THESIS TITLE

SIMULATION AND STUDY OF 5G TECHNOLOGIES AND FEASIBILITY OF DEVICE-TO-DEVICE COMMUNICATION IN LTE

by

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SIMULATION AND STUDY OF 5G TECHNOLOGIES AND FEASIBILITY OF DEVICE-TO-DEVICE COMMUNICATION IN LTE

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Acknowledgements

We would like to thank Almighty Allah, our parents and the teachers who have guided us till this point in life.

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Abstract

For us to meet the demands of fifth generation technologies, device-to-device (D2D) communication is foreseen to be an important part of fifth generation networks. Device-to-device communication brings significant improvement in user's throughput, battery life, communication delay, and resource usage. Device-to-device links share the same resource with the cellular links that results in interference between cellular users and D2D user equipment’s. This interference can be managed by suitable resource allocation algorithms. The selection of D2D or cellular communication mode is also a hot research issue. Many research works are available in literature on the aforementioned issues regarding D2D communication, but there is no survey available in the literature. To facilitate the researchers, we present a detailed and systematic survey on resource allocation, interference management, and mode selection in D2D communication in this paper. Initially, the taxonomy-based overview of D2D communication is provided, and the classification of the works is outlined. Then, the works regarding mode selection are reviewed in detail. Furthermore, interference management schemes to handle the interference caused by the underlying nature are also surveyed. Then, the available literature on resource allocation schemes in D2D perspective are presented. Finally, some open research problems are identified that deserve further research.

Chapter 1

Introduction

5G networks are the next generation of mobile internet connectivity, offering faster speeds and more reliable connections on smartphones and other devices than ever before.

Combining cutting-edge network technology and the very latest research, 5G should offer connections that are multitudes faster than current connections, with average download speeds of around 1GBps expected to soon be the norm.

The networks will help power a huge rise in Internet of Things technology, providing the infrastructure needed to carry huge amounts of data, allowing for a smarter and more connected world.

With development well underway, 5G networks are expected to launch across the world by 2020, working alongside existing 3G and 4G technology to provide speedier connections that stay online no matter where you are.

The concept of Device-to-Device (D2D) transmissions underlaying LTE-Advanced network involves signals transmitted from one cellular user equipment (UE) being received at another cellular user equipment without passing through cellular infrastructural nodes (e.g. eNB, HeNB, etc.). This thesis is concerned with the numerical method for estimation of feasibility of device-to-device communication in LTE .Direct D2D technologies have already been developed in several wireless standards, aiming to meet the need for efficient local data transmission required by variant services in personal, public and industrial areas. Examples are Bluetooth, ZigBee in wireless personal area networks (WPANs), and Wi-Fi Direct in wireless local area networks (WLANs). The need of frequent communication between nearby devices becomes critical now with the capability of smart devices for content share, game play, social discovery, etc. whereas the conventional UL/DL transmission mode in cellular network fails to address this demand efficiently. Proximity-based social/commercial services and applications show great prospects. In order for operators to address this huge market and to offer their subscribers ubiquitous connections, operator-controlled direct D2D transmissions are studied in the context of next-generation wireless communication systems, such as LTE-Advanced and WiMAX. The D2D technologies aim to support the local discovery, identification and to enhance the network capacity and coverage.

Pushed by Qualcomm, D2D is proposed as a Rel.12 3GPP feature. D2D Study Item got approved in 3GPP SA1 (Services working group) in 2011, called ProSe (Proximity- based Services), and was complete in May 2013, at which time a corresponding Study Item began in RAN1 (Radio Access Network Working Group) to define the necessary support in the LTE radio interface. In the feasibilities study for ProSe [TR2,], use cases and potential requirements are identified for discovery and communications between UEs that are in proximity, including network operator control, authentication, authorization, accounting and regulatory aspects. A part from general commercial/social use, it also addresses Public Safety communities that are jointly committed to LTE. The work in D2D physical and MAC layer specification is ongoing.

Discussion includes evaluation requirements, D2D channel model, resource use, ProSe discovery and ProSe communication, etc.

The final chapter concludes the thesis and future research directions are proposed.

Research is in progress on fifth generation (5G) technologies with main focus on spectral efficiency, network throughput, and communication delay.

Chapter 2

Introduction to D2D Technologies

4.1 2.1 Overview

The main purpose of this chapter is to survey the background of D2D technologies, The prospect of integrating D2D in cellular network, and possible requirements. As is well-known, out-band (operating in unlicensed band) D2D technologies have been developed decades ago. Nowadays there exist several different protocols and standards, such as Bluetooth, ZigBee, NFC, Wi-Fi Direct, etc. In section 2.2, existing out-band D2D technologies will be presented and compared. The coexistence of D2D and cellular transmission has been brought up long time ago in some pioneer literature studies.

Basically two forms of architecture are mentioned: multi-hop D2D relay and one-hop direct D2D between endpoints. The focus of literature studies are presented in section 2.3. Integrating D2D in LTE-Advanced network is a recent research topic that attracts many industrial interests and is being rapidly developed in the 3GPP LTE standardization. In section 2.4, firstly interests and challenges of providing D2D capabilities in LTE network are analyzed. Then the launch of LTE D2D as study items in 3GPP LTE standardization is introduced. Use cases and scenario that support D2D usages at service level are drafted in 3GPP and several examples are illustrated in this section.

4.2 2.2 Existing out-band D2D technologies

Face to the great prospect of applications with wireless D2D transmission in personal, public and industrial areas, many competitive out-band D2D technologies have already been developed. A brief comparison of several popular D2D standards are listed in the table below.

6 *CHAPTER 2: INTRODUCTION TO D2D TECHNOLOGIES*

Standard	Bluetooth	ZigBee	NFC	Wi-Fi Direct
Range (nominal)	10m(~100m for Class 3 radio)	~100m indoor LoS, ~ 1.6km outdoor LoS, extended range due to mesh network	<0.2m	~200m
Discovery energy consumption	Low in v4.0 Low Energy, High otherwise	Low	Low	Fair with power management
Set-up time	<0.006s with BLE, <6s otherwise	<0.02s	<0.1s	<15s
Reliability	Good in v4.0 due to dedicated advertising channels	Good due to Mesh topology	Good due to point-to-point topology	Sometimes poor due to asynchronous channel scan
Security	vulnerable - discovery is unencrypted and no trusted authentication of device identification	vulnerable (similar as Bluetooth)	secure due to its extreme short range point-to-point topology, encryption supported	vulnerable (similar as Bluetooth)
Maximum Rate	24 Mbps (v3.0 +HS)	250Kbps	106/212/424 Kbps	250Mbps
Strength	wide range of service support due to co-existence of Bluetooth Classic/High Speed/Low Energy protocols	Low energy low cost, mesh networking capability, suitable for sensor network and infrared replacement	Extremely simple setup, security, suitable for contactless payment	High speed content sharing, game playing, etc. Pervasive use of Wi-Fi radio

Bluetooth

Bluetooth is probably the most well-known technology which is created by Ericsson in 1994 and was originally developed as RS-232 data cable replacement for short-range communications, such as phones, headsets, keyboards and mice. It was standardized as IEEE 802.15.1, for wireless personal area network (WPAN) with fixed, portable and moving devices within or entering personal operating space. Bluetooth technology now goes way beyond that. High-speed data transfer (up to 24 Mbit/s) is enabled by the use of a Generic Alternate MAC/PHY (AMP) in Bluetooth Core Specification Version

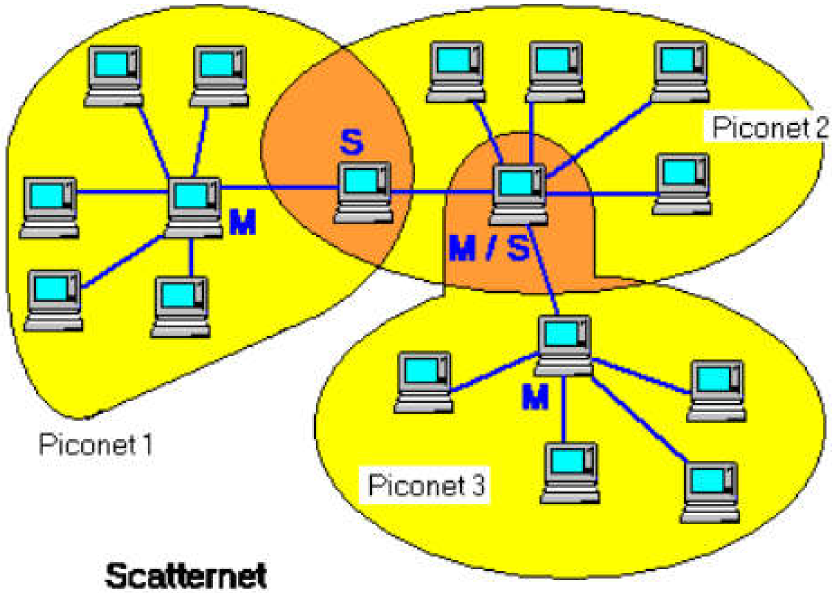

Figure 2.1 — Bluetooth piconet and scatternet structure

Bluetooth Core Specification provides both link layer and application layer definitions, which includes device and service discovery as a fundamental part of the protocol. A Bluetooth device can search for other Bluetooth devices either by scanning the local area for Bluetooth enabled devices or by querying a list of bonded (paired) devices. If a device is discoverable, it will respond to the discovery request by sharing some information, such as the device name, class, and its unique MAC address. Using this information, the device performing discovery can then choose to initiate a connection to the discovered device.

Bluetooth technology operates in the unlicensed ISM band at 2.4 to 2.485 GHz, using a spread spectrum, frequency hopping, full-duplex signal. The applied adaptive frequency hopping (AFH) improves resistance to interference by avoiding using crowded frequencies in the hopping sequence. The range of Bluetooth technology is application specific and may vary according to class of radio used in an implementation (up to 100m).

ZigBee

ZigBee is best suited for periodic or intermittent data or a single signal transmission from a sensor or input device, intended for embedded applications requiring low data rate, long battery life and secure networking. Typical applications include: smart lighting, remote control, safety and security, electric meters, medical data collection, embedded sensing, etc. It is the leading standard for products in the area of home/building automation, smart energy, health care, etc.

ZigBee is based on IEEE 802.15.4 standard, and complete the standard by adding Four main components: network layer, application layer, ZigBee device objects (ZDOs) and manufacturer-defined application objects. Its network layer natively supports both star and tree topology, and generic mesh networks. Radios in a mesh network can talk to many other radios (devices) in the network, not just one. The result is that each data packet communicated across a wireless mesh network can have multiple possible paths to its destination. This flexibility provides high reliability and more extensive range. One of the prominent feature of ZigBee is its low-power and its low latency. ZigBee nodes can sleep most of the time, and can go from sleep to active mode in 30ms or less. For this reason, ZigBee is favored in monitor and control sensor systems, especially with battery-operated devices. But the low rate of ZigBee makes it less suitable for social use D2D communication between mobile phones. Bluetooth and wi-Fi direct, for example, can adapt to a much large range of mobile applications.

NFC

NFC is a set of standards for smartphones and similar devices to establish wireless communication with each other by bringing them into close proximity, usually no more than 10 cm. NFC uses magnetic induction between two loop antennas located within each other's near field, effectively forming an air-core transformer. Typical NFC applications include contactless payment, digital name card exchange, information exchange, access control, fast pairing and connection establishment for other D2D technologies such as Wi-Fi Direct. NFC alone does not ensure secure communications. Higher-layer cryptographic protocols such as SSL can be used to establish a secure channel. However, due to its extreme short range and point to point mode operation, NFC is naturally more secure than other existing D2D technologies. According to ABI research [ABI, b], NFC handsets shipped in 2012 is 102 million, and are anticipated to increase by 481% from 2012 to 2015. Although NFC becomes a popular standard for smartphone D2D connection, due to its extreme short range, similar as ZigBee, it is not suitable for most of the D2D mobile applications.

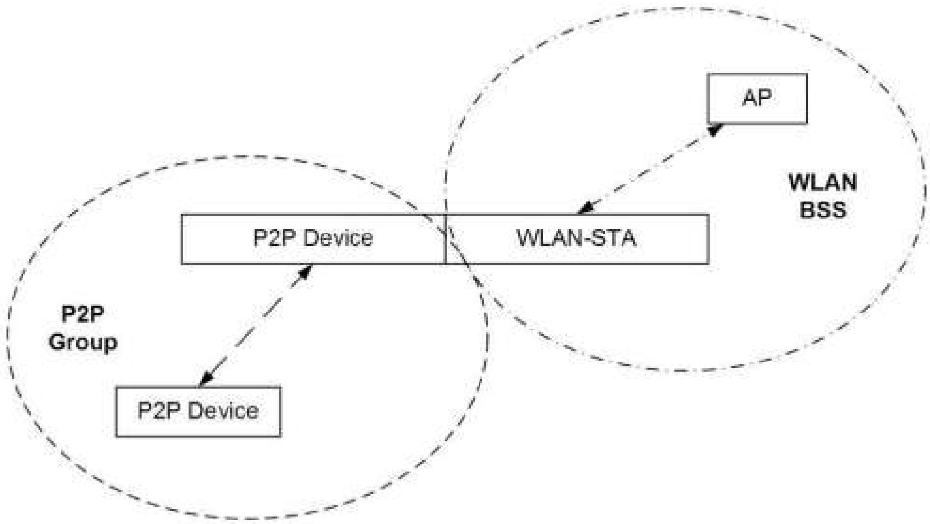

Figure 2.2 — Wi-Fi Direct network structure

Wi-Fi Direct

Wi-Fi (IEEE 802.11) standard is the dominant way in WLAN communication, Notably for Internet access. Although ad-hoc mode of operation is already enabled in Wi-Fi standard, known as independent basic service set (IBSS), the poor interoperability and standardization of setting up IBSS network, as well as the lack of security and efficient energy use impede commercialization of direct device to device connectivity functions. With the increasing demand of easy content sharing, display, synchronization between proximate devices, the Wi-Fi Alliance released Wi-Fi CERTIFIED Wi-Fi Direct specifications which define a new way for Wi-Fi devices to connect to each other directly at typical Wi-Fi rates (up to 250Mbps) and range (up to 200 meters). Wi-Fi Direct is initially called Wi-Fi Peer-Peer(P2P). As P2P, instead of D2D, is the term used in Wi-Fi Direct specification, we conform to this terminology in the following part of introduction to Wi-Fi Direct technology

2.3 The coexistence of D2D and cellular transmission In literature studies

The coexistence of D2D and cellular transmission has been mentioned in literature studies for about ten years. D2D in cellular network can exist in two different forms (Figure 2.3). In one form, the pair of D2D users are endpoints (source and sink) of a communication session. In another form, at least one D2D user of the pair act as a relay to form a multi-hop connection between the base station and the endpoint user. Many have proposed to leverage D2D link to increase the system capacity or cellular network coverage, or to balance traffic load between different base stations.

Multi-hop D2D relay

Authors in [Luo et al., 2003], [Bhatia et al., 2006], [Zhao and Todd, 2006], [Papadogiannis et al., 2009], [Law et al., 2010], [Li et al., 2008], [Raghothaman et al., 2011] have proposed multi-hop D2D relay for cellular transmission for the purpose of cellular capacity enhancement.

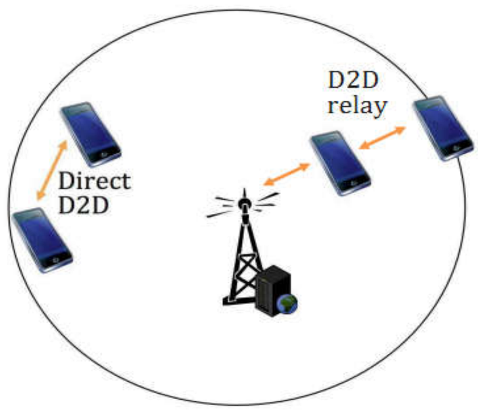

Figure 2.3 — Two forms of D2D: Direct D2D and D2D relay

2.4 LTE D2D

In 2.4.1 potential usages that might base on cellular user proximity are firstly listed. Principle functions that need to be provided by LTE D2D in order to support these proximity-based usages are analyzed. Implementation challenges to both operators and device manufacturers are discussed. Then in 2.4.2 The progress of LTE D2D in 3GPP standardization is presented. The design guideline provided by 3GPP covering different D2D use cases and scenarios is summarized.

2.4.1 Interests and challenges of D2D-enabled LTE network

With the popularity of smart devices, and the potential huge market of proximity-based services and applications, there is an urgent need to integrate D2D mode transmissions in the next-generation cellular network to enable efficient discovery and communication between proximate users, and to eventually provide ubiquitous connections and a rich range of services to mobile users.

The potential usages that might base on mobile user proximity can be categorized as follows:

• Commercial/social use: local discovery and interaction with connected devices,

• Interactive local guidance: interactive guidance for customers, tourists, commuters, and users of commercial and public services, using smart beacons, sensors and content servers embedded within objects in the environment. For example, advertisements from nearby stores/restaurants, presentation of art pieces in museums, flight/subway information, vacancy in parking lots, etc. From service receivers' perspective, a user might preset personalized interests in order to be alerted by services from nearby area, such as notification of a sale, ticketing, restaurant recommendations, traffic jam warning, events organization etc.

• Connection to M2M/V2V: D2D-enabled devices can serve as a controller of Machine-to-Machine (M2M) and Vehicle-to-Vehicle (V2V) networks. They can further provide cellular network connection to M2M/V2V, serving as gateways between M2M/V2V and cellular networks.

• Social discovery: discovery of nearby persons linked by social network (e.g. Facebook, LinkedIn), with mutual interests (e.g. professional, personal), or attending a same event (e.g. party, concert, match), etc.

• Entertainments: usually involves a large variety of personal devices, such as mobile smart devices, game consoles, cameras, TVs, screens, storage memories. Typically for content sharing, local gaming, and local multicasting.

b. Enhanced networking: D2D technology can be used to enhance the connectivity of devices to an infrastructure network - typically for access to the Internet or operator services. Usages can be divided into two sub-categories:

1) Traffic offload: from cellular infrastructure network to D2D link when the two endpoint devices are in proximity. The D2D communication can be either in operator's licensed band or in WiFi band if both devices are equipped with WLAN antenna. The traffic can be data or voice/video call. The D2D offloading might alleviate network congestion, enforce the link quality and reduce the power use between two proximate devices.

2) Coverage extension: A device obtains access to an infrastructure network (Inter- net or cellular network) through the assistance of one or more devices that act as relays or access gateways This can provide network coverage to devices that

Figure 2.4 — D2D usage example: Interactive local guidance

Figure 2.5 — D2D usage example: Connection to M2M/V2V

Figure 2.6 — D2D usage example: Social discovery

Figure 2.7 — D2D usage example: Entertainments

We identify three principle functions that allow LTE D2D to address the above-Mentioned potential services.

1) D2D discovery:

D2D discovery is a process that allows devices in physical proximity to discover each other using LTE radio technology. In the general case, this discovery is performed within LTE network coverage and under the control of the operator (e.g. with radio resources assigned by the operator, and authorized by the operator). But it is also desired that discovery can be performed with partial (in which one UE of the D2D pair is under the network coverage and another one is not) or no network coverage.

LTE D2D might support much larger discovery range comparing to other wireless D2D technologies such as Bluetooth and Wi-Fi Direct. The use of licensed spectrum may allow for more reliable discovery than other D2D technologies operating in unlicensed ISM band. The SIM card can be used for authentication and holding discovery permissions, especially the 3rd parties/merchants permissions to discover users. The D2D discovery developed for LTE network could even potentially replace the Wi-Fi Direct for establishing a WLAN Wi-Fi connection between two proximate Wi-Fi capable UEs. The operator could manage the proximity information (e.g. distance information, the network location area code, radio coverage status user discovery capabilities, and preference, etc.), offering to its users/partners the opportunity to use/build advanced proximity-based services.

2) D2D data communication:

D2D data communication allows data path happening directly between proximate D2D UEs instead of passing through eNBs. The operator could offload its network from proximity-based service traffic by switching data traffic from an infrastructure path to a direct D2D path with service continuity. In contrasts to the pending issues with the current existing D2D technologies on the data/traffic protection, secured D2D communications can be enabled by operator's management, which will boost the usages. The operator's control also enables a QoS framework which provides differential treatment based on D2D services, data traffic flows, and subscribers, etc. In case that network coverage is not available, similar to the direct D2D discover function, the direct D2D communication is expected to function autonomously with pre-configure parameters.

3) D2D relay:

D2D relay allows multi-hop paths to be formed between an infrastructure network (Internet or cellular network) and an endpoint UE. D2D relay can be used to enhance data throughput of cell-edge users, but can be also used to share connection to an endpoint UE lack of direct access to the infrastructure networks. D2D relay can extend network coverage for both indoor and outdoor UEs, with low cost, which complements the current coverage extension solutions in LTE using heterogeneous network (HetNet) such as Pico cell and Femto cell.

The integration of the D2D capabilities in LTE network poses challenges to both operators and device manufacturers. The operator is face to:

• Technical complexity of service management (e.g. user preference, privacy issues, frequency of discovery inquiries, QoS monitoring of D2D link, charging policy, etc.)

• Sensitive privacy issues in tracking user location and activities, collecting user preference and habitude, or selling user information to other actors imply privacy stakes.

• Interoperation of different operators (e.g. share spectrum, user location informa tion, user preference) to enable users subscribing to different operators to discover and communicate to each other.

On device manufacturers' side, development of D2D compatible devices with the

New discovery and direct communication capability also involves higher cost and complexity. Design of sensing ability, gateway function, efficient battery consumption, advanced security, etc. can be very complicated.

2.4.2 D2D in 3GPP LTE standardization

Initially integrating D2D in LTE-Advanced network was strongly pushed by Qualcomm, who developed previously a proprietary technology called FlashLinq into its radios that allows cellular devices to automatically and continuously discover thousands of other FlashLinq enabled devices within 1 kilometer and communicate, peer-to-peer, at broadband speeds without the need for intermediary infrastructure. Unlike Wi-Fi Direct's peer-to-peer technology, Qualcomm's FlashLinq can share connectivity to a cellular network. In FlashLinq discovery, public/private expressions qualifying basic information about the device or user are mapped to tiny 128-bit packages of data to be broadcasted. FlashLinq is a synchronous TDD OFDMA technology operating on dedicated licensed spectrum and is featured by its high discovery range (up to a kilo- meter), discovery capacity (thousands of nearby devices) and distributed interference management.

2.5 Conclusion

In this chapter, the background of D2D technologies is introduced. Four popular out- band wireless D2D technologies: Bluetooth, ZigBee, NFC, Wi-Fi Direct have been presented. Their usage cases, market prospects, network structure, PHY/MAC characteristics (rate, power, range, etc.) are compared. The topic of integrating D2D into cellular network has appeared in literature study decades ago but has not received enough attention. The hybrid D2D and cellular network architecture in literature study can be roughly divided into two categories: Multi-hop D2D relay and direct D2D between endpoints. D2D relay is mainly proposed to increase the cellular network capacity or coverage, or to balance traffic load between different base stations. Although in some works, direct D2D communication between endpoint UEs does have been proposed to replace inefficient UL/DL mode transmission between proximate UEs, as the usages were quite limited before the emergence of 4G network and smartphone, the literature studies were not abundant.

As the need of proximity-based services increases rapidly with the popularity of smart mobile devices, integrating D2D into the LTE-Advanced network appears as a promising solution and attracts great interests. The potential usages are analyzed and are categorized into social/commercial use and networking enhancement. To address these potential usages, three principle functions: direct D2D discovery, direct D2D communication and D2D relay, are identified. Challenges to operators and device manufacturers are also anticipated.

With the increasing interests shown by industrial actors in integrating D2D into LTE network, study items of LTE D2D are taking off in different 3GPP technical specification groups, from service level to physical and MAC layer. Apart from social/commercial use, 3GPP decided that LTE D2D should also address public safety communities. The progress of LTE D2D in 3GPP standardization is presented. The LTE D2D system design guideline is completed in 2013 by 3GPP, which analyses conditions, service flows and potential requirements that are necessary for supporting variant proximity-based usages. Principle use cases and scenarios covered by this guideline for general commercial/social use and network offloading are summarized.

Chapter 3

Coordinated Scheduling of in-band D2D data communication

4.1 Introduction:

The purpose of this chapter is to propose a method for resource allocation in uplink for D2D users in a complex cell. As mentioned in the previous chapter, the key problem in D2D data communications interference management. Two kinds of interference are introduced by in-band D2D: inter-D2D interference, and interference between D2D and cellular transmission. Particularly, the interference from D2D to cellular transmission should be strictly controlled to minimize the impact of D2D transmission on existing LTE cellular transmissions.

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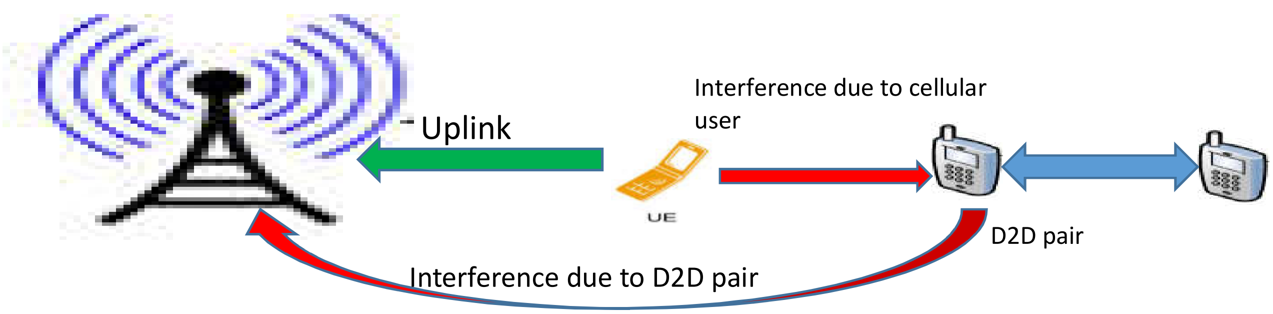


Figure : interference in a cell if eNB ,cellular user and D2D pair are in the same line

In section 4.2, literature studies on in-bandD2D resource coordinationis firstly reviewed, followed by an in-depth discussion on important scheduling considerations. Section 4.3 describes assumed scenario in our study and objectives. A complete method is proposed in section 4.4.Section 4.5 concludes the contribution of this chapter.

4.2 Scheduling issues in coordinated in-band D2D scheduling :

In this section, literature studies on in-band D2D resource coordination is reviewed. Their focuses and deficiencies are analyzed. Important scheduling considerations are discussed.

4.2.1 Literature studies on in-band D2D resource coordination:

Although efficient spectrum sharing between D2D and cellular UEs is quite a new topic, paradigms of spectrum sharing in cognitive radio networks have been widely studied. In a network supporting cognitive radio, unlicensed users (secondary users)sense the spectrum of wireless service providers (WSPs) and opportunistically use the spectrum that is normally assigned to licensed users (primary users) but not being used at a particular time and geographic location. The admission of a secondary user to the spectral resources is often called admission control. Both centralized and distributed admission control methods have been investigated in literature studies. Many have used a SINR-based criterion and have assumed the constraints that the interference caused by secondary users on the primary network has to be kept below a maximum allowable limit, [Xing et al., 2007], [Islam et al., 2007], [Le and Hossain, 2008],[Kim et al., 2008], [Tadrous et al., 2010], [Tadrous et al., 2011]for example.Inspired by the admission control works (notable [Tadrous et al., 2011]) in cognitive radio networks, the authors of [Liu et al., 2012]propose a coordinated set-based admission control (SAC) algorithm for D2D links. The optimization criterion of centralized admission control algorithm SAC is to maximize the number of admitted D2D links, with QoS and power constraints. The capacity of the admitted set is further maximized by distributed power optimization (DPO). Due to the fact that capacity optimization is not directly treated in a centralized scheduler. A simplified admission control mechanism is taken by articles[Doppler etal., 2009],[Janis et al., 2009], [Yu et al., 2009]by assuming that a cellular resource block is admitted by only one D2D link in the cell. D2D resource and power are under full control of eNB in order to avoid intra-cell interference. Yet in another article [Xu et al., 2010], resources of each D2D link are decided in a distributedway,usingcontentionbasedCSMA/CAprotocolinD2DMAClayer.Acertain level of coordination is achieved as eNB provides additional position information to D2D users in order that D2D links avoid reusing the same spectrum as UL UEs which locate closely to D2D receivers, in which way interference from UL UE to D2D receivers is avoided.

Some studies concentrate on D2D transmission in UL channels [Liu et al., 2012],[Xu et al., 2010], [Yu et al., 2009]. In [Liu et al., 2012], interference is controlled through a centralized set-based admission control algorithm. Under the transmit power limit and QoS constraints, a set of D2D UEs that can sharing the same resources withUL UE is calculated iteratively by the algorithm. eNB should gather channel conditions,QoS level and other related information from D2Ds. However in a practical system,this exchange of information is too much to be realistic. In [Xu et al., 2010], the author assumes that LTE fractional power control can be used in D2D so that interference from D2D to eNB can be avoided efficiently. On the contrary, interference from UL UE to D2D is addressed. Each D2D pair autonomously determines the resource allocation and interference is avoided by using position information's tracked and broadcasted by eNB. In [Yu et al., 2009], interference is mitigated through power optimization in reuse mode and mode switching if reuse mode becomes inefficient.

In [Doppler et al., 2009], [Janis et al., 2009], [Chen et al., 2012], D2D reusing both DL and UL channels are both studied. In [Doppler et al., 2009], interference fromD2D to cellular UEs are controlled through power limitation and mode switching. In[Janis et al., 2009], interference from D2D to eNB in UL channel and from DL UE toD2D in DL channel is limited by power control. User diversity in macro cell is exploited to further mitigate interference.

Some articles addressing centralized D2D scheduling also propose that eNBs, as central coordinators, could choose the most efficient transmission mode for each potentialD2D pair. That is to say, after detecting data flows between a pair of UE transmitter and receiver in proximity, the eNB decide whether this pair of UEs is scheduled inD2D mode using D2D resource allocation strategy, or in conventional UL plus DL mode using UL and DL resources respectively. Some articles propose that D2D mode selection is performed before D2D link establishment. In [J. E. Korneluk and Rodrigues,],[L. Sun and Jia,], a D2D distance dependent criterion is suggested to switch betweenD2D mode and UL/DL mode. Authors of [Xu and Wang, 2012] distinguish twos scenarios: D2D UEs and cellular UEs share the same RBs and use different RBs. For the first scenario, a minimum interference sustained by eNB is considered to make the decision on transmission mode. Whereas a system throughput based mode selection criterion is proposed for the second scenario.[Doppler et al., 2009], [Yu et al., 2009], [Doppler et al., 2010]proposethatD2Dmode selection is performed during resource allocation phase: Three modes are compared:

• Non orthogonal resource sharing mode: RBs are shared between a D2D link and a cellular link.

• Orthogonal resource division mode: D2D links use resources that are unoccupied by cellular UEs.

• Cellular mode: D2D traffic is relayed via eNB as in conventional UL/DL mode. Scenario of containsonlyoneD2Dlinkandonecellular link. For each RB, the eNB selects one out of the three modes to maximize the sum rate. In [Doppler et al., 2009], the total spectrum is split into several sub bands.

Both cellular UE and D2D UE are assigned to a single sub band at a time. eNB assigns the mode for a UE peer offering the highest throughput taking into account the amount of resources each mode will get.

4.3 Assumed scenario in our study and objectives :

We have calculated the SINR and Throughput and corresponding probability of D2D communication in a 3 sector cell .We have calculated for one sector in a cell but considering different position of cellular user in the cell .D2D communication usually occur in cell edge area .So we varied or D2D position in the edge area and cellular user position in all over the cell.

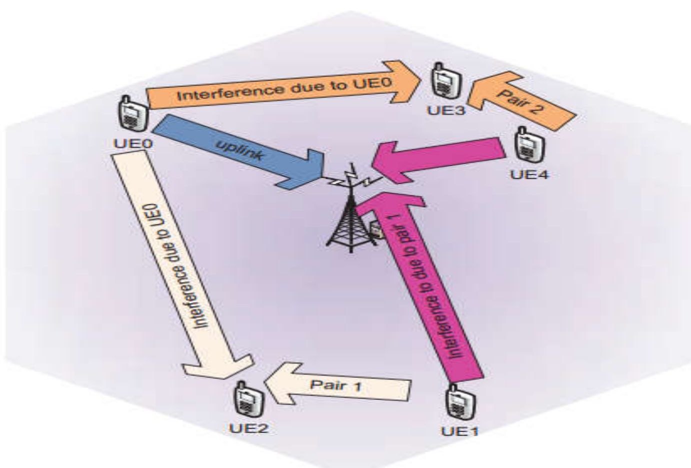
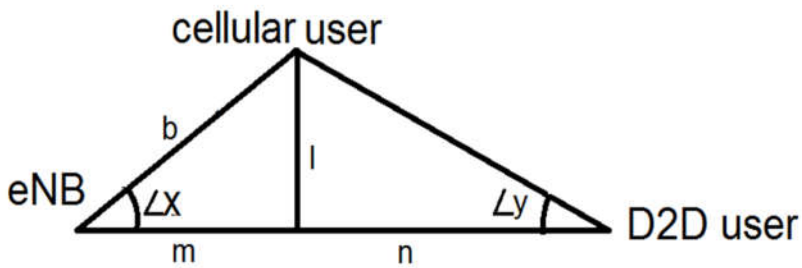


Figure: interference in a cell where cellular users and D2D pair are in random position

4.3.1. calculation method :

We assumed in a sector of a cell cellular user and d2d pair are positioned like below :



Here we can calculate the distances using these equations:

b= m/ cos(x);

l=b*sin(x);

y=inv.tan(l/n);

a= n/(cosy);

Here, m+n =190 meter (for the simulation we used cell radius 190 m)

Now we can see that if we change the position of cellular user keeping D2D user position fixed then we can get all the distances and angular position of cellular user by changing randomly any value of angle ‘x’ and distance ‘b’ . by changing these value we can get various cellular user to D2D user distances and calculate SINR in between them .

For calculation purpose we can use these equations:

- **Total path loss** :

$PL_{dB,B,u}(.)= 40(1-4*(10^{\wedge}-3)h_b)*\log_{10}(d/1000)-18\log_{10}(h_b)-21\log_{10}(f_c)+80$

Here fc is the carrier frequency in MHz

h_b is the base station antenna height (in meter)

- **Linear gain between the eNodeB and a user u is:**

$G_{Bu}=10^{\wedge}-(PL_{dB,B,u})/10$

- **For D2D communication, the gain between two UEs u and v is :**

$G_{uv} = K_{uv}(d_{uv})^{-\alpha}$

Here,

Constant path loss exponent α,

Normalised constant K_{uv};

d_{uv}=distance between transmitter u and receiver v.

- **SINR of the D2d receiver d during uplink phase is:**

$\gamma_d^{UL} = (P_d * G_{dd})/(N_O + I + P_C * G_{Cd})$

- **SINR of eNodeB is :**

$\gamma_{eNB}^{C} = (P_C * G_{CB})/(N_O + I + P_d * G_{dB})$

- **Power :**

$P = P_o + \alpha * PL + 10\log 10 M + \triangle TF + f_{TPC}$

Here,

P=Physical uplink shared channel power;

Po =Basic parameter for open-loop set points in power control ;

α=parameter used to reduce the effect of PL(varies between 0 to 1);

PL=Path Loss;

M=The number of resource blocks allocated on the sub frame ;

$\triangle$ = Depends on Modulation and Coding Scheme (MCS)

fTPC =Closed loop fine power adjustment

SIMULATION ASSUMPTIONS:

3 Sector cells (uniform distribution of cellular user)	
Cell Radius	200m
Constant path loss exponent(a)	3
Carrier frequency(fc)	2000 MHz
Base station antenna height(hb)	25m
Constant for target bit error rate(α)	-1.5/ln(5*10^-6)
Receiver's thermal noise density(N0)	3.98107*10^-9
Intercell interference(I)	10^-8
Normalised constant K_{uv}	1

4.4 Conclusion:

In this chapter we discussed about our proposed calculation method. One thing need to mention that our calculation had been done for uplink case .In the next chapter we will show our simulation result.

Chapter 4

Simulation

With our 5G link level simulator we want to enable performance evaluation of future physical layer access schemes. For this we aim to maintain high flexibility of simulation scenarios and parameter settings. We not only support various waveforms and channel codes in general, but also allow these parameters to be different from cell to cell. This facilitates investigation of co-existence and interference of 4G and possible 5G physical layer schemes. Again, in our link level simulator there exists no underlying geometry. A cell should be thought of a collection of nodes (one base station and several users) rather than a physical area.

To further explain simulations with different waveforms in different cells, consider the exemplary cellular network topology as shown in Fig. 1. How such a topology is set up, is described in more detail in Section 6.1. Here we assume two cells, each with one base station. Users one and two are attached to base station one and therefore belong to cell one while user three is attached to base station two and belongs to cell two. The wireless channels $h_{i,j}$ are indicated with double arrows where the first subscript i indicates the base station and the second subscript j indicates the user. Desired or primary channels are shown in solid black while interference or secondary channels are shown in dashed red.

While all nodes belonging to a cell must have the same waveform, channel code, total number of subcarriers[1] and number of symbols per frame (frame duration), these settings might be different for nodes of another cell. To enable discrete simulation of several nodes and many wireless channels, the sampling rate is a common parameter for all cells. Further, the frame duration, that is the number of samples per frame, has to be equal for all cells, independent of the employed waveform and modulation such that interference and desired signals can be superimposed.

For our example, assume that OFDM is used in both cells, but cell one employs a subcarrier spacing of 15kHz while cells two employs a subcarrier spacing of 30kHz. In order to obtain the same total bandwidth, the number of subcarriers in the first cell must be double the one in the second cell. Let's assume 72 subcarriers for cell one and 36 subcarrier for cell 2. Similarly, the number of symbols per frame in the second cell must be double the number of symbols in the first cell. As we choose the first cell to be LTE-A compliant, there are 15 total symbols (including the guard symbol for Cyclic Prefix (CP)) per frame in cell one and 30 symbols per frame in cell two. While there is a 15th OFDM symbol in an LTE-A frame spent on CP in cell one, we follow this idea and use two symbols of a frame for CP in cell two to obtain the same number of samples per frame. Still, the sampling rate has to be the same for all nodes and is a common parameter. The parameters described above are entered in a scenario file the following way

[1] Of course, the scheduled bandwidth may be different from user to user.

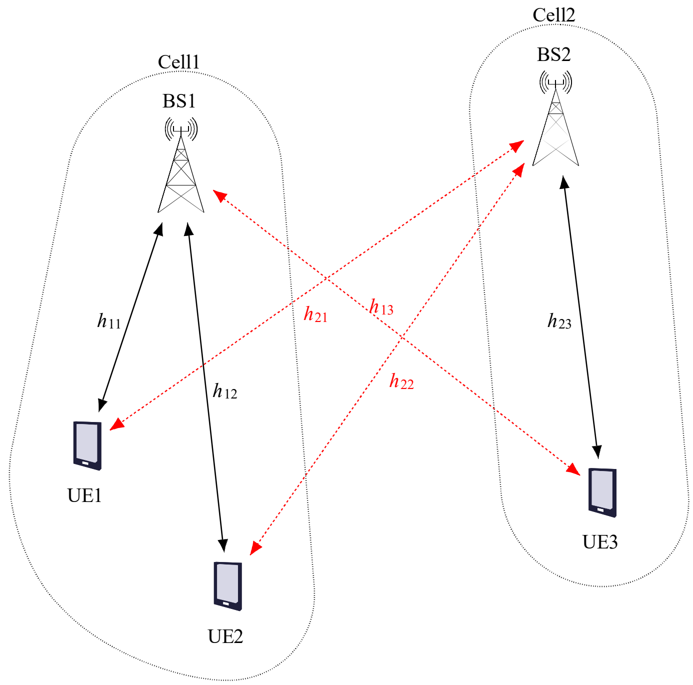


Fig: An example of network systems

```
scStr.modulation.numerOfSubcarriers = [72, 36];     % per BS
scStr.modulation.subcarrierSpacing  = [15e3, 30e3]; % per BS
scStr.modulation.nSymbolsTotal      = [15, 30];     % per BS
scStr.modulation.nGuardSymbols      = [1, 2];       % per BS
scStr.modulation.samplingRate       = 15e3*72*2;
```

Where the array index corresponds to the base station index, except for the sampling rate, which has to be the same for all nodes.

As the number of subcarriers and users are chosen individually for each cell, also the schedule has to be adapted accordingly. The schedule is fixed over time, that is, it stays constant for all frames, and for all symbols within a frame. For user assignment, blocks of subcarriers are designated to users of a cell. This schedule is then considered for up- and downlink. The number of users and total subcarriers has to correspond to the topology and modulation settings. The schedule has to be entered in a scenario file the following form

```
scStr.schedule.fixedSchedule{1} = [ 'UE1:36,UE2:36' ];           % BS1
scStr.schedule.fixedSchedule{2} = [ 'none:18,UE3:18' ]; % BS2
```

There is a schedule for each base station or cell. In our example there are two users attached to base station one, namely user one and user two. The total number of subcarriers is 72 and we chose to share them equally on the two users. Since the subcarrier spacing is doubled in cell two, the total number of subcarriers is 36 here. The first half of this bandwidth is left unassigned by the keyword *none* while the second half is assigned to user three. In this way, user three is scheduled on the exact same frequency resources as user two.

Depending on the desired simulation scenario, the interference channel from user three to base station one is critical in this setup. If a high attenuation of interference channels is set according to Section 6.1, cell one and cell two will not influence each other. If a low attenuation is selected, significant interference from user three to users one and two will occur. In this setting, users three and one will interfere although they are not overlapping in frequency since they are not orthogonal due to the different subcarrier spacings. If the co-existence of users with different subcarrier spacings is subject of investigation, the interference link attenuation may be set to the same value as the channel's path loss. In this case, interference channels and desired channels are generated following the same statistics with the same average channel power and are therefore equivalent. Considering the received signals at base station one, it is not distinguishable if user three is within cell one or cell two. By this method, users within one cell that employ different modulation schemes can be simulated.

Simulation Examples and Scenarios

We include several pre-defined simulation scenarios within the download package of our simulator. The easiest way to define simulation settings is via the scenario files located in the Scenarios folder. We provide some ready-tosimulate scenario files with the simulator, that are described in Section 4.2.

However, there might be simulations and comparisons which cannot be obtained by the 5G Link Level Simulator in its original form directly. Since the simulator is implemented in a modular way, using object oriented programming, parts of it might be reused within a different simulation script. We provide simulation examples in the Examples folder, that re-use parts of the simulator by exploiting objects. These examples are described in Section 4.1.

Simulation Scripts

This section describes simulation scripts that are provided in the Examples folder and do not exploit the whole implemented Vienna 5G Link Level Simulator structure. To run this example simulations, execute the desired script directly in Matlab.

Channel Coding with Short Block Length

The example script shortBlockChannelCoding.m performs a comparison between the channel coding schemes of convolutional, turbo, LDPC, and polar codes for the case of short block length combined with a low code rate. Such scenario has its importance in various applications, such as the control channels in cellular systems, and also in the Fifth Generation (5G) Massive Machine Type Communication (MMTC) and Ultra-Reliable and Low-Latency Communication (URLLC) use cases. As mentioned in the introduction of the section, this example uses the coding object in a separate manner from the simulator. With this way, we set the target length and code rate irrespectively of the number of scheduled resources or the target CQI code rate. The simulation is then setup according to Table 1. Once the simulation is finished, the script calculates the confidence intervals and plots the results. It is clearly visible in the results that the polar code is the clear winner in such scenario. At the FER of 10^{-2}, we observe a lead for the polar code of about 1dB against the LDPC code and of 1.5dB against the turbo and convolutional codes. This result, however, does not alone rule out the choice of the coding scheme, as there are other considerations with respect to the decoding latency, hardware implementation, etc.

Channel Coding

The first block in the processing chain is the channel coding, where redundancy is added to provide error correction and detection capabilities for the wireless transmission. The simulator supports the four candidates (or were candidates) of 5G: convolutional, turbo, LDPC, and polar codes. The aim was to have a single structure that can handle the four coding schemes simultaneously, with challenges arising due to the different requirements of the different coding schemes. Table 6 summarizes the supported schemes, their construction, and the corresponding decoding algorithms.

Table 6: Supported channel coding schemes.

scheme	construction/ encoding	decoding algorithms
turbo	LTE	Log-MAP Linear-Log-MAP MAX-Log-MAP
LDPC	5G NR	Sum-Product PWL-Min-Sum Min-Sum
polar	currently custom	SC List-SC CRC-List-SC
convolutional	LTE	Log-MAP MAX-Log-MAP

The procedure of the channel coding is identical across all the aforementioned schemes. We describe in the following subsections the main steps.

8.1 Block Length Calculation and Segmentation

The first step is to determine how many information bits are supported by the current transmission. This depends on how many resources are scheduled, the modulation order, and on the code rate. The modulation order and code rate are obtained using the current CQI. Once this is determined and depending on the chosen coding scheme, filler bits might be added to the block when its length does not match the size of the interleaver (in case of the turbo code) or the dimensions of the parity check matrix (for the LDPC code). If the block length is too long, then code block segmentation is performed. For the turbo and convolutional codes, the segmentation follows the LTE standard, while for the LDPC code, it follows the current 5G specs. For the polar code, the segmentation is similar to that of the turbo code, but it has more granularity in the selection of the block length, since the polar code does not require a strict set of input lengths.

8.2 Convolutional Code

The implementation of the convolutional code is based on the LTE standard [6]. More specifically, it is a tail-biting convolutional code, meaning that the starting and ending states of the encoder is the same. In the simulator, we pass this state directly to the decoder (i.e., gene-aided). This should not have an impact on the performance of the code, however, it will reduce the decoding complexity, as the decoder does not have to spend time figuring out that state. The encoder is implemented using a shift register, and it is initialized with the last bits of the information block, guaranteeing that the initial and final states of the encoder are the same, i.e., tail-bitten.

The decoder is based on the Bahl-Cocke-Jelinek-Raviv (BCJR) algorithm [7], which is the efficient implementation of the bit-wise Maximum A-Posteriori (MAP) decoder. The supported algorithms are the 'Log-MAP', that is the original MAP algorithm in the log domain, and the sub-optimal 'MAX-LogMAP' which provides lower complexity.

8.3 Turbo Code

Similar the convolutional code, the turbo code is also based on the LTE standard [6]. The encoder consists of two recursive constituent convolutional encoders. The encoders are initialized with zeros, and the final states are tracked through trellis-termination.

The iterative (turbo) decoding is based on the BCJR algorithm. It supports the 'Log-MAP', 'MAX-Log-MAP', and the 'Linear-Log-MAP' algorithms. The latter uses a linear function to approximate the exponential correction term in the original MAP algorithm.

8.4 LDPC Code

The LDPC code is based on the current 5G NR specs [8]. The employed code is quasi-cyclic and therefore allows easy adaptation of of the parity check matrix to different input lengths. The standard defines two base parity check matrices, or as it is called, a Base Graph (BG). Depending on the code rate and the input length, either BG 1 or BG 2 is used. One BG is better suited for short lengths and low code rates, while the one is more suited for long lengths and high code rates. Thanks to the diagonal and double-diagonal structures of the parity check matrix, the encoding can be carried out with low complexity. The encoding is systematic, and at the output of the encoder, a certain amount of the systematic bits are punctured. These punctured bits never enter the circular buffer.

The decoder is based on layered Belief Propagation [9] or usually called Sum-Product algorithm. The layering is utilized through the Column Message Passing schedule [10]. The supported decoding algorithms are 'Sum-Product', the lower complexity 'Min-Sum', and the 'PWL-Min-Sum', where PWL stands for Piecewise Linear. Similar to the turbo decoder, it uses linear functions to approximate the correction terms.

8.5 Polar Code

The construction of the polar code (i.e., finding the frozen set) is currently based on method in [11]. Once the set is found, the next power-of-two polarization transform is selected. In case the codeword length does not match the generator matrix (polarization transform) size, then the extra positions from the bottom of the generator matrix are set to zero and then removed at the output. At the decoder side, the Log-Likelihood Ratio (LLR) of these positions is set to a high value, reflecting a $+\infty$ LLR. The generator matrices for sizes above 512 are precalculated for faster operation

The decoder is based on Successive Cancellation (SC) and its extensions of List-SC and Cyclic Redundancy Check (CRC)-aided List-SC.

8.6 Interleaving and Rate Matching

For the turbo and convolutional codes, the rate matching procedure is identical to the standard. The interleaving is carried out directly on each of the three streams at the encoder output, i.e., subblock-interleaving. After interleaving, the streams are passed to the circular buffer, where puncturing and/or repetition is performed in order to meet the output length, and consequently the target code rate. For the turbo code, part of the systematic stream is skipped at the first transmission from the circular buffer.

For the polar code, the whole non-systematic codeword is interleaved. The main rate adaption is carried out at the input of the generator matrix, by adjusting how many bits are frozen. After interleaving, the codeword is passed to the circular buffer, where further slight puncturing or repetition is performed in case the codeword does not exactly match the target length.

As for the LDPC code, we follow the 5G NR chain, in which the systematic codeword is passed to the circular buffer directly without interleaving. The codeword is then punctured/repeated in order to meet the target length. After the codeword is rate matched, it is then interleaved using a rectangular interleaver. The interleaving pattern depends on the modulation order.

Object Usage

The object is initialized in the following manner:

```
ChannelCodingObj = Coding.ChannelCoding( ...
                    'Turbo', ...                          % coding scheme
                     'Linear-Log-MAP', ...                % decoding algorithm
                   1/2, ...                               % code rate
                  8 ...                                   % iterations/list size
);
```

Once the object is initialized, the next step is to update the object parameters based on the required input or output length. This can be done in two ways, the first one is

```
inputLength = ChannelCodingObj.update('Output', N, R, Qm,
    SoftBufferRatio);
```

where N, R, Q_m, and SoftBufferRatio are the output length, code rate, modulation order, and soft-buffer rate-matching ratio, respectively. This is used when the output length is known and you would like to get how many information bits are needed at the input.

```
ChannelCodingObj.update('Input', K, R, Qm, SoftBufferRatio);
```

Alternatively, it can be used in the following way

where K is the input length. In this case, the function update() does not return anything and the output length is set automatically based on the input length. Beside calculating the input length, the function update() prepares the object for codeblock segmentation, and in the case of LDPC and polar codes, the update function also performs LDPC lifting, and construct the appropriate polar code. This function has to be called every time the code rate or the output code length changes. The rest of the object usage is straightforward, the

```
codedBits = ChannelCodingObj.encode(inputBits);
...
decodedBits = ChannelCodingObj.decode(channelLLRs);
```

encoding and decoding is carried out through

The parameter SoftBufferRatio controls how much of the circular buffer is used (i.e., soft rate matching). Its value ranges from 0 to 1, with 1 indicating that the full circular buffer is used.

Modulation Waveforms

Orthogonal Frequency-Division Multiplexing

CP-OFDM (CP-OFDM) is the most prominent multicarrier scheme and is applied, for example, in Wireless LAN and LTE-A. CP-OFDM employs a rectangular transmit and receive pulse, which greatly reduce the computational complexity. Furthermore, the CP implies that the transmit pulse is slightly longer than the receive pulse, preserving orthogonality in frequency selective channels. Thus, frequency-selective broadband channels transform into multiple, virtually frequency flat, sub-channels (subcarriers) without interference. This allows the application of simple one-tap equalizers, corresponding to maximum likelihood symbol detection in case of Gaussian noise. Furthermore, the channel estimation process is simplified, adaptive modulation and coding techniques become applicable, and MIMO can be straightforwardly employed. Unfortunately, the rectangular pulse in OFDM leads to high out-of-band emissions. This is one of the biggest disadvantages of CP-OFDM. Additionally, the CP simplifies equalization in frequencyselective channels but also reduces the spectral efficiency. In order to reduce the OOB emissions, 3GPP is currently considering windowing and filtering, see the next subsections.

One of our most important implementation aspects is that we consider a fixed sampling rate f_s instead of a fixed Fast Fourier Transform (FFT) length N_{FFT}, as often done in literature. The main reason for a fixed sampling rate is to enable a fair comparison between different subcarriers spacings and to guarantee that a specific channel power delay profile fits approximately the sampling rate. Additionally, the sampling rate is often predetermined by real world hardware and cannot be changed easily. The relationship between FFT size, sampling rate and subcarrier spacing F is:

$$N_{\mathrm{FFT}} = \frac{f_{\mathrm{s}}}{F}. \tag{10.1}$$

Note that the FFT size must be larger or equal than the number of active subcarriers. In practice, the FFT size will always be larger than the number of active subcarriers. For example, in 10MHz LTE-A, we have 600 active subcarriers and an FFT size of 1024. We also advise to use a (much) larger FFT size than the number of active subcarriers.

The OFDM object can be initialized by:

```
OFDMobject = Modulation.OFDM(...
L,...                  % Number of subcarriers
K,...                  % Number OFDM symbols in time
F,...    % Subcarrier spacing (Hz) fs,...    % Sampling rate (Samples/s) fI,...    %
Intermediate frequency of the 1st subcarrier (Hz) false,... % Transmit real valued signal,
true/false TCP, ... % Length of the cyclic prefix (s)
TZG ...                       % Length of the zero guard time (s), (frame)
);
```

whereas we always consider a block transmission of L subcarriers and K OFDM symbols. The intermediate frequency f_I corresponds to a circular shift of the FFT.

A given symbol vector $\mathbf{x} \in \mathbb{C}^{L\times K}$, for example chosen from a QAM signal constellation, can then be modulated by:

```
s = OFDMobject.Modulation(x);
```

where **s** represents the transmitted signal in time. The demodulation, on the other hand, can be performed by applying the following method on the received time signal **r**

```
y = OFDMobject.Demodulation(r);
```

In case of a back-to-back transmission, $\mathbf{r} = \mathbf{s}$, we will recover the transmitted data symbols, that is, $\mathbf{y} == \mathbf{x}$.

For a concrete implementation of our OFDM object (without unnecessary overhead), we refer to the example file in "Example/Comparison 5GWaveforms.m".

WOLA

The windowed OFDM scheme is called OFDM with WOLA [12]. At the transmitter, the edges of the rectangular pulse is replaced by a smoother function (windowing) and neighboring WOLA symbols overlap in time. The receiver also applies windowing but the overlapping and add operation is performed within the same WOLA symbol, reducing the inter-band interference. Fig. 7 illustrates the WOLA concept. Compared to CP-OFDM, the time spacing is increased by $T_{w,tx} + T_{w,rx}$. However, the CP can usually be reduced because some small interference is often acceptable.

The WOLA object can be initialized by:

```
WOLAobject = Modulation.WOLA(...
L,...                     % Number of subcarriers
K,...    % Number OFDM symbols in time F,...    % Subcarrier spacing (Hz) fs,...    %
Sampling rate (Samples/s) fI,...    % Intermediate frequency of the 1st subcarrier (Hz)
```

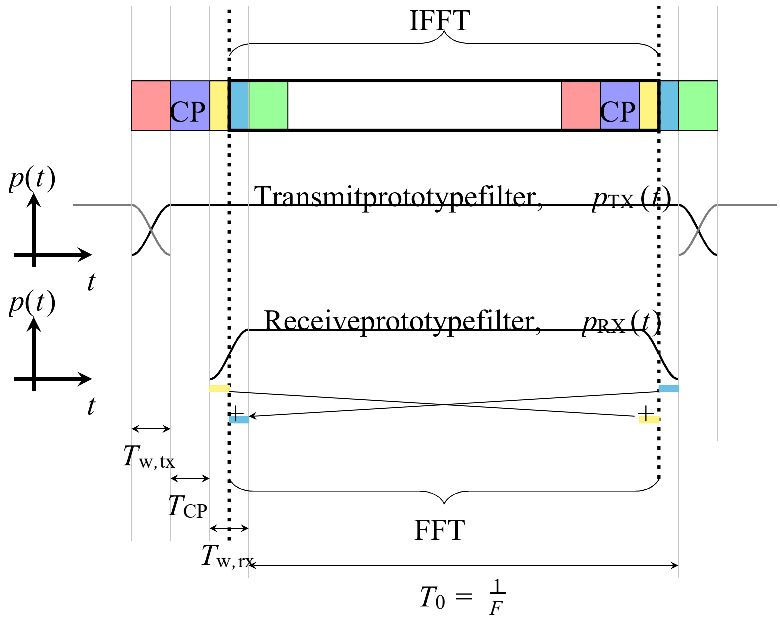


Figure 7: Illustration of WOLA

```
  false,... % Transmit real valued signal, true/false TCP, ... % Length of the cyclic prefix
  (s)
TZG ...                          % Length of the zero guard time (s), (frame)
  TWTX, ... % Length of the window overlapping (s) at the TX
  TWRX ... % Length of the window overlapping (s) at the RX
);
```

It works similarly as the OFDM object, see Section 10.1, but has the additional option of $T_{w,tx}$ and $T_{w,rx}$, representing the window length at the transmitter and at the receiver. The window function itself is based on a (root) raised cosine function.

Universal Filtered Multicarrier

UFMC is filtered OFDM technique proposed as one of the candidates for new 5G waveforms below 6GHz. The main advantage of this scheme is a better fragmentation of spectrum and more suppressed side lobes compared to OFDM.
The implementation of UFMC in this code is based on Nokia's proposal of transceiver structure.[13]

Transmitter

The assigned bandwidth in UFMC is divided into multiple subbands according to different user

```
for m = 1:obj.Nr.ResourceBlocks n = (m-1)* obj.Nr.SubcarriersPerRb+1:(m-
1)*obj.Nr.
    SubcarriersPerRb+obj.Nr.SubcarriersPerRb;                    b              =
reshape(DataSymbolsTemp(n,:),obj.Nr.SubcarriersPerRb,obj.
    Nr.MCSymbols); end
```

requirements and services.

On each of those subbands we apply Inverse Fast Fourier Transform (IFFT) with corresponding length. By doing this we obtain the transmit data in time domain. The choice of the transmit window is arbitrary. We choose Hanning window since it maximizes the side lobe attenuation. Before we do subband filtering, we shift each filter to the center frequency of the corresponding subband:

```
freqShift (l) = exp(2*pi*1i*(l-1)*(centralFreq-1)/obj.
      Implementation.FFTSize);
```

We apply this subband filter on the transmit data from the same subband. Unlike OFDM, UFMC uses Zero-Postfix (ZP) instead of CP in order to avoid inter-symbol interference in a case of high delay spread channels. The length of ZP is chosen to be one sample shorter than the filter length. In order to obtain the total transmit signal we summarize all subbands transmit signals together.

Receiver

At the receiver side we apply N-FFT, resulting in the same complexity level as CP-OFDM. In order to apply N-FFT we do some modifications of the received signal. First, we decompose our received signal into two parts, so called *body* and *tail*. Then we transform this received vector by copying the *tail* to the beginning of the signal:

```
receiveSignalTemp(1:guardLength,:) = ReceivedSignalResh(1:
  guardLength,:) + ReceivedSignalResh(obj.Implementation.
      FFTSize+1:end,:);
```

Filtered-OFDM

The second filter-based OFDM scheme considered within 3GPP is f-OFDM [14]. Here, the number of subcarriers for one subband is usually much higher than in UFMC and often includes all subcarriers belonging to a specific use case. The idea of f-OFDM is quite simple: we modify a conventional CP-OFDM transmission by applying digital filtering at both, transmitter and receiver. If the total CP length is longer than the combined filter length, we restore orthogonality in an AWGN channel. However, some (small) interference is usually acceptable to keep the overhead low. The induced interference can be adjusted by the filter length and the CP length ($T_{\mathrm{CP,f}}$). The filter itself is based on a sinc pulse (perfect rectangular filter) which is multiplied by a Hann window; other filters are also possible [14], but currently not implemented.

The FOFDM object can be initialized by

```
FOFDMobject = Modulation.FOFDM(...
L,...                          % Number of subcarriers
  K,...     % Number OFDM symbols in time F,...         % Subcarrier spacing (Hz) fs,...        %
  Sampling rate (Samples/s) fI,...     % Intermediate frequency of the 1st subcarrier (Hz) false,...
  % Transmit real valued signal, true/false TCP, ... % Length of the cyclic prefix (s)
TZG ...                             % Length of the zero guard time (s), (frame)
  TFTX, ... % Length of the transmit filter (s)
  TFRX, ... % Length of the receive filter (s)
  TCPF ... % Length of the additional cyclic prefix (s).
);
```

Again, this is similar to OFDM, see Section 10.1, but with the additional option of $T_{\mathrm{f,tx}}$ and $T_{\mathrm{f,rx}}$, representing the filter length at the transmitter and at the receiver. Furthermore, we have an additional CP with length $T_{\mathrm{CP,f}}$ to combat the effects of filtering. To total CP overhead is then given $T_{\mathrm{CP,total}} = T_{\mathrm{CP}} + T_{\mathrm{CP,f}}$.

FBMC

Although 3GPP decided that FBMC will not be employed in 5G [15], FBMC still has many advantages over OFDM, namely, much lower OOB emissions and a maximum symbol density (i.e., no CP overhead) [16]. Those advantages, however, come at the price of sacrificing the complex orthogonality condition with the less strict real orthogonality condition. In many cases, however, this has either no, or only a minor influence on the performance. In other cases, such as channel estimation or some MIMO methods, on the other hand, special treatment of the imaginary interference becomes necessary. Fortunately, there exists many efficient methods to deal with those challenges [16]. The signal generation in FBMC is similar to that of windowed OFDM, see Fig. 8, whereas we ignored receive filtering to keep the illustration simple.

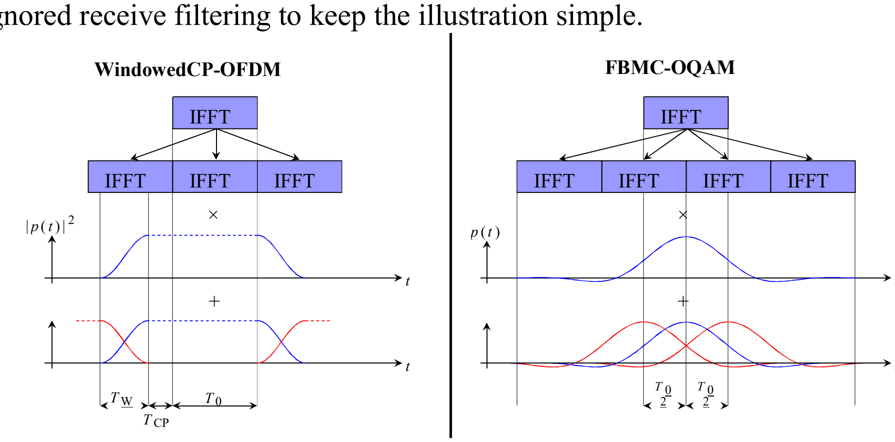


Figure 8: The signal generation in FBMC and windowed OFDM requires the same basic steps [16]. The initialization of the object is similar to OFDM:

```
FBMC = Modulation.FBMC(...
L,...                        % Number of subcarriers
  K,...    % Number FBMC symbols in time F,...        % Subcarrier spacing (Hz) fs,...       %
  Sampling rate (Samples/s) fI,...     %  Intermediate  frequency  of  the  1st  subcarrier  (Hz)
  false,...% Transmit real valued signal, true/false
  'PHYDYAS-OQAM',... % Prototype filter (Hermite, PHYDYAS, RRC)
  O, ...    % Overlapping factor, e.g., 3,4,5,6,7,8 0, ...   %  Initial  phase  shift,
  e.g., pi/2 true ... % Polyphase implementation, true/false
);
```

Non-Orthogonal Multiple Access (NOMA)

NOMA is a key technology for next generation communications systems. It allows the users to access the available resources in a non-orthogonal manner, and in turn allowing the system to accommodate more users compared to the case of OMA. This would of course require employing advanced receivers in order to cope with the induced interference between those users. On top of that, many NOMA schemes fit naturally in the context of grant-free access, allowing the users to access the resources more often and therefore reducing the latency. These two aspects; massive connectivity and low latency operation, are main components of the future systems, and NOMA is able to tackle both of these issues in a natural manner.

In the current version of the simulator, we support the 3GPP MUST technique. It is a downlink power-domain NOMA version that works by superimposing a maximum of two users on the same resources in the powerdomain. The gain provided by this scheme is maximized when the two imposed users have a large difference in their channel quality, i.e., a user with good channel conditions (NearUE) and a user with bad channel condition (FarUE). A typical example for a FarUE would be a cell-edge user. In the simulator, the notion of strong and weak users can be controlled through `scStr.simulation.pathloss` parameter. The superposition works by assigning the FarUE with most of the transmit power. Then, at the receiving side, Successive Interference Cancelation (SIC) can be used to first detect the high power user, subtract its signal from the total received signal, and then proceed to detect the low power user. Alternatively, one can view the superimposed signal as just a normal signal with symbols being drawn from a super composite constellation. This in turns allow us to perform the detection using a Maximum Likelihood (ML) detector running on the composite constellation. In the standard, FarUE is limited to 4QAM, while NearUE can use up to 64QAM. This further simplifies the detection process for the FarUE, since it can treat the received superimposed signal as legacy 4QAM and proceed to detect its signal as if NearUE is just an extra noise. On the other hand, this also means that the BS does not need to transmit control information to the FarUE about the MUST operation, which is always a good thing. Furthermore, the standard defines three power ratios that control the allocation of the power between the two superimposed users. This can be controlled using the `MUSTIdx` parameter. The default value in the simulator is 2, which is the middle power ratio.

MUST is enabled by scheduling two users at the same resources. For example, assume you would like to have UE1 and UE2 to operate in MUST mode. They need to be scheduled in the following way

```
scStr.schedule.fixedScheduleDL{1}                    = ['UE1:72,UE2:UE1'];
```

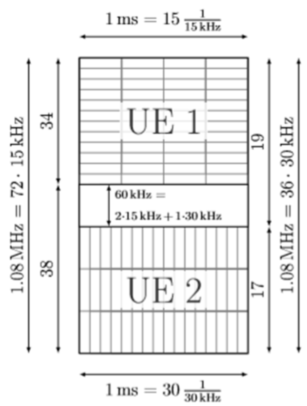
This way, UE1 will be the NearUE and UE2 is the FarUE.

When it comes to producing results with MUST, it is recommended to use the transmit power of the BS as the sweeping parameter. The path loss parameter can then be used to set the quality of the user channels, as shown in the simulation scenario of Section 4.2.5.

Chapter 5

5G Simulation results

5.1
Multilink scenarios

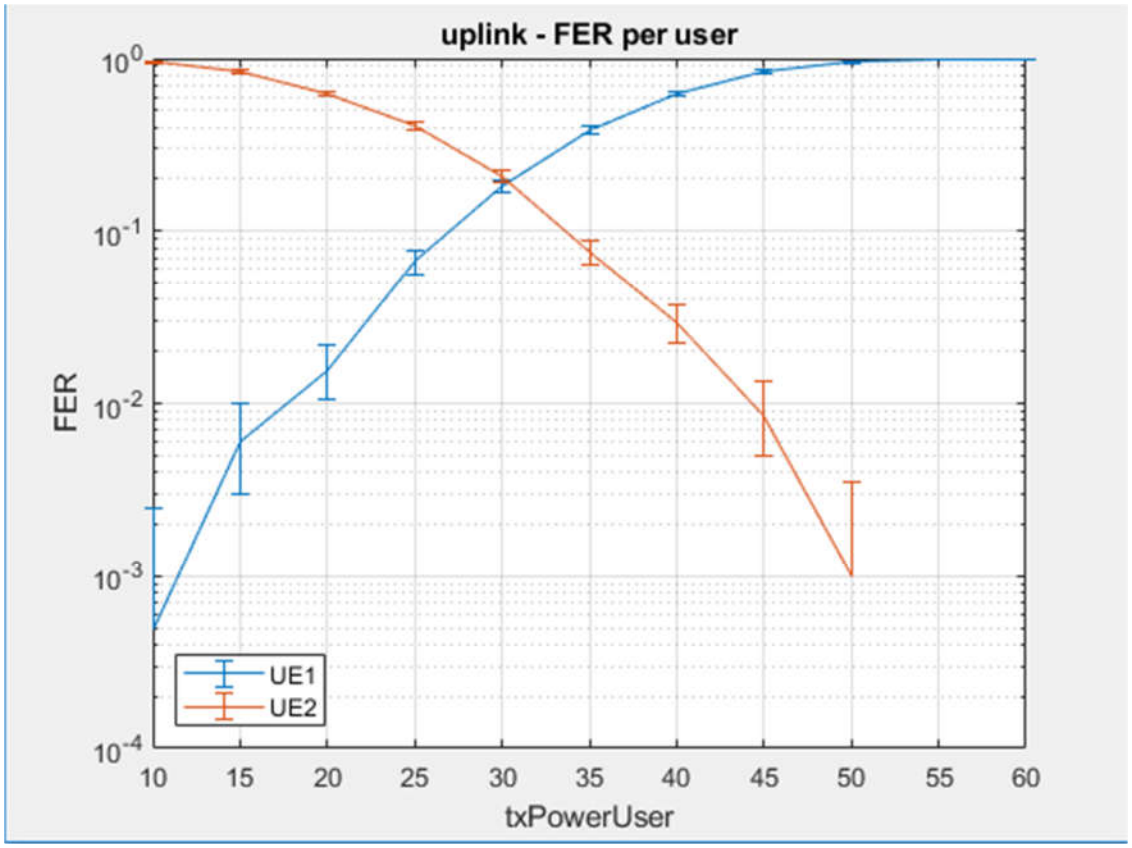


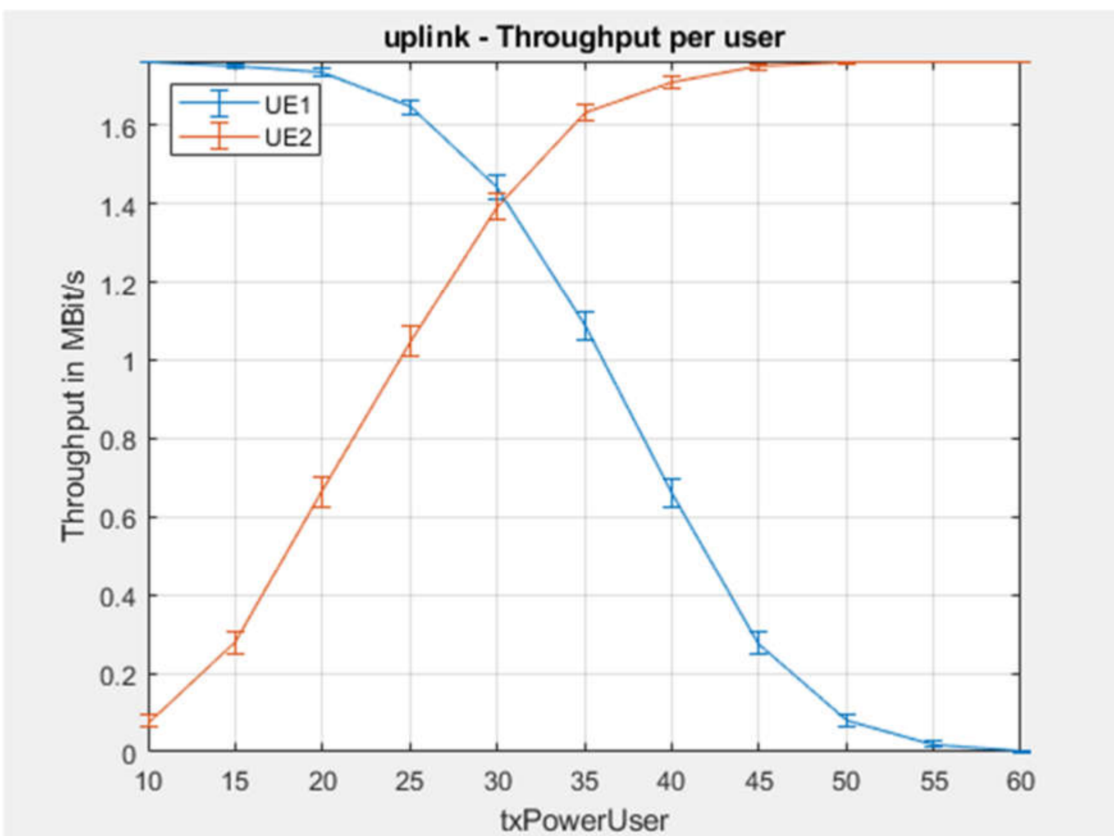
Resource allocation within a cell

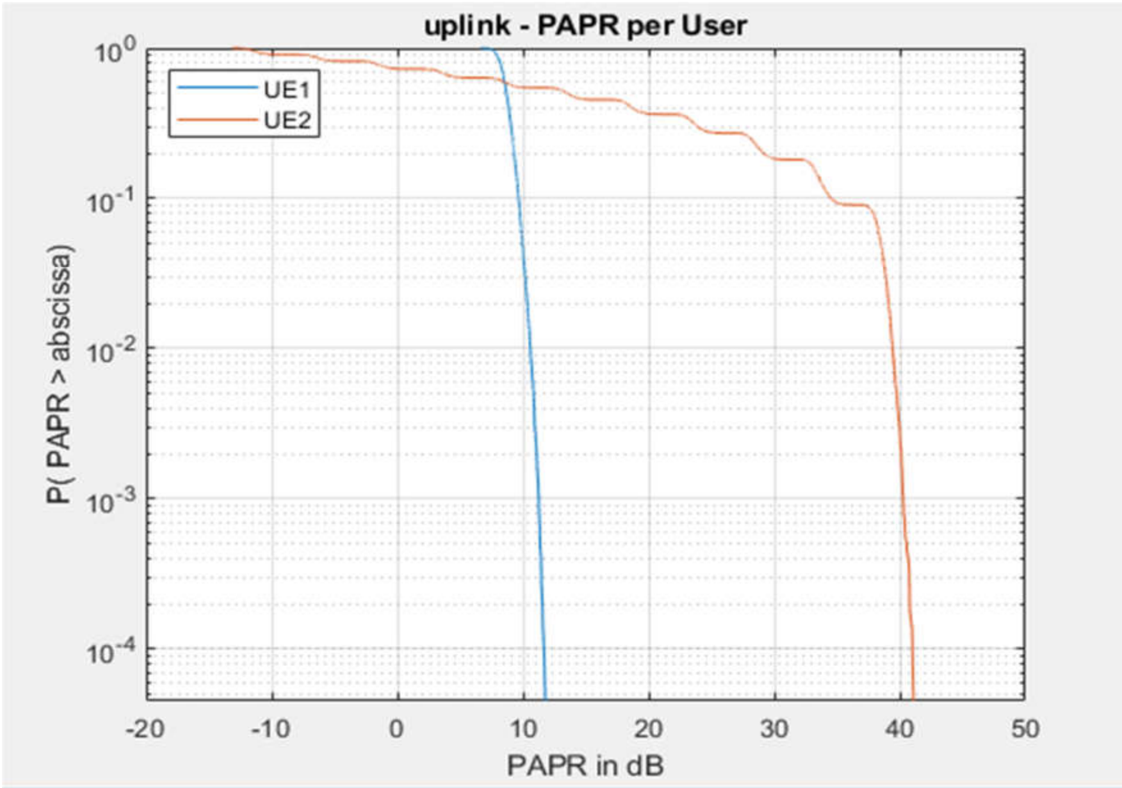
parameter	value		
waveform	OFDM	f-OFDM	FBMC
filter type/length	-	7.14 µs	PHYDYAS-OQAM
CP length	4.76 µs	4.76 µs	-
subcarrier spacing	User 1: 15 kHz, User 2: 30 kHz		
guard band	2×15 kHz $+ 1\times30$ kHz $=$ 60 kHz		
bandwidth per user	34×15 kHz $= 17\times30$ kHz $=$ 0.51 MHz		
modulation/coding	64 QAM/LDPC, r = 0.65 (CQI 12)		
channel model	block fading Pedestrian A		

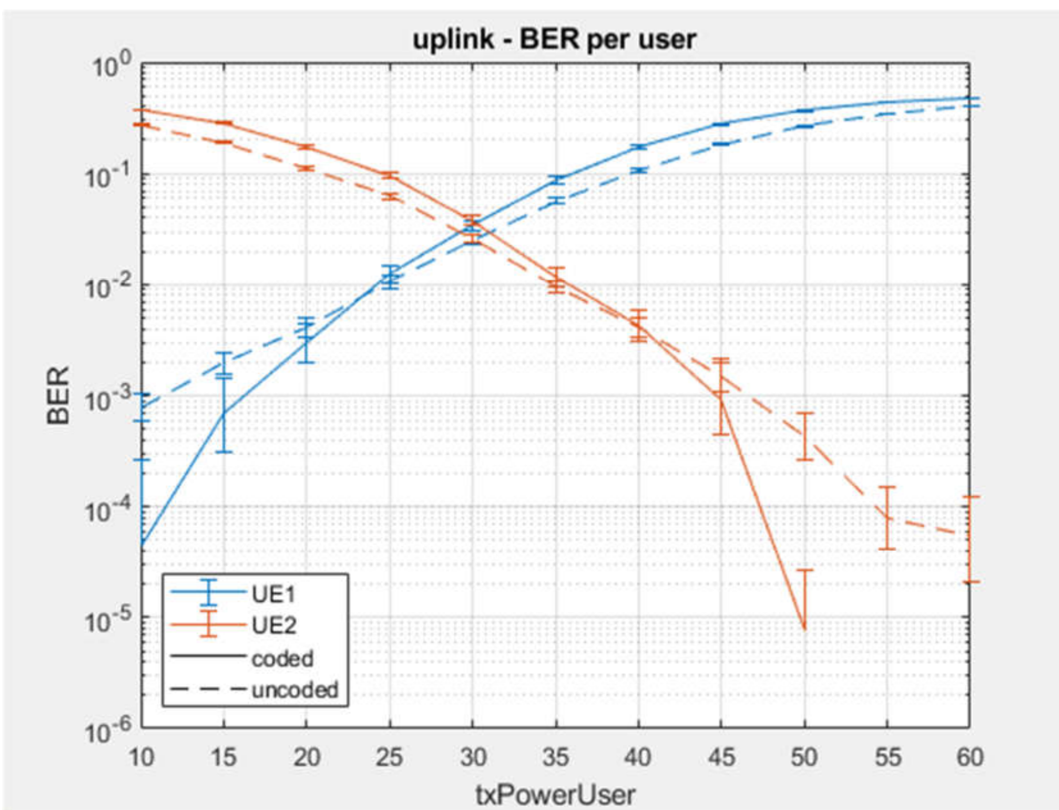
Table 2: Multi-link scenario simulation parameters overview.

Parameter List

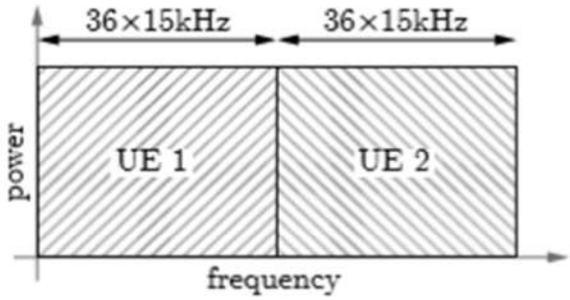

uplink - FER per user
FER
txPowerUser
UE1
UE2
10
15
20
25
30
35
40
45
50
55
60


uplink - Throughput per user
Throughput in MBit/s
txPowerUser
UE1
UE2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
10
15
20
25
30
35
40
45
50
55
60

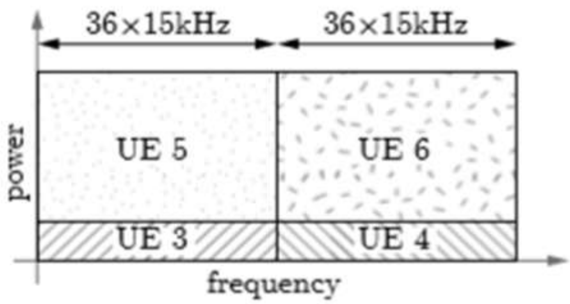

uplink - PAPR per User
UE1
UE2
P(PAPR > abscissa)
PAPR in dB


uplink - BER per user
UE1
UE2
coded
uncoded
BER
txPowerUser

5.2 NOMA SIMULATION RESULTS



User schedule for the OMA case.

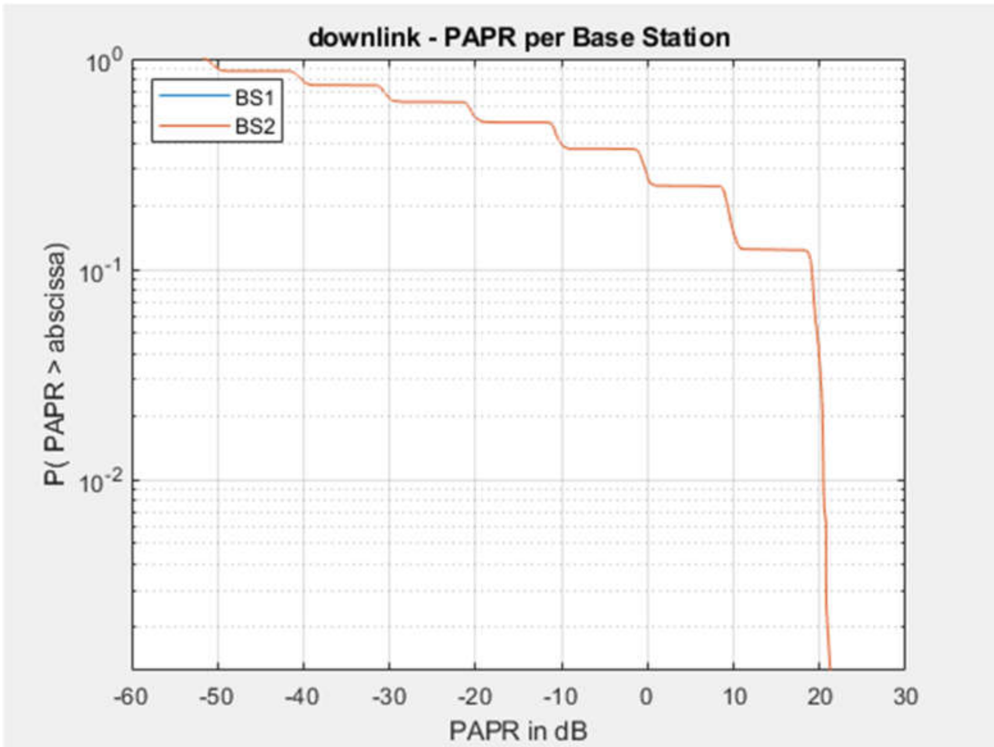


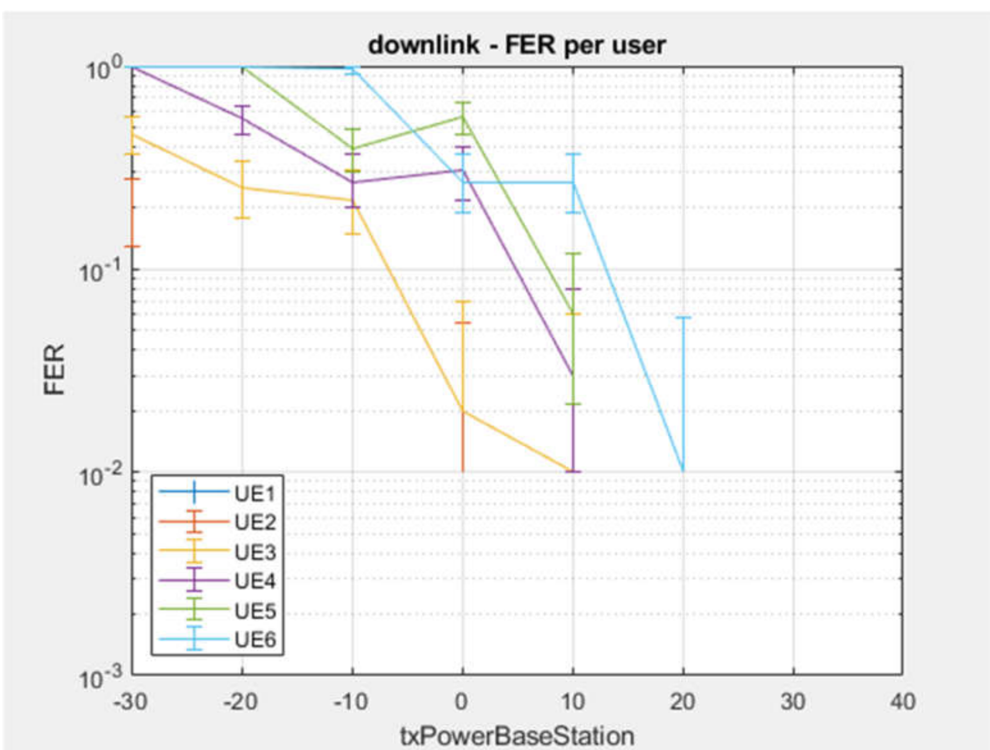
User schedule for the NOMA case.

User Assignment for NOMA

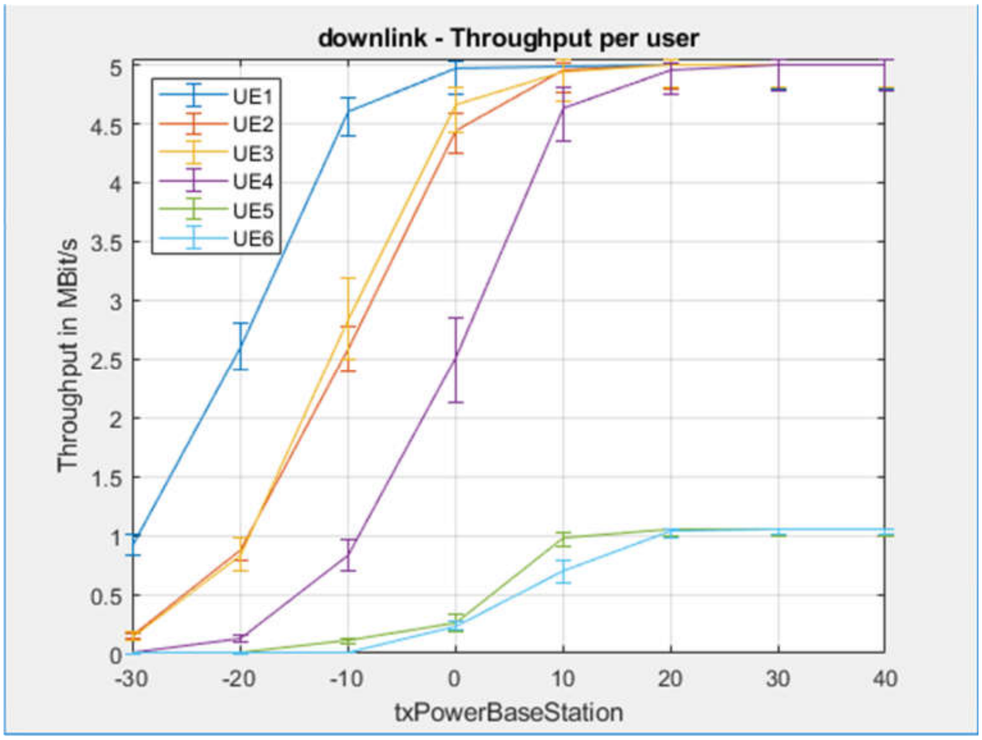
parameter	value	
cells	OMA	NOMA
number of users	2	4 (2 strong, 2 cell-edge)
path-loss	80, 90 dB	strong: 80, 90 dB cell-edge: 110, 115 dB
NOMA receiver	-	ML
MUST power-ratio	-	fixed (second ratio)
bandwidth	1.4 MHz (72 subcarriers)	
waveform/coding	OFDM, LDPC	
MIMO mode	2×2 CLSM	
modulation/code rate	adaptive (CQI based)	
feedback delay	no delay (ideal)	
channel model	Pedestrian A	

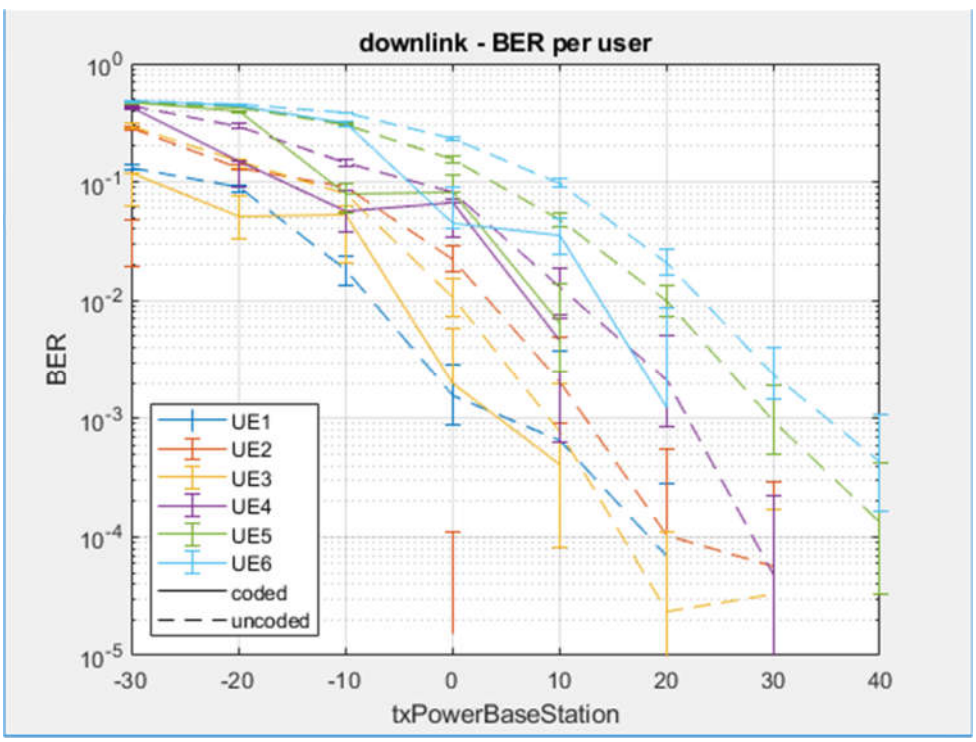
The simulation parameters for NOMA





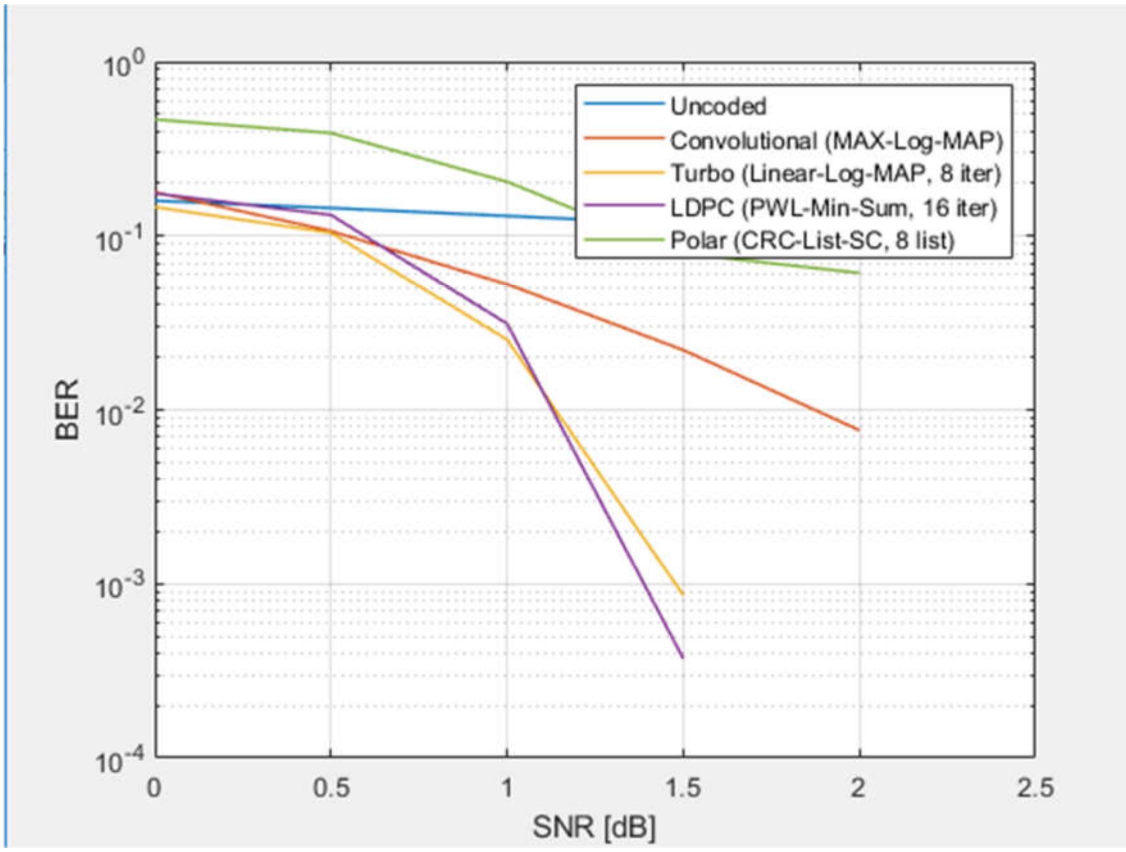
PAPR and FER per base station



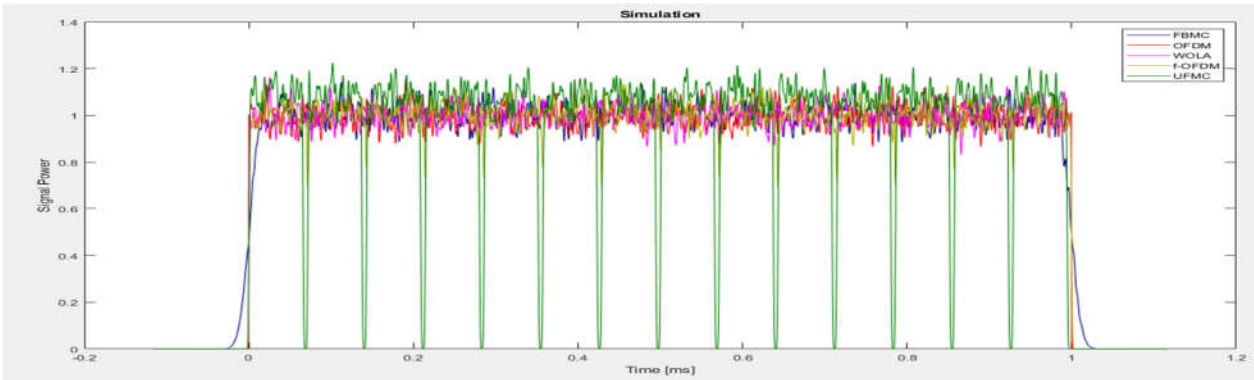


Throughput and BER per base station

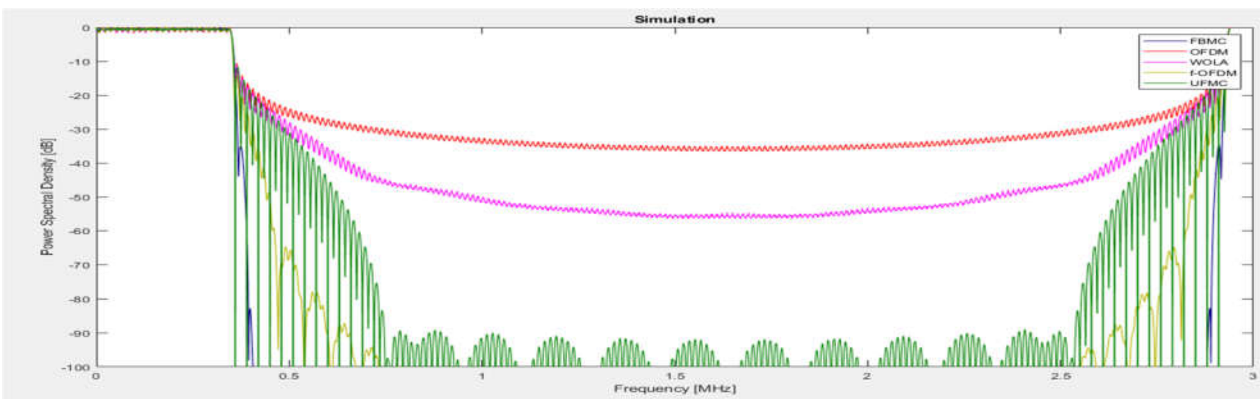
5.3 Comparison between various coding schemes



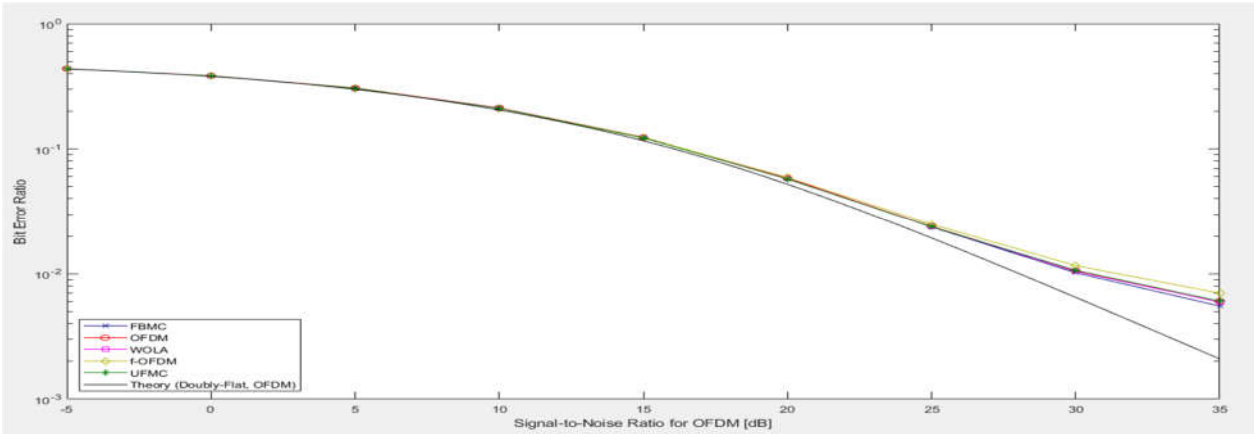
5.4 Comparison between various processes



Signal Power vs Time for various multi-carrier schemes



PSD vs Frequency for various multi-carrier schemes



BER vs SNR for various multi-carrier schemes

Chapter 6

Conclusion

In this paper, we presented an extensive survey on mode selection, interference management, power control, and resource allocation in D2D communication that is foreseen to be an importantpartof5Gnetworks.Thepaperstartswithatutorial overview of D2D communication, its operation, its types, and the advantages and limitations of each type. Device-to-device communication can be categorized into inband and outband where the inband communication can be further subdivided into underlay and overlay. Moreover, the outband D2D communication can be subdivided into controlled and autonomous modes. Inband D2D makes reuse of the licensed spectrum for D2D transmissions, while in outband D2D, unlicensed spectrum is used for D2D transmissions. The main issue of D2D communication is the interference from D2D UEs to CUs and vice versa that is faced in underlay D2D because the reuse of the same cellular licensed spectrum is done in underlay D2D communication. The other categories of D2D communication do not face such problem. This interference from D2D UEs to CUs and vice versa can be avoided by using the appropriate interference management, power control, spectrum allocation, and mode selection techniques. Therefore, in this paper, we provided a detailed survey on mode selection, interference management, power control, and resource allocation in D2D communication. First of all, the works regarding, whether to select D2D or cellular mode for communication, ie, mode selection are reviewed in detail. Then, management schemes for the interference from D2D UEs to CUs and vice versa are surveyed under centralized and distributed D2D communication. Then available

literature on spectrum allocation and power control schemes are surveyed under the major categories of centralized and distributedapproaches.Furthermore,theworksundercentralized and distributed spectrum allocation and power control schemes are subcategorized on the basis of optimization criteria. All the categories and subcategories are surveyed in detail. The work in each category is summarized in tabular form as well. And at the end, some open research directions are outlined that need the attention of researchers.

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