selection is based on the channel quality between DUE and eNB. In other words, among different candidate DUEs, a DUE with the highest channel quality is selected for data relaying. An example of coverage extension using D2D communications has been depicted in Fig. 11b.
- *Proximity Based Group Gaming*: Another interesting application of D2D communication is proximity based gaming where users in close vicinity can play a real time interactive game of their mutual interest (Fig. 11c). In [101], Saund et al. have proposed a mechanism for proximity based gaming over IEEE 802.11 networks. According to their proposed mechanism, a wireless device (e.g. UE) can detect and measure the radial proximity of its neighboring devices via their RSS. Based on radial proximity, it can establish connection and initiate the gaming request.
- *Proximity Based Advertisement*: Proximity based advertisement or proximity marketing is another interesting application of D2D communications where UEs in a desired proximity are detected by D2D access points. The detected DUEs are sent enticing marketing messages (see Fig. 11d). Peng et al. [102] have studied a similar clustering mechanisms for D2D- multicast communications. Using game theory, they have proposed and analyzed their practical clustering strategy. Their simulation results show that in a high user density network, the proposed mechanism can significantly reduce the average transmission time. An algorithm for geographical proximity based group formation and D2D advertisement dissemination is proposed in [103]. The groups are formed based on angular distances among target-areas and the physical distances between the D2D access points and the target-areas.

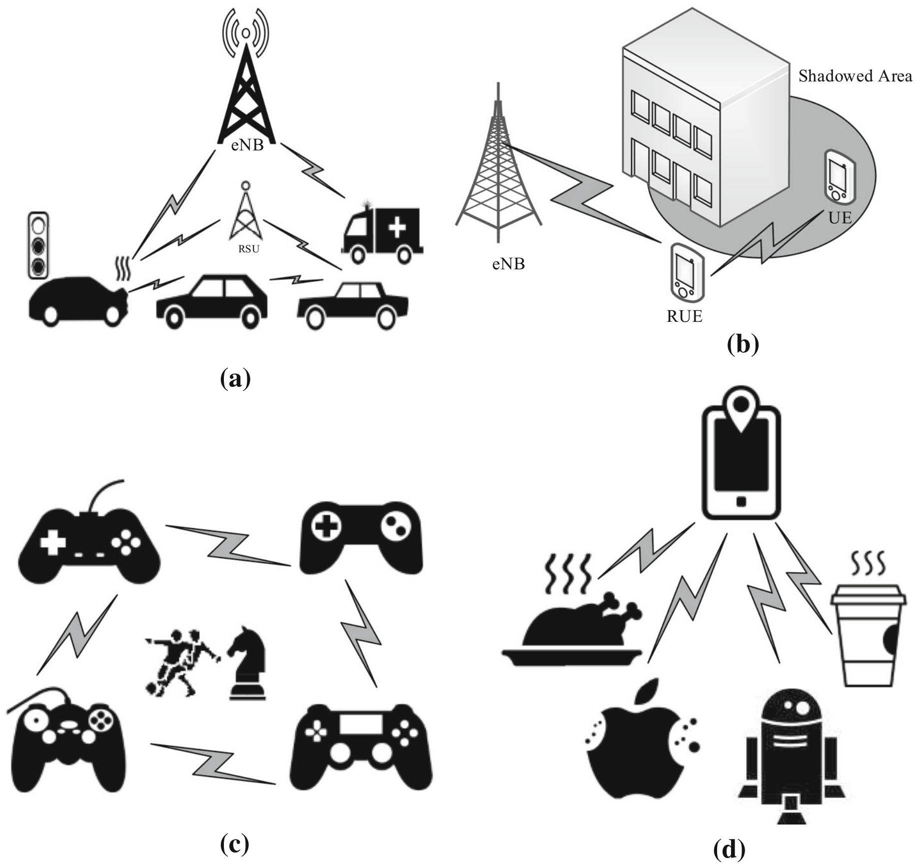


Fig. 11 Different D2D applications. **a** V2X, **b** coverage extension, **c** proximity based group gaming, **d** proximity based advertisement

4.2 Open Research Issues

Although D2D communications has been thoroughly studied in recent years by both 3GPP [104] and academia, there are still some areas that require further research. In this section we will discuss some of the open research issues in the current state of the art.

- *Resource Sharing in Heterogeneous Networks*: A heterogeneous network (HetNet) consists of various types of fixed small cells such as femto-cells and pico-cells. These smalls cells are deployed underlying macro-cell such that they share the traffic load of macro-cell by providing reliable network services to the static users in densely populated areas [105, 106]. It is expected that these small cells will be densely deployed in future HetNets [107]. Since both D2D communications and these small cells will reuse the same frequency bands, the interference management will be much more challenging. In such HetNets, DUEs will cause interference to both macro-CUEs and small cell CUEs. The situation where DUEs and small cells are deployed underlying macro-cell is studied in [108, 109]. The authors in [110] have proposed that

D2D based relay communications should be implied to improve the SINR of UEs which are located in high interference zone of a HetNet.
However, in all aforementioned studies, the DUEs either act as a relay UE or reuse the available spectrum as a secondary user. To the best of our knowledge, there is no research work conducted which extensively studies this challenging interference scenario where all macro-CUEs, small cell CUEs, and DUEs reuse the same available spectrum. In addition to interference management, another interesting scenario will be enabling D2D communications between UEs located under different HetNet eNBs. Imagine the changes required in frequency allocation, transmit power control and management signaling in a situation where two DUEs are in close proximity but are served by different small/macro cells. Such a scenario will become more interesting with the inclusion of moving small cells [111] in future HetNeTs.

- *Mode Selection During Mobility*: Mode selection in D2D communications has been discussed in great detail in Sect. 2.3 [60–65]. However, most of these papers have considered a dynamic or semi-static D2D mode selection for only static UEs. Since it is expected that in near future, a significant number of users will be mobile, a more intelligent, robust and dynamic mode selection mechanism is required. In high mobility environments, the channel condition might change very rapidly and switching from one mode to another will not only increase the decision complexity but will also incur more signaling overhead. Therefore, further investigation is required to design an optimal mode selection strategy for moving DUEs.
- *Energy Efficiency*: In D2D communication, DUEs that are close by communicate directly and hence require much smaller transmit power than the legacy users. Various energy efficient D2D communications schemes [44–59] have been discussed in Sect. 2.2. Most of these recent works have studied the impact of various proposed algorithms from the perspective of legacy radio communications. The issue of energy efficiency becomes more critical in the case of D2D relaying applications such as coverage extension, public safety, etc. The problem is that both the relay UE and Isolated UE (IUE) it is serving are energy constrained. In effect, the network lifetime is highly dependent upon the battery life of the RUEs and IUEs. One of the interesting solutions proposed in [112] is the use of RF energy harvesting for recharging the batteries of RUEs. The authors have proposed a wireless energy harvesting scheme where RUEs harvest energy from the received signals of the eNB, and then utilizes the harvested energy to relay the information to IUEs. Their results show that energy harvesting increases the battery life of the RUEs and consequently improves the network lifetime. The similar type of concepts with different relaying modes [113–115] can be investigated for other complex environments where RUEs can harvest energy not only from the received information signals but also from the interference signals (such as neighboring eNBs and RUEs). To further increase the network lifetime, IUEs can also harvest energy to increase their battery life from ambient sources.
- *Multi-cell D2D Communications*: Most of the recent studies consider the network scenario where both D2D Tx and Rx are located in the same cell. However, this simplified assumption limits the scope of D2D communication. In order to exploit the full advantage of D2D communications, further investigation is required for more complex network scenarios where D2D Tx and Rx are located in two different cells. This multi-cell D2D scenario can become more interesting if mobility is also considered. More specifically, an efficient hand-off mechanism should be in place for the case when an ongoing D2D session has to be moved to a different cell. The authors in [116] have proposed mobility management solutions that are meant for DUEs which

are handing over together. According to the D2D-aware handover scheme proposed in [116], the handover is deliberately postponed until the RSS of DUEs fall below a certain threshold. On the other hand, the D2D-triggered scheme treats DUEs as a group while executing the handover. The simulation results reported in [116] show that the proposed mobility solutions can significantly improve the D2D end-to-end latency and reduce the overall network signaling overhead. However, the present state of mobile D2D communication still requires thorough examination.

- *Security Issues*: Ensuring security is vital for successful integration of D2D communication with existing legacy cellular networks. Despite the overarching need for security, little effort has been done to address this issue in the context of D2D communication. A shared key based authentication and key management scheme has been proposed by Alam et al. [117]. The authors have analyzed the security threats for three different network scenarios namely: (1) D2D communication without user application, (2) D2D communication with user application and D2D communication in public safety. Nevertheless, these network scenarios are very simple, and more complex scenarios should be investigated where DUEs belongs to different operators and different eNBs. Secondly, most existing works have only examined key management and authentication issues. Several other kinds of security threats such as replay attack, denial of service attack, and man in the middle attack also exist and need quick addressing.
- *Performance Evaluation and Numerical Analysis*: The performance evaluation of new D2D communication schemes have either used custom-designed simulators or have used numerical analysis. There is no doubt that these performance evaluation methods are very helpful in analyzing the potential gains of D2D communication, however, due to various simplified assumptions that the simulations make, the considered network environments are far from reality. Furthermore, most of these recent studies have considered full-buffer traffic model where UEs always have data to transmit. However, this assumption does not reflect the true behavior of users in real time networks. We believe that conducting a large scale experimental study or using well known network simulators such as Omnet++ [118], NS3 [119], and OPNET [120] will provide deeper insights into D2D communications. At the same time, it must be noted that establishing a testbed is expensive and has running/maintenance costs.
- *D2D Communication in 5G Networks*: The fifth Generation (5G) cellular networks are expected to use millimeter-wave band to accommodate the dramatically increasing data traffic [121, 122]. The cell size of such 5G networks will be very small (up to 200 meters) as compared to the legacy LTE networks. Therefore, D2D communications can play a vital role in extending the otherwise small coverage region. Qiao et al. [123] have studied D2D communications underlaying millimeter-wave 5G network. The authors have proposed a resource sharing mechanism for the DUEs. Furthermore, they have also discussed the frequent handoffs and user discovery issues in millimeter-wave 5G D2D networks. Nevertheless, more detailed investigation is required to fully incorporate the D2D communications in future 5G networks.

5 Conclusion

D2D communication in LTE-A networks has recently attracted significant research interest from both industry and academia. This has resulted in considerable research effort been made in this area. In this paper, we have presented a detailed overview of the cutting edge research work that is still ongoing in D2D communications. More specifically, we have taken up a classified discussion on commercial and public safety D2D communication. We have examined a number of previous works reported under each class. Detailed discussion on D2D resource allocation, power efficiency and D2D mode selection are also covered, as these constitute the most fundamental issues. We have also extensively reviewed the peer discovery, relay selection and experimental prototypes developed for public safety D2D communications. In view of these research works that have been thoroughly covered in this survey, we finally provide a detailed discussion on various open research issues in this area.

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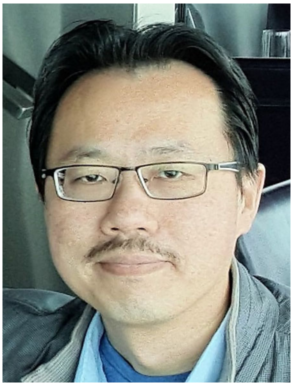

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