A Survey of Device-to-Device Communications: Research Issues and Challenges

Furqan Jameel, Zara Hamid, Farhana Jabeen, Sherali Zeadally and Muhammad Awais Javed

***Abstract*—Device-to-Device (D2D) communication has emerged as a promising technology for optimizing spectral efficiency in future cellular networks. D2D takes advantage of the proximity of communicating devices for efficient utilization of available resources, improving data rates, reducing latency and increasing system capacity. The research community is actively investigating the D2D paradigm to realize its full potential and enable its smooth integration into the future cellular system architecture. Existing surveys on this paradigm largely focus on interference and resource management. We review recently proposed solutions in over explored and under explored areas in D2D. These solutions include protocols, algorithms, and architectures in D2D. Furthermore, we provide new insights on open issues in these areas. Finally, we discuss potential future research directions.**

***Index Terms*—Device-to-Device (D2D) communication, device discovery, mobility management, mobile networks, resource allocation, security.**

I. Introduction

The increasing number of mobile devices along with the plethora of multimedia applications such as mobile gaming, High Definition (HD) movies and video conferencing have triggered rapid advances in cellular technology and services. These developments coupled with the need for data access anytime, anywhere from any device have led to an increase in demand for higher data rates and Quality of Service (QoS) provisioning. Today, it is not uncommon to see multiple devices owned by same user being connected to the Internet, through cellular network, wireless networks and so on all of which are generating large amounts of traffic. It is estimated that between 2010 and 2020 there will be a 500-fold increase in wireless cellular data traffic [1] which will in turn stress the available network resources.

Cellular networks have so far been able to maintain QoS and provide good user experience in isolated areas, but current techniques in these networks will not be able to meet the increasing capacity demands of future mobile users in close proximity to each other, such as in a shopping mall or a concert. Discussions of a new standard (referred to as 5G) are underway in the academia and industry in order to meet the requirements of future cellular networks. The exact definition of 5G is not clear but it takes into consideration a wider range of use cases. 5G networks are expected to support existing and emerging technologies as well as integrate new solutions to meet the increasing demand for data rates [2]. These drivers have motivated research efforts toward efficient spectrum utilization in 5G cellular networks.

One solution for improving spectral efficiency is densification of existing cellular networks by reducing cell size [3] and adding more network resources. Reducing cell size also leads to higher data rates, lower power consumption and lower delays due to the close proximity of cell users and Base Stations (BSs). However, additional infrastructure is required to implement small cells, which results in increase in deployment and maintenance cost [4].

Another promising solution for improving spectrum utilization in next generation cellular networks is Device-to-Device (D2D) communication. D2D communication enables direct communication between nearby mobile devices without the involvement of a BS or the evolved NodeB (the radio part of an E-UMTS radio transmission site). D2D is being considered as a key enabling technology in 5G cellular networks due to the inherent need for high data rate, delay constrained, and QoS specific communication.

D2D communication has always been present in the unlicensed spectrum, but it was not investigated in the licensed spectrum for the first three cellular generations. D2D was introduced in the fourth generation, after LTE release 12 in 2012 [5]. In earliest works on D2D communication, Lin *et al.* [6] proposed a multi hop cellular network to improve throughput by using cellular devices as relays. Later, Janis *et al.* [7] proposed a D2D radio that works to enable peer to peer communication between mobile nodes by reducing interference. In addition, the power level of D2D communication is selected based on the cellular UpLink (UL) power control information to limit the interference to the cellular BS. The authors also presented a mode selection algorithm to improve reliability of D2D communication, where a mode is either a dedicated resource assignment for D2D communications or shared resource assignment for D2D communications with the cellular traffic [8]. In this work, the BS has knowledge of the state information of all involved channels to help it select the optimal resource sharing mode between the cellular user and the D2D pair and to coordinate the transmit power so that the expected throughput is maximized.

5G is expected to be the most widely used wireless technology which will provide data transfer rates higher than 1 Gbps, better spectral efficiency, lower power consumption and solve the devices' limited storage capacity issues. Direct

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TABLE I: List of acronyms.

Acronym	Full form
AN	Artificial Noise
AuC	Authentication Center
AZ	Azimuth Spread
BE	Bandwidth Efficiency
BPC	Binary Power Control
BS	Base Station
CAC	Call Admission Control
CARD	Context Aware Resource Discovery
CCF	Computing and Communication Foundations
CISE	Computer and Information Science and Engineering
CNS	Computer and Network Systems
CODEC	Cellular Network based Device-to-Device Wireless Communication
COAST	Connected Open plAtform for Smart objecTs
CQI	Channel Quality Indicator
CRNTI	Cell Radio Network Temporary Identifier
CROWN	Cluster-based Resource Block Sharing and pOWer allocatioN
CSI	Channel State Information
CUEs	Cellular User Equipments
C-LOR	Co-Location Object Relationship
C-WOR	Co-Work Object Relationship
D2D	Device-to-Device
DL	DownLink
DRPS	Disaster Relief and Public Safety
DS	Delay Spread
DSRC	Dedicated Short-Range Communication
DUEs	D2D User Equipments
ECCS	Electrical, Communications and Cyber Systems
EE	Energy Efficiency
eNB	Evolved NodeB
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
FSO	Free Space Optical
FP7	Framework Programme 7
GPSR	Greedy Parameter Stateless Routing Protocol
HD	High Definition
HetNets	Heterogeneous Networks
HTs	Horizontal Topics
HSR	Human Social Relationship
HSS	Home Subscriber Server
ITS	Intelligent Transportation System
JACMSPA	Joint Admission Control, Mode Selection, and Power Allocation Problem
LBS-AOMDV	Load Balancing based Selective Ad-hoc On-demand Multipath Distance Vector
LoS	Line of Sight
LTE	Long Term Evolution
METIS	Mobile and Wireless Communication Enables for the Twenty Information Security
MFG	Mean Field Game
MIMO	Multiple Input Multiple Output
mm-wave	Millimeter-wave
MPR	Market Pricing Relationship
MU-MIMO	Multi User MIMO
NSF	National Science Foundation
OAA	Optimization using Outer Approximation Approach
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OLSR	Optimized Link State Routing Protocol
OOR	Ownership Object Relationship
OSI	Open System Interconnection
P2P	Peer-to-Peer
P-Area	Proximity Area
PKI	Public Key Infrastructure
ProSe	Proximity Services
QoS	Quality of Service
RATs	Radio Access Technologies
RGCPA	Revised Graph Coloring-based Pilot Allocation
RPAs	Radio Protocol Architectures
RRC	Radio Resource Control
RRM	Radio Resource Management
RS	Reuse Channel Selection
RSUs	Road Side Units
SAVI	Science Across Virtual Institutes
SCMA	Sparse Code Multiple Access
SINR	Signal to Interference and Noise Ratio
SOCA	Social Overlapping Community-Aware
SRS	Sounding Reference Signal
TDMA	Time Division Multiple Access
TDD	Time Division Duplex
TTP	Trusted Third Party
UE	User Equipment
UL	UpLink
VANETs	Vehicular Ad-hoc NETworks
V2V	Vehicle to Vehicle
V2I	Vehicle-to-Infrastructure
V2X	Vehicle-to-Pedestrian
WiFiUS	Wireless Innovation between FInland and US
WFD	Wi-Fi Direct
WPAN	Wireless Personal Area Network

communication between devices in proximity will result in higher throughput and lower latency as compared to communication of these devices through the nearest base station which could be congested due to high traffic load. This will also help alleviate load on backhaul network and improve overall network capacity. By narrowing radio transmissions to the point-to-point connection between devices, D2D communication can provide better reuse of available spectrum. Moreover, direct transmission between devices can be achieved with lower transmission power, resulting in improved energy efficiency. Furthermore, D2D communication can provide many more benefits such as fairness, congestion control and QoS guarantees. D2D communication is particularly advantageous at enhancing cell coverage and throughput at the cell edge area where the signals are much weaker. Although, D2D communication has many advantages, there are still many open challenges to successfully implement this technology. In particular, D2D communication will require efficient device discovery mechanisms, intelligent mode selection (D2D or cellular) algorithms, complex resource management techniques, mobility management procedures and robust security protocols.

A. Fundamentals of D2D communications

The potential of D2D to revolutionize next generation cellular communication has resulted in the integration of D2D in many areas including public safety services [9], vehicular networks [10], cellular offloading [11], multi hop relaying [12] and proximity based services [13]. D2D communication can support local data services efficiently through unicast, groupcast and broadcast mechanisms. Tinder, Waze and Facebook are suitable examples of social proximity based applications for D2D communication. Streaming services like Google Chromecast, IPTV, etc. can be facilitated by D2D communication by forming clusters and groupcasting data within a cluster. Data offloading also presents as an interesting use case, where a device having good internet connectivity can act as a hotspot. Base station can offload/cache data at such a device during peak hours and other devices can download data from this device using direct links. D2D communication is classified as Inband D2D (occurring on cellular spectrum) and Outband D2D (occurring on unlicensed spectrum) as shown in Fig 1.

1) Inband D2D communication: In the case of inband communication the cellular spectrum is shared by both D2D and cellular communications. Inband D2D is further categorized into underlay and overlay.

- **Underlay inband communication** In this case, D2D User Equipments (DUEs) compete with Cellular User Equipments (CUEs) and opportunistically access resources occupied by cellular users, resulting in improved spectral efficiency. Dedicated resource blocks are assigned to the cellular users, and the D2D transmitter reuses these resource blocks for direct communication [14]. Underlay communication enhances the performance of cellular networks by providing high spectral efficiency, however it causes interference in cellular communication by D2D communication and vice versa. Although this limitation can be removed by the implementation of complex resource allocation methods, the latter results in higher computation overhead at the base station.
- **Overlay inband communication** In overlay communications, a portion of the cellular spectrum is dedicated for D2D communication. This reduces the interference problem as both types of communications take place in their separate spectral bands. The advantage of this scheme is that it improves the scheduling and power control in direct D2D communication [15] and it offers improved spectral efficiency and signal strength in relay assisted networks [16], [17].The major limitation of overlay inband communication is that the portion of cellular spectrum dedicated for D2D communication might be used inefficiently which leads to poor resource utilization and system throughput.

2) Outband D2D communication: In Outband D2D, cellular devices use licensed cellular spectrum for communication while the D2D communication takes place through unlicensed spectrum, usually ISM bands. As the cellular and D2D communications occur in different spectrum bands, so the outband communication completely eliminates the spectrum interference issue in cellular link caused by D2D pair and vice versa. However, outband D2D faces issues in coordinating communications over two different bands because D2D communication occurs on a second radio interface. Outband D2D communication has two subcategories: Controlled D2D and Autonomous D2D.

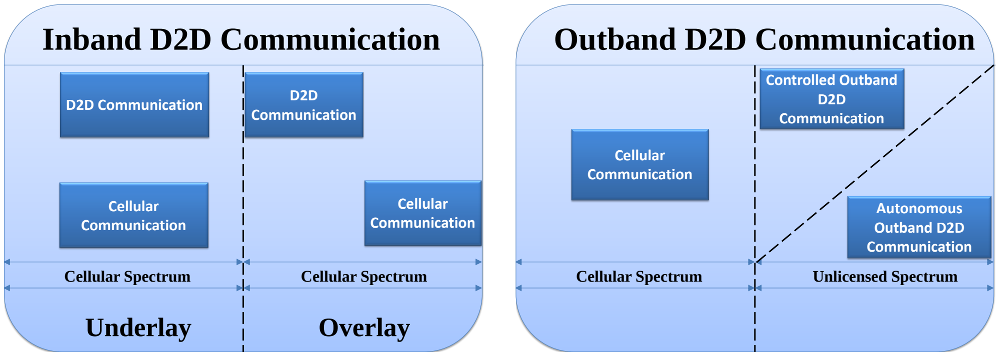
- **Controlled outband communication**
  In this type of communication, the coordination between radio interfaces such as Bluetooth, ZigBee or Wi-Fi Direct is controlled by the cellular network. Spectrum resources are pre-allocated to D2D users so that they can fairly contend and utilize the ISM band resources [26]. In addition, BS can can prioritize the transmission of particular users to meet the QoS requirements. This, consequently, increases the performance of the system in terms of throughput and resource management. However, one evident drawback of this approach is increased signaling overhead with the increase in network size. This deteriorates the performance of network due to considerably long delay.
- **Autonomous outband communication**
  In autonomous outband, cellular links are controlled by the base station while the devices communicating in D2D mode are responsible for the control of D2D communication. This approach significantly lessens the workload of cellular network and since no major changes are required during BS deployment, this is also an attractive solution for operators and mobile service providers. The D2D network is responsible for resource allocation to newly entering devices and which reduces the signaling overhead of the system [27]. This inherent benefit also makes the deployment of BS relatively easier as the devices can spread different traffic requests among themselves [28]. This reduces the overhead on the cellular network.

  A significant challenge in outband D2D communication is in coordinating the communication over two different bands because usually D2D communication happens on a second radio interface (e.g., WiFi Direct and bluetooth). Data packets need to be encoded and decoded because the two interfaces use different protocols. Also the uncontrolled nature of unlicensed spectrum increases security risks and imposes constraints on QoS provisioning. Additionally, the devices can use D2D and cellular communication simultaneously only if they have two wireless interfaces (e.g. Wi-Fi and LTE).

B. Motivation and contributions

There has been a plethora of work on interference management and improving spectral efficiency in D2D communications. However, comprehensive surveys that discussed all aspects, requirements and challenges of D2D communications are largely missing. In [18] the existing literature on D2D is categorized under inband and outband D2D communication. In [20] the authors have provided a detailed survey on experimental prototypes and current state-of-art in D2D communications for LTE. In [22], the authors presented a literature review and current state of art on D2D communication from the perspective of interference management. In [23], the authors focused on different use cases and technologies that support D2D communications. They also highlighted interference management, power control and resource allocation issues in D2D communications.

Table II compares the contributions of this survey over other past surveys on D2D. In contrast to these past surveys, we categorize the work done in D2D in terms of



(a) (b)

Fig. 1: (a) Inband and (b) Outband Overview.

TABLE II: Comparison of our survey with existing surveys.

Reference	Year	Focus/ Objective	Device discovery	Mode selection	Interference management	Power control	Mobility management	Security and privacy	Economics	Integration with 5G technologies
[18]	2014	Review of literature on Inband & Outband communication			*	*				
[19]	2014	Relay Selection & Power Consumption				*				
[20]	2015	Review of literature on Interference & Resource Management with respect to Inband & Outband communication			*	*				
[21]	2015	Resource and Interference Management, Mode Selection		***	***		**	**		
[22]	2016	Review of literature on Interference Management in D2D		*	***					
[23]	2016	Power Control & Interference Management			*	*	*			✓
[24]	2017	Review of literature on security & privacy						***		
[25]	2017	Review of literature on security						***		
Our Survey		Review of literature on under explored and over explored areas in D2D (Device Discovery, Resource Management, Mode Selection, Power Control, Mobility Management, Security)	***	***	***	***	***	***	***	✓

* Review of state-of-the-art ** Open Research Issues *** {Review of the state-of-art + Open Research Issues}

major research challenges including device discovery, mode selection, resource management (interference management and power control), mobility management and security. Our main objective is to provide the reader an up-to-date, state-of-the-art paper of what has been done (protocols, proposed solutions and algorithms) on D2D communications to date and identify issues that still remain to be addressed. More specifically, the major contributions of this paper can be summarized as:

1) We present several ongoing D2D research projects which will be useful for motivated readers interested in the field of D2D communication.
2) We describe the fundamentals and discuss research results achieved so far on various important D2D topics including: centralized/decentralized discovery process, mode selection schemes, resource allocation techniques that leverage interference management and power control techniques, mobility management frameworks and handover strategies, security issues with an emphasis on physical layer security techniques, economic aspects of D2D communications with a particular focus on game theoretic pricing strategies and finally D2D applications for 5G technologies. For all these D2D areas, we also identify open research issues that need further investigation in the future.

The rest of the paper is organized as follows. In Section II, we present D2D enabling technologies and research projects. Section III provides discussion on D2D device discovery methods. In Section IV, we discuss mode selection techniques along with related works. Section V and VI present a review of resource allocation and mobility management techniques in D2D communication. In Section VII, we discuss security and privacy related issues. Section VIII discusses economic aspects of D2D communications. The application of D2D in future 5G technologies is presented in Section IX. Finally, Section X provides concluding remarks. Table I provides the list of acronyms used in this paper.

II. D2D USE CASES, ENABLING TECHNOLOGIES, RESEARCH PROJECTS AND TAXONOMY

A. *D2D communications use cases*

The research attention given to D2D communication is not only because of its performance gains but also due to new applications' practical requirements. Figure 2 shows some of the key applications and use cases of D2D communications.

1) Traffic offloading: In this scenario, the devices are in the communication range of the BS and are using the licensed spectrum for D2D communication. In this communication scenario, D2D communication can be used to reduce the load of BS. For instance, if the users are mobile and it is difficult to maintain the QoS, the best option is to use delay-tolerant services for network offloading. However, if one or both the communicating parties are stationary, then D2D links can be used for offloading peer-to-peer services such as social gaming and cooperative streaming with improved results [29].

2) Provision of emergency services: This type of application scenario occurs when there is no network coverage. A typical example of this use case would be in emergency situations when the cellular infrastructure is completely or partially damaged due to a natural disaster (such as flood, hurricane, and earthquake). The devices in proximity can autonomously establish connection with each other and start D2D communication even in the absence of network operator or any central entity such as a BS. This use case is quite similar to Mobile Ad-hoc NETworks (MANETs). However, there is a key difference between these two approaches. For instance, MANETs use unlicensed spectrum for communication whereas D2D communications occur on reserved licensed spectrum.

3) Extension of cellular coverage: Cellular users at the edge of the cell or out of cell coverage area generally experience poor received signal strength and increased channel fading. The cellular device can relay its transmission to the BS by establishing a D2D link with a device in proximity. This can significantly improve the throughput of the network which is commonly affected by the edge users.

4) Reliable health monitoring: Reliable communication is an important requirement of future health monitoring applications. Devices attached to patients need to continually communicate with the sink nodes to monitor the health of the patients. The short range communication through D2D links can provide sufficient reliability and security to achieve a fully operating health monitoring system. Moreover, since the devices can communicate with the BS and access the Internet, doctors can remotely access the record of a particular patient.

5) Mobile tracking and positioning: Accurate positioning and object tracking are an important part of wireless communications as many location-based routing protocols heavily depend on this information [30], [31]. Conventionally, wireless devices are located with the help of satellite services. In addition to a higher cost of these services, satellite-based positioning performs poorly for indoor conditions due to increased fading. D2D communication has the potential to solve this problem by deploying common outdoor terminals. If the location of these pre-deployed terminals is known, then various trilateration and multilateration [32] based positioning techniques can be used to estimate the position of both outdoor and indoor mobile devices with good accuracy.

6) Data dissemination: Another emerging application of D2D communications is data dissemination which use direct data and proximity-based transmission features. Besides improving the probability of reception of data, the aforementioned service can also generate new sources of revenue for the operators. For instance, shopping malls can forward promotion and discount offers to the people who walk around the mall. Theaters can send the information regarding movie release dates and show times to the people who walk into the cinema. Additionally, advertising agencies can target a specific group of people using social-aware D2D communications [33], [34] for promoting a particular product.

B. Enabling technologies

Cellular communication systems are presently characterized by the BS and cellular devices. A novel architecture was proposed in [35] to allow mobile devices to communicate with each other using a short-range communication architecture. They also proposed to use the term "mobile devices" instead of "mobile terminals" because, in contrast to conventional cellular architecture, the services do not terminate at the device. The idea of combining cellular and ad-hoc architecture was also proposed by the authors of [36]. The architecture was proposed for multi-player gaming, whereby ad-hoc links were used for the actual game and the cellular links were used for updating maps and distribution of high scores in the network. In subsequent years, the same authors proposed Cellular Controlled Short-Range Communications (CCSRC) [37] which combined features of both licensed and unlicensed spectrum. They also exploited intra-network and inter-network cooperation to achieve benefits of security, energy efficiency, and spectrum efficiency. The requirements of short-range (D2D) links were also discussed besides air interface and multi-mode platform requirements to enable CCSRC.

Based on above-mentioned studies, some ad-hoc short-range communications technologies have also been proposed which include RuBee, Z-Wave, ANT, Insteon and RFID. Both Z-Wave and Insteon are proprietary technologies and work on 2.4 GHz and 900 MHz respectively. ANT has a simple protocol stack and was used in some Nike shoes for collecting data of athletes during workout. ANT is also a proprietary technology and is able to communicate with iPods. RFID and Rubee have been implemented on small silicon ships and have been used for tracking objects. They are also considered to be one of the most cost effective low-power solutions for short-range communications. Table III provides brief comparison of the aforementioned technologies with relatively well-established and standard technologies such as Zigbee, Bluetooth Low Energy (BLE), Bluetooth 4.0, Ultra-Wide Band (UWB) communications for distributed, short-range data transfers.

1) Zigbee: Zigbees operation is based on the IEEE 802.15.4 standard and targets low-data rate applications. The Zigbee alliance has been working on industrial automation, smart home and office solutions as they normally operate at data rates between 20 to 250 kb/sec. Zigbee can provide multi-hop routing and supports three types of network topologies, i.e. mesh, cluster tree, and star. Some recent studies have also suggested their use in wireless body area networks for indoor environments such as homes or hospitals [38].

Fig. 2: Common use cases of D2D communications.

TABLE III: Overview of different D2D technologies.

Standard/ Technology	**Zigbee**	**BLE**	**Bluetooth 4.0**	**UWB**	**RFID**	**RuBee**	**ANT**	**Z-Wave**	**Insteon**
Coverage area	30 - 100 m	10 m	10 m	<10 m	100 m	30 m	Home area	30 m	Home area
Frequency band	ISM	2.4 GHz	2.4 GHz	3.1 - 10.6 GHz	860 - 960 MHz	131 KHz	2.4 GHz	900 MHz	902 - 924 MHz
Network topology	Mesh/Star	Star	Star	Star	Peer-to-peer	Peer-to-peer	Mesh/Star	Mesh	Mesh
Data rate	250 Kb/sec	1 Mb/sec	3 - 24 Mb/sec	480 Mb/sec	10 - 100 Kb/sec	9.6 Kb/sec	1 Mb/sec	9.6 Kb/sec	13 Kb/sec

2) BLE technology: BLE is an improved version of Wibree and Bluetooth Low End Extension (BLEE). It was first introduced by Nokia in 2004 in order to provide connection between small devices and mobile terminals. It can provide improved data rates (i.e. up to 1 Mb/sec) with faster synchronization as compared to Bluetooth 2.0. BLE products can be divided in two categories namely standalone chips and dual-mode chips. The standalone chips can only communicate with each other while the dual-mode chips can also communicate with other devices.

3) Bluetooth 4.0: Initially, Bluetooth technology was designed to replace RS232 cables for connecting personal devices through wireless medium. It has the capability to support both data and audio traffic which is one of the reasons of popularity of Bluetooth headsets. Bluetooth 4.0 has also incorporated the 802.11 protocol adaption layer which allows the file transfer rate up to 24 Mb/sec. However, a single piconet supports only a small number of active slaves (i.e seven). Therefore, it is often considered when a large amount of data needs to be transferred for a short duration. Some commercial products such as Sony's PlayStation 3, digital cameras, printers and carkits are already using Bluetooth 4.0.

4) UWB communications: As per the Federal Communications Commission (FCC), UWB communications take place below the bandwidth limit of 500 MHz from 3.1 to 10.6 GHz frequency range. This makes UWB particularly suitable for environment sensitive indoor communications. Commercial products such as video players and wireless monitors use the aforementioned range for transferring data up to 480 Mb/sec. UWB is also considered to be an ideal contender for precise localization in the indoor environment which can complement the functions of a Global Positioning System (GPS).

C. Large-scale projects

The practical implementation and deployment of D2D communications in the real world are only possible through the integration of different enabling technologies. It may be worth mentioning that a comprehensive discussion of each D2D enabling technology is beyond the scope of this paper. However, our objective here is to highlight the role that each technology is likely to play in the future deployment and adoption of D2D communications. Further, we discuss real testbeds and standardization efforts for D2D communications in 5G.

1) Mobile and wireless communication enables for the twenty information security (METIS I & II): METIS is a research project under the research Framework Programme 7 (FP7) [2]. The project aims toward a future world where all users can share data, access and interact with anything anywhere and anytime. Its main objective is to lay the foundations for a 5G mobile and wireless communications system for which it has designed a system concept that delivers the necessary efficiency, versatility, and scalability. METIS I project described a set of five Horizontal Topics (HTs) to develop the overall system concept. An HT integrates a subset of the technology components to provide the most promising solution to one or more test cases. Direct D2D communications is one of the HTs.

METIS project aims to leverage direct D2D communication as an "all connected world" communication system. The main goals of METIS D2D are: maximize coverage in terms of availability and reliability, cost efficiency in term of traffic loading, spectrum efficiency and supporting emerging new services such as Vehicle to Vehicle (V2V), Vehicle-to-Infrastructure (V2I) and Vehicle-to-Pedestrian (V2X). METIS D2D concept further focuses on optimizing selected key technological components to address different technical challenges. METIS proposes a flexible air interface management scheme that will allow the air interface to be individually configured based on system conditions and service requirements. Moreover, a hybrid device discovery scheme is being investigated that can benefit from the advantages of both centralized and distributed discovery schemes. Different forms of D2D relay communications will also be supported by METIS. METIS I project was completed in 2015 and METIS II [39] project will continue the activities that were initiated in METIS I, including efforts to allow the support for D2D communications in 5G.

2) CODEC: The Cellular Network based Device-to-Device Wireless Communication (CODEC) project [40] is funded under FP7 framework. It focuses on efficient resource management in D2D Cellular communications which is essential for achieving energy efficiency, spectral efficiency and QoS for several applications. CODEC aims to provide resource management in two use cases namely, direct D2D communications and D2D relay communications to support proximity-based, multicast, broadcast and unicast applications in D2D communications. The road map of this project is that first a generic analytical framework will be proposed to analyze the performance of resource management techniques in both use cases. Once the framework has been designed and tested, resource management techniques will be initially developed for a single cell and then extended to a multicellular network. So far the project has investigated many aspects of D2D communication including D2D based caching and traffic offloading based on users' content preference and willingness to share the content, The project has also evaluated the improvement in QoS especially for real-time video transmission when adopting D2D communications. The framework has been extended by the researchers to accompany fractional frequency reuse.

3) WiFiUS: In 2011, the National Science Foundation (NSF) Directorate for Computer and Information Science and Engineering (CISE), through its Division of Computer and Network Systems (CNS), Tekes - the Finnish Funding Agency for Innovation, and the Academy of Finland came together to jointly fund the Wireless innovation between Finland and US (WiFiUS) [41]. NSF, Tekes, and the Academy of Finland have supported a set of projects in the area of wireless networking, establishing new collaborations among researchers from the US and Finland under the Science Across Virtual Institutes (SAVI) program. After the success of initial collaborations, the NSF, Tekes and Academy of Finland has set out to broaden the scope of the collaboration by including a wider set of issues related to wireless networking. The program has also included NSF CISE Division of Computing and Communication Foundations (CCF) and NSF Directorate for Engineering's Division of Electrical, Communications and Cyber Systems (ECCS) under its umbrella to address a wider set of topics related to wireless networking.

One of the collaborations under this program is between Aalto University, Finland and University of Southern California, USA [42], [43]. The project aims to investigate D2D communications at millimeter-wave (mm-wave) frequencies. In particular, the project aims to address four main challenges: (i) measurement of D2D propagation channels at mm-wave frequencies, (ii) neighbor discovery, iii) implementation of dynamic beam tracking as per the changes in strongest multipath component, and iv) improving the reliability of transmission.

4) Wi-Fi direct: Bluetooth and Wi-Fi both operate in the unlicensed spectrum and are widely adopted technology for direct communication between devices. Traditional utilization of Wi-Fi and Bluetooth for D2D Communication does not guarantee security or QoS.

To address the D2D usability problem, Wi-Fi-Direct (WFD) has been introduced recently [44]. WFD does not require a Wi-Fi infrastructure and it enables direct communication with the least possible user cooperation and interaction. WFD allows for D2D link setup and communication without the involvement of an AP. WFD leverages the infrastructure mode of WiFi and lets devices negotiate who will take over the responsibilities of an AP, thus allowing devices to dynamically establish peer-to-peer groups. WFD provides the same QoS and energy conserving mechanisms as in Wi-Fi infrastructure mode. However there are several challenges in securing WFD technology [45].

Commercial demand of WFD keeps increasing as a cellular-assisted D2D communication technology. In WFD, devices can dynamically take up the roles of an AP or a client. These roles could be undertaken by a device simultaneously if the device consists of multiple physical radios or implements mechanism for time sharing the channel.

5) 3GPP LTE standardization: The main cellular system that is expected to implement the D2D communications is Long Term Evolution - Advanced (LTE-A) which was proposed by the 3G Partnership Project (3GPP) as a new network standard to provide support for the increasing number of wireless applications and services. The 3rd Generation Partnership Project (3GPP) unites (seven) telecommunications standard development organizations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC), known as Organizational Partners and provides their members with a stable environment to produce reports and specifications that define 3GPP technologies. It has played a pivotal role in the success of LTE and its widespread adoption by mobile industry. The standardization work on D2D technologies in 3GPP started in 2011 as part of the 3GPP Release 12 (Rel12). The work is done under the Work Item Proximity Services (ProSe) and has made significant progress so far. But the number of required specifications that meet the identified requirements is largely exceeding the capabilities of 3GPP for Rel12 (given also the other topics of Rel12). The work on D2D technologies in 3GPP has focused on a set of use cases which were identified to fit the needs of both public safety and commercial mobile networks.

LTE-A promises to provide true 4G speeds, allowing bigger data payloads and faster speed. Providing local area services is an important design consideration for future network technologies, but unlicensed spectrum reuse may be inconvenient for local service providers because it may lead to inefficient utilization of resources and compromise the QoS in the absence of a base station or a central controller. Therefore, incorporating D2D communications in licensed bands has been more attractive. In licensed band, LTE-A technology is the most suitable candidate for realizing efficient D2D communications. With D2D capability, LTE-A-enabled devices will be able to discover other physical devices in the physical proximity of each other and communicate with each other using a direct path.

In addition to increasing the capacity of the network, another design goal of 3GPP is to provide provision for public safety networks that require support for urgent communications in the case when the BS has been degraded due to a natural calamity. Therefore, 3GPP has identified two main areas to use LTE for public safety applications: Group communications and ProSe. After Release 12, ProSe will support urgent D2D in following three scenarios:

- In-coverage: This scenario occurs when the User Equipment (UE) is within the range of eNodeB (eNB).
- Out of coverage: This scenario occurs when the UE is out of the coverage of eNBs.
- Partial coverage: This scenario occurs when some UEs are within the coverage of eNBs and some UEs are not.

D. Taxonomy

The taxonomy of D2D communications is mainly composed of five aspects of networking namely, device discovery, mode selection, resource management, mobility and security, as shown in Figure 3. The main aspects of device discovery in D2D communications are asynchronous and quick device discovery schemes. Besides rapid discovery, these schemes also need to be energy-efficient. However, the main challenges are the frequency of discovery and the synchronization of devices. Mode selection is also important for efficient D2D communications, however, main schemes are distance cut-off, link gain and guard zone schemes. Despite these advances, challenges such as mode alteration overhead and stable mode selection still exist. Resource management for power control and reduced interference have been explored in-depth in the literature and several approaches such as game theoretic optimization, linear optimization, admission control and graph theoretic optimizations have been previously proposed. But issues such as device densification and role of interference in D2D communications are still under-explored. Handover is another issue and handover schemes such as D2D handover assistance and QoS-aware D2D have been proposed. Rapid mobility and determination of suitable handover criteria are major issues that require further research in the future. Security is another issue in D2D communications. Both physical and application layer authentication schemes have been proposed. However, their full acceptance and deployment are hindered by a lack of standardization effort and they also do not really address the security and energy tradeoff issue.

III. Device discovery

A fundamental design requirement for D2D networks is device discovery which enables devices to discover potential candidates in the proximity and establish a direct connection with them. To accomplish this task, devices share beacon signals among themselves to gather information such as device location/ distance, channel state and device ID etc. This information is used by devices to evaluate the feasibility of grouping into a pair with each other. If the discovery phase and communication phase take place simultaneously, it is called *a-posteriori* discovery, whereas device (peer) discovery is the precondition for D2D communication in *a-priori* discovery. Generally, device discovery in D2D communication can be categorized in two types (1) Centralized Discovery and (2) Distributed Discovery.

A. Classification of device discovery schemes

1) Centralized discovery: In centralized discovery, devices discover each other with the help of a centralized entity or typically a BS. The device informs the BS regarding its intention to communicate with nearby devices. The BS initiates the message exchange between two devices to obtain essential information such as channel conditions, interference and power control policies based on the network requirements. The participation of the BS during the device discovery process can be complete or partial based on the pre-configured suite of protocols [46].

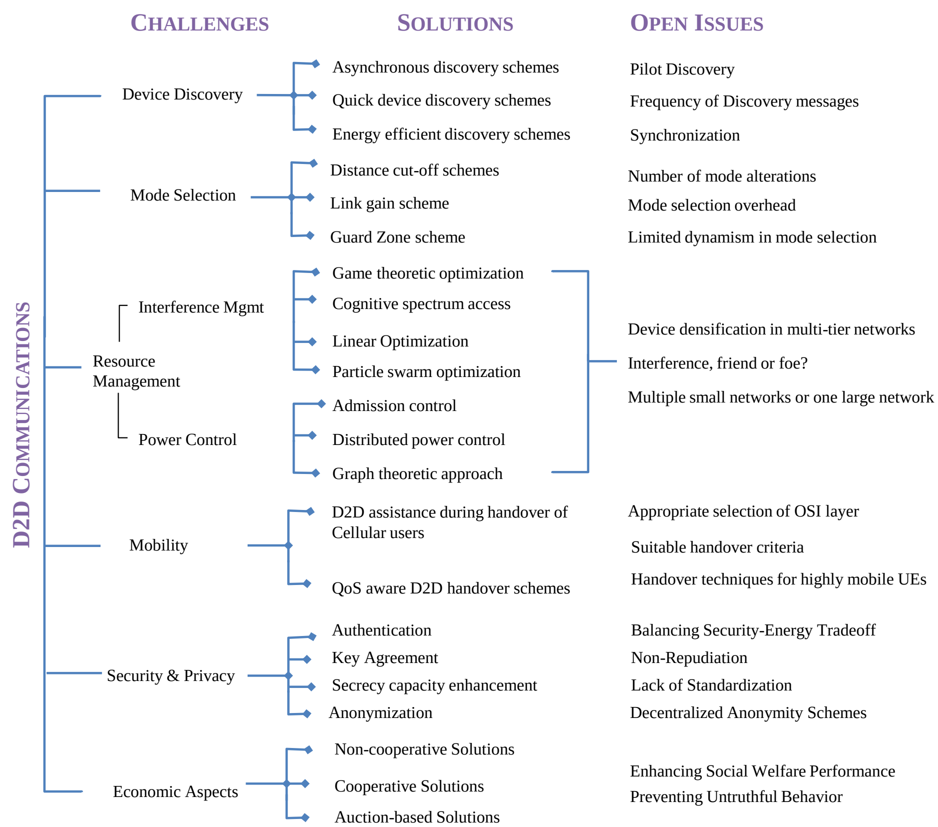


Fig. 3: Challenges, solutions, open issues of D2D communications.

If the BS is completely involved, the devices are not allowed to initiate device discovery with each other. Every message among devices is coordinated by the BS. In this case, the devices only listen to the messages transmitted by the BS and send messages to it in order to initiate the device discovery process. If the BS is only partially involved, the devices send messages to each other for device discovery without obtaining prior permission from BS. However, the devices involve the BS to communicate the path gains and Signal to Interference and Noise Ratio (SINR) level of each device. This helps the BS to determine the feasibility of communication between devices. Finally, the BS requests both devices to start the communication. Fig 4 shows the discovery procedures for both the complete and partial involvement of BS.

2) Distributed discovery: The distributed discovery approach allows the devices to locate each other without the involvement of BS. The devices transmit the control messages periodically to locate the nearby devices. However, issues of synchronization, interference and power of beacon signal frequently arise in the distributed mode.

B. *Recent advances in device discovery schemes*

A beaconing device discovery scheme was presented in [47] where devices transmit beacon signals in parallel slots using Orthogonal Frequency Division Multiple Access (OFDMA). Devices scan for beacon signals to discover other devices in proximity during device discovery phase. In this beaconing scheme, slots are selected based on the criterion of minimum interference. Tang *et al.* [48] proposed a discovery process where neighboring devices detect potential D2D partners by overhearing Sounding Reference Signal (SRS) symbols during UL transmissions. In LTE, each device is scheduled on the SRS channel regularly to allow the eNB to collect information for UL channel scheduling. The devices can identify other devices which have a high SRS as their neighbors.

Zhang *et al.* [49] and [50] proposed adaptive approaches to discover devices in the nearby proximity. In [49], the probing rate of device discovery is varied based on the information obtained from the social domain. The social domain information consist of community and centrality of a particular device. In [50], nodes stay asleep until the probability of contact with device is low and wake up to probe for nearby devices when the probability of device discovery is high. It was also found that the lifetime of devices can be increased by varying the accuracy of device discovery.

Hong *et al.* in [51] proposed a novel power control method for efficient D2D communication. The authors proposed the resource selection scheme namely sensing based selection and compared it with random selection [52] for LTE application. An example of LTE resource allocation, depicting discovery resource unit and discovery period, for device discovery is provided in Figure 5. It was shown that the performance for sensing based selection degrades when sensing result are outdated or when mobility of devices is rapid. However, the sensing based selection scheme generally out performs the random selection scheme in distributed D2D networks.

Lee *et al.* in [53] presented a novel device discovery scheme

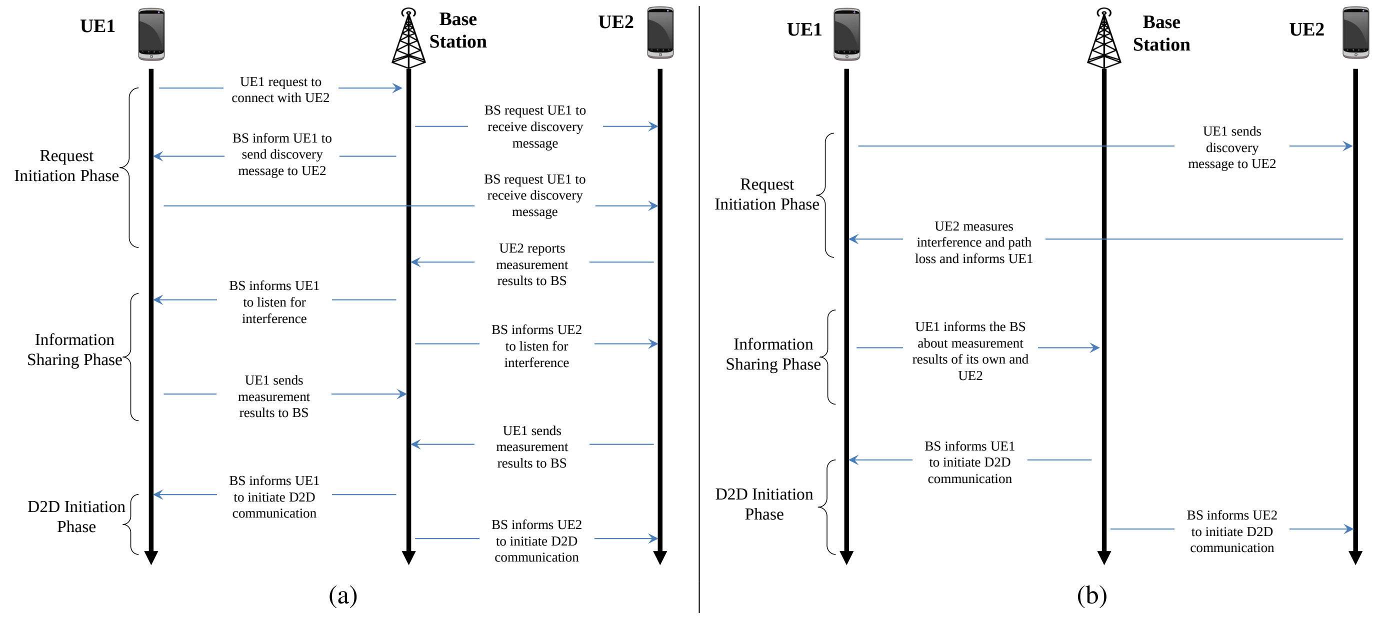


Fig. 4: Centralized device discovery (a) Complete involvement of BS (b) Partial involvement of BS.

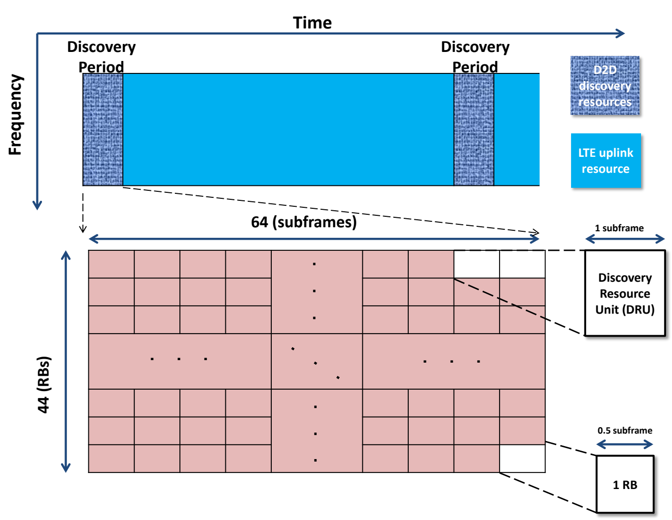


Fig. 5: Device discovery resources in LTE.

based on the correlation of wireless channels. The BS makes a rough estimate of the location of users by comparing these channel components with the referenced UL measurements. Beacons are scheduled to be transmitted based on the values of Delay Spread (DS) and Azimuth Spread (AZ) nearby users. The authors found that power consumption can be reduced by up to 70% in comparison to conventional technique FlashLinQ [54], when using their proposed scheme.

In order to ensure quick device discovery, the authors in [55] proposed a fast pairing approach by using Inverse Popularity Pairing Order (IPPO) technique instead of conventionally used Kuhn-Munkres algorithm by [56]. Signature based device discovery method was proposed by Zou *et al.* in [57]. The paper provides an efficient way to minimize the collisions during discovery phase while using minimum physical resources. Autonomous device discovery method based on FlashLinQ [58] was proposed by Baccelli *et al.* in [54]. Significant energy consumption of devices is a serious concern during device discovery phase. Furthermore, in the face of continual probing, this issue becomes more critical. Therefore, the authors in [59], [60], [61], [62] provided energy efficient device discovery schemes while improving performance of the network.

The authors in [63] proposed the Tic-Toc discovery rendezvous protocol for nodes to transmit and listen. This protocol provides better average-case and worst-case discovery latency compared to the existing protocols. An oblivious neighbor discovery protocol was presented by Chen *et al.* in [64]. It was found that the oblivious neighbor discovery protocol guaranteed discovery with minimal discovery delay in the asynchronous and heterogeneous environment. In a similar work on asynchronous device discovery, the authors in [65] compared and discussed four possible solutions to mitigate the loss of orthogonality of subcarriers in Orthogonal Frequency Division Multiplexing (OFDM) Networks. These solutions include extended cyclic prefix, advanced receiver timing, dynamic receiver timing positioning, and semi-static receiver timing positioning with multiple timing hypotheses. Arcia *et al.* proposed an architecture for asynchronous assistance for topology discovery. In their work, a Topology Manager is used to generate an optimal scanning sequence. Their results yielded a 30% to 70% improvement in discovery rate in chaotic deployments. In [66] the authors leverage Q-Learning [67], [68] techniques to extend the functionalities of asynchronous neighbor discovery protocols while minimizing energy consumption and discovery latency.

There is an extensive literature on minimization of device discovery delays in D2D communication. Li *et al.* in [69] proposed a method that outperforms traditional device discovery methods even when the congestion occurs in the network. Specifically, the initiating peer device transmits the discovery request frame and responding peer device reply with a responding frame. Both of these frames are transmitted using a common channel and in accordance with a superframe structure. This results in a quick discovery of devices even for large congested networks. Campolo *et al.* in [70] modeled a device discovery scenario. In their model, the authors used dual-radio devices, and computed the mean service discovery time and the service channel utilization by considering the disruption periods. The model also takes into account different channel and mobility conditions of devices. Li *et al.* [71] proposed the Connected Open plAtform for Smart objecTs (COAST) which includes remote sensing by on-demand deployment of additional (possibly involving a 3rd party) services on the same or another smart object. COAST also provides the necessary platform services to support run-time adaptation, monitoring, and data analysis.

Prasad *et al.* [72] investigated energy-efficient device discovery techniques. The proposed scheme in [72] performs D2D discovery procedures only when there is a high probability to find other UEs subscribed to the same service. The results show that significant energy savings can be obtained using their proposed discovery mechanism. In another work [73], Prasad *et al.* proposed a scheme that offloads the discovery process from not only UEs but also to the LTE core network. The authors also analyzed the energy consumption profiles of various discovery mechanisms.

Zhou *et al.* in [74] proposed a three-dimensional iterative matching algorithm to maximize the sum rate (which is the sum of channel rates) of D2D pairs weighted by the intensity of social relationships (a list of social relationships is provided in table IV) while guaranteeing the QoS requirements of both cellular and D2D links simultaneously. In cellular networks, the users have multi-dimensional social attributes and multiple interests, due to which they may have similarities with more than one community. These multi-dimensional social attributes of the users effects their social relationship which leads them to form overlapping communities. In this context, Wang *et al.* in [75] proposed a scheme to dynamically estimate the roles of overlapping community users in various communities. The scheme dynamically adjusts the beacon detection rates according to the connection status of other intra-community and inter-community users to improve the system energy efficiency and neighbor discovery rates. It was shown that these overlapping community users can act as a bridge to improve data sharing during device discovery process. Table V presents an overview of the works discussed above along with some other significant studies on device discovery.

TABLE IV: Overview of different social relationships [74].

Relationship	Metrics
Contact History	1) Contact interval: time interval between two contiguous contacts; 2) Contact Frequency: reciprocal of time interval; 3) Contact Duration: average duration of each contact
Social Similarity	Devices in Contact Book
Contribution History	Reciprocity Index: amount of data that a device provides other over the total amount of data that both devices share

C. Open Research Issues in Device Discovery

Next, we present some of the challenges of device discovery.

1) Pilot discovery: In order to discover other devices in close proximity, a pilot discovery signal is transmitted by the device. However, this signal can be easily picked up by nearby devices. The information carried by pilot signals can also affect other devices in case of an inappropriate scheduling. In this context, design parameters such as radio resources and the structure of pilot message play significant role.

2) Frequency of discovery messages: The performance of D2D users is affected by the number of discovery messages. Even when the discovery messages have a pre-specified design and structure, the frequent dissemination of discovery messages by devices can cause significant interference for other devices in the network. In contrast, if the number of discovery messages is very low, then the information regarding neighboring devices can become stale. To address this problem, proper scheduling schemes in the network can be introduced to minimize frequency of discovery messages. Another solution can be in the form of social interaction between communities to speed up the device discovery using minimum number of discovery messages.

3) Synchronization: Typically, in D2D communication, the devices in the network are synchronous with the BS. This implies that scheduling and frame timings are specified by the BS. However, it becomes a challenge during the discovery of devices when second device lies outside the coverage range of the BS with which the first device is connected. In the case of asynchronous discovery, the devices have to continuously search for other devices in the neighborhood.

IV. MODE SELECTION

In contrast to conventional cellular networks, in D2D, UEs can communicate directly with the BS. This ability of devices to communicate with the BS and with each other significantly improves the performance of network in terms of throughput and delays. However, it also introduces new design challenges such as network overloading and resource management. Moreover, two communicating UEs can work in the same, different or hybrid mode, which makes network management more complex. Typically, UEs can choose one of the following four modes of communication as shown in Fig 6:

- **Pure cellular mode** When the availability of resources is low and when interference is very high due to which D2D communication is not possible, pure cellular mode is used. In this mode D2D users cannot transmit their data.
- **Partial cellular mode** In this case, two UEs are able to communicate through the BS without co-channel spectrum sharing.
- **Dedicated mode** In this mode, UEs communicate with each other using dedicated spectrum resources.
- **Underlay mode** In this mode, D2D users and CUEs share the UL and DL resources.

TABLE V: Overview of device discovery issues and recently proposed solutions

Device discovery issue	Reference	Method/ Technique	Description
Asynchronous device discovery	[63]	Tic-Toc rendezvous protocol	Tic-Toc provides separate discovery schedule for nodes to "transmit" and "listen". It can provide better average-case and worst-case discovery latency compared to existing protocols.
	[64]	Directional antennas	An oblivious neighbor discovery protocol. It achieves guaranteed discovery with minimum worst-case discovery delay in the asynchronous and heterogeneous environment.
	[65]	Multicarrier transmission	Compared and discussed four possible solutions including extended cyclic prefix, advanced receiver timing, dynamic receiver timing positioning, and semi-static receiver timing positioning with multiple timing hypotheses.
	[76]	Bouncing strategy	Proposed neighbor discovery protocols for two problems. First, a protocol for the asynchronous symmetry neighbor discovery problem. Second, an efficient protocol (utilizing Bouncing strategy) called Blind-Date.
	[77]	Directional antennas	Proposed an analytical model for one-way asynchronous system with directional antennas. Compared time-slot consumption in asynchronous system with synchronous system. The neighbor discovery process is extended for the one-way asynchronous discovery algorithm to a two-way asynchronous discovery algorithm.
	[78]	Optimization of scanning sequences	Proposed architecture for asynchronous assistance for topology discovery. The role of a Topology Manager for generating optimal scanning sequences is also discussed. Results show that this approach results in 30% to 70% improvements in discovery rate in chaotic deployments.
	[66]	Context Aware Resource Discovery (CARD) framework	Leverages Q-Learning techniques to extend the functionalities of asynchronous neighbor discovery protocols, while minimizing energy wastage and discovery latency.
Quick device discovery	[69]	Use of Common Channel and Group Channels	Proposed a method that outperforms traditional device discovery methods in terms of device discovery delays.
	[79]	Signature-based discovery	Proposed discovery channel having well dispersed subcarriers to tolerate the frequency selectivity. Proposed scheme improves the discovery ratio. It is also more frequency selective fading tolerant compared with other approaches.
	[70]	Service advertisement and access mechanisms	The model considers dual-radio devices, and computes the mean service discovery time and the service channel utilization by considering the disruption periods. It also takes into account different channel and mobility conditions.
	[80]	Mobile inference engine	The mobile inference engine supports semantic web technologies and implements both standard (subsumption, satisfiability, classification) and non-standard (abduction, contraction, covering) inference services.
	[71]	Connected Open plAtform for Smart objecTs (COAST)	It includes remote sensing by on-demand deployment of additional services on the same or another smart object. COAST also provides the necessary platform services to support run-time adaptation, monitoring, and data analysis.
Energy efficient discovery	[72]	Proximity Area (P-Area) and dynamic geographical region assessment	Enables UEs to perform D2D discovery procedures only when there is a high probability to find other UEs subscribed to the same service. The energy consumption profiles of various discovery mechanisms were evaluated. The results showed significant energy savings using the proposed discovery mechanism.
	[73]	Social application-based discovery mechanism	Offloads the discovery process from not only UEs but also the LTE core network. Also analyzed the energy consumption profiles of various discovery mechanisms.
	[81]	3-D iterative matching algorithm	Proposed algorithm converges to a stable matching. Achieves more than 90% of the optimum performance with a computation complexity 1000 times lower than the exhaustive matching algorithm. The number of UEs can be increased significantly by incorporating social relationships into the resource allocation design.
	[74]	Bayesian non-parametric modeling	Proposed a three-dimensional iterative matching algorithm to maximize the sum rate of D2D pairs weighted by the intensity of social relationships while guaranteeing the QoS requirements of both cellular and D2D links simultaneously.
	[75]	Social Overlapping Community-Aware (SOCA) neighbor discovery	Proposed scheme that dynamically estimates the roles of overlapping community users in various communities. The beacon detection rates are dynamically adjusted according to the connection status of other intra-community and inter-community users to improve the systems energy efficiency and neighbor discovery rates.
	[82]	Performance analysis of network-assisted D2D Discovery	Derived approximate expressions for the distance distribution between two D2D peers conditioned on the core network's knowledge of the cellular network layout, assuming that the base stations are distributed according to the Poisson distribution. Assessment is provided for D2D discovery probability and key system parameters such as network intensity and transmit power.
	[50]	Adaptive wakeup scheduling	Proposed an approach that significantly reduces energy consumption without degrading the performance of opportunistic networks. Results show that this scheme saves 30% in energy while keeping the same performance in most scenarios. It enhances the performance in terms of the average delivery ratio and delivery delay by over 15%, compared with the existing best wakeup techniques.

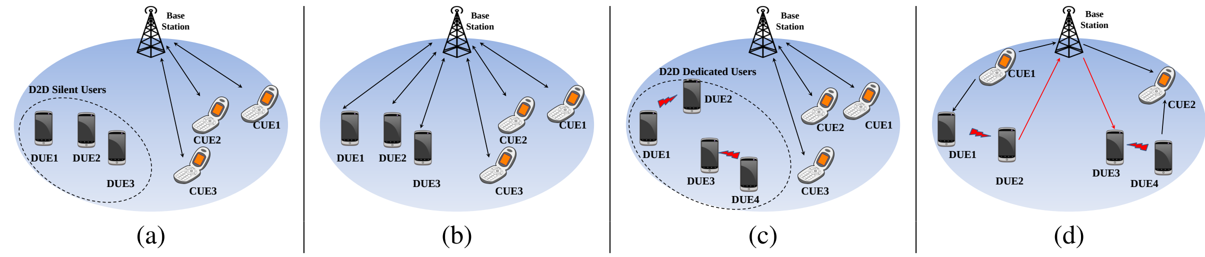


Fig. 6: Modes of communication in D2D networks (a) Pure cellular mode (b) Partial cellular mode (c) Dedicated mode (d) Underlay mode

TABLE VI: Sum rate for each mode

Mode	**UL cellular**	**DL cellular**	**UL D2D**	**DL D2D**
Pure cellular mode	$\log\big(1 + P_b\lvert g^H h\rvert^2\big)$	$\log\big(1 + P_b\lvert f^H h\rvert^2\big)$	0	0
Partial cellular mode	0	0	$\min\Big(\frac{1}{2}\log(1 + P_d\lvert g^H h\rvert^2), \frac{1}{2}\log(1 + P_c\lvert h^H f\rvert^2)\Big)$	$\min\Big(\frac{1}{2}\log(1 + P_d\lvert g^H h\rvert^2), \frac{1}{2}\log(1 + P_c\lvert h^H f\rvert^2)\Big)$
Dedicated mode	0	0	$\log\big(1 + P_d\lvert h\rvert^2\big)$	$\log\big(1 + P_d\lvert h\rvert^2\big)$
Underlay mode	$\log\big(1 + \frac{P_d\lvert h\rvert^2}{P_b\lvert h\rvert^2+1}\big)$	$\log\big(1+\frac{P_d\lvert h\rvert^2}{P_b\lvert h^H f\rvert^2+1}\big)$	$\log\big(1 + \frac{P_b\lvert g^H h\rvert^2}{P_d\lvert g^H h\rvert^2+1}\big)$	$\log\big(1 + \frac{P_b\lvert h^H f\rvert^2}{P_d\lvert h\rvert^2+1}\big)$

A. Reference system model

In this subsection we present a brief overview of the reference system model for mode selection. We assume a cellular network in which CUEs communicate in UL or DL modes using the orthogonal resource block. Let $U = \{U_j j = 1, 2, 3, ..., N\}$ and $D = \{D_i | i = 1, 2, 3, ..., M\}$ represent the set of CUEs and D2D pairs, respectively. Additionally, let $R = \{R_k | k = 1, 2, 2N-1, 2N, ..., L\}$ be the resource pool, where 1 to $2N-1$ represents the UL chunk and $2N$ to L represents the DL chunk. The distance between a potential D2D user and the BS is represented as $r_{c,i}$. Also, the link distance between a single D2D pair and the path loss exponent are given by $r_{d,i}$ and α, respectively. The UL rate and DL rate for above mentioned 4 modes are given in Table VI where P_b, P_c and P_d represents the transmit power of BS, CUE and D2D pair, respectively. Moreover, h_i, h_{ib},h_{ic} and h_{cb} represents the channel between D2D pair, BS and DUEs, DUE and CUE and BS and CUE, respectively. Also, f and g are the BS transmit precoder and receive precoder, respectively. Based on this preliminary model, the mode selection schemes can be broadly classified into three categories:

1) Distance cut-off scheme [83]: This is the simplest selection criteria. A potential D2D transmitter selects the D2D mode if the link distance for a D2D pair is less than a specified threshold, otherwise the cellular mode is selected. It is mathematically given as

$$r_{d,i} < \gamma, \tag{1}$$

where γ is the pre-defined threshold.

2) Link gain scheme [84]: A potential D2D transmitter chooses the D2D mode if the biased D2D link quality is at least as good as the cellular UL link quality. It is can be written as

$$r_{c,i}^{-\alpha} < T_d r_{d,i}^{-\alpha}, \tag{2}$$

where T_d is the bias factor that controls traffic offloading from the cellular infrastructure to the D2D mode of communication.

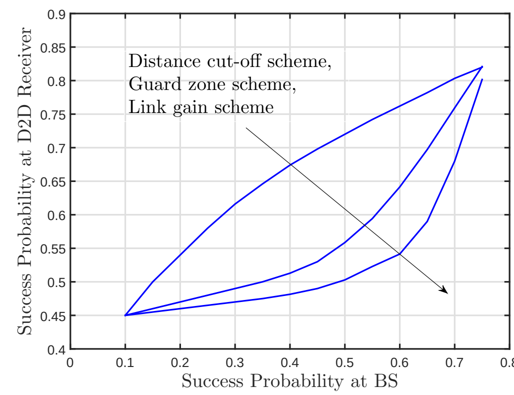


Fig. 7: The success probability at the BS versus the success probability at the D2D Receiver [86].

At one extreme, setting $T_d = 0$ disables the D2D communication. At the other extreme, setting $T_d = \infty$ forces each potential D2D UE to communicate via the D2D mode.

3) Guard zone scheme [85]: A potential D2D transmitter chooses the D2D mode if the cellular link distance is greater than the guard distance. It is represented as

$$r_{d,i} > R_g, \tag{3}$$

where R_g is the guard zone radius centered at the BS. To avoid severe interference at the BSs, potential D2D transmitters located within the guard zones are required to operate in cellular mode and share the UL resource with the original cellular UEs in a Time Division Multiple Access (TDMA) fashion. These UEs are referred to as D2D transferred cellular UEs in the rest of the paper. The DLs of these UEs share the original cellular DL. In contrast, potential D2D UEs located outside the guard zones operate in D2D mode and reuse the cellular UL frequency for transmitting.

We can compare the selection mode schemes in terms of their effect on the BS (i.e., the success probability at BS) and the D2D UEs (i.e., the success probability at the cell-edge-located D2D receiver, which is the worst case scenario). Fig. 7 depicts the success probability at the D2D receiver versus the success probability at the BS. From the figure, we can see that, under the same value of BS success probability, the distance cut-off scheme has the highest success probability at D2D, followed by the guard zone scheme and the link gain scheme. This is because D2D UEs with less power are in D2D mode, thereby reducing the interference at the D2D receiver for the distance cut-off scheme.

B. Recent advances in D2D mode selection

Many works in the D2D literature propose to use joint mode selection and resource allocation to improve the capacity of the network via traffic offloading. Present studies on D2D have focused on three modes [87]. One mode is pure cellular and the other modes are reuse D2D and dedicated modes [88]. The interference for each sharing mode along with D2D and cellular link quality was considered in [89]. The authors in [90] presented a joint power control and optimum resource allocation between D2D and cellular users. The cellular user with better channel conditions shares the resources with the D2D pair to minimize the interference. In [91] Liu *et al.* studied the overlay and underlay mode selection in the presence of relay. They showed that the underlay mode is more appropriate when cellular users are close to the BS than the D2D users. In [92] Yu *et al.* maximized the throughput of system while guaranteeing QoS requirements of cellular and D2D users. Finally, in [93] the authors used Multiple Input Multiple Output (MIMO) precoding techniques to achieve higher throughput in all modes by reducing interference.

From above discussion we observe that the direct D2D mode may not be completely advantageous due to the restricted offloading capability of devices. It is due to the possibility of a large separation between the communicating devices and the poor channel quality of the D2D pair [94], [16]. In this case, the coverage range of the network can be increased using intermediate relays which also enable the traffic offloading capability of the network [95], [96]. In particular, the possibility of using intermediate relays also introduces two new modes in addition to the conventional D2D modes. One of these modes is the relay-assisted D2D mode, which can be used for communication between the source and the destination D2D devices with the help of a relay. The other mode is the local route mode, which enables the source and the destination D2D devices to communicate using the intermediate BS as a relay station. Both the relay-assisted and local route modes are shown in Figure 8. In order to support all the modes of communication, there is a strong need to design robust and adaptive protocols. These protocols should be designed for both independent UEs and relay-capable UEs. However, current releases of D2D standards failed to provide any clear definitions of Radio Protocol Architectures (RPAs) in relay-based D2D modes. In addition to this, the involvement of relay-enabled D2D modes also makes the channel assessment and subsequent scheduling procedures more complex. Hence, designing a low powered and minimal overhead signaling scheme remains a challenge. Moreover, the BS should be able to optimize the communication by changing the mode of devices in each subframe while maintaining a fair distribution of resources [92].

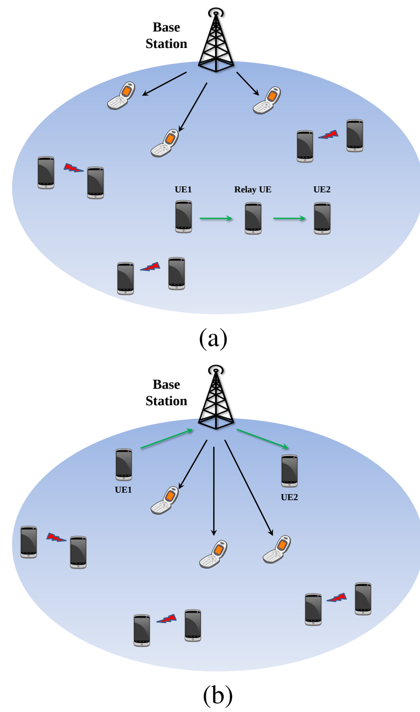


Fig. 8: Relay-based modes of communication in D2D networks (a) Relay-assisted (b) Local route.

C. Open Research Issues in D2D Mode Selection

Now we discuss some research challenges in mode selection in D2D.

1) Number of mode alterations: One particular challenge when considering mode selection is how often the mode alteration should be done. Due to the random nature of wireless channel, mode alteration may take place frequently depending on the number of scatterers and mobility of devices. In addition to this, most studies consider single cell scenario (where D2D pairs are attached to a single BS) to make the analysis straightforward and easy to follow. Hence, more research efforts need to focus on the provisioning of lasting solutions to minimize the number of alterations in mode selection process.

2) Mode selection overhead: Mode selection can incur a significant amount of overhead. This overhead includes channel estimation and control signaling. It is worth noting that channel estimation can be done based on the Channel State Information (CSI) of links. However, it will greatly affect the performance of network because the CSI of links can become outdated. More precisely, minimizing the mode selection overhead is important to increase the lifetime of devices.

3) Dynamic mode selection: Most of the studies in literature take static network scenario into account. These studies mostly focus on downlink scenario [97], [98], [99] where D2D pairs communicate through BS. As it is apparent, that the dynamic switching between different modes either performed heuristically [97], [98] or using brute force [99] brings sub-optimal improvements in the performance gains of the network. Similarly, the works of [87], [100], although present non-static mode selection, do not consider any mobility of the user devices. These observations call for requirement of complex mode selection schemes that can be dynamically applied to realistic scenarios.

V. Resource management

Resource management typically takes place simultaneously with mode selection. Efficient management of resources can significantly mitigate interference, conserve power and maximize throughput. Interference mitigation and power consumption are related to the issue of resource management. We briefly present both of these topics in this section. Table VII presents a brief summary of some of the challenges and solutions related to resource management in the recent literature.

A. Interference management

Proper allocation of spectrum resources is of critical importance for maintaining the required level of QoS in the network. With the addition of D2D users in cellular networks, the issue of interference becomes more complex [101], [102], [103], [104], [106], [106], [107], [108], [111]. Future cellular networks will have to support various heterogeneous devices and large scale deployment of macro-small cell networks (where conventional cellular network is overlaid with many low power base stations), thereby making management of interference more critical as well as challenging. With the integration of D2D communication, the cellular architecture has evolved into a two tier cellular system. A two-tier cellular network consists of a macro cell tier and a device tier. A macro cell tier consists of cellular communications from base station to cellular users and a device tier involves D2D communications. Two types of interference can occur in this two-tier scenario: co-tier and cross-tier. Co-tier interference occurs between D2D pairs when the same resource block is allocated to more than one D2D user within the same tier network. Cross tier interference occurs between cellular users and D2D users. Cross-tier interference arises when a resource block dedicated to a cellular user is reused by one or multiple D2D users. If cellular users and D2D users share the same channel resources in the UL communication then the source of interference is the D2D transmitter and the victim is the cellular base station. In the same situation the cellular user also becomes the source of interference and the D2D user becomes the victim. In the case of a DL communication the base station causes interference to D2D receivers and D2D transmitters interfere with DL cellular communication.

Different interference mitigation approaches exist in literature, which can be broadly categorized into centralized [126], [127], [106], distributed [128], [129], [130], [131], [132], [133], [134], [135] and semi-distributed [136], [137], [138], [139]. In the centralized approach, a central controller (eNB) is responsible for allocating resources to both cellular and D2D users while monitoring cell-wide information regarding SNR, channel state information and interference level of each user. However, the complexity of centralized interference management approach increases with increasing number of users because a single entity needs to collect and process large amounts of information. Therefore, a centralized approach is considered more suitable for small size networks.

In the distributed approach there is no central entity and the devices opportunistically access the channel that is actively in use by cellular users. This approach requires frequent exchange of information between neighboring D2D users. The approach also requires the devices to overhear ongoing cellular communications to collect information regarding channel quality and free resource blocks which can cause devices to consume a lot of power. The distributed approach scales well to larger networks but requires complex interference avoidance algorithms to ensure high quality cellular communications along with reliable D2D communications. The semi-distributed approach is a hybrid approach where interference management is done at different levels of network involvement. These approaches focus on reducing signaling overhead and computational complexity at the eNB.

Inter cell device-to device interference is another important issue that needs to be addressed particularly in LTE-A networks. As the same frequency is reused across the cell, the edge UEs may be allocated the same sub-carriers, thus causing inter cell interference between users at the cell edge. These UEs at the cell edge use high power to reach the eNB, causing strong signal interference. Cell edge users face interference from strong and weak signals from adjacent cell UEs and eNBs. This situation becomes even more complex in macro-small cell deployment, where cell users within the small cell try to attach itself to the high powered eNB of the macro cell instead of the low powered eNB of the small cell. The same scenario occurs when a cell edge user tries to attach itself to the eNB of another small cell in the proximity. D2D communication introduces additional inter cell interference in both UL and DL communication. In the case where UL resources are being used for D2D communications, D2D transmissions near the cell edge cause interference to neighboring eNBs and similarly D2D receivers receive interference from cellular devices transmitting to the eNB at the cell edge. In the case where DL resources are being used for D2D transmissions, D2D transmitting devices interfere with cellular devices receiving normal communications on DL resources. Conversely, in the same scenario eNBs interfere with ongoing D2D communications.

1) Recent advances in interference management: In [140], authors proposed a guard zone based interference mitigation scheme in which D2D users within a certain geographical area inside a cell are forced to operate in the pure cellular mode. Theoretical and numerical results of performance metrics such as successful transmission probability and average throughput of CUEs validated the improvement achieved by the proposed scheme.

Chui *et al.* in [141] discussed the interference cost of D2D offloading. Here, the authors leverage MIMO techniques in a multiuser D2D environment. A systematic strategy was

TABLE VII: Brief summary of resource management methods for D2D.

Resource management	Reference	Year	Problem	Solution
Interference management	[101]	2016	Joint D2D mode selection and interference management	Linear interference alignment technique
	[102]	2013	Maximize system throughput	Particle swarm optimization
	[103]	2016	Maximize throughput subject to an interference temperature constraint	Game theoretic optimization using Stackelberg game
	[104]	2012	Increase mean throughput, minimize average delay	Queuing, Decision process model
	[105]	2012	Maximize sum rate while guaranteeing the QoS of both cellular and D2D users	Linear Optimization
	[106]	2015	Maximize sum rate and increase coverage probability	Stochastic geometry
	[107]	2016	Maximizing the performance while satisfying the QoS requirements	Interference management algorithm
	[108]	2015	Analysis of channel access probability, increase spectral efficiency	Cognitive spectrum access
	[109]	2017	QoS aware interference management	Graph theory based sub-optimal solution for power adoption and relay selection
	[110]	2017	Network-wide D2D performance enhancement and interference management	Graph theory based solution using Concatenated Bi-partite Matching (CBM) method
	[111]	2016	D2D-based safety-critical V2X communications	Cluster-based Resource block sharing and pOWer allocatioN (CROWN) Heuristic algorithm
Power control	[112]	2016	Distributed power control	Mean Field Game (MFG) theoretic framework
	[113]	2016	Power Control under imperfect wireless CSI	ON-OFF power control scheme and truncated channel inversion
	[114]	2017	Reduction in the training sequence overhead and minimization of its contamination in D2D underlay massive MIMO networks	Revised Graph Coloring-based Pilot Allocation (RGCPA) algorithm
	[115]	2016	Improvement in the maximum number of DUE pairs number under specific QoS	Call Admission Control (CAC) scheme
	[116]	2016	Joint optimization of network centric and user centric models	Game theoretic approach by using Stackelberg game
	[117]	2016	Joint Admission Control, Mode Selection, and Power Allocation Problem (JACMSPA)	Optimization using Outer Approximation Approach (OAA)
	[118]	2016	Mode selection (choosing between cellular or reuse or dedicated mode), resource allocation (in cellular and dedicated mode), and power control (in reuse mode)	Geometric vertex search approach
	[119]	2015	Reuse channel Selection (RS), and power control to achieve optimal performance	Optimal power control obtained by D.C. (difference of two convex functions) programming
	[120]	2015	Maximize Binary Power Control (BPC)	Near-optimal extended BPC scheme
	[121]	2015	Minimize circuit power consumption	Optimal power control scheme using a distributed power algorithm
	[122]	2017	Power allocation under Sparse Code Multiple Access (SCMA)	Graph theoretic approach
	[123]	2016	Maximize total energy efficiency and optimize individual energy efficiency	Optimization using Dinkelbach and branch-and-bound methods
	[124]	2015	Energy-efficient resource allocation in overlay LTE networks	Optimization using Dinkelbach and Powell-Hestenes-Rockafellar augmented Lagrangian methods
	[125]	2016	Energy-efficient power control for D2D pairs underlaying cellular networks	Optimization using generalized fractional programming and provisioning of tight lower bound on energy efficiency

adopted to check the cross-pair interference at the antenna combinations. Furthermore, a bucket based Degree of Freedom algorithm was introduced for effective usage of multiple antennas to eliminate interference. It was shown that throughput was improved upto 218.8% as compared to traditional interference mitigation techniques.

An interference mitigation technique for distributed D2D systems was presented by Rim *et al.* [133]. The authors used frequency spreading technique in order to satisfy the outage probability constraint and hence, reduce interference. The results show that the proposed technique is suitable for interference mitigation for devices present at the edge of the cell. However, it is not much effective for devices in the central region of the cell. Yang *et al.* in [142] addressed the interference issue for devices operating in full duplex mode. A graph theory based approach was adopted to optimize spectrum utilization. More specifically, a graph Coloring based Resource Sharing (GCRS) scheme was presented to optimize the problem with minimum complexity.

Wu *et al.* [143] proposed a cross-layer system for Peer-to-Peer (P2P) file sharing approach among devices. The cross-layer framework jointly considers context information of physical layer transmissions, an interference cancellation scheme, an enhanced Greedy Parameter Stateless Routing

Protocol (GPSR) to support multi-hop communications and a Radio Resource Management (RRM) scheme to maximize throughput while guaranteeing the QoS of cellular users.

The authors in [144], considered the transmission of video messages through D2D infrastructure. An optimization problem was formulated using peak signal to noise ratio as a constraint. The resulting optimal policy proposed in the paper greatly improves throughput as compared to undifferentiated interference strategy. The optimal policy is then applied to real world video streaming application where improvements in throughput are also observed.

In [145] the authors proposed a two-stage relay selection scheme to maximize the total throughput and guarantee QoS requirements. In the first stage, the candidate relay nodes are determined based on a selected cell coverage range. In the second stage, the optimum relay node is selected from the candidate nodes based on the transmission power and the SINR to guarantee QoS. Another relay selection scheme is presented in [146] where resources are allocated to two-hop relay links based on the maximum received SINR. Then an optimal relay node is selected according to the $\max - \min$ criteria of channel capacity of the D2D relay link.

Li *et al.* [147] proposed a call admission control algorithm based on interference analysis. Whenever a new DUE pair wants to access the network, the latter will calculate the QoS of all existing cellular and D2D communications to determine if the new call is allowed or not. If the new call creates interference with the existing cellular and D2D communications and compromises their QoS, the call is not allowed.

B. Power control

The process of adjusting power levels in base stations during DL transmissions and in UEs during UL transmissions is known as power control [112], [105], [113], [114], [84], [115], [116], [117], [118], [119], [120], [121], [122], [134], [123]. Increasing the transmit power of a device is desirable because it increases the link capacity but it will also cause an increase in the interference between the devices sharing the same cellular resources. Power control strategies also help conserve energy resources. Resource allocation involves strategies that are used to allocate radio resources (such as time slots in TDMA or frequency bands in Frequency Division Multiple Access (FDMA)) to different users/devices. Resource allocation plays an important role in meeting the instantaneous increase in demand for resources. Joint optimization of power control and resource utilization are vital to improve system capacity and the overall system throughput. In this section, we discuss different power control and resource management approaches [148], [149], [150], [151], [131], [152] that emphasize combining power control with mode selection and link adaptation techniques for achieving optimal system performance.

There are two broad categories of power control algorithms which include centralized [84], [153] and distributed [112], [134]. In centralized algorithms, the power control and resource allocation decisions are made by the BS, whereas in the distributed approach power control and resource allocation are performed independently by the UEs. LTE power control is an example of a centralized algorithm. An efficient power control algorithm should consider important parameters such as maximum transmit power, number of resource block, target received power per resource block and path loss.

1) Recent advances in power control schemes: Jung *et al.* [154] proposed a power efficient mode selection and a power allocation scheme for cellular networks where the same cellular spectrum is used for D2D transmission and cellular communications. The mode selection method decides whether the device will operate in cellular mode or D2D mode. The power efficiency is defined by the ratio of system capacity and total available power of the system. The proposed scheme measures the power efficiency for all possible modes of the devices communicating in cellular and D2D mode. Once the power efficiency is computed, a mode sequence with maximum power efficiency is selected.

In [155] the authors proposed an algorithm that reduces the power consumption of OFDMA based systems with integrated D2D communication. This algorithm forms a CSI matrix based on the UL and DL subcarrier in OFDMA-based cellular networks. The CSI matrix consist of generalized grid of $M \times N$, where M is the number of users and N is the number of subcarriers. The authors considered two modes of communication namely, cellular mode and direct mode. The proposed scheme first allocates the joint resource to the users communicating in cellular mode and then it performs the mode selection and resource allocation for the users communicating in D2D mode. Devices using cellular links will operate in the same way as the traditional cellular systems but the devices in direct mode can communicate in both modes. Direct communication between the devices is only allowed if the two communicating devices are in close proximity (so that the required transmission power level is below a pre-defined threshold) and far from the base station. The results show that the proposed solution reduces the power consumption of OFDMA based D2D networks in DL transmission by 20% compared with the traditional OFDMA systems without D2D integration.

In [156], the authors utilized the interior point method to evaluate optimal power for D2D communications. The aim of the authors is to minimize the computation complexity for which the interior point method was approximated. This was achieved by replacing inversion of Hessain matrix with a diagonal metrics. This simplification led to quick updation of Newton method. The results demonstrate that near optimal throughput is achieved with relatively lower computational complexity. In [157], the authors addressed the non-convexity of sum rate maximization problem subject to power constraints. The authors address this problem by modeling the power allocation problem as a potential game. By using the convergence property of potential games, two iterative algorithms were proposed. The proposed solutions converge to one of the local maxima of the objective function while outperforming the conventional rate maximization schemes in the literature.

Wang *et al.* [158] proposed a scheme to allocate power and radio resources efficiently to improve the power efficiency of cellular devices communicating in the network. The authors proposed an iterative combinatorial auctioneer algorithm where the D2D users (also called bidders) contend for the channel access and the cellular wireless medium is considered as the auctioneer. The authors in [159], [160] used the Peukert's Law (which expresses the change in capacity of batteries at different discharging rates) to characterize the non-linear effects in battery and also modeled the battery lifetime. They allowed multiple D2D pairs to share the same channel simultaneously thereby increasing the channel utilization. By using simulation tests, they showed that the battery life of D2D UEs becomes lower than that of cellular UEs if the distance between D2D UEs becomes greater than 0.8 of the cell radius. Thus it is beneficial to restrict devices to communicate directly if they are at certain specific distance from each other.

C. Open research issues in D2D resource management

Some research challenges regarding resource management are listed below:

1) Device densification in multi-tier networks: In a dense heterogeneous network, interference management is a critical issue. This is because the underlay spectrum sharing becomes more difficult than the existing single-tier systems when multiple BS are involved in the network. Moreover, due to various access restrictions (such as public and private, and so on), interference level varies in cells. The dynamic nature of heterogeneous networks also requires adaptive resource allocation strategies. Therefore, it is critical to manage resources efficiently in D2D heterogeneous network.

2) Interference, friend or foe?: Interference in D2D networks can be used to gain various advantages in terms of security and RF energy harvesting [161], [162], [163]. For security, the interfering signal can be used for friendly jamming in order to deteriorate the receiving signal at the potential eavesdropper [164], [165]. Specifically, this use of interference provides secrecy of data by decreasing the SINR at the eavesdropper which results in high decoding errors. In addition to this, interference signal can be used for ambient RF energy harvesting. This RF energy can be used to charge devices at the edge of the cell. However, doing so can increase the cost of the hardware because the circuitry used for information decoding cannot be used for energy harvesting. Therefore, a separate energy harvesting module is required to be employed inside the receiver such that the power of received RF signal is divided into two streams; one for energy harvesting and the other for information decoding. Moreover, to date, there is not much work done in D2D literature that takes advantage of efficient utilization of interference for provisioning of link security or energy harvesting.

3) Multiple small networks or one large network: The issue of resource management in D2D is directly connected to the number of users in the network. The resources (both power and frequency) can be fairly managed in small networks, however as the number of users increases, it becomes very difficult to accommodate all users in a single network. Technically, the network performance mainly degrades due to increased number of antennas, large overhead of CSI feedback and high complexity of decoding and precoding metrics. How many users should be allowed to enter the network, how to make decision (centralized or distributed) and how to allocate resources within a sub-network, are some of the critical issues that need to be addressed.

VI. Mobility management

Mobility management is an essential component of D2D communication paradigm. Since UEs may change their location while communicating with each other, their connectivity could get interrupted. Therefore, a mechanism is required that handles the communication when UEs are mobile. For D2D applications such as bulk data transfer or cellular offloading between devices in close proximity, evaluating mobility patterns of UEs and their impact on communication reliability is a key challenge [166], [167], [168], [169], [170], [171], [172], [173], [174], [175], [176], [177], [178].

A. Fundamentals of Mobility Management in D2D Communication

Mobility management consists of two complementary operations namely, location management and handoff management [179], [180]. Location management enables the network to track the attachment points of mobile terminals between consecutive communications as they roam around the networks. Handoff (or handover) management enables the network to maintain the users' connection as the user moves from one attachment point to another (as shown in Fig 9). Horizontal handoff arises between homogeneous networks/systems when the signal strength of the serving base station deteriorates below some threshold. Vertical handoff arises between heterogeneous systems and can be user initiated or network initiated. In the former case, user initiates the handoff. In the latter case, the network initiates the handoff when it decides to distribute the overall network load among different systems. The vertical handoff decision relies on multiple factors such as type of application (streaming, conversational), minimum bandwidth, delay preferences, power requirements, observed network load, estimated data rates, and so on. Such contextual information can be used to create profiles and make trajectory predictions that can assist in making optimized handover decisions.

A popular feature of future cellular networks is the design of multiple small cells (femto/pico) which create multilayer topologies. Another feature is the existence of user devices that support multiple Radio Access Technologies (RATs). Such multi-layer topologies and multi-RAT environment enable network densification which results in higher spatial frequency reuse and higher network capacity but makes the handover decision more complex and challenging. The existence of co-channel interference along with small cells appearing and disappearing quickly as UE devices move in a multi-RAT/multi-layer environment bring about additional challenges to execute the handover process in a timely manner. Hence, the users mobility can diminish the expected densification gain. In order to improve the densification gains, it is necessary to design handover solutions that reduce the handover rate and control overheads. The implementation of separate control and user

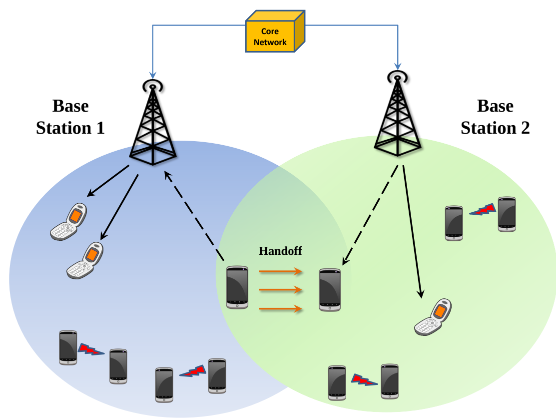


Fig. 9: Typical handoff scenario in D2D Communication.

planes have demonstrated to provide lower control overhead and handover failure rate in [181]. The separation of control and user planes also provides flexibility to take handover decision with the help of very little control information.

B. Recent advances in D2D mobility management

Most of the work in D2D mobility management is related to efficient handover selection. Doppler *et al.* [182] recommended that D2D should be created or designed for stationary link with restricted mobility as an underlay in cellular networks. The handoff can take place inside a cell, either when interference is high or when D2D transceivers are out of range such that the communication between devices is not possible due to fading and signal attenuation. Through vertical handoff and mode selection, handoff can be executed from D2D links to the cellular link. D2D transmission links provide direct communication when moving from one cell to another cell or by switching to the cellular mode before horizontal handoff. IP connections are handed over from D2D links to cellular links and vice versa. This could work well when we have have multiple valid IP addresses which allow routing in the user plane through either a direct D2D link or an IP tunnel of the cellular network.

The authors of [183] proposed a handover scheme that utilizes direct D2D communication to assist cellular users at the cell-edge avoid interruption and minimize delays while moving between cells. Users that move to a different cell can establish D2D links with devices in close proximity to take advantage of better channel quality and get uninterrupted downloading. The eNB is responsible for D2D session establishment, power control and resource management functions. The handover decision is triggered by the eNB based on Channel Quality Indicator (CQI) feedback given to it by the UEs. The handover process can be divided in to three phases: handover preparation, execution, and completion. In the first phase, the UE sends the channel related information to its serving eNB, which decides whether to initiate the handover process based on certain conditions such as average fade duration and average level crossing rate. The execution is the phase where the information of UE and its behavior is transferred to the other cell. In the completion phase, the acknowledgments are exchanged between cells and the status of UE is updated in the new cell.

Considering that D2D communication occurs between devices in close proximity, the authors of [184] proposed a seamless handover scheme that jointly considers the handover of the pair of devices involved in D2D communications. In the handover phase, the source eNB sends a handover request message to the target eNB. On receiving the request message, the target eNB determines if it can provide the same QoS as the source eNB. If it can provide the required QoS, then it notifies the ProSe function about the D2D handover. The ProSe function authenticates the identity of the ProSe UEs prior to allowing the UEs to handoff. Then the target eNB reserves Radio Resource Control (RRC) resources for the UE to use over the radio link and allocates a Cell Radio Network Temporary Identifier (CRNTI) to the moving UEs. Once the target eNB has allocated resources, it sends a message to the source eNB indicating that it has allocated resources for the mobile UE. Next, the source eNB requests the UE to perform a handover.

In [185] the authors proposed two solutions to D2D handover in an underlay network. The first solution is the D2D-aware handover solution, where the serving BS postpones handover of a pair of DUEs (moving out of coverage of the BS) to another BS until the signal quality of the serving BS falls below a pre-defined threshold. The pre-defined threshold is the minimum requirement in terms of link quality to maintain the D2D control. On the contrary, if the DUEs perform a handover and move under the control of another BSs, it can lead to significant performance degradation. Once the link quality of the serving BS falls, pair of DUEs jointly handover to the other BS. The second solution called the D2D triggered handover solution clusters the members of a D2D group within a minimum number of cells or BSs. This results in reduced network signaling overhead caused by the inter-BS information exchange.

The impact of mobility on the relationship between Energy Efficiency (EE) and Bandwidth Efficiency (BE) in D2D communications is investigated in [186]. The authors proposed an EE-BE aware scheduling scheme with a dynamic relay selection strategy. In addition to the above studies, some other solutions for mobility management problems are listed in Table VIII which highlight the proposed solutions and performance metrics used for evaluation.

C. Open research issues in D2D mobility management

This section discusses some of the mobility management challenges for D2D UEs that need to addressed in future.

1) Appropriate selection of Open System Interconnection (OSI) Layer: To handle mobility management, each layer of OSI model provides possible solutions [187]. Protocols such as Session Initiation Protocol (SIP) and Mobile Stream Control Transmission Protocol (mSCTP) support mobility services at the application layer and transport layer respectively. Similarly, Mobile IP (MIP) at the network layer and many data link layer access technologies implement functions to deal with mobility issues. In the context of D2D, selection of an appropriate

TABLE VIII: Brief summary of mobility management in D2D communication.

Reference	Problem/ Objective	Solution	Performance Metric(s)
[166]	Evaluation of the effects of heterogeneous user and device mobility on the performance of mission critical Machine-Type Communications (mcMTC)	Modeling the availability of alternative connectivity options i.e., D2D links and drone-assisted access	Connection availability, Reliability of Data
[167]	Replication of content in social network services becomes difficult due to receiver limited bandwidth and storage capacities	Replication scheduling and designing a distributed algorithm using historical, local, and partial information of the devices	Content delivery
[168]	Improving spectrum efficiency for mobile users	Monotone submodular maximization using time-efficient greedy algorithm	User average contact rate, Data offloading ratio
[169]	Handover strategy between various radio cells	Analytical Modeling using Reference Point Group Mobility (RPGM) mobility model	Blocking probability of originating D2D calls, Handover failure probability
[170]	Analysis of chaching performance bottleneck for mobile devices	Stochastic geometry approach to analyze the impact of mobility on caching	Coverage probability
[171]	Mobility-assisted content transmission and resource allocation	Optimal Resource Allocated Content Transmission (RACT) algorithm by leveraging contact patterns of users	Successful transmission
[172]	Analysis of impact of mobility pattern of D2D users in bidirectional cellular network	Closed form and asymptotic expression of outage probability for cellular and D2D links	Outage Probability
[173]	Impact of mobility on the performance of cached D2D	Analytical model for different file-size distributions (Exponential, Uniform, or Heavy-Tailed)	Service Success Probability
[174]	Impact of mobility on D2D mode selection	Stochastic modeling and derivation of closed-form expression of D2D mode transition rate	Average D2D mode transition rate
[175]	Mode selection and resource allocation for mobile D2D	Graph based mobility assisted heuristic optimization scheme	Average transmission rate, Total successful shared contents
[176]	Effective and cheap communication solutions for the deployment of smart services	Always Best Packet Switching (ABPS) scheme	Handover downtime
[177]	Mobility management by addressing issues like latency and power consumption	Review of work on mobility management and proposition of new mobility management framework	Sum rate, Spectrum efficiency
[178]	Interference due to mobility of users in the cell	Three Step Resource Allocation in Mobility (RAM) scheme	Throughput

layer to handle mobility management is a critical issue which may be different for different modes and require further investigation.

2) Suitable handover criteria: Since D2D UEs experience interference from multiple sources in the network, therefore, handover from one cell to another cell should consider the QoS requirements of the devices as well as the availability of resources in the new cell. Moreover, future D2D UEs are likely to be equipped with energy harvesting capabilities. Therefore, the criteria of handover can drastically change if the amount of harvested energy is also taken into consideration. Suitable handover criteria can hence enhance the lifetime and performance of devices.

3) Handover techniques for highly mobile UEs: For vertical handover, UEs need to operate on controlling and signaling frequencies. However, this results in a significant increase in interference and deterioration of instantaneous SNR especially when the mobility of devices in the network is high. Since D2D UEs are envisaged to be highly mobile (e.g. in Vehicular Ad-hoc Networks (VANETs)), therefore frequent handovers are likely to be made, which may increase the interference level in the network. So, joint interference mitigation and handover techniques need to be developed that can improve overall performance of D2D communications.

VII. Security and privacy in D2D communications

So far research and standardization efforts in D2D communication have focused mainly on architecture, interference, and resource management. Security aspects for the D2D environment have been largely ignored by both academia and industry. D2D communications present a hybrid architecture where both distributed and centralized approaches are coupled together. It is therefore vulnerable to some of the same security and privacy threats being faced by both cellular and ad-hoc wireless networks. D2D communications face several security threats that can affect authentication, confidentiality, integrity and availability of the network. Thus, D2D communications require efficient security solutions to enable secure, private, and trusted data exchange between devices and cellular network; and proximity-based direct communication without any assistance from cellular network.

In scenarios where the cellular network is responsible/engaged in coordinating D2D communications it is necessary to secure connections between the user and the base station. Existing cryptographic mechanisms that encrypt messages being sent over the physical interface can be used to secure radio channels from well-known security threats such as eavesdropping, replay attacks, message modification, and node impersonation. Current cryptographic solutions encrypt messages by using a shared secret (either a symmetric shared key or public key) which mandates the involvement of the base station or a Trusted Third Party (TTP). In this case, security functions are managed by Public Key Infrastructure (PKI). Such security mechanism is not feasible in the case of direct D2D communications because of absence of the cellular infrastructure. Further, due to the large numbers of mobile devices, the variety of manufacturers and differences in standards; preloading secret keys in the devices is not a practical solution.

For D2D communications, application layer security combined with physical layer security could provide an efficient and secure solution. A cross layer security framework such as the one proposed in [188] could improve reliability of D2D communications. In the cross layer security framework, physical layer provides wireless link security, whereas, application layer ensures authentication through watermarking. Together, both layers can ensure confidentiality and integrity of data as it passes through the wireless channel. A graphical illustration of their proposed model is shown in Fig 10.

When a user device is far from the base station, the user cannot directly communicate with it. In this case, the user can communicate with the BS by relaying messages through the intermediate devices. D2D relay communication expands the coverage of cellular network and also improves the service quality at cellular edges. But at the same time, D2D communication faces serious security challenges. The intermediate nodes involved pose some risks to the integrity and confidentiality of the data in transit. To keep the users data secure from the malicious intermediate nodes is also a challenge in D2D communication.

Privacy is another impeding challenge for adoption of D2D communications, because D2D presents a dynamic environment where communication between different devices has different context-specific sensitivity level. The extent to which a user might want his personal data to be published is highly context-dependent. It is important to design access control schemes that allow users to specify which data is transmitted and to whom. A lot of important personal information is being implicitly shared (e.g. location, time of communication) during D2D communications. Any adversary eavesdropping on these communications might not be able to understand the encrypted content but mining seemingly innocent looking data collected over a long period of time will allow the adversary to reveal useful information regarding users communication patterns. Cellular devices are exclusively associated to a single person and therefore, communication patterns such as location, time, duration of communication, device type, type of service request and so on, generated from information, can be used to identify a particular user of the device. Anonymity preserving methods are employed to disassociate personal information such as location from the users identity to preserve privacy. Pseudonymity is a special type of anonymity approach that assigns a persistent pseudonym to each user to mask his/her identity. However, anonymity schemes usually require a TTP, but the assumption of a central TTP authority is unrealistic for D2D communications. The opportunistic nature of D2D communications requires decentralized privacy preserving schemes. These schemes also need to consider how privacy can be maintained during the exchange of context information in group communications.

Proximity-based D2D communications give rise to several privacy issues such as location privacy and device specific privacy. Location privacy refers to the sensitive association of a user identity with his/her location. However, providing location privacy is challenging, because in order to perform device discovery and make use of proximity based services

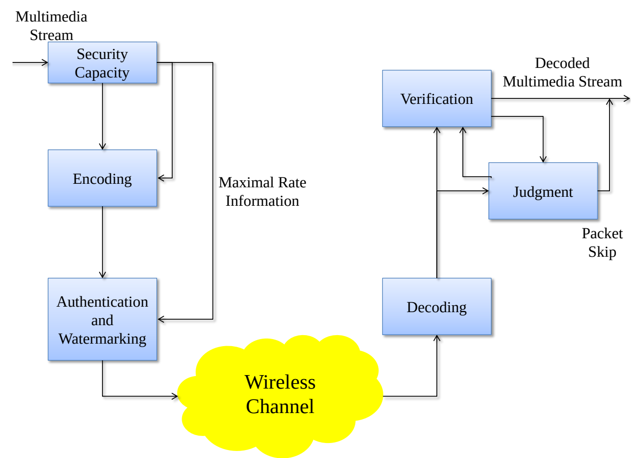


Fig. 10: Joint Physical-Application Layer Security Scheme [188].

it is necessary to exchange location information with nearby devices. Device specific privacy refers to the mobile platform that can provide certain basic security mechanisms. These basic security requirements include securely storing data using a device specific key, ensuring software operate in isolation from each other and that each external device is able to confirm a compliant platform version. We need to consider important privacy requirements such as anonymization, encryption of client side data, minimizing personal data and defining privacy policies for access control, during the design phase of device architecture.

Privacy schemes present a significant challenge also because they contradict with certain security requirements. For example, pseudonymization hides a users true identity which may be necessary to perform authentication. Further, anonymity schemes must ensure that malicious users are not able to take advantage of anonymity to perform illegal actions.

A. Recent advances in D2D security and privacy

Physical layer security is a recent concept which proposes to shift the security functions from the upper layers to the physical layer. As shown in table IX, this technique has proven to be very successful to ensure security against threats like eavesdropping (both passive and active) and man-in-the middle attacks. More specifically, physical layer security refers to techniques that exploit the physical characteristics of wireless channels and multiple antennas. In the context of D2D communication, physical layer security is emerging as a prominent solution for provisioning of wireless link security between pair of devices [189], [190], [191], [192]. It is also being used for jamming to reduce the ability of eavesdroppers to intercept sensitive communications [193], [194].

Spectrum sharing in D2D can produce a significant amount of interference among CUEs. Therefore, several research efforts have been exploring novel techniques that can minimize interference in order to enable secure and reliable D2D communication [195]. Interestingly, as we mentioned earlier, interference in D2D communication can be used to enhance network security by using it as artificial interference [196]. To be more specific, the interference generated from a D2D user

TABLE IX: Various applications of physical layer security.

Security Issue	Reference	Network Type	Solution
Authentication	[200]	Wireless sensor networks	Physical layer channel response based on fast authentication
	[201], [202]	Wireless network	Fingerprinting
	[203], [204]	Wireless Body Area Networks	Wireless channel exploitation
	[205]	Mobile network	Time varying carrier frequency offset
	[206]	Cognitive radio networks	Authentic tag generation by one way hash chain
Key Agreement	[207]	Mobile networks	Opportunistic beamforming and frequency diversity
	[208]	Mobile networks	Deep fade detection for randomness extraction; Light-weight information reconciliation
	[209]	Mobile networks	Vector quantization and clustered key mapping
Secrecy capacity enhancement	[210], [194]	Cooperative wireless network	Optimization
	[211]	Wireless Sensor Networks	Best node selection
	[212]	Massive MIMO	Random array transmission
	[213]	Smart Grid	Random spread spectrum
	[214]	Cognitive radio networks	Cooperative jamming
	[215]	Cellular networks	Stochastic geometry and random matrix theory

can be used against eavesdroppers to confuse their reception capability. The authors in [197] jointly optimized the access control and power of RF links when the links were subjected to an eavesdropping attack. Later, the authors in [198] extended their work by applying the same optimization strategy for large-scale D2D networks. For the case of multiple eavesdroppers and multiple antennas, the authors of [199] considered the DL transmission and provided a robust beamforming technique to maximize the secrecy rate (i.e., the difference between the rate of legitimate and eavesdropping links) using minimum amount of power.

Zhang *et al.* [216] proposed a secure data sharing protocol for D2D in LTE Advanced networks. The application scenarios related to this protocol is time deterministic (i.e., the data is available for a certain time) and specific. To share data, the content providing server must pre-register and join the cellular network. The content providing server is subject to malicious attacks in its unprotected domain. However, Zhang's protocol [216] does not ensure availability and dependability. Goratti *et al.* [217] proposed a security protocol related to the establishment of direct communication links among D2D devices. The proposed protocol addressed LTE security issues such as authentication and identification. The key idea of the protocol was broadcasting beacons containing security related information to the nearby devices. Based on a pre-distribution key management scheme, the protocol gets a random encryption key from wireless sensor network. This pre-distribution scheme helps D2D in selecting the encryption key from a pool of keys owned and managed by eNB. The key information is embedded into the subfield of the beacon frames and broadcast to the network.

The importance of Artificial Noise (AN) in the area of physical layer security is enormous. In fact, it is the AN that if added in a controlled manner, will make the whole difference between the way signal is interpreted at legitimate receiver and eavesdropper. The magnitude of AN that adds to the signal therefore distribution of this AN is an important concerns. It may be noted that in ideal case, the power to transmit signal should be minimized, however, in order to secure the message, additional power is added in the form of AN. This asks for algorithms to be developed for optimum power allocation. The jamming signal generated by D2D transmitted can also act against any potential eavesdropper in the near vicinity. The authors in [198] extended their previous work [197] to exploit the interference generated by D2D transmitter. Analytical results and weak performance criterion were derived to find the secrecy regions. However, mode selection was preset and non-colluding eavesdroppers were considered in the system model. Ouyang *et al.* provided maximal ratio transmission strategy along with power allocation schemes to provide link security during D2D communication from a friendly jammer [218]. Subsequently, the authors in [219], [164] provide friendly jammer selection method and derive upper and lower bounds of power allocation an illustration is shown in Fig 11. Here, M eavesdroppers listen the legitimate communication between transmitting and receiving device through wiretap link. In order to deteriorate the reception of these eavesdroppers, N helper/ jammer nodes transmit jamming signals over the jamming link which cause large decoding errors at the eavesdroppers.

Jung *et al.* [220] proposed a communication protocol to overcome the issue of secure routing in D2D ad-hoc communication by integrating group key agreement and routing control information. The group key agreement procedure is initiated whenever a new node joins the network or when two networks merge. Each node in the network is authorized by a certificate authority. Each new node joining the network is provided the group key upon successful authentication. The group key is used to secure group routing messages. Each group key has a validity time after which the group key agreement process is re-initiated.

Panaousis *et al.* [221] proposed a secure message delivery protocol to discover route with the shortest path and the lowest security risk in D2D ad-hoc communication. The selection of the most secure route is made not only by detecting malicious messages for every route but also by taking into

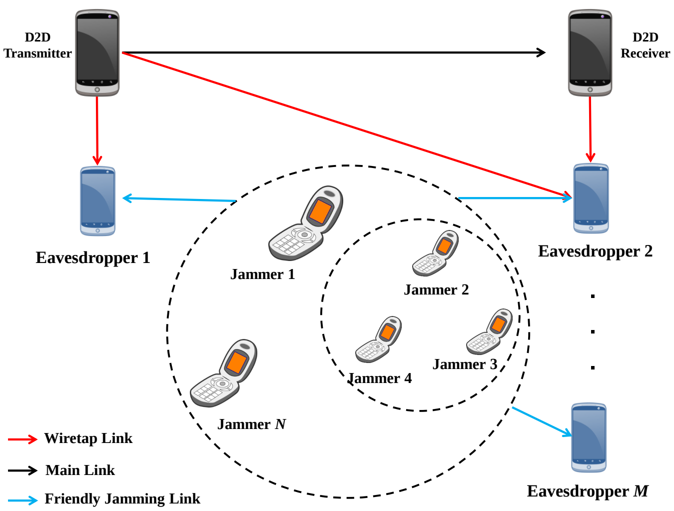


Fig. 11: D2D friendly jamming network setup [164].

consideration the QoS and the energy cost. Route and device configuration matrices are used to support authentication and non-repudiation security requirements. Route dependability and availability are supported through QoS, energy cost, and risk management.

Two group anonymous authentication and key exchange protocols are proposed for both network covered and network absent D2D communications in [222]. In the first scenario, different UEs authenticate each other with group information regarding public safety services provided by the core network whereas in the second scenario, the k-anonymity secret handshake scheme, public key encryption and zero-knowledge proof are used to provide group anonymous authentication. The group anonymous protocol supports revocability and traceability to revoke and expose the identity of malicious D2D user. The zero-knowledge prover computes the random number generated by the Authentication Center (AuC) or the Home Subscriber Server (HSS) and compares it with the number generated by secure hash function. By comparing these two numbers, identity of suspicious D2D users are detected.

In [223], the authors proposed a privacy preserving spatiotemporal scheme. Spatiotemporal matching is based on the location of D2D devices. The spatiotemporal profile of each device is maintained by keeping track of the devices' whereabouts. The spatiotemporal profile matching of two devices determines the mutual level of trust. Devices with similar spatiotemporal profiles are more likely to stay longer within each other's transmission range.

In [224], the authors presented a trust-based relay node selection scheme. The trust value at each node is calculated by taking into consideration past experience (such as successful delivery of messages and decoding errors at relay) from direct interactions and knowledge from other users. Each node maintains a trust table of all of its neighbors and selects a relay node based on updated trust values in the device reputation table. The trust values are calculated based on three parameters namely, SNR, energy, buffer capacity and reliability of device. The relay selection is then divided into two cases: 1) Relay selection with two parameters, 2) Relay selection with the combination of three parameters.

Ometov *et al.* [225] proposed a social-based trust computation scheme that divides different social features in two classes namely: user-based and device-based social features. The authors introduced different social features such as human social relationship, market pricing relationship, co-location object relationship, co-work object relationship that are particularly relevant to D2D communications. A brief description of these social features and their corresponding values are provided in table X. The authors proposed a weighted function that considers both classes of social features. The functions behavior depends on the weights that are assigned. Higher weights can be assigned to either user-based social metrics or device-based metrics depending on the requirements of a particular application.

B. Open research issues in D2D security and privacy

Based on the security issues we have identified above, next we present some research challenges for D2D security that need to be addressed in the future.

1) Balancing security-energy tradeoff: For resource-constrained D2D devices, it is not beneficial to use security techniques that consume a lot of energy. As a result, energy-efficient secure protocols must be developed in order to ensure optimal usage of the devices' resources. Cryptographic schemes (for message integrity and authentication) often rely on the complexity of key generation. This complexity in algorithm results in high energy consumption and increased hardware complexity. It is worthwhile to note that the energy cost of asymmetric key generation algorithms is highest, followed by symmetric key generation and hash algorithms [226]. This proves that using only one type of algorithms for provisioning of security and privacy may not be a suitable approach from energy point of view. Therefore, research efforts should be focused towards hybrid protocols which can be used for dynamic selection of algorithms based on the network conditions.

2) Non-repudiation: Non-repudiation is critical for ensuring data integrity inside the D2D network. However, current efforts on D2D communication lack complete security architecture for user and device authentication. Moreover, mobile nodes leaving and joining the network need to cooperate with existing network members to optimize the performance of network. More specifically, there is need to develop a scalable and flexible authentication framework that can support fast authentication of mobile devices and users as they join or leave the network. A suitable trust management and authentication system will help in securing data of existing members of the network.

3) Lack of standardization: There are no standards and global policies to ensure secure interaction of D2D user equipment. Moreover, authentication mechanism for different applications could vary which makes it difficult to ensure interoperability. Therefore, a standard document is required that addresses issues such as procedure for secure user interaction with a particular application, amount of data users need to

TABLE X: Social relationship factors between devices [225].

Relationship	**Description**	**Typology**	**Trust value** ($0 \rightarrow 1$)
Human Social Relationship (HSR)	Degree of familiarity with neighbors	User-driven	[0-1]
Market Pricing Relationship (MPR)	Interaction between services triggered by environment	User-driven	0.2
Ownership Object Relationship (OOR)	Relationship between objects owned by the same person	Device-driven	1
Co-Location Object Relationship (C-LOR)	Objects sharing personal experiences (e.g., cohabitation)	Device-driven	0.8
Co-Work Object Relationship (C-WOR)	Objects sharing public experiences (e.g., work)	Device-driven	0.6

share for ensuring privacy and security information database management. These issues become even more critical especially in the decentralized D2D communication environment.

4) Decentralized anonymity schemes: The opportunistic, self-organizing and peer-to-peer nature of D2D communications, require anonymity schemes that are not dependent on centralized third parties. Further, these schemes need to address the issue of anonymity abuse in the absence of a single trusted center. There exist some proposals of distributed privacy schemes in adhoc and vehicular networks [227] [228], but so far this issue has not been fully explored in the context of D2D communications.

VIII. Economic aspects of D2D Communications

This section discusses various issues of D2D communications with respect to economics. First, we look at various aspects of information economics such as the importance of information and the price of information. Then, we provide review of recent works on incentive-based D2D communications.

A. Importance of information

Gathering information is an important aspect of economic models. Specifically, the information is used for making decisions about a particular device in the network. Moreover, the decision about whether or not a particular resource needs to be assigned to an entity in the network, is generally made based on the given information about that entity. Depending on the quality of information, the value of information can be negative, zero, or positive. The value of this information helps the system design in the following ways:

- An optimal decision to maximize the payoff can be made if the knowledge of system states is available.
- An optimal information source can be selected among many sources. For instance, in D2D communications where several devices want to communicate within a cell, the D2D pairs with largest information value can be chosen to optimize network performance.
- Information gain (which is the difference between value of information and the cost of collecting that information) can be maximized for D2D networks.

B. Issue of information's price

After determining the value of information, the next step is assigning it a price tag. Information, like other tangible things, can be treated as goods which can be sold in the market. There are several characteristics of information as an economic good which we describe below:

- There are different levels of cost. For instance, the fixed cost incurred from the deployment and system design is usually higher than the variable cost of maintenance, distribution and reproductions of information. D2D is considered to be a cost effective solution because the deployment cost is minimal as it uses the existing infrastructure.
- Quality dependency is another aspect when it comes to pricing the information. Different consumers value the information differently which depends on the quantity, quality, and reputation (reliability of information source).
- Different sets of information can be combined together to enhance the value of information. For instance, a D2D relay can broadcast the video with different resolutions based on the incentive provided to it.
- Timing and the amount of information are also important aspects of information economics. Both transaction-based and subscription-based pricing models exist which provide access to services and information at different time and rates. For instance, a subscription-based pricing model would be suitable for streaming the video among devices.

C. Review of incentive-based solutions for D2D communications

The economic features of D2D communications are different from the conventional cellular networks. Moreover, due to existence of CUEs and DUEs within the same cells, competition is inevitable. The unique characteristics of D2D communications make it difficult to determine an appropriate optimization technique for them. Therefore, the optimization techniques adopted for cellular networks may not be suitable for D2D communications. Additionally, the complex interaction of devices allows them to adapt their choices according to the network requirements, which is difficult to model using existing economic models. Game theory has recently offered several solutions to analyze, model and design the competitive situations between DUEs and CUEs. It is worth pointing out that in game theory, prices are fictitious and used to control and coordinate the transmission of information in the network. In other words, the prices in game-theoretic models are system parameters, but they do have economic interpretations. Some of the recent incentive based solutions are discussed below:

1) Non-cooperative solutions: In this type of game, the DUEs are commonly competing for resources and can be viewed as players. The authors of [229] investigated the resource allocation issue when a DUE is located at the edge of two cells. With the help of a non-cooperative Cournot game, they were able to mitigate the inter-cell interference. The authors considered three possible scenarios:

- CUEs in both cells use UL resources.
- CUEs in both cells use DL resources.
- CUEs in one cell use DL while the CUEs in the other cell use UL resources.

Based on the concept of leaders and followers, the authors of [230] used the Stackelberg game to optimize the allocation of resources. The CUEs were considered as the leaders while the DUEs were assumed to be the followers in the game. The leaders own the channel resources and charge some fee if any follower requires the resources. The same authors extended their work in [130], by incorporating D2D sum rate with the Stackelberg game.

In a similar work, the authors of [231] modeled interactions between D2D-tier and cellular-tier using the Stackelberg game. They also noted that the relationship between a BS and DUEs is similar to the hierarchical (leader/follower) structure. The authors proposed to maximize their profit using tolerance margin. It was shown that the minimum exchange of information is required when using uniform pricing algorithm.

Due to the increase in the number of multimedia files, traditional link capacity improvements methods are not sufficient. Therefore, the authors of [232] explored the behaviors of people for buying and selling online videos in the D2D communications environment. They modeled a file competition mechanism where data is managed by DUEs with minimum involvement of the BS. Then, they used the Stackelberg game to maximize the utility of both the buyers and sellers of videos.

Based on the work of [233], [234] the authors of [235] considered different application requirements to improve the performance of heterogeneous D2D networks. A user-centric association scheme was proposed and an energy-efficient solution was provided using a two-stage Stackelberg game. The proposed solution was compared with the exhaustive search method. The authors observed that the proposed optimal algorithm requires a smaller number of iterations to adapt to changes in the network.

2) Cooperative solutions: Using social aware cooperative games, the authors of [236] mitigated the cross-tier and co-tier interferences. A resource allocation problem was formulated. To maximize the utility of the social group, the authors proposed a Social Group Utility Maximization (SGUM) game [237], [238]. The results show that the SGUM solution increases the utility up to 50 %. The authors also pointed out that the fairness was also improved as compared to random selection and coalition game [239] solutions.

The authors of [240] proposed a coalition game based resource allocation scheme and developed a transferable utility function. Although each user intends to maximize his/her own utility, there is an incentive in cooperating with other users. The authors showed that the spectrum efficiency can be increased when the players of the game cooperate with each other.

The problem of resource allocation in large-scale D2D networks was investigated in [239]. Specifically, the authors addressed the resource allocation problem among CUEs and DUEs by using a coalition game. As a result, it was found that the sum rate can be improved from 20% to 65%. However, they only considered single-cell scenarios and analyzed intra-cell interference.

In [241], Wu *et al.* investigated the problem of uplink resource sharing in D2D communications. The authors proposed a non-transferable coalition game for D2D multimedia communications. The energy efficiency and the cost (in terms of mutual interferences) were considered for the players cooperation, which considerably improved the performance of networks as compared to other state-of-the-art solutions.

3) Auction-based solutions: The auction-based games utilize the concept of buyers and sellers to address the resource allocation issues. In particular, the authors of [242] proposed a resource allocation method which was inspired by the sequential second price auction scheme. Spectrum resources were auctioned by the pairs in sequence which also improved the user fairness.

The authors of [242] extended their work in [243] by proposing an iterative combinatorial auction technique which allows efficient allocation of DL resources in D2D networks. More specifically, the bidders are allowed to submit multiple bids and ask the prices in each auction round. The D2D links act as goods and by assigning these links to appropriate bidders the sum rate utility function is maximized. Similar to [243], the authors in [244] proposed a reverse iterative combinatorial auction scheme to maximize the sum rate in DL D2D networks.

The authors in [245] proposed a two-phase auction-based resource allocation scheme. This scheme maximizes the fairness while simultaneously minimizing the interference. The auction-based distributed resource allocation scheme was proposed for multi-tier D2D communications in [129]. The main emphasis was on maximizing spectral efficiency without leaking interference in the macro-BS network. The reverse auction mechanism for load balancing in D2D communications was proposed in [246], [247]. These works analyzed improved resource management and enhanced the power control in D2D communications. The authors of [248] designed a multi-hop communication scenario to address the completion among secondary service providers. The authors proposed an opportunistic auction scheme to minimize the uncertainty of spectrum availability. Through simulations, the authors showed that the opportunistic auction scheme can improve the efficiency of cognitive mesh assisted cellular network.

D. Open research issues in economics of D2D communications

This section discusses some challenges related to the economic aspects of D2D that need to addressed in the future.

1) Enhancing social welfare performance: From an economic perspective, social welfare refers to the sum of economic surplus which includes both consumer and operator surplus. An efficient pricing policy for D2D communications should be aimed at improving social and pareto-optimality. The pricing methodology needs to coordinate between different network entities to maximize social welfare. Service pricing schemes that exploit the relationship between pricing and resource management (interference and power control) need to be further investigated to enhance the overall network performance as well as improve customer satisfaction and maximize revenues.

2) Preventing untruthful behaviors: The BS is responsible for collecting all the information related to power costs, content availability, interference and channel gain from UEs. However, information communication is asymmetric and the BS may not be completely aware of the true situation of a UE. A malicious/selfish UE may exploit this limitation and take undue rewards from the BS by sending false information to the BS (e.g. falsely portraying services provided as a D2D transmitter). Hence there is a need for well-designed schemes that can prevent DUEs from any untruthful behaviors.

IX. D2D COMMUNICATIONS IN 5G TECHNOLOGIES

Although unprecedented progress has been made in D2D communication over the last few years, there are many challenges that still need to be addressed before this technology can be used for 5G networks. As illustrated in Figure 12, we now discuss how D2D communication can be applied to future 5G technologies and applications.

A. Hyper-dense networks

Next generation networks are expected to move from the centralized based networks to a more random and non-linear Heterogeneous Networks (HetNets) [249]. Private organizations are likely to deploy a mixture of networks component (including femto-cells, Road Side Units (RSUs) and Wi-Fi access points) in an ultra dense network environment. A dense network environment such as the one in Hetnet presents different kinds of opportunities and challenges in contrast to traditional cellular networks [250]. The co-existence of large number of devices can also be used to exploit social networking. More specifically, trust based hyper dense networks can be used to ensure secure exchange of information between devices [49] while consuming minimum resources of the network. The devices can also adjust themselves in way such that users demanding common content can be timely facilitated. This can resultantly ensure efficient utilization of resources while simultaneously reducing the burden of BS [251] by reducing the transmission of redundant content to the users. The authors in [252] exploited the social networking by providing incentives to relays. It was shown that the proposed incentive based relaying mechanism considerably improves the energy efficiency of D2D networks. Despite these advances, special attention should be provided to design issues [253] pertaining to authentication, trust matrix formulation and mobility of devices in the network.

Interference in Hetnets is another concerning issue. In this context, interference from nearby access points and small networks is expected to increase exponentially which will degrade the performance of D2D users. Although network-coded interference cancellation schemes can be useful, these techniques require *a priori* knowledge of the channel. Additionally, the practicability of power adaptation strategies may also need to be re-evaluated because small interval of coherent time can affect the power adaptive transmissions per time-slot.

B. Multi user MIMO (MU-MIMO) and massive MIMO

MU-MIMO is a key technology that has been applied to numerous systems including LTE UL to obtain higher user diversity gain. The integration of MU-MIMO with D2D can further improve spectral efficiency but it also results in an increase in intra-cell and inter-cell interference. Several works [254] proposed resource allocation and interference management schemes to achieve higher performance gains. However, tradeoff between performance and complexity [255] can significantly increase with the integration of D2D in 5G MU-MIMO.

In addition to MU-MIMO, massive MIMO techniques can be appealing to improve the uplink reliability of D2D communication in cellular networks. For the case of massive MIMO, an antenna array of very large size is used at BS to serve multiple users in the network for given resource block [256]. It is ensured that channel for all the users is nearly orthogonal. This allows simple transmission or reception signal processing techniques while mitigating the impact of interference [257], [258]. This consequently implies that using massive MIMO along with D2D for uplink communication can perform close-to-zero interference using energy efficient techniques at the devices. Despite this distinctive advantage of using massive MIMO for D2D communication, the effect of interference for cellular-to-D2D links still exist. Specifically, for a particular size of antenna array and increasing number of devices, the D2D uplink can experience considerably large interference. In this regard, the authors in [259] performed analysis of D2D communication for cooperative feedback schemes under Frequency Division Duplexing (FDD). It was shown that cooperative feedback schemes provide improved sum rate as compared to non-cooperative feedback techniques. In a similar work [260], the authors proposed optimal power allocation algorithm for D2D aided massive MIMO systems which was found to increase the sum-rate in comparison to the sum-rate of baseline protocols. The work of [260] was extended for limited CSI sharing and dual regularized feedback cases in [261] and [262], respectively. Though these advances are significant, yet problems like poor channel estimation due to interference and the tradeoff between D2D users scaling require more focused research efforts.

C. Energy harvesting in D2D communication

The detrimental effects of exponential rise in mobile communication on the atmosphere of earth have started to become more apparent with each passing day. The prognosis provided by [263], indicates that the carbon footprint of mobile communications will annually increase upto 11 Mto CO2 by 2020, which is equal to the carbon footprint of 2.5 million households in entire Europe. Although mobile communication

Fig. 12: Uses of D2D communications in 5G technologies.

footprint currently contributes a portion of global CO2, yet it is imperative to lessen its linear rise in the future [264]. Thus, to lower this energy consumption solutions like dedicated and ambient energy harvesting have been proposed. In this regard, RF energy harvesting (i.e. storing energy via electromagnetic waves) has gained considerable research interest. It is mainly due to dual nature of RF signal i.e., ability to transfer information and power simultaneously. This is why this technique has recently been investigated in mobile networks [265], cognitive networks [266], [267] and relay assisted networks [268], [269].

D2D devices are typically powered by pre-charged batteries. Due to the frequent transmission of messages, most of their energy is dissipated while transmitting and processing RF signal. These devices become idle once their batteries are fully drained. One promising solution to address this challenge is to enable these devices to harvest energy from renewable energy sources. The harvested energy can significantly improve the lifetime of the device and the network. Despite few pioneering works [108], [190], [270] in energy harvesting aimed at D2D communication, research in this area is still in its infancy. The authors in [108] proposed spectrum access techniques to harvest RF energy for D2D DL and UL channels. In another work, Liu *et al.* of [190] proposed power transfer techniques for a D2D communication network. In particular, their proposed approach harvests energy from power beacons using the spectrum of the primary BS. The authors of [270] proposed an energy harvesting assisted relaying protocol for mobile relays that can support D2D communication. A low complexity transmission protocol was presented based on the CSI of the energy harvesting relays.

D. Leveraging other spectrum bands

In recent years, several research efforts have focused on exploiting the spectrum bands which have not been used in the earlier generation of networks [271], [272], [273]. A promising solution for the future 5G cellular network is mmWave communication [274]. mmWave contains a wide range of carrier frequencies operating over the frequency band of 3-300 GHz. It provides short range, high bandwidth (multi-gigabits-per second) connectivity for cellular devices. The mmWave band has several desirable features which include high bandwidth, compatibility with directional transmissions, reasonable isolation, and dense deployment. In mmWave cellular networks, by using D2D communication, direct concurrent links can be supported, resulting in an enhanced network capacity [275]. The authors in [276] discussed challenges of implementation of mmWave technology for 5G technologies and emphasized on the impact of users mobility on the performance deterioration. However, to address this concern, the authors in [277] noted that directional antennas would be needed for successful integration of D2D networks underlying mmWave architecture. It is evident that mmWave along with D2D communication can generate significant revenue for network operators and mobile service providers [278], yet the high absorption rate and prolong exposure to mmWave can be detrimental for human race. In this backdrop, the authors in [278], while emphasizing on blockage of mmWave transmission in highly populated areas and its impact on human health, suggested to conform the mmWave technology with the predefined regulations/ standards of FCC. However, mmWave technology also suffers from certain limitations which include: coverage, capacity and QoS guarantees. mmWave suffers from high propagation loss which needs to be compensated by high gain with directional antennas.

The mmWave channels suffer from significant attenuation due to inability of short mmWave band wavelengths to diffract around obstacles. Interruption in Line of Sight (LoS) communication due to a moving obstacle can cause link outage. Furthermore, limited penetration capability could restrict mmWave connectivity to a confined space. For example outdoor mmWave signals may be confined to outdoor structures such as car park or street and limited signals may penetrate inside buildings [279]. In view of capacity enhancements offered by mmWave in D2D networks, it is required that more research efforts be aligned to optimize the design of hardware interfaces and to minimize the hazardous effect of mmWave transmission. In this regard, hybrid RF/mmWave for point-to-point and multi-point communications can be exploited to mitigate the effects of mmWave. Similar to mmWave, Free Space Optical (FSO) communication [280] is also expected to provide an increase in network bandwidth. However, as with mmWave, FSO also faces challenges such as heavy rain and fog. The performance of FSO quickly degrades in non-LOS conditions [280], [281]. In the GHz band, D2D communication can be used to forward data at higher rates which can also reduce delays and drainage of current spectrum bands.

E. Vehicular ad-hoc network

In VANETs a large number of safety and warning messages are exchanged among vehicles and between the vehicles and RSUs [282], [283], [284]. But high mobility of vehicles, dynamic road topologies, high multi-path fading, collisions due to hidden node etc. are challenges for reliable VANET communications [285], [286]. The variations in shadowing and fading are more prevalent in Vehicle-to-Vehicle (V2V) communication as compared to D2D communications, especially in densely populated urban environments. The resource management schemes assuming perfect channel estimation cannot produce optimal performance [119]. The IEEE 802.11p standard which is based on Dedicated Short-Range Communication (DSRC) technology has been introduced to support Intelligent Transportation System (ITS) applications in VANETs. However, IEEE 802.11p suffers from intermittent connectivity due to insufficient transmission range and lacks widespread deployment. In contrast LTE provides a good solution to the problem of intermittent connectivity due to the high mobility in VANETs [287]. However, in the case of high vehicle density, the eNB will be overwhelmed by the large number of safety critical beacon messages directed towards it. In such scenarios it may be more feasible for vehicles to directly communicate with each other rather than through the eNB. In this regard, the schemes developed for D2D communication have emerged as strong contender for provisioning of reliable and secure V2V communication. As a partial solution, the authors in [288] provide power control and resource allocation scheme for V2V communication while schemes for optimization of data rates and minimization of latency were proposed in [289]. D2D links can also be utilized to develop communication links between futuristic autonomous vehicles as a mean of failure recovery mechanism [290]. Specifically, this setup can act as adhoc network for provisioning of services where the backhaul cellular media is not available. However, more efforts are required in the domain of standardization to materialize this useful concept. Undoubtedly, D2D offers an opportunity to utilize the radio interface to directly communicate between devices in a vehicular network with low end-to-end delay and high reliability [291]. This is particularly useful because VANETs depend on real-time information and D2D communication can provide significant benefits without negatively affecting the cellular network [292].

F. IoT communication

Rapid developments in IoT technologies have opened up many opportunities with respect to energy management and green communication [293]. IoT includes different type of communication architectures such as D2D, human to device, and device to human. In this context, communication between devices can be either intra-domain or inter-domain for heterogeneous networks [294]. The D2D networks have close resemblance to future IoT networks. Particularly, D2D networks are considered to be an integral part of wider concept of IoT implementation. Furthermore, D2D communication in IoT can significantly improve the robustness of applications and connectivity among IoT devices [295]. It is, therefore, necessary that the deployment of D2D networks be made compatible with the requirements/ protocols of IoT [296]. However, owing to lack of standardization, the wide spread implementation of IoT and subsequently D2D integration with IoT is still a far cry [297], [298]. In a multi-node scenario, the communication between devices can be single hop or multiple hops. For single-hop communication, network infrastructure such as BS or access point is used. In case of multi-hop communication, inter-device communication is used to enable end-to-end communication between the transmitting device and the receiving device [299]. Since IoT applications require global access to the wireless channel, efficient wireless access mechanism need to be developed. Moreover, IoT applications require efficient and distributed scheduling techniques at devices to provide flexible transmission of data. By addressing these aforementioned issues, D2D communication can be leveraged as a vital technology for future IoT communications.

X. Conclusion

D2D communication is expected to provide many benefits over conventional cellular networks. D2D communication shows great promise as one of the most promising and favorable paradigms for future networks. In this survey, we have provided a detailed review of existing D2D technologies along with its various characteristics such as device discovery, mode selection, resource management, mobility management and security. This paper has also demonstrated the advantages of D2D in forthcoming 5G technologies. Although D2D communication is a relatively new idea, but significant amount of research in D2D has recently opened up a range of related research issues that should be investigated in the future. This survey will help future readers better understand the D2D concepts and technologies and enable them to have a good grasp of future research opportunities that have been identified in the field of D2D communication.

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