Device-to-Device Communications in LTE-Advanced Network

Junyi Feng

N° d'ordre : 2013telb0296

Sous le sceau de l'Université européenne de Bretagne

Télécom Bretagne

En habilitation conjointe avec l'Université de Bretagne-Sud

Ecole Doctorale – sicma

Device-to-Device Communications in LTE-Advanced Network

Thèse de Doctorat

Mention : Sciences et Technologies de l'information et de la Communication

Présentée par **Junyi Feng**

Département : Signal et Communications

Laboratoire : Labsticc Pôle: CACS

Directeur de thèse : Samir Saoudi

Soutenue le 19 décembre

Jury :

M. Charles Tatkeu, Chargé de recherche, HDR, IFSTTAR - Lille (Rapporteur)
M. Jean-Pierre Cances, Professeur, ENSIL (Rapporteur)
M. Jérôme LE Masson, Maître de Conférences, UBS (Examinateur)
M. Ramesh Pyndiah, Professeur, Télécom Bretagne (Examinateur)
M. Samir Saoudi, Professeur, Télécom Bretagne (Directeur de thèse)
M. Thomas Derham, Docteur Ingénieur, Orange Labs Japan (Encadrant)

Acknowledgements

This PhD thesis is co-supervised by Doctor Thomas DERHAM from Orange Labs Tokyo and by Professor Samir SAOUDI from Telecom Bretagne. I feel very grateful to them for having offered me this opportunity to study on this very interesting thesis topic. Thomas has keen sense of technology developments and market trends, as well as wide knowledge in the field of telecommunication. I appreciate much the discussions with him, which always inspired me a lot and were a real delight. He has influenced me a lot with his passion towards work. I have also learned a great deal from tutorage of Samir, for paper writing and publishing, for developing a rigorous way of research, and for efficient time management. I would like to sincerely thank both of them for their consistent support, encouragement and precious advice over the entire period of my studies, as well as their assistance with the preparation and proofing of this documents.

I would also like to thank Letian RONG and Martin MACUHA, with whom I worked on this thesis in the first year of my PhD. Working with them was a great pleasure and has helped me to quickly seize the study issues at the initial stage of my PhD.

This thesis work was interrupted for about 5 months in 2011 due to the Japanese Fukushima nuclear accident, and thereafter I returned back to France to continue my work. I would like to thank both Orange Labs and Telecom Bretagne for their concession and their assistance for the relocation. In particular, I deeply acknowledge Professor Ramesh PYNDIAH, dean of department Signal and communication in Telecom Bretagne, for the kind reception and his continuous support in the following part of my thesis.

I am very grateful to my friend Xiwen JIANG, Florian COSTE and Paul FRIEDEL, for their interest in my study and their great help on my thesis work. I am indebted to many other friends for their support and encouragement.

Finally, I would like to thank my family for their long-standing support and care. Their love and understanding made it possible for me to complete this study.

Contents

Acronyms

AFH Adaptive Frequency Hopping

AMC Adaptive Modulation and Coding

AMP Alternative MAC/PHY

AoA Angle of Arrival

AoD Angle of Departure

AP Access Point

API Application Programming Interface

ARQ Automatic Repeat Request

AWGN Additive White Gaussian Noise

BLE Bluetooth Low Energy

BLER Block Error Rate

BSS Base Station Subsystem

CDF Cumulative Distribution Function

CDM Code Division Multiplexing

CFO Carrier Frequency Offset

CoMP Coordinated Multipoint

CP Cyclic Prefix

CQI Channel Quality Indication

C-RNTI Cell Radio Network Temporary Identifier

CSI Channel State Information

CSIT Channel State Information at the Transmitter

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance

DL Downlink

DM-RS Demodulation RS

DPO Distributed Power Optimization

DRX Discontinous Reception

DTX Discontinous Transmission

D2D Device to Device

EESM Exponential Effective Signal to Interference plus Noise Ratio Mapping

EPC Evolved Packet Core

eNB eNodeB

ESM Effective SINR Mapping

E-UTRA Evolved Universal Terrestrial Radio Access

E-UTRAN Evolved Universal Terrestrial Radio Access Network

FEC Forward Error Correction

FDD Frequency Division Duplexing

FDMA Frequency Division Multiple Access

GPS Global Positioning System

GSM Global System for Mobile Communications

HARQ Hybrid Automatic Repeat Request

HeNB Home Node B (over E-UTRAN)

IBSS Independent Basic Service Set

ICI Inter-Carrier Interference

ICIC Inter-Cell Interference Coordination

IMT-Advanced International Mobile Telecommunications

InH Indoor Hotspot

IoT Internet of Things

ISI Inter-Symbol Interference

ISM Industrial Scientific and Medical

ITU International Telecommunication Union

ITU-R ITU Radiocommunication Sector

LTE Long Term Evolution

LTE-A Long Term Evolution Advanced

LoS Line of Sight

L2 Layer2

L3 Layer3

MAC Media Access Layer

MCI Maximum Channel to Interference ratio

MCS MAP Communication Server

MCN Multihop Cellular Network

MIMO Multiple-Input Multiple-Output

MIESM Mutual Information Effective SINR Mapping

MNO Mobile Network Operator

NFC Near Field Communication

NLOS Non Line of Sight

OFDM Orthogonal Frequency Division Multiplexing

OFDMA Orthogonal Frequency Division Multiple Access

PAPR Peak to Average Power Ratio

PBCH Physical Broadcast Channel

PCFICH Physical Control Format Indicator Channel

PDCCH Physical Downlink Control Channel

PF Proportionally Fair

PFS Proportional Fair Scheduling

PHICH Physical Hybrid-ARQ Indicator Channel

PMI Precoder Matrix Indication

ProSe Proximity-Based Services

PRACH Physical Random Access Channel

PSD Power Spectral Density

PSS Prixmary Synchronization Signal

PUSCH Physical Uplink Shared Channel

PUCCH Physical Uplink Control Channel

P25 Project25 or APCO-25

QoS Quality of Service

RACH Random Access Channel

RAN1 Radio Access Network Working Group

RAR Random Access Response

RA-RNTI Random Access Radio Network Temporary Identifier

RB Resource Block

RF Radio Frequency

RI Rank Indication

RIT Radio Interface Technologies

RMa Rural Macro

RRC Radio Resource Control

RS Reference Signals

Rx Receiver

SAC Set-based Admission Control

SAE System Architecture Evolution

SA1 Services Working Group

SA2 Architecture Working Group

SC-FDMA Single Carrier Frequency Division Multiple Access

SIG Special Interest Group

SINR Signal to Interference plus Noise Ratio

SISO Single-INput Single-Output

SRIT Sets of Radio Interface Technologies

SRS Sounding Reference Signal

SSL	Secure Sockets Layer
SSS	Secondary Synchronization Signal
STA	Station
S-TMSI	SAE Temporary Mobile Subscriber Identity
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TETRA	Trans European Trunk Radio System
TSG	Technical Specification Group
TTI	Transmission Time Interval
Tx	Transmitter
UE	User Equipment
UL	Uplink
UMa	Urban Macro
UMi	Urban Micro
UPnP	Universal Plug and Play
VoIP	Voice over IP
WAN	Wide Area Network
Wi-Fi	Wireless Fidelity
WBAN	Wireless Body Area Network
WIMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
ZC	Zadoff Chu
ZDO	ZigBee Device Object
3G	3r Generation
3GPP	3rd Generation Partnership Project
4G	4th Generation

Abstract

Device-to-device (D2D) communication is a promising new feature in LTE-Advanced networks. In conventional cellular networks, devices can only communicate with the base station via uplink or downlink paths. It fails to meet the ever-increasing demand of proximity-based social/commercial services and applications. The innovative architecture of D2D underlaying LTE networks is therefore brought up to enable efficient discovery and communication between proximate devices. With D2D capability, devices in physical proximity could be able to discover each other using LTE radio technology and to communicate with each other via a direct data path. Apart from the general social/commercial use, the LTE D2D is further expected to address Public Safety communities.

This thesis is concerned with the design, coordination and testing of a hybrid D2D and cellular network. Design requirements and choices in physical and MAC layer functions to support D2D discovery and communication underlaying LTE networks are analyzed. In addition, a centralized scheduling strategy in base station is proposed to coordinate D2D data communication operating in LTE FDD downlink spectrum. The scheduling strategy combines multiple techniques, including mode selection, resource and power allocation, to jointly achieve an overall user performance improvement in a cell. Finally the performances of D2D data communication underlaying LTE system are calibrated in a multi-link scenario via system-level simulation. D2D data communication is scheduled by base station with the proposed scheduling method and the hybrid D2D and cellular system is compared to pure cellular system, in which all traffics must go through base station.

The simulation results show that considerable performance gains are achieved by enabling direct D2D data paths to replace conventional uplink-plus-downlink data paths for local data traffic between proximate devices, and by allowing non-orthogonal resource reuse between D2D and cellular downlink transmission. The initial tests demonstrate that the proposed scheduling method successfully mitigates interferences resulting from the intra-cell resource reuse.

Résumé

La communication device-to-device (D2D) est un nouvel aspect prometteur dans les réseaux LTE-Advanced. Dans les réseaux cellulaires traditionnels, les mobiles peuvent seulement communiquer avec la station de base via des liaisons montantes ou descendantes. Cette technologie échoue pour satisfaire la demande toujours croissante des différents services et applications de proximité. L'architecture innovante de D2D reposant sur les réseaux LTE est donc mise en place pour permettre une détection efficace et une communication de proximité entre mobiles. Grâce aux communications D2D, les mobiles de proximité sont capables de se détecter entre eux en utilisant la technologie radio LTE et de communiquer entre eux via un lien direct. En dehors de l'utilisation commerciale et/ou sociale de manière générale, la technologie LTE D2D est aussi attendue pour des applications en sécurité publique.

Cette thèse porte sur la conception, la coordination et les tests d'un réseau hybride avec la technologie D2D et les communications cellulaires. Les exigences de conception et les choix des fonctions dans la couche physique et MAC qui permettent la détection D2D et la communication reposant sur les réseaux LTE sont analysés. De plus, une stratégie de planification centralisée dans la station de base est proposée afin de coordonner les communications de données D2D en liaison descendante pour le réseau LTE FDD. Cette stratégie de planification combine de multiple techniques telles que le mode de sélection, l'allocation des ressources et d'énergie, afin d'améliorer les performances des utilisateurs dans une cellule. Enfin, les performances des communications de données D2D reposant sur le système LTE sont mesurées à partir d'un simulateur, au niveau système, avec un scénario comportant de multiples liens de communication. L'échange de donnée via une communication D2D est coordonnée par la station de base avec la méthode de planification proposée. Les performances du réseau hybride D2D/cellulaire ainsi obtenu sont comparées à celles obtenues par un pure système cellulaire dans lequel tout le trafic passe par la station de base.

Les résultats de simulation montrent des gains considérables en terme de performances tout en permettant un lien direct pour le trafic de données local entre mobiles de proximité et l'usage des ressources non-orthogonales entre les transmissions D2D et les transmissions en mode descendantes cellulaires. Les premiers tests montrent que la méthode de planification proposée réduit avec succès les interférences résultantes des ressources intra cellulaire.

CHAPTER 1 Introduction

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 usage prospects, design issues, coordination and testing of a hybrid D2D and cellular network.

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.

The coexistence of D2D transmission and cellular transmission has been investigated in literature studies in variant forms since some ten years ago. In some studies, D2D is used to form multi-hop link for the purpose of capacity or coverage extension [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]. In some studies, D2D works in ad-hoc manner and opportunistically accesses the licensed spectrum [Sankaranarayanan et al., 2005], [Menon et al., 2005], [Huang et al., 2008], [Huang et al., 2009]. Interests on operator-controlled direct D2D data transmission did not come out a lot until recently, when abundant usage cases of local data transmission emerge with the popularity of smart mobile devices. Klaus Doppler in the Nokia research center has leaded some pioneer works on in-band operator-controlled D2D data transmission since 2008. Their published works concentrate on different centralized interference coordination techniques in base stations, including mode selection, D2D resource allocation and power control, etc. [WIN, 2009], [Doppler et al., 2009], [Yu et al., 2009], [Janis et al., 2009], [Doppler et al., 2010]. Some initial performance analysis shows considerable throughput gain resulted from D2D mode transmission alternative to conventional UL/DL mode transmission. However in their works, the interference coordination techniques are mostly discussed under some specific layout setting, for example, in [WIN, 2009], [Yu et al., 2009], [Doppler et al., 2010], only one D2D link and one cellular link are concerned, and in [Janis et al., 2009] same number of D2D links and cellular links are imposed. The metrics for determining performance are only locally optimized and are oversimplified. It lacks performance metrics for the multi-link hybrid D2D and cellular system as a whole, and an integrated scheduling strategy which works in arbitrary network layouts.

The user needs, interworking architecture, and technique choices of D2D being integrated into advanced cellular networks were mostly left unaddressed. Scheduling method and potential performance gain were not adequately exploited. It was in this context that this thesis started in 2010, aiming at getting insight into design of D2D-enabled LTE networks on the purpose of supporting future proximity-based social/commercial services and applications.

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.

This thesis surveys the development of both in-band (operating in operator's licensed band) and out-band (operating in unlicensed band) D2D technologies, together with opportunities and requirements of integrating D2D into LTE-Advanced networks, in order to understand the functions that LTE D2D should perform and the roles that network operators should play.

The design of LTE D2D physical and MAC layer is a wide topic. Our work outlines design requirements and choices in realizing two main features: D2D discovery and D2D data communication. Options and preferred solutions to incorporate in LTE the ability for devices to discover each other directly over the air and to communicate directly between them are identified.

Furthermore, a scheduling method in base station to coordinate D2D data transmission operating in the same licensed band is proposed. We target a very challenging topology in which local traffics are high enough to cause overload to the cellular network. The scheduling method aim to increase spectral efficiency gain (and thus offload the network) by allowing spatial reuse of the licensed spectrum between D2D and cellular UEs. The proposed scheduler does not have constraint on D2D range and number of D2D pairs in a cell. Therefore it can deal with different situations: both poor and good

D2D channel conditions, dense or sparse D2D deployment. Such generic D2D scheduling design is innovative, which permits to give an insight into system performances under simulation settings that approaching reality.

We have also tested the proposed scheduler by system-level simulation in multi-link network environment. Performance metrics, such as per user average data throughput, cell spectral efficiency are analyzed, comparing to pure cellular networks.

In Chapter 2, the background of D2D technologies is firstly surveyed. Existing outband D2D technologies are presented. Focuses of literature studies on coexistence of D2D and cellular networks are also outlined, followed by the LTE D2D standardization process in 3GPP. Potential usages that might be promoted by cellular user proximity are listed. To support these usages, we analyze general functions that need to be provided by LTE D2D. Implementation challenges are also discussed.

Chapter 3 aims to identify physical and MAC layer design options and preferred solutions in order to enable devices in LTE to discover and communicate to each other directly over the air and to allow the LTE network to enable, manage, and control direct D2D discovery and communications under control of eNB. Related LTE physical and MAC specifications are firstly reviewed. Modifications and enhancements to LTE that allow incorporating D2D capability are then investigated, including D2D resource use strategies, D2D synchronization, D2D discovery procedure and interference management for D2D data communication.

In Chapter 4, a centralized scheduling strategy in eNB to coordinate in-band D2D transmission under coverage is proposed. Firstly, literature studies on in-band D2D resource coordination are reviewed, followed by an in-depth discussion on important scheduling considerations. Different approaches and their interests are compared. Then studied scenario and scheduling objectives are described. Suggested scheduling strategies, combining multiple interference coordination techniques are detailed.

Chapter 5 evaluates the scheduler proposed in Chapter 4 through system-level simulation in a multi-link network model. A general description of evaluation methodology is firstly given. System simulation approaches, as well as channel models are presented. Choices of deployment scenario, network layout, parameters and assumptions are then detailed. Performance metrics, mainly the per user average throughput and the system spectral efficiency are simulated in different settings. Finally, the chapter is concluded by a discussion.

Chapter 6 concludes the thesis and future research directions are proposed.

CHAPTER 2

Introduction to D2D technologies

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.

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.

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

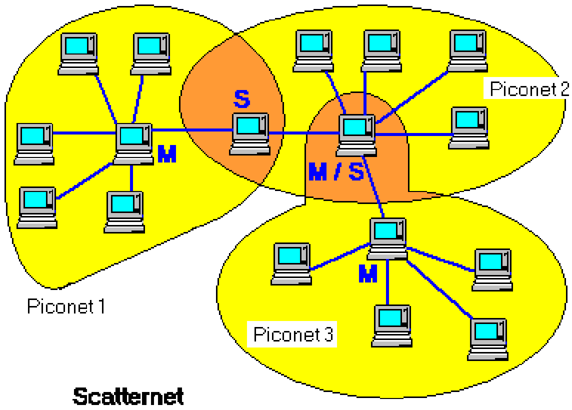


Figure 2.1 — Bluetooth piconet and scatternet structure

3.0 +HS, where the low power connection models of Bluetooth is still used, while large quantities of data can be transported over the high speed Wi-Fi radio. A new feature of Bluetooth low energy (BLE) protocols is introduced in the most recent Bluetooth v4.0, optimized for devices requiring maximum battery life instead of a high data transfer rate, for example, in favor of WBAN (Wireless Body Area Network), IoT(Internet of Things). BLE consumes between 1/2 and 1/100 the power of classic Bluetooth technology and enables new Bluetooth Smart devices (typically battery-operated sensors) operating for months or even years on tiny coin-cell batteries. Classic Bluetooth, Bluetooth high speed, and Bluetooth low energy (BLE) protocols altogether brings up prolific applications in different markets including automotive, consumer electronics, health and wellness, mobile telephony, PC and peripherals, sports and fitness, and smart-home. Bluetooth is managed by the Bluetooth Special Interest Group (SIG), which has now more than 19,000 companies in the areas of telecommunication, computing, networking, and consumer electronics. The installed based Bluetooth-enabled devices alone reached 3.5 billion in 2012 and is forecasted to grow to almost 10 billion by 2018 according to ABI research [ABI, a].

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).

Bluetooth standard is based upon a master-slave structure. One master may communicate with up to 7 slaves in a piconet (ad-hoc computer network using Bluetooth technology). Each device in a piconet can also simultaneously communicate with up to 7 other devices within that single piconet and each device can also belong to 7 piconets simultaneously. Connection of multiple piconets forms a scatternet in which devices could simultaneously play the master role in one piconet and the slave role in another. Through this topology, a Bluetooth device is capable to connect to many devices.

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.

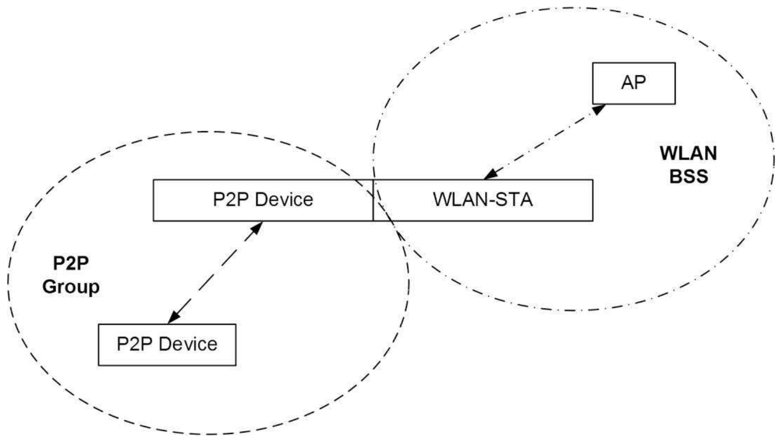


Figure 2.2 — Wi-Fi Direct network structure

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-to-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.

Wi-Fi devices will be able to form direct connection groups quickly even when an access point or router is unavailable. But different to the ad-hoc mode operation, Wi-Fi Direct resembles traditional infrastructure Access Point (AP) to Client operation, with the P2P Group Owner assuming the role of the AP and the P2P Client assuming the role of station (STA). It is rather an extension to the ubiquitous infrastructure mode of operation with dynamic configured access point. The Wi-Fi Direct certification program does not require special hardware, so some vendors may offer software upgrades. However, non-upgraded legacy Wi-Fi (except 802.11b-only) devices can also connect with a Wi-Fi Direct device by simply considering the P2P Group Owner as a traditional AP. A Wi-Fi Direct-certified device might connect to a regular infrastructure network and Wi-Fi Direct group at the same time. The performance of a particular group of Wi-Fi Direct devices depends on whether the devices are 802.11a, g, or n (802.11b is not supported), as well as the particular characteristics of the devices and the physical environment.

As part of the specification, there are multiple mandatory mechanisms that must be filled by P2P devices in the group:

- P2P Discovery

- P2P Group Operation
- P2P Power Management

The basic P2P discovery procedure consists of Device Discovery, Service Discovery (optional), and Group Formation. Device Discovery is intended to determine which P2P Devices may attempt to connect by Scan and Search mechanisms. The first step of Group Formation is to determine which device will act as P2P Group Owner, for example, by exchanging device attributes to negotiate, or by autonomous initiative. Once the respective roles are agreed, the next step is to establish a secure communication using Wi-Fi Protected Setup. The optional Service Discovery can be performed to determine compatibility information on the services offered by a discovered P2P Device before the decision of Group Formation. Variant higher layer service advertisement protocol types such as Bonjour and UPnP can be implemented.

P2P Group operation is very similar to Wi-Fi infrastructure BSS operation. We can see a P2P Group Owner as a temporary AP which starts, maintains and ends a P2P group session.

P2P power management supports power save mechanisms for both P2P Group Owners and P2P clients. Two new procedures: Opportunistic Power Save and Notice of Absence, allow the P2P Group Owner to be absent for defined periods in a P2P Group with all devices fully Wi-Fi Direct capable.

Wi-Fi Direct is by far the most competitive D2D technology threatening Bluetooth, offering similar capabilities, with higher rate and longer range. It may penetrate into many device segments (e.g. consumer electronics), gains the potential to replace Bluetooth for applications that don't rely on low energy and offer a single-technology solution for worldwide Wi-Fi users.

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.

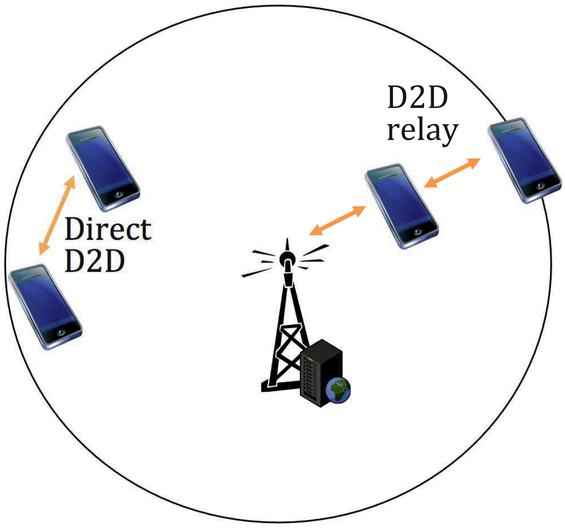


Figure 2.3 — Two forms of D2D: Direct D2D and D2D relay

In [Luo et al., 2003], the authors propose hybrid architecture with IEEE 802.11 based secondary network to increase cell's throughput. The architecture is based on relaying the traffic from base station to mobile nodes with better channel quality. Received relays then use ad-hoc network to deliver information to the destination. The authors propose several ways how to discover and select relay nodes. 3G base station selects relays based on their DL channel quality. The authors also proposed crediting system to motivate users to use their mobile nodes as relays. In [Bhatia et al., 2006], the same authors extend their work to solve the issue of multicast. In pure 3G network, the multicast throughput decreases with increase of multicast group size due to conservative strategy (uses the lowest data rate of all the receivers). By relaying, the throughput of 3G downlink multicast can be significantly increased.

In [Zhao and Todd, 2006], different relay selection criteria are compared: ad-hoc relaying with low relative interference, with best link and with shortest distance. Selection of relay based on the link quality or interference significantly overcome the selection based on the distance.

In [Papadogiannis et al., 2009], the author proposed a dynamic UE relay selection algorithm which reduce signaling and feedback by limiting the number of potential relay candidates for a specific target mobile station. Comparing to the optimal relay selection algorithm, where all the UEs in the cell are considered as candidates for a specific target mobile station, this distance based relay candidates preselecting is proved to significantly reduce the overhead without compromising performance.

In [Law et al., 2010], the performance of implementing multi-hop mobile relay in downlink cellular system is analytically computed. The author argues that for the hexagonal cellular network, by careful parametric choices, the capacity due to range extension through multi-hop relaying can exceed that of the corresponding pure cellular network by as much as 70%. The UE relays used are half-duplex and communication link eNB to relay UE and UE-UE link use separate frequency band.

In [Li et al., 2008], multihop cellular networks (MCN) are investigated as promising candidate of 4G wireless network for future mobile communications. The authors provide survey of MCN-type architectures and split into three categories: fixed relays, mobile relays and hybrid relays, and comprehensive comparison of those architectures is provided. In the latter part, economics for MCNs are analyzed and the authors claim that mobile relay is more economically feasible in the long term since they could adapt to network growth.

Very recent work covering direct UE-UE communication for relaying has been done by InterDigital,Inc [Raghothaman et al., 2011]. Their initial results shown more than 2 times gain in cell edge throughput and 50% gain in average cell throughput when compared to Reuse 1 macro deployment. It is also shown that by using UE as a relay, significant reduction in the required base station deployment density can be achieved (up to 15 times to maintain 95% coverage with 384 kbps UL service in a Manhattan Grid deployment). Moreover, power increased power consumption from relaying is compensated by lower power consumption due to shorter connection duration from higher data rates.

In another article [Zhou and Yang,] , D2D relay is triggered to balance load among neighboring cells. When one cell becomes congested, transmission between an endpoint user and its donor cell can be relayed to a neighboring cell via multihop D2D relay. Multihop route is established based on the number of hops, battery lifetime of the nodes along the route and moving direction of the mobile host. This relaying architecture allows adaptive load balancing and avoids traffic congestion by several congestion states of the base station and reporting the congestion to the mobile nodes.

Direct D2D between endpoints

The pioneer work on the in-band coexistence between primary and secondary network [Adachi T, 1998] proposed overlay system based on low power direct D2D communication between close mobile terminals. The authors show that system has advantages of frequency reuse, reduction of interference due to low power communication and reduction of battery consumption. Switching to direct communication is based on the comparison of the strength signals of base station and destination mobile terminal.

Opportunistic approach for licensed spectrum utilization based on primary and secondary network is proposed in [Sankaranarayanan et al., 2005]. The authors assume TDMA/FDMA based GSM cellular network. Secondary network operates in non-intrusive manner and does not interact with primary network. The restriction for secondary network is that it operates only over the resources which are unused by primary network. The authors also assume that every device in secondary network poses hardware that provides capability for spectrum sensing. The resources on the downlink are utilized for secondary network operation. The sensing module obtains slot boundaries and create up-to-date map of available slots. Then special MAC layer is proposed which operates over GSM MAC and allows operation in unused slots. For device discovery issue, the commonly agreed channel is proposed, over which initial handshake and selection of desirable channel is performed. It is shown that bandwidth utilization can be significantly improved by utilization of unused downlink spectrum. However, such system is purely dependent on the primary network's operation, therefore it is suitable only for best effort traffic without QoS constraints. It also requires sensing module for operation in secondary network.

In [Menon et al., 2005] impact of in-band D2D transmission on the primary network is evaluated by comparison of outage probability for underlay and overlay spectrum sharing techniques, where underlay system is evaluated also when interference is avoided by cognitive sensing over the wideband. The overlay system also assumes dynamic spectrum sensing techniques. The evaluation shows that spectrum underlay without cognitive sensing has very poor performance, thus severe impact on the primary network. They also show that spectrum underlay with utilization of cognitive radio has better performance than spectrum overlay with cognitive radio. However, in both cases when cognitive radio is used, perfect sensing is assumed. Moreover, continuous detection and tracking transmission opportunities require high complexity of transmitters in the secondary network.

In [Huang et al., 2008], the authors consider overlay of an ad hoc network onto underutilized uplink of FDD cellular system. Transmission network capacity is analyzed for case of blind transmission, where transmitters of secondary network are randomly selecting sub-channel for communication, and for the case of frequency mutual exclusion, where secondary transmitters select from subset of sub-channel which is not used by primary network. It is shown that frequency mutual exclusion outperforms blind transmission. However, blind transmission in licensed spectrum is not realistic due to huge impact on the primary network and frequency mutual exclusion requires secondary transmitters to detect sub-channels unused by primary network.

In [Huang et al., 2009], the same authors analyze cellular and mobile ad-hoc network coexistence in the licensed uplink spectrum and capacity trade-off. The authors firstly review most common methods of how to share spectrum. Then the capacity trade-off between the coexisting cellular and ad hoc networks is analyzed for spectrum overlay and spectrum underlay. For simplicity the transmission power of transmitter is fixed as well as distance between transmitter and receiver of secondary network. The authors investigate impact of interference as well as when interference cancellation techniques are employed. From the developed relation for transmission capacity is clear that capacity can be increased by decreasing the distances between secondary transceivers, by increasing the base station density and link diversity gains or by employing interference cancellation techniques.

Some recent studies on D2D communication as an underlay to a cellular network have been leaded by Klaus Doppler in the Nokia research center. In one of their proposal to [WIN, 2009], gains from D2D communication in terms of sum rate improvement in a single cell scenario is evaluated compared to a single cellular user. The overall throughput in the cell is maximized by choosing optimal spectrum sharing mode between a D2D pair and a cellular UE. The results of this study give insights on the maximum benefits in terms of overall performance that D2D underlay communication can provide. In [Yu et al., 2009] power optimization methods are proposed to mitigate interference between D2D and macro links. The sum-rate is maximized under the maximum transmit power and a set of rate constraints to the cellular and D2D users. In [Janis et al., 2009] multi-user diversity in a cell is leveraged and a resource allocation scheme for mitigating intra-cell D2D-to-DL and UL-to-D2D interference was proposed. The D2D underlay is optimized while a target performance level of the cellular network is maintained. In [Doppler et al., 2009] D2D communication session setup and management mechanism is proposed. D2D session setup using dedicated SAE signaling and supported new address format is detailed. The application (or the user) at the requesting UE needs to decide whether to prefer initiation of a D2D session or a regular session.

Remarks

In most literature works about integration of cellular and D2D communication, general description of the architecture is provided and the focus is on the theoretical anticipation of performance gain (such as system capacity, coverage extension, load balancing, etc.). However several important considerations are lacking in the current studies:

1. Performance metrics are often oversimplified, without taking into consideration the overall user satisfaction.
2. Proposed schedulers are often of limited use to some specific settings, and are not general enough to offer an adequate perception on performances that such D2D solutions might give in a real multi-link cellular system.
3. Feasibility analysis of LTE protocol layer support is mostly overlooked. Basic technical requirements and choices for interworking of two different technologies need to be analyzed.

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, objects and people; personalized services built around the contextual information obtained

- **Enhanced networking**: improved connectivity (coverage, speed, cost, etc) to network services by leveraging other local devices

a. Commercial/social use: proximity-based services might involve both mobile and fixed devices, for example, smartphones or tablets owned by private users, sensors owned by public sectors, advertising gadgets owned by retail stores, etc. Typical examples of usages include:

   - 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. A user might also do a real-time search to find momentary interested proximate services.
   - 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 (Internet 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

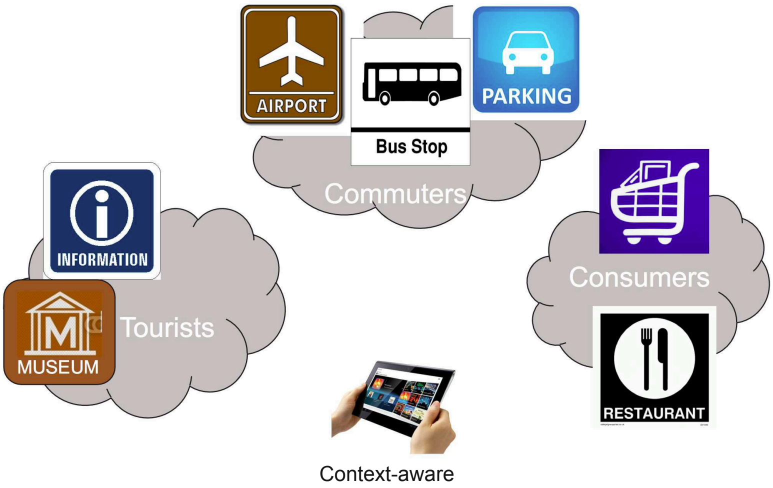


Figure 2.4 — D2D usage example: Interactive local guidance

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

have poor or no network connectivity - such as in indoor environment, at the edge of rural cell, or in the case of failure of local base stations.

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 discovery

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 information, 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 kilometer), discovery capacity (thousands of nearby devices) and distributed interference management.

Qualcomm planned to adapt FlashLinq to the 3GPP architecture using the LTE radio interface and proposed D2D in LTE-A as a study item in 3GPP. The work item called ProSe(Proximity-based Services) in 3GPP TSG SA1(Services working group) was complete in May 2013. Feasibilities study for ProSe is presented in TR 22.803 [TR2,]. The purpose is to identify use cases and potential requirements for discovery and communications between UEs that are in proximity, including network operator control, authentication, authorization, accounting and regulatory aspects. A part from Commercial/social use, it also address Public Safety communities that are jointly committed to LTE. The work in TSG SA2 (Architecture working group) is ongoing. The purpose is to evaluate possible 3GPP technical system solutions for architectural enhancements needed to support ProSe based on the SA1 service requirements. TSG RAN1 (Radio Access Network working group) study items have also been proposed for LTE Rel 12 including two subfeatures: ProSe discovery and ProSe communications, to define the necessary support in the LTE radio interface.

[TR2,] covers principle use cases and scenarios of ProSe, in which conditions, service flows and potential requirements suitable for different usage types are analyzed. This document serves as an essential guidance for D2D system design. Primary examples of use cases and scenarios concerning general commercial/social use and network offloading are summarized below. Public safety is omitted here as it concerns a lot personalized services and thus many additional use cases and scenarios. The following terms defined by 3GPP will be used in the description of D2D use cases:

- ProSe Discovery: a process that identifies that a UE is in proximity of another, using E-UTRA.

- ProSe Communication: a communication between two UEs in proximity by means of a E-UTRAN communication path established between the UEs. The communication path could for example be established directly between the UEs or routed via local eNB(s).

- ProSe-enabled UE: a UE that supports ProSe Discovery and/or ProSe Communication.

- LTE D2D: series of technologies featured ProSe capability.

Use cases and scenarios

- Restricted/open ProSe Discovery: basic scenarios for ProSe Discovery that can be used for any application. With restricted ProSe Discovery, a ProSe-enabled UE discovers another ProSe-enabled UE in proximity if has the permission of the target UE, while with open ProSe Discovery, a ProSe-enabled UE discovers other ProSe-enabled UEs without permission by the discoverable UEs. For example, the restricted scenario might apply to usage case of friend discovery in social network where the personal privacy is sensible, and the open scenario might apply to shop/restaurant advertisement, where shops and restaurants have no privacy issue and are open to be discovered by all other ProSe-enabled UEs in proximity. Potential requirements include, for example:

  - the operator's capability on dynamical control of the proximity criteira for ProSe discovery
  - the operator's capability on authorization of UE discovery operation
  - operator policy and user choice intervene in ProSe discovery and result in different results

- Network ProSe Discovery: in this use case, it is the MNO (Mobile Network Operator) which verifies that one UE has the permission to discover another UE and is in proximity of another UE. This might applies to the scenario where one UE want to discover a specific target UE. It requires that the network be able to determine proximity of two ProSe-enabled UEs and inform them of their proximity.

- Service continuity between infrastructure and E-UTRA ProSe Communication paths: in this use case, the operator is able to switch user traffic (one or more flows of the data session) from the initial infrastructure communication path to ProSe communication path and latter return back to an infrastructure path, without perceived by the users. It requires that the operator be able to dynamically control the proximity criteria (e.g. range, channel conditions, achievable QoS) for switching between the two communication paths. The system shall be capable of establishing a new user traffic session with an E-UTRA ProSe Communication path and maintaining both of the E-UTRA ProSe Communication path and the existing infrastrucutre path, when the UEs are determined to be in range allowing ProSe Communication.

- ProSe-assisted WLAN Direct Communications: WLAN direct communication can be used between ProSe-enabled UEs with WLAN capability when they are in WiFi Direct communications range, based on ProSe Discovery and WLAN configuration information from the 3GPP EPC. It requires that the switch is subject to operator policy and user consent. the operator is able to switch data session between infrastructure path and WLAN ProSe communication path. Furthermore, several use cases related to ProSe-assisted WLAN Direct Communications are proposed, including:

  - Service management and continuity for ProSe Communication via WLAN: It requires that the infrastructure network shall be able to determine whether two ProSe-enabled UEs are within WLAN direct communications range and whether the WLAN direct link can provide the necessary QoS to support the end user application. It shall ensure service continuity, and be capable of QoS requirements of all data flows when negotiating a communication path switch for a given end user application.

- Concurrent E-UTRAN Infrastructure and WLAN proximity communication: It requires that the EPC shall allow these two communication paths concurrently used between ProSe enabled UEs.
- Network Offloading via WLAN ProSe Communication:
  It requires that the EPC shall be able to request a UE to perform a path switch between the infrastructure path and WLAN direct path for some or all of the UE's traffic sessions based on the load in the 3GPP network.

- ProSe Application Provided by the Third-Party Application Developer: the operator may provide ProSe capability features in a series of APIs to third-party application developers for application development. Benefiting from the cooperation between the operator and third-party application developers, the user can download and use a rich variety of new ProSe applications created by third-party application developers. It requires that the operator's network and the ProSe-enabled UE shall provide a mechanism to identify, authenticate and authorize the third-party application to use ProSe capability features. The operator shall be able to charge for use of ProSe Discovery and Communication by an application.

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

Physical and MAC layer characteristics of LTE D2D

3.1 Overview

In the previous chapter, three principle functions: D2D discovery, D2D data communication and D2D relay, which allow LTE D2D to address potential usages, have been identified. In this chapter, the focus is on the D2D discovery function and D2D data communication function only. We aims to identify physical and MAC layer design options and preferred solutions in order to realize these two D2D functions in LTE PHY/MAC framework. However, proposing a complete PHY/MAC layer design solution is far beyond the capability of this individual thesis work. This chapter highlights design aspects related to resource use, synchronization, random channel access and interference management, which are cruxes to D2D discovery function and to D2D data communication function.

A generic design of D2D discovery and transmission procedures across all the scenarios is preferred. Three coverage scenarios can be distinguished:

- In coverage: Both D2D transmitter and receiver are under the network coverage.
- Out of coverage: Both D2D transmitter and receiver are out of network coverage.
- Partial coverage: Either D2D transmitter or receiver is out of network coverage.

It is required that in-band D2D operates under the control of network when the network coverage is available so that the impact of in-band D2D transmission to the current LTE network is manageable. That is to say, the network is able to identify, authenticate and authorize D2D UEs participating in D2D discovery, and is able to determine resources and power of direct D2D transmissions. Meanwhile, a design that allows UEs to perform D2D functions whether they are under network coverage or out-of-coverage is desired. However, as in-coverage is the main situation for both general and public safety specific scenarios [TR2,], a design considering network control is the essential start. Additional self-organization features enabling D2D functions without coverage could be built on that main D2D system afterwards. This allows simplifying implementation and specification. It is worth noting that D2D should work in inter-operator scenario where D2D transmitter and receiver locate in different operatorsâ network. The inter-operator scenario, together with the out of network scenario, implies that D2D transmitter and receiver might be originally not synchronized to each other and the initialization of D2D link should be able to act in an asynchronous fashion.

Another important requirement is that the D2D design should reuse as much as possible the current LTE physical and MAC features in order to minimize core and RF specification impacts from the integration of D2D into LTE radio access.

It is crucial to understand existent LTE physical and MAC framework in order to integrate D2D functions. Therefore in this Chapter, key LTE physical and MAC layer characteristics and procedures for both uplink and downlink transmissions are firstly reviewed. Design options and preferred solutions, for random channel access in D2D discovery, and for interference management of D2D data communication, are identified.

3.2 LTE Physical and MAC layer Specifications

In this section, LTE physical and MAC layer specifications, relevant to our consideration of D2D discovery and communication design, are reviewed.

Channel access methods are fundamentals in wireless communication system, and are tightly related to resource allocation method and interference management techniques. In section 3.2.1, Orthogonal Frequency-Division Multiple Access (OFDMA) downlink channel access method and Single-Carrier Frequency Division Multiple Access (SC-FDMA) uplink channel access method used in LTE network are presented. It is required that in-band D2D link use compatible channel access method so that the intra-spectrum interference is manageable.

In order for two entities to communicate efficiently, it is essential that the transmitter and the receiver have the same notion of time. Furthermore, OFDM-based channel access is highly sensitive to carrier frequency errors. Therefore both timing and frequency synchronization should be achieved at the initial stage of communication. An LTE UE can only be scheduled for transmission with an eNB if its transmission timing is synchronized to the eNB. In LTE, UEs synchronize its downlink timing and frequency to eNB via cell search procedure, and its uplink timing to eNB via uplink Random Access. The transmitter of synchronization signals include its identity in the synchronization signals in order to be identified by the receiver. The detailed LTE downlink and uplink synchronization procedures are presented in section 3.2.2, for a better understanding of D2D synchronization issues and D2D discovery procedure design.

Once a UE get synchronized to eNB and authenticated by the network, its downlink or uplink transmission is scheduled by the eNB. Resource assignment is based on channel estimation and is conveyed to UEs via control signaling. The concrete transmission procedure is introduced in section 3.2.3.

Section 3.2.4 presents the interference scenario in current LTE networks. Interference coordination techniques specified for macro inter-site scenario and macro-pico

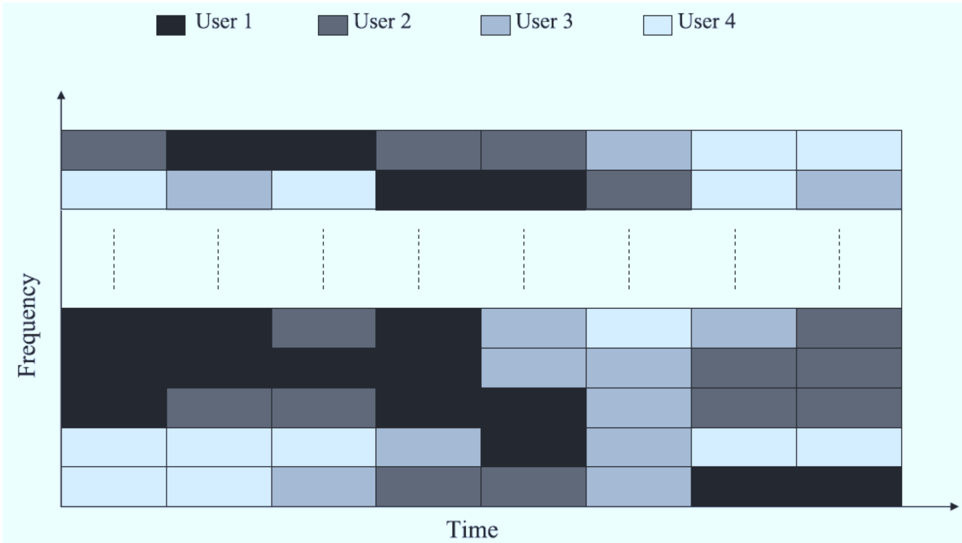


Figure 3.1 — Resource Allocation Principle in LTE

scenario are introduced.

3.2.1 Channel Access Method

A channel access method allows terminals connected to the same transmission medium to share the same communication channel. A channel access method is based on a physical layer multiplexing method, and concerns MAC layer protocols dealing with issues such as addressing, assigning multiplex channels to different users, and avoiding collisions. It is critical to achieving good system performance. The LTE downlink adopts OFDMA as multiple access method. It is an extension of OFDM modulation scheme to the implementation of a multiuser communication system. In OFDMA, subsets of subcarriers are distributed to different users at the same time so that multiple users can be scheduled to receive data simultaneously. In LTE, OFDMA is combined with time partition so that the basic unit of resources allocated to one user is a subset of subcarriers for a specific time duration. This basic unit in LTE consists of 12 continuous subcarriers for a duration of 1 ms (one slot) is termed a Resource Block (RB), which is the smallest unit of resource that can be allocated to one user. Such an OFDMA/TDMA mixed strategy used in LTE downlink is depicted in Figure 3.1.

It enables a scheduler to assign resources dynamically and flexibly, based on time-variant frequency-selective channel of each user, and thus makes it possible to achieve high spectral efficiency and QoS of each individual. The primary advantage of OFDM over single-carrier schemes is its robustness against multipath distortions. Channel equalization at the receiver can be highly simplified due to the flat channel condition over a narrow band (a subset of subcarriers) created by OFDM mechanism.

However, one of the major drawbacks of multicarrier transmission is the high peak-to-average power ratio (PAPR) of the transmit signal. Time domain signal of OFDM symbol varies strongly due to the fact that it is actually the superposition of sinusoidal waves, each corresponds to a frequency domain data symbol independently modulated

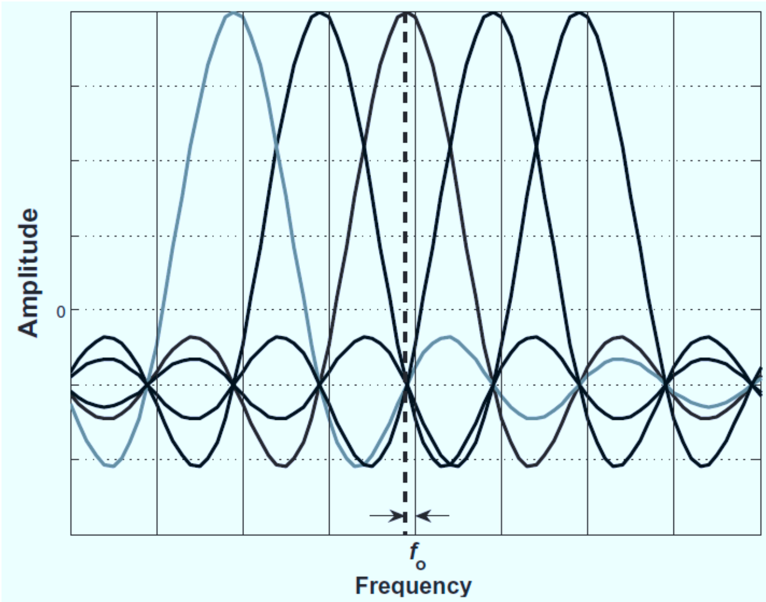


Figure 3.2 — Loss of orthogonality due to inaccurate frequency offset

by a different subcarrier (such that the amplitude of each sinusoidal wave depends on the corresponding constellation point presenting the frequency domain data symbol). The high PAPR causes inefficient power consumption and challenges amplifier design.

Therefore in LTE uplink, where UE power efficiency is demanding and costly amplifier is unaffordable, SC-FDMA featuring low PAPR is adopted as multiple access method. The SC-FDMA signal looks like single-carrier, but is actually generated in a multicarrier process very similar to OFDMA. However, unlike OFDM, in SC-FDMA the signal modulated onto a given subcarrier is not a single data symbol but a linear combination of all the data symbols transmitted at the same time instant. Therefore in each symbol period, all the transmitted subcarriers of an SC-FDMA signal carry a component of each modulated data symbol. In time domain the superposition of sinusoids has its single-carrier property, which results in a much lower PAPR.

3.2.2 Frequency and timing synchronization

The design of an OFDMA system poses stringent requirement on frequency and timing synchronization. OFDMA is highly sensitive to Carrier Frequency Offset (CFO) and time-varying channels. Carrier Frequency Offset refers to the difference between radio frequencies in the transmitter and the receiver. Frequency errors typically arise from a local oscillator frequency drifts between the transmitter and the receiver. It might also result from phase noise in the receiver, or relative movement between the transmitter and the receiver (Doppler spread). Inaccurate compensation of Carrier Frequency Offset destroys orthogonality among subcarriers and produces Inter-Carrier Interference (ICI), as illustrated in Figure 3.2.

OFDMA is insensitive to timing synchronization errors as long as the misalignment remains within the CP duration. However, Inter-Symbol Interference (ISI) and ICI

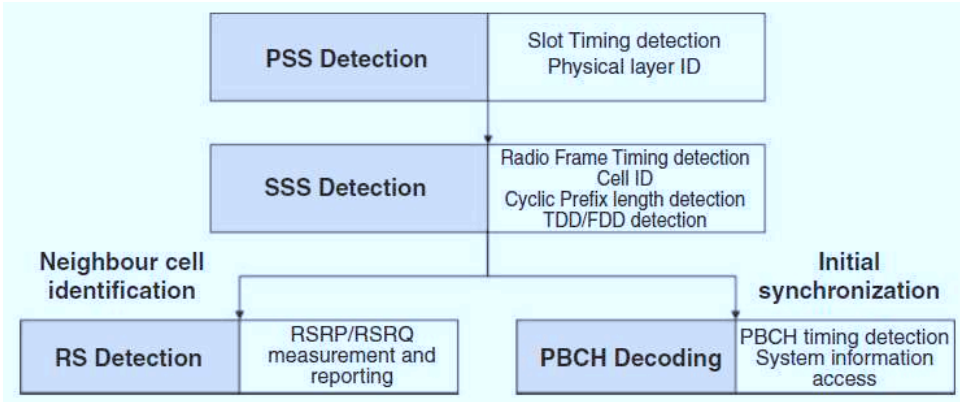


Figure 3.3 — Cell Search Procedure

may occur with long-delay-spread channels. Initial timing in LTE is normally acquired by the cell-search and synchronization procedures. Thereafter, for continuous tracking of the timing-offset, two classes of approach exist, based on either CP correlation or Reference Signals (RSs).

In LTE, the frequency and timing synchronization is accomplished by cell search procedure and uplink random access. The cell search procedure allows UE acquiring symbol and frame timing, and compensate carrier frequency errors resulted from mismatch of the local oscillators between the transmitter and the receiver as well as the Doppler shift caused by any UE motion. The cell search synchronization procedure leverages two specially designed downlink broadcast signals: the Primary Synchronization Signal (PSS) and the Secondary Synchronization Signal (SSS). These two signals not only enable the frequency and timing synchronization, but also indicate the physical layer cell identity, the cyclic prefix length and cell duplex mode (Frequency Division Duplex (FDD) or Time Division Duplex (TDD)). Depending on whether it concerns the initial synchronization or the neighbour cell identification, after the detection of these two signals, the user either decodes the Physical Broadcast CHannel (PBCH) to acquire crucial system information, or detects Reference Signals (RS) transmitted from neighbour cells for cell reselection or handover. The cell search and synchronization procedure is summarized in Figure 3.3.

The detection of the PSS has to be non-coherent, as the UE does not have a priori knowledge of the channel at the beginning of cell search synchronization. The construction of the PSS is from Zadoff-Chu (ZC) sequences, which is in particular suitable for non-coherent detection due to its flat frequency-domain autocorrelation property and its low frequency offset sensitivity. The fixed position of the PSS in a radio frame enables a UE to acquire the slot boundary timing independently of the Cyclic Prefix (CP) length.

The detection of the SSS is coherent, based on the assumption that the channel coherence time is significantly longer than the elapsed time between PSS and SSS (one OFDM symbol in FDD and four OFDM symbols in TDD). The position of the SSS in FDD and TDD is different, in addition, the CP length is unknown a priori to the UE, therefore by checking for the SSS at four possible positions, cell duplex mode and CP length can be both determined. The PSS in every subframe is the same, therefore the detection of PSS does not accomplish frame timing acquisition. The SSS in the first and second subframe alternates, enabling the UE to establish the position of the 10ms radio frame boundary.

In the frequency domain the PSS and SSS are mapped onto the central six Resource Blocks (RBs), indifferent to the system bandwidth, which allows the UE to identify the system center frequency. The downlink system bandwidth is informed by System Information (SI) carried by PBCH. PBCH is also mapped onto the central six RBs regardless of the system bandwidth as PSS and SSS as the UE have no prior knowledge of the system bandwidth.

Uplink time synchronization for a UE must be achieved in order that a UE can send uplink data or control information to eNB. Contrarily to the downlink broadcast way, the uplink received waveform is a mixture of signals transmitted by multiple users, each affected by its proper synchronization errors. Therefore signals of each user must be separated from the others in order to successfully synchronize the timing and frequency. In LTE the uplink time synchronization is achieved via Random Access CHannel (RACH) and contention is resolved by leveraging a preamble signature. The RACH comes in two forms, allowing access to be either contention-based or contention-free. In order to reduce the latency of synchronization procedure, the eNB has the option to initiate contention-free procedure in certain cases by assigning a dedicated preamble signature. Contention-based RACH is applicable in all use-cases and is initiated by a UE by randomly choosing a random access preamble signature. The Contention-based random access procedure consists of four-steps:

Step 1
The UE randomly chooses a random access preamble signature. Similar to the PSS used in downlink synchronization, the preamble signature is also based on ZC sequences.

Step 2
The eNB sent the Random Access Response (RAR) and addressed with a Random Access Radio Network Temporary Identifier (RA-RNTI), identifying the time-frequency slot in which the preamble was detected. UEs collided by selecting the same signature in the same preamble time-frequency resource whould each receive the RAR. If the UE does not receive a RAR within a time window pre-configured by the eNB, it goes to Step 1 and selects another preamble signature. The RAR conveys the identity of the detected preamble, a timing alignment for uplink transmission, an initial uplink resource grant for transmission of the Step 3 message, and a temporary Cell Radio Network Temporary Identifier (C-RNTI).

Step 3
The UE send the Layer2/Layer3 (L2/L3) message on the assigned Physical Uplink Shared CHannel (PUSCH). It carries the C-RNTI if the UE already has on (RRC_CONNECTED UEs) or an initial UE identity (the SAE Temporary Mobile Subscriber Identity (S-TMSI) or a random number). Colliding UEs are not aware of their collision, and will also collide in the same uplink time-frequency resources when transmitting their L2/L3 message.

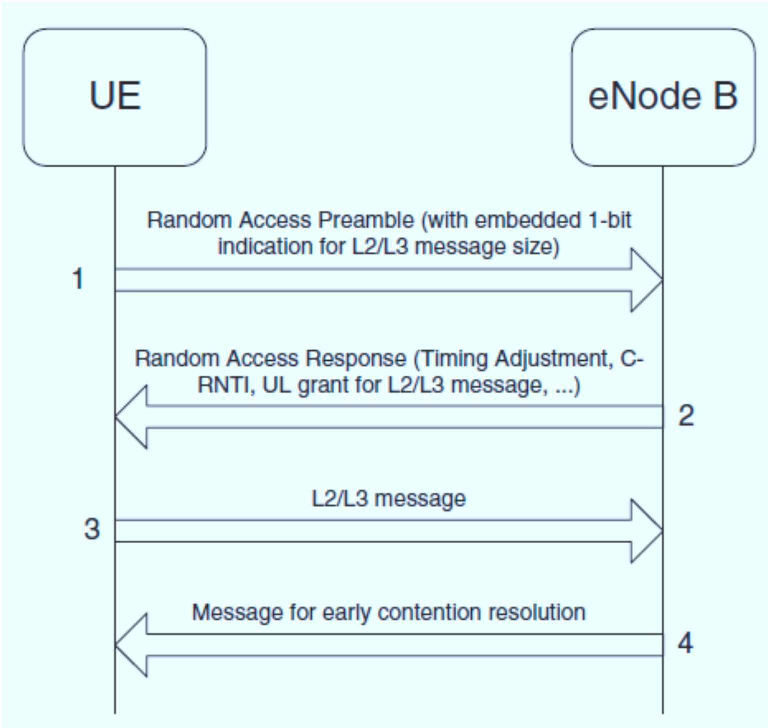


Figure 3.4 — Contention-based RACH procedure

Step 4

The contention resolution message uses HARQ. It is addressed to the UE identity (C-RNTI or an initial UE identity) whose L2/L3 message in Step 3 has been successfully decoded and is followed by the HARQ feedback transmitted by the UE which detects its own identity in the contention resolution message. Other UEs understand there was a collision, transmit no HARQ feedback, and can quickly exit the current random access procedure and start another one.

3.2.3 Transmission procedure basics

In order to communicate with an eNB, the UE must firstly identify the broadcast transmission from an eNB and synchronize to it. This is achieved by means of special synchronization signals embedded in the OFDM structure described before. In RRC_CONNECTED, the E-UTRAN allocates radio resources to the UE to facilitate the transfer of data via shared data channels. The dynamic frequency and time resource allocation is indicated by a control channel, which should be monitored by the UE. In downlink transmission, the UE estimates the channel condition based on the reference signals inserted in the OFDM structure in order to perform coherent demodulation. Similarly, in uplink transmission, coherent demodulation is also facilitated by reference signal based channel estimation. The uplink DeModulation RSs (DM-RSs) of a given UE occupies the same bandwidth as its PUSCH/PUCCH transmission and are time-multiplexed with the data symbols.

The scheduling strategy is not specified by the standard, but is left to operators'

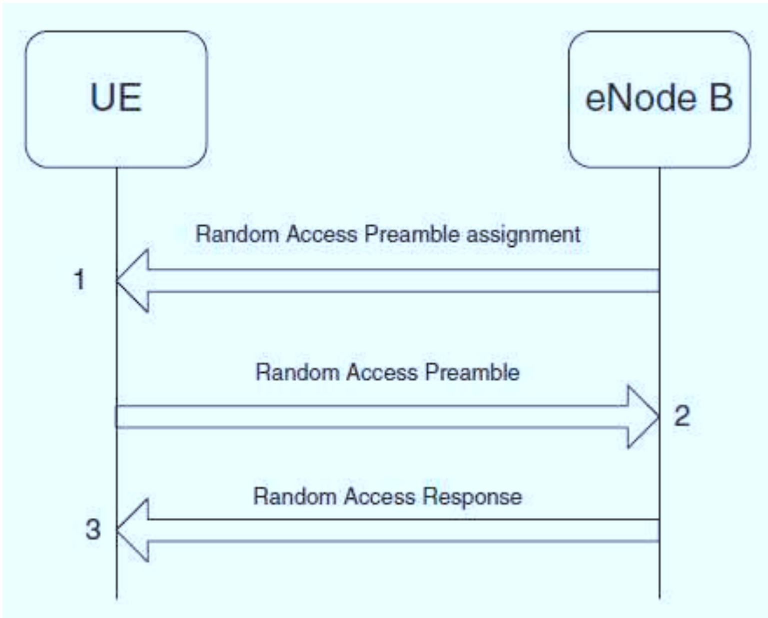


Figure 3.5 — Contention-free RACH procedure

choices. Most scheduling strategy need information about channel conditions, buffer status, priorities of data flows, interference from neighboring cells, etc.

The radio channel condition is a key factor to the UE performance. The quality of the signal depends on the channel quality, the level of interference from other transmitters, and the noise level. In order to optimize system capacity and coverage, the transmitter should try to match the modulation, coding scheme to the variations in received signal quality for each user. This technique is called link adaptation or adaptive modulation and coding (AMC). Furthermore, the radio channel condition contributes to higher spectral efficiency as the multi-user scheduling in time and frequency can take advantage of the user channel frequency selectivity.

Information about the channel conditions at the eNB is obtained in different manner in LTE downlink and uplink. In downlink, it is usually the UE which measures the instantaneous channel status and report to the network the recommended transmission configuration on the downlink shared channel. In uplink, the eNB may directly make its own estimate of the channel status by using Sounding Reference Signals (SRSs) or other signals transmitted by the UEs.

The channel status report in downlink is the recommended value based on UE estimation. The eNB's final decision is not necessarily the same. It might consist of one or several pieces of information: Channel-quality indication (CQI), representing the data rate that can be supported by the channel, taking into consideration the SINR and the characteristics of the UE's receiver. A CQI points to a modulation scheme and coding rate combination predefined in CQI table. Rank indication (RI), providing the preferred number of spatial-multiplexing transmission layers in MIMO system. Precoder matrix indication (PMI), providing the preferred beamforming pattern in each spatial-multiplexing transmission layer in MIMO system.

3.2.4 Interference coordination

Resources allocated to different users in a macro cell are usually orthogonal to avoid intra-cell interference. Main interference might come from transmitters in neighbouring cells on the same resources known as Inter-Cell Interference (ICI) and might impact the throughput performance, especially that of cell-edge users. In LTE Rel.10 heterogeneous network deployments is supported, where small cells (picocells or femtocells) overlay within the coverage area of macrocellular network. Heterogeneous deployments sharing the same spectrum enables higher spectral reuse but present more challenge to interference coordination.

In LTE Rel. 8/9, the main mechanism for Inter-Cell Interference Coordination (ICIC) for homogeneous macrocellular networks is normally assumed to be frequency-domain-based. In downlink it is possible to exchange signalling between eNBs over the X2 interference to indicate the plan of transmit power on different frequency bands. In uplink it is possible for an eNB to inform neighboring eNBs of the measurements of the average uplink interference plus noise on different frequency bands or its plan on cell-edge user resource allocation in the near future. The scheduling strategy of the eNB may impose restrictions on resource use in time and/or frequency in order to avoid ICI. In uplink, the eNB can also control the power offset for cell edge UEs in order to compensate their vulnerability to ICI.

In LTE Rel.10, time-domain enhanced ICIC (eICIC) techniques are introduced, mainly focused on co-channel interference mitigation of the control channels in macro-pico scenario. As the pico eNB has much lower transmission power than macro eNB, the interference received from the macro eNB would be significantly higher. Frequency-domain based interference avoidance mechanism is of limited benefit for the synchronization signals, Physical Broadcast Channel (PBCH), cell-specific Reference Signals (RSs) or control channels (PDCCH, PCFICH, and PHICH) as their time-frequency locations are fixed. Time-domain eICIC in LTE Rel.10 uses Almost Blank Subframes (ABSs) to reduce downlink transmission power and/or activity in certain subframes of one layer of cells in order to mitigate the interference from macro eNB towards the UEs served by the picocell.

3.3 LTE D2D PHY and MAC layer design choices

After reviewing LTE physical and MAC layer specifications, in this section we will propose D2D design choices, taking into consideration the compatibility and impacts to the current LTE physical and MAC framework. We start with resource use and synchronization issues, which are fundamental and determinative to transmission efficiency and are common to both D2D discovery and D2D data communication functions. Then design aspects of D2D discovery and D2D data communications are analyzed separately.

3.3.1 General consideration of D2D resource use

In principle, D2D may use a combination of UL and DL spectrum for FDD and UL and DL subframes for TDD. Modification on RF design of current UE devices is necessary. The problem is quite different for TDD UE and FDD UE. In TDD, the traditional half-duplex UE antenna put constraints on D2D transmission. As conventional TDD UEs are not able to transmit and receive at the same time, when UEs are transmitting in D2D mode, it cannot receive downlink signals from eNB at the same time. Therefore, UEs transmitting in D2D mode might miss important information transmitted from eNB. Similarly, in TDD uplink scenario, D2D receiver cannot transmit signals to eNB in the mean time. An advanced full duplex antenna might allow a D2D UE to transmit and to receive simultaneously on the same carrier, but can have the problem of leakage, antenna size, and high cost, etc. Therefore full duplex antenna is not a practical solution for the moment. An alternative solution can be time resource partition for cellular and D2D transmission, which effectively avoid this simultaneous transmission and reception problem, but at the expense of spectral efficiency gain. In case that spectral efficiency is a concern, it is possible to trade off scheduling complexity for spectral efficiency, for example, use semi-static time resource partition or even dynamic scheduler for resource allocation.

In FDD systems, UEs do not conventionally transmit signals on the downlink spectrum or receive on uplink spectrum. Therefore, in-band D2D requires implementations on UE RF to enable transmitting and/or receiving on an additional spectrum. In addition, the same isolation problem as what we mentioned in TDD case might also occur. RF interference can be severe when a UE receives on the DL band from eNB and transmits on the DL band to another UE at the same time, and vice versa for the UL band. Implementation of full duplex D2D is technically difficult as the requirement of RF isolation between Tx and Rx chains may be quite severe. Alternatively, D2D resource could be scheduled to avoid concurrent transmission and receiving on the same band.

For in-band D2D transmission, it is possible to allocate dedicated resources, or to allow overlapping resource use between D2D transmission and cellular transmissions. In dedicated resource use, a certain part of licensed spectrum is reserved uniquely to D2D transmission, and therefore interference between D2D and cellular transmissions is avoided. But this method makes worse use of spectrum than overlapping resource use, as it does not adapt to D2D load in a cell.

In overlapping resource use, interference avoidance is quite challenging. It is possible to avoid intra-cell interference by, for example, centrally assigning orthogonal resources to D2D and cellular UEs in the same cell. However, avoidance of inter-cell interference between D2D and cellular transmission in neighbor cells requires cooperation of neighboring eNBs to jointly perform inter-cell interference coordination, which can be highly complicated. The performance gain of the overlapping resource use scheme therefore largely depends on the applied interference management techniques. Note that resource allocation and many other interference management techniques are effective only when transmissions are synchronized. The D2D synchronization issues will be analyzed in the following section.

3.3.2 Synchronization

Synchronization is fundamental and determinative to transmission efficiency. Synchronized communication allows efficient spectral reuse with interference coordination. In synchronous mode, energy consumption of transmission is much lower.

As introduced before, transmission of data and control channels in current LTE system is basically time-synchronized. Multi-carrier modulation, such as OFDMA or SC-FDMA, requires not only time synchronization but also tight frequency synchronization. Typically only synchronization errors of up to a few percent of the subcarrier spacing are tolerable in OFDM systems. Therefore if D2D uses multi-carrier modulation as in LTE DL and UL, tight time and frequency synchronization are required in order that interference can be coordinated.

LTE synchronization is achieved through unsynchronized procedures and channels. DL synchronization is conducted by eNBs broadcasting PSS/SSS every 5ms. "Always on" DL synchronization is indispensable so that UEs will not miss important system information and UEs receive DL data in an efficient way. On the contrary, UL synchronization is conducted in an "on demand" fashion. A UE that is inactive for a certain period of time is allowed to lose uplink synchronization to save UE battery and radio resources. It resumes UL synchronization procedure through random access channel PRACH when it has signals to transmit.

To support D2D services in LTE, new channels, signals, and procedures need to be developed and it is fundamental to consider which D2D channel/procedure shall operate in a synchronous way, and which ones can operate in an asynchronous way.

D2D discovery is required to work in cellular networks where the cells are not time-synchronized (e.g. inter-operator discovery), and in scenarios where there are only partial or no network coverage. It is necessary that discovery is able to operate in an asynchronous fashion. Other unsynchronized operation might include control signaling procedures for setting up connections or triggering a session between connected entities.

It is preferred, however, that D2D discovery and control signalling procedures mentioned above can perform in a synchronized fashion whenever they are allowed, so that performance advantages of synchronous transmission can be fully exploited. The method to achieve "always on" synchronization for D2D UEs will be explained afterwards.

D2D device discovery can be followed by direct communication if necessary, which includes a session setup and resource assignment procedure. It is desired that time synchronization be achieved before session setup, for example, in D2D discovery phrase, so that direct communication can take full advantage of synchronous transmission (resource and energy efficient, interference controllable, etc.).

Time synchronization techniques can be classified into two categories: global synchronization and local synchronization. Global synchronization requires that all the UEs in the network agree on the same time and each UE tries to minimize its offset with respect to all other UEs. Global synchronization has two approaches: synchronize directly to a common global reference such as GPS, and synchronize via network-wide message exchanging. Neither of these two approaches is suitable for LTE D2D. In the first approach, time synchronization is accurate, but the implementation cost of hardware receiver to decode the out-of-band clock signal (e.g. a GPS) is high. In addition, GPS signals have poor penetration through walls and therefore, this is not a suitable solution for indoor UEs. In the second approach, high messaging overhead might be incurred, and synchronization accuracy might be poor in large-scale network. UEs need to regularly monitor the synchronization channels to acquire their neighborsâ synchronization references. Due to user mobility and time-varying topology, convergence might be slow. Furthermore, such scheme would have large impact on LTE specifications and UE implementations. Finally, global synchronization assumption is not compatible with the requirements for D2D to be operated between cells and different operators, which are typically not globally synchronized.

Different from global synchronization, in local synchronization, UEs are not synchronized to a unique common reference, but to a local reference. Since D2D communication will be local, local synchronization is more suitable where a UE reduces the offsets with respect to the neighbors. The local reference can be the cellular network, a UE cluster head (device acting as local synchronization master and broadcasting D2D synchronization signals), or one of the devices in a D2D pair. The cellular network should have higher priority as a synchronization reference as it is more reliable. In case that a UE is out of coverage, it can either send request for synchronization relaying, or start broadcasting own synchronization signals.

Local synchronization can either be performed in an "always on" fashion or in an "on demand" fashion. In "always on" fashion, a UE continuously tracks the reference timing and adjusts its timing error, whereas in "on demand" fashion, a UE synchronizes to a local reference node only when needed (e.g. synchronize to a target UE when a D2D communication channel is going to be established). The "always on" fashion might lead to more efficient D2D discovery. For instance, if D2D UEs have a common notion of time, they can broadcast and detect D2D discovery signals in assigned time resources. This organized D2D discovery activities could be much more efficient in resource use and UE battery life than random unsynchronized D2D discovery.

In order to take advantage of efficient synchronous transmission, it is preferred that D2D UEs keep synchronized to an available local reference node whenever they are in coverage of a cellular network or a UE cluster head. The "always on" synchronization can be achieved by letting local reference nodes regularly transmit synchronization signals. The design challenge lies in timing inconsistency resolution. Interference can occur when asynchronous local reference nodes transmit synchronization signals simultaneously. Decoding time multiplexed synchronization signals can be difficult. If these local reference UEs are under the network coverage, it might be desired that the network coordinates the timing error between different local reference UEs in the cell to avoid interferences from unaligned synchronization signals. For example, the network can allocate to each reference UE the resource, the power and the period for D2D synchronization signal transmission. In order to limit signaling overhead, the coordination can function in a semi-persistent way. The resource reserved to different local reference UEs can be time-division multiplexed or frequency-division multiplexed. eNBs can further assign to each reference UE the synchronization signature that should be transmitted in order to avoid collision. In LTE, initial synchronization signals PSS and UL random access preambles are both constructed from ZC sequences, which can be recovered from multiplexed signals due to its flat frequency-domain autocorrelation property and its low frequency offset sensitivity. ZC sequence enables low receiver complexity for decoding and is suitable to be reused to construct D2D synchronization signals. Reusing ZC sequence structure reduces costs on UE RF modification.

On the other hand, if local reference UEs are out of the coverage of the network, timing inconsistency between neighbouring reference UEs should be resolved by additional protocols, otherwise interference could be a problem.

Another constraint in synchronization signal design is the potential high power consumption on the reference UE side. In LTE, synchronization signals are broadcasted by eNB every 5ms, which would be a drain on the UE battery if D2D synchronization signals are broadcasted so often. A low duty cycle should be used to conserve UE power.

3.3.3 D2D discovery

To fulfill the requirements for the purpose of D2D discovery over the air, two functions are essential:

1. Proximity detection: UEs can be aware of the existence of other nearby UEs supporting D2D.
2. Identity detection: UE can detect the identification of nearby UEs supporting D2D.

The procedure of D2D discovery generally starts with proximity detection, followed by identity detection. To realize proximity detection, an obvious solution is to apply a scan/search mechanism using beacon sequences, as used in other D2D technologies, e.g. Bluetooth and Wi-Fi Direct. A UE, which is willing to be detected by nearby UEs, can broadcast beacon sequences. As the detection of beacon sequences can be the first contact of two D2D UEs, and as D2D transmitter and receiver might be originally unsynchronized (e.g. in different operatorsâ network, or in out-of-network scenario), UEs must be able to decode asynchronous beacon sequence. It is preferred that synchronization can be achieved through beacon sequence at the initial stage of D2D discovery so that subsequent messages can benefit from synchronized transmission. A structure similar to RACH preamble in LTE UL synchronization can be applied to beacon sequence design if SC-FDMA is used for D2D, or PSS/SSS like synchronization signals can be applied if OFDMA is used for D2D.

After the transmission of beacon sequence for proximity detection, there are two ways to convey UE identity associated with the beacon sequence: either by transmitting a subsequent message containing its identity or via network signalling. In the latter method, UEs report their detected beacon sequences to the network, and the network may inform UE the corresponding identity by higher level signalling. However, this method incurs additional overhead and power consumption. Moreover, if either of the discovering and discovered UEs is out of network coverage, special signalling mechanism needs to be designed for identity detection. For example, either the out-of-coverage UE tries to get access to network through UE relay, either an alternative UE-UE identity exchange mode is designed for out-of-coverage case. On the contrary, the first method offers a network coverage independent discovery solution and it simplifies signalling design. Both proximity detection and identity detection are based on discovery signal, therefore inquiring of the identity and service related information from the network could be avoided. It will be interesting to investigate if the structure of transmitting a beacon sequence plus a subsequent message can offer a universal solution for all use cases and discovery types.

Due to network dynamics such as UE mobility, UE's turning on/off, etc., the set of UEs in proximity of a UE can change over time. UEs should regularly perform detection in order to update its knowledge of proximate UEs. UEs that want to be discoverable need to regularly transmit discovery signals. In order to allow an efficient discovery, a UE which wants to participate in discovery should be able to perform discovery whether it is in RRC_CONNECTED state or RRC_IDLE state. New RRC states may need to be defined with respect to discovery. The design should scale to allow large number of UEs to participate in discovery.

Full duplex D2D is excluded due to the self-interference problem and high cost. Half duplex D2D operation is assumed, where a UE transmitting discovery signals can not receive discovery signals transmitted by other UEs. This leads to the need of arranging transmission and receiving turns in a way that UEs have the possibility to detect other UE's signal in a reasonable time. The most power efficient arrangement will be that half of the UEs in a group are transmitting while the other half is listening on one time instant, and on another time instant, the compositions of the transmitting and receiving groups are changing in order that two UEs will not always transmit at the same time and fail to detect each other. The recomposition of the transmitting and receiving groups can be randomly decided by each UE on its own, or under the network control. The latter is evidently more resource efficient. Furthermore, the number of UEs that can transmit simultaneously depends on the multiplexing method and available discovery resources on each time instant.

The resource use of D2D discovery signal is a key design factor and can be decomposed into several design choices:

1. Whether D2D uses dedicated resources or overlapping resources with cellular transmissions.

2. Whether D2D operates in DL or UL resources.

3. In case of dedicated resource use, how to multiplex D2D discovery signals with cellular transmission.

4. How do multiple D2D links multiplex.

As mentioned in section 3.3.1, if D2D uses dedicated resource, interference from D2D transmission to cellular transmission could be avoided, whereas if D2D uses overlapping resources with cellular transmission, interference management can be challenging. Asynchronous discovery signals transmitted from D2D UEs out-of coverage or from D2D UEs belonging to other operatorsâ networks might beyond the control of an eNB.

Therefore D2D discovery signals using overlapping resources might severely interfere cellular transmission. As a result, dedicated resource use is preferred in order to protect cellular communications.

D2D can operate in both UL and DL resources. However, using UL resources only has several advantages. Firstly, existing LTE UE RF transceiver can be reused and implementation cost can be saved. Secondly, regulatory constraints in some countries obstruct UEs in FDD deployment from transmitting on the DL band. Therefore D2D discovery using UL band in FDD system and UL subframes in TDD system is preferred.

When operating in UL resources, D2D and UL transmission can either be frequency multiplexed, or time multiplexed. Frequency multiplexing implies that discovery resources are spread out in time, and thus UEs participating in discovery need to be awake for a longer duration, which leads to inefficient power consumption. Time multiplexing is efficient for receiver energy consumption, for example, some subframes are reserved for D2D discovery and PUSCH does not appear in these subframes.

A UE participating in discovery is often interested in discovering all the UEs in proximity. The signals received from multiple UEs can be time multiplexed, frequency multiplexed or code multiplexed.

- Code multiplexed discovery signals are vulnerable to near-far problem. The received discovery signals from D2D UEs located far from the detecting UE might be of much lower power than those from D2D UEs located nearby. As a result, low-power signals could be hardly recovered from the mixed signals. Therefore code multiplexing is not suitable for D2D discovery signals.

- Time multiplexing is resource inefficient. We have proposed previously that to save energy, D2D discovery resources should not disperse in time, and therefore it is preferred that discovery resources rather spread out in frequency, for example, some subframes are reserved for D2D discovery, in which PUSCH does not appear. In another word, the reserved resources for D2D discovery will be narrow in time and large in frequency. As a result, time multiplexing is resource inefficient as it can serve only a few D2D transmitters, which can not satisfy the large-scale discovery need. Meanwhile the total band is allocated to each D2D, which is more than necessary as discovery signals contain very few bits.

- Frequency multiplexing is more suitable for large-scale discovery activities than time multiplexing and the near-far problem is less severe than code multiplexing. However, decoding parallel signals increase the receiver computational cost and the dynamic range of the receiver limits the number of beacons that can be successfully detected in the same subframe.

The proposed resource use scheme is illustrated in Figure 3.6.

A network-assisted D2D discovery procedure (Figure 3.7) can be described as follows:

1. eNB makes semi-static resource reservation for discovery activities, and broadcast it to all the UEs in the cell. UEs are therefore informed of the resources in which they could detect discovery signals.

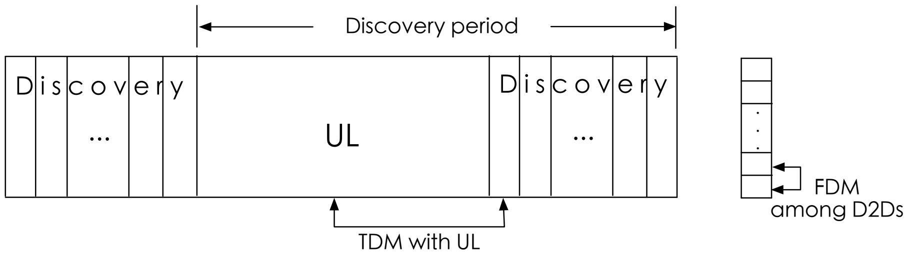


Figure 3.6 — Possible design of discovery resource use

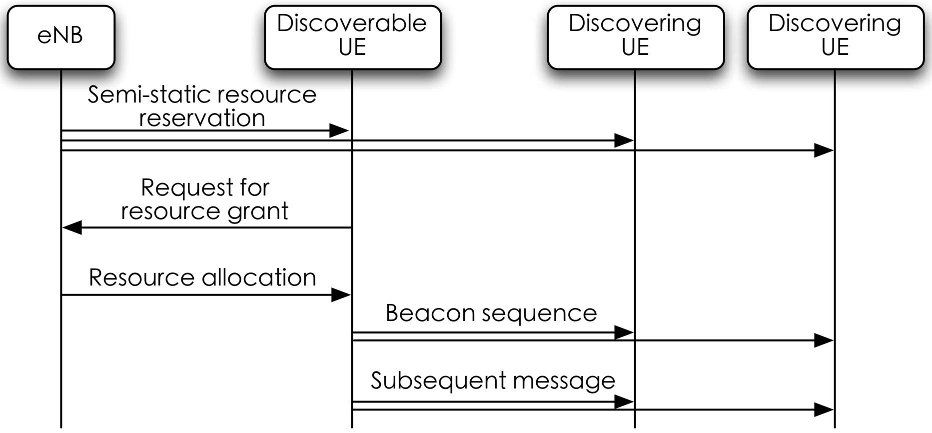


Figure 3.7 — Network-assisted D2D discovery procedure

2. UEs, which are willing to be discovered, request for resources grant.

3. eNB dynamically assigns resources to each individual D2D UE which has requested for resources.

4. UEs transmit their beacon sequence and subsequent messages in allocated resources, in order to be detected and identified. Other UEs listen to discovery signals on reserved resources.

3.3.4 D2D data Communication

Contrary to D2D discovery signal, which contains only a few bits, D2D data traffic often involves data streaming, local gaming, etc., and thus can be much heavier. In addition, the total traffic varies a lot in time. Therefore dedicated resource use is inefficient for D2D data communication. Overlapping resource use with cellular transmission is highly desired in order to make better use of the scarce licensed spectrum.

The key problem in overlapping resource use is interference management. Most importantly, interference from D2D to cellular transmission should be strictly controlled by the network in order to protect cellular transmission when D2D UEs are in coverage or in partial coverage. Management of inter-D2D interference is also necessary for efficient D2D data Communications. In LTE, intra-cell interference is managed by an

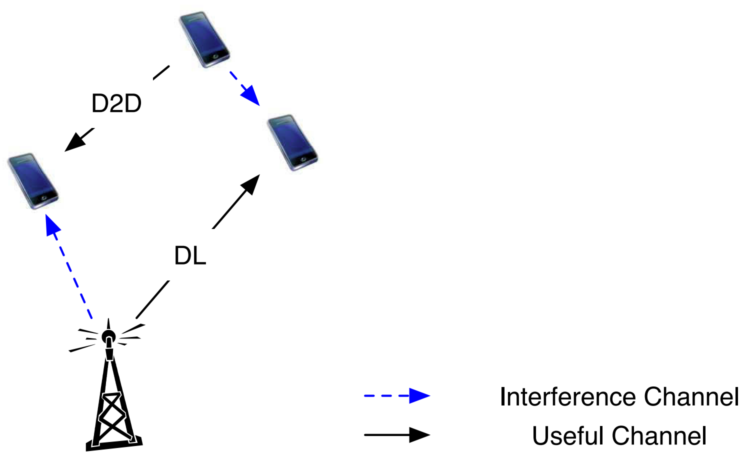


Figure 3.8 — Near-far problem in hybrid network with overlapping resource use

eNB by orthogonalizing the resources allocated to UEs whereas inter-cell interference is naturally alleviated by associating UEs to the strongest eNB.

When D2D using overlapping resource is introduced in a cell, the interference scenario becomes much more complicated. The prominent near-far problem might occur, as a receiver is not necessarily closer to its corresponding transmitter than to other transmitters in network, as illustrated in Figure 3.8. This near-far problem also exists in LTE small cell. For example in femtocell case, macrocell UEs may experience large interference when they move close to closed subscriber group HeNBs (CSG-HeNBs). In picocell case, Cell Range Expansion (CRE) enables higher user offloading from macrocell eNodeBs on to picocells, by requiring UEs preferentially select a picocell eNodeB even when it is not the strongest cell. Therefore the UEs connecting to the picocell eNodeB with large-bias CRE can suffer from severe interference from the macrocell eNodeB since the received signal power of the macrocell eNodeB is larger than that of picocell eNodeB for such UEs.

In small cell case, a low-power node has certain autonomy to allocate a group of carriers to its subscribers within its coverage. Interference is mostly controlled by coordinating lower-power nodes and high-power eNBs (advanced ICIC techniques), in resource allocation and power control. While in D2D case, both D2D resources and power should be under the networkâs control in order that the coordination between hybrid macrocell and D2D communications using overlapping resources is achieved and near-far problem is avoided.

To coordinate the hybrid communication and to achieve efficient resource reuse, we identified four techniques that can be used.

1. Resource allocation: Resource can be orthogonal between D2D and cellular transmissions, and/or among D2D transmissions in order to alleviate intra-cell interference. However, the spectrum might be underutilized, which leads to suboptimal system performance. Intra-cell resource reuse based on location information or SINR estimation might lead to an optimal use of resources.

2. Power control: Power control is another key elements to manage interference and to

solve the near-far problem. Power control is also applicable to cases where network control is not available.

3. HARQ: HARQ is a retransmission mechanism, which can enhance D2D performance in a spatial reuse scheme by simple repetition of D2D transmission in multiple subframes. Useful signal energy is accumulated at the D2D receiver and D2D transmission range is extended. HARQ is especially beneficial to D2D transmissions out of network coverage, where interference can be severe, and required transmission range of public safety applications can be long (at the order of kilometers).

4. Mode selection: mode selection allows a soft switch between D2D mode and conventional UL/DL mode communications in order to achieve efficient resource use, which should be decided by eNB.

Usually eNBs are the main entities to perform coordination, and the central coordination in eNBs requires signaling support, for example, reports of channel measurement, assignments of resources and power, etc. We can distinguish three levels of centralization.

- Fully centralized: In LTE and other cellular technologies, the operation of mobile terminal is fully controlled by the network. Fully centralized control over D2D data Communications implies that eNB is responsible for all functions that relate to air interface parameters such as transmission mode, resource allocation, power control, feedback mode, etc. The centralized coordination optimizes the usage of spectrum resources and minimizes the interferences as QoS of each D2D link is controlled. It is suitable for scenarios where a small number of D2D UEs communicate with each other over long time period. However, it does not scale well. As the amount of D2D pairs increases, the coordination complexity and signaling overhead may become unaffordable.

- Partly centralized: In this design option, a part of the eNB functions is delegated to UE terminal. For instance, the eNB still performs major control functions such as mode selection, resource management, etc. But the control of each particular D2D transmission is left to UEs, with the necessary configuration and assistance information provided by the network. In case that the D2D density is high, this approach is more attractive than a fully centralized approach as it scales well and may substantially reduce system overhead and eNB design complexity without necessarily sacrificing performance. The drawback of this partly centralized design is that it cannot be directly applied for out of network coverage scenario, similar to fully centralized approach.

- Distributed: This design option assumes that the channel access and interference control functions are implemented at the UE side. It may require election of a cluster head or coordinator node (as in some already implemented distributed protocols: Bluetooth, Wi-Fi Direct, etc.). It requires no network assistance, instead, it uses contention-based protocols which implies low efficiency in resource

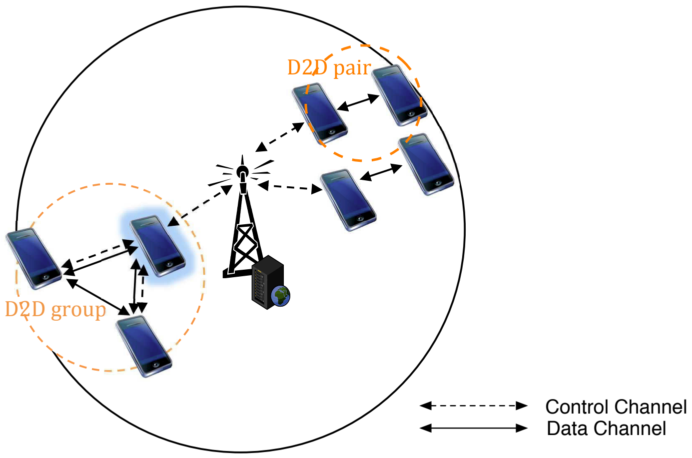


Figure 3.9 — Partly-centralized D2D resource assignment on group-basis VS. fully-centralized D2D resource assignment on pair-basis

use and weakness in interference control and collision resolution. Therefore when network node is available, distributed protocols should be avoided. While in out-of coverage case, this is the only way in which D2D can function.

It can be seen that the choice of centralization level should depend on D2D deployment. When network nodes (eg. eNBs) are absent, distributed control of D2D data communication is the only way to work. Whereas centralized control is preferred when network nodes are available. In the scenarios where a cell contains only a small number of D2D UEs, full-centralized control over each D2D pair might be the most convenient choice. On the other hand, if D2D density is high and D2D traffic is opportunistic, partly centralized coordination can be much more efficient than fully centralized coordination. We propose partly centralized resource allocation scheme where eNBs assign resources to D2D UEs on group basis rather than on pair basis.

Contrary to fully centralized coordination, where resources are assigned by eNB to each UE, the proposed partly centralized resource allocation takes two steps. In the first step, a set of resources is assigned by eNB to a local D2D cluster head. In the second step, the D2D cluster head decides how to share the resources among D2D links in the cluster. Resources assignment on group basis can be very practical in groupcast scenario or in hotspot areas and the two-step allocation method can substantially reduce the eNB signalling overhead. The difference of group-based and pair-based resource allocation scheme is illustrated in Figure /reffig:D2Dgrouppair.

3.4 Conclusion

In this chapter, physical and MAC layer design requirements, options and preferred solutions for a good function of D2D discovery and D2D data communication in LTE networks are discussed.

Our study concentrates on design aspects of resource use, synchronization, random channel access and interference management, which are most essential to D2D discovery and D2D data communication. Relevant LTE characteristics and procedures, including channel access method, frequency and timing synchronization, transmission procedure basics, and interference coordination methods, have been firstly reviewed. The impact on current LTE physical and MAC layer specifications has been taken into consideration in the design of LTE D2D. The reuse of existing LTE characteristics has been favored.

The main contribution of this chapter is summarized as follows:

- General consideration of D2D resource use is discussed. We investigated necessary modification on UE RF design to support D2D transmission and consequent constraints that might be put on D2D resource use in both TDD and FDD systems. Dedicated and overlapping resource use between in-band D2D and cellular transmission are compared. Advantages and disadvantages of each resource use scheme are distinguished.

- Synchronization choices, which are determinative to transmission efficiency, are investigated. Advantages of synchronized communication are pointed out and we proposed that D2D channel and procedure operate in synchronized way whenever they are allowed. Possible techniques to realize a synchronous D2D system have been analyzed and we proposed that D2D UEs achieves "always on" synchronization to a local reference node in order to take advantage of efficient synchronized transmission. Relevant issues, such as choices of local reference node, synchronization signal structure, and power consumption, are discussed.

- Design of D2D discovery signal structure, discovery resource multiplexing, and discovery procedure is proposed. A beacon sequence structure similar to LTE RACH preamble is proposed to realize proximity detection. Two different way to convey UE identity are compared. Transmitting a message containing UE identity via a direct D2D link, associated with the beacon sequence, is a more generic design comparing to using network signalling to convey UE identity as it can work also in out-of-coverage case. Different discovery resource multiplexing methods are compared. A possible solution is proposed in which: dedicated resources for D2D discovery are reserved periodically in LTE uplink resources, dedicated resources for D2D discovery consist of continuous subframes in which PUSCH does not appear (time multiplexing with PUSCH), and in these reserved discovery subframes, D2D links are frequency multiplexed. Finally, a network-assisted D2D discovery procedure is proposed in case of in-coverage.

- Interference coordination techniques are proposed for D2D data communication using overlapping resource with cellular transmission. Overlapping resource use is preferred for D2D data communication in order to make better use of the scarce licensed spectrum. Near-far interference problem that can be caused by overlapping resource use is investigated. Four techniques are put forward to coordinate the hybrid D2D and cellular communication and to achieve efficient resource reuse. Coordination with three different centralization levels is discussed: fully centralized, partly centralized, and distributed. We propose that the choice of centralization level depends on D2D deployment. Furthermore, a deployment-dependent resource allocation strategy is proposed for D2D data communication.

CHAPTER 4 Coordinated Scheduling of in-band D2D data communication

4.1 Introduction

The purpose of this chapter is to propose a scheduling method in eNB to coordinate in-band (use licensed spectrum) D2D data transmission. The ultimate aim of the scheduling is to fulfill the expectations of all the users in LTE network, whether they are transmitting in D2D mode or in UL/DL mode.

As mentioned in the previous chapter, the key problem in D2D data communication is 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.

The most essential technique to manage interference is resource assignment. How to efficiently allocate resources to users in a cellular system with hybrid modes of transmission is the crux to an overall user performance gain. A scheduling algorithm tends towards the best possible performance, while do not imply severe complexity and signaling overhead need to be designed.

In section 4.2, literature studies on in-band D2D resource coordination is firstly reviewed, followed by an in-depth discussion on important scheduling considerations. Section 4.3 describes assumed scenario in our study and scheduling objectives. A complete scheduling solution 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, the complexity is reasonable.

A simplified admission control mechanism is taken by articles [Doppler et al., 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 distributed way, using contention-based CSMA/CA protocol in D2D MAC layer. A certain 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 with UL 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 informations 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 from D2D 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 to D2D 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 potential D2D 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 in D2D 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 between D2D mode and UL/DL mode. Authors of [Xu and Wang, 2012] distinguish two 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] propose that D2D mode 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 [Yu et al., 2009], [Doppler et al., 2010] contains only one D2D link and one cellular 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 subbands. Both cellular UE and D2D UE are assigned to a single subband 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.

4.2.2 Considerations on scheduling hybrid D2D and cellular transmissions

In section 4.2.1, scheduling methods of in-band D2D transmission in literature studies have been reviewed.

- Different choices on how the cellular spectrum is reused by D2D links are proposed.

  - Concerning the centralization level of eNB's control over D2D resource management, fully centralized, partly centralized and distributed D2D resource management have all covered by literature studies.
  - Concerning the way multiple D2D links access the spectrum, SINR-based admission control algorithm is mentioned. Frequency/time multiplexing way on per-cell basis is also investigated.
  - Concerning the D2D usage of spectrum, UL resources only or DL resources only or both UL and DL resources could be possible.
  - Concerning the selection of transmission mode, both large-scale parameter dependent and small-scale parameter dependent algorithm have been suggested. With the former, the decision of whether using D2D mode or UL/DL mode is usually made before D2D link establishment, whereas with the later, the mode selection is performed dynamically, as the channel condition changes.

- Many have proposed power control techniques associated with resource allocation to mitigate the interference resulted from resource reusing. The focus is mostly on the control of interference from D2D transmission to cellular transmission. Some has also investigated in the techniques to control interference from cellular to D2D transmissions.

- Resource allocation is usually optimized according to targeting performance metrics. Some has proposed aggregate throughput gain as performance metric. Yet some consider D2D as secondary users, and macro links are scheduled firstly ignoring D2D users, so that cellular and D2D links are optimized separately.

However, it still lacks a mature solution to efficiently allocate resources to users in a cellular system with hybrid modes of transmission to achieve overall user performance gain. To fulfill this goal, some important scheduling considerations that are not fully addressed by the literature works are discussed below.

1) System performance metrics
   The general goal of scheduling algorithm in eNB is to allocate the RBs and transmission powers for each subframe in order to optimize a function of a set of performance metrics, for example maximum/minimum/average throughput, maximum/minimum/average delay, total/per-user spectral efficiency or outage probability. In a practical system, the purpose of scheduling is typically to fulfill the expectations of as many users of the system as possible, taking into account the QoS requirements of their respective applications [Stefania Sesia, 2011]. For full-buffer traffic model, well-known performance metrics include the maximum channel to interference ratio (MCI) [Pokhariyal et al., 2006], the proportional fair (PF) [Norlund et al., 2004], earliest deadline first (EDF) [Chiussi and Sivaraman, 1998], etc. MCI exploits the frequency-selective channel to maximize the sum of the transmitted data rates to all users. It is a typical example of opportunistic scheduling. While PF scheduler (PFS) pays also attention to latency, and ensures a minimum data rate for each user rather than maximizes total data rate. It makes a flexible compromise between opportunistic scheduling and fair scheduling, and is often

considered as a practical scheduling criteria. EDF is designed to deal with realtime QoS constraints regardless to the momentary user's channel quality. In a hybrid D2D cellular system, cellular transmission quality should still be maintained in priority. Introduction of D2D mode should not impair the fulfillment of cellular UE expectations. Therefore, eNBs should take control over D2D resource management to limit interference impact resulted from D2D transmission on cellular transmission, as well as to limit inter-D2D interference. It is generally difficult to solve an optimization problem that jointly describes the D2D and cellular performance metrics. To simplify the computational complexity, separability of optimization problems for D2D and cellular resource allocation is usually desired.

Optimization problems reflecting a global view of system performance is often lacking in the literature studies of hybrid D2D and cellular network. For example, several articles propose to allocate D2D resources according to an aggregate throughput gain in a resource block, which only targets a local optimization criterion, and therefor fail to achieve optimal performances in a system point of view. The concrete optimization problem formulation depends on the D2D traffic type and specified scheduling objectives.

2) A generic scheduling strategy
A real system contains multiple links and multiple cells, and both good-conditioned links and bad-conditioned links. Therefore scheduling method should be generic enough to deal with arbitrary network layout (e.g. with random number of links) and arbitrary channel conditions, instead of being limited to some specific cases. Such scheduling design is challenging when mutual interference from spatial resource reuse by multiple links in the system is taken into consideration. In LTE Rel. 8 and 9, frequency domain based Inter-Cell Interference Coordination (ICIC) is used to jointly allocate resources for users in neighbouring macro cells. With the integration of in-band D2D into the LTE cells, the spectrum is more densely reused, with more spontaneous reuse topology, and thus the scheduling becomes more complicated.

In addition, the D2D architecture introduces a new scheduling choice, which allows flexible switch between D2D mode and conventional UL/DL mode. Unlike in current LTE system, where the association of UEs to base stations are decided before link establishment, the switch between D2D mode and UL/DL mode transmission can be a frequency/time dependent scheduling choice. The mode selection choice enables more efficient resource use, adapting to channel conditions, especially that of D2D links. A generic scheduling should be capable to treat poor D2D links properly, as well as good D2D links. Mode selection is a key technique to be incorporated into scheduling strategy to address outage D2D users.

A generic scheduling for overlaying spectrum use in hybrid D2D and cellular system with moderate complexity is required. However, such a generic scheduler design in literature studies is scarce. Some authors propose resource allocation strategies for the scenario that only one D2D pair and one UE exist in the cell. The resulted scheduling method can not be evidently extended to scenarios containing multiple links as system performance metrics are lacking. To work with arbitrary number of D2D links, some have also proposed distributed scheduling strategies, but a centralized scheduling strategy is required by LTE D2D to enable eNBs to control the D2D resource use. Some authors propose centralized resource allocation strategies for arbitrary number of D2D links, based on a SINR criterion, which need iterative measurement, computation, and feedback of evolving interference level in each iteration of SINR computation, and therefore can be way too complicated to be implemented in a real system.

3) Realistic complexity and signaling overhead
As already mentioned in the considerations of "system performance metrics" and "a generic scheduling strategy", realistic complexity is highly desired for a scheduling to work in a practical system. The formulation of optimization problems should make a compromise between optimal intended performance metrics and optimization complexity. It has been proposed that the way to simplify the resolution of system performance metrics can be to keep a certain level of separability in formulation of optimization problems for D2D and cellular resource allocation. The resolution of system performance metrics should not imply rapidly increasing complexity with the increase of link numbers. Iterative SINR-based resource scheduling method should be avoided as the number of iteration will largely depend on the number of links and the interference level in each iteration of SINR computation evolves, which actually implies iterative measurement, computation, and feed back of evolving interference channels which is not realistic.

Signaling overhead of scheduling strategies is another concern in a practical system. In a centralized scheduling method, channel state feedback and resource assignment are via control signaling. An important constraint for the efficiency of centralized scheduling algorithm is the accuracy of the eNB's knowledge of the channel quality for the active UEs in the cell. The manner in which such information is provided to the scheduler in LTE differs between uplink and downlink transmissions. In practice, for the downlink this information is provided through the feedback of Channel Quality Indicators (CQIs) by UEs, while for the uplink the eNodeB may use Sounding Reference Signals (SRSs) or other signals transmitted by the UEs to estimate the channel quality. The frequency with which CQI reports and SRS are transmitted is configurable by the eNB, allowing for a trade-off between the signaling overhead and the availability of up-to-date channel information. If the most recent CQI report or SRS was received a significant time before the scheduling decision is taken, the performance of the scheduling algorithm can be significantly degraded. Due to the introduction of in-band D2D, an interference aware scheduler requires much more channel measurements and feedback overhead. It is critical to have scheduling method which balances well between best possible performance and affordable overheads, in order that signaling overheads does not impede the efficiency of a practical system.

One solution that can be adopted to alleviate overheads is that eNB does not take full control of D2D data Communications. For example, eNB only provides additional information to D2D, and D2D users make their own decision in resource use and power control. Another solution is that eNB scheduler makes decision on long-term channel parameters such as pathloss parameters, instead of instant channel states. Therefore the frequency of measurements and feedback can be reduced. This method works when user mobility is low. eNB can also vary the scheduling cycle according to different QoS requirements. For example, assign D2D fixed frequency resources and power for a period of time.

4.3 Description of studied scenario and objectives

This thesis studies the D2D offloading effect. To this end, we examine a cellular network which, originally is overloaded by D2D traffic. This can be modeled by assuming high density of D2D UEs and resource consuming D2D traffic (imaging the usage cases of multimedia sharing, local gaming, etc). Meanwhile, D2D is less likely to be used for services like voice video call,etc, therefore we can reasonably suppose that D2D traffic is not delay-demanding and the index of QoS can be D2D data rate averaged over time. We would like to know, if with proper interference management, D2D mode could benefit cellular network by offloading local traffic. Therefore we need to define coordination functions in eNB, and propose resource allocation and power assignment strategies in eNB (and in D2D too, if D2D is not centrally scheduled by eNB). This work is interested in examining the interference management potentiality of a totally centralized scheduler in eNB. We also want this scheduler to be general enough, performs well in any condition of D2D distance or D2D number. That is to say, this scheduler should be able to judge at what distance D2D mode becomes no more interesting than UL/DL mode, and be able to deal with user fairness in high density case.

Our objective is to check the maximum offloading capability of D2D, therefore we do not suppose that D2D is of lower priority as many articles do. On the contrary, we let D2D UEs reuse as many resources as possible as long as macro transmissions are not impaired. With this strategy, it is possible that D2D obtains much higher rate than macro UEs. However, it does not mean that we prioritize D2D to macro UEs in the hybrid network. We aim at proposing a eNB scheduler which maximizes spectral efficiency gain while guaranteeing an improved overall user throughput. The overall user throughput can be judged by CDF(Cumulative Distribution Function) versus per UE throughput or by CDF versus SINR degradation per UL/DL transmission.

A FDD cellular network and DL spectrum sharing is considered. We study a single cell scenario, containing M DL UEs and N potential D2D pairs. We would like to distinguish two terms used in this chapter: “potential D2D” and “D2D”. As we said before, whether D2D mode is adopted or not will be left to the decision of eNB scheduler in our study. “potential D2D” is a term we use, before transmission mode selection, to designate a pair of nearby source-sink UEs. However, potential D2D does not necessarily operate in D2D mode. “D2D” points to a pair of UEs scheduled in D2D mode by mode selection algorithm. For example, we might have K DL UEs and J D2D pairs after mode selection. But the total number of active links in DL spectrum does not change, which means that: $J + K = M + N$, $J \leq N$ and $K \geq M$.

We assume that all the users in the cell are of low velocity, therefore channel characteristics vary slowly over time.

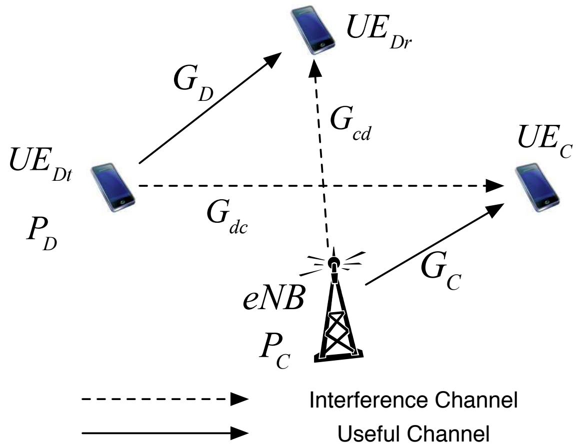


Figure 4.1 — Resource sharing between DL UE and D2D UE. Solid lines indicate useful links. Dashed lines indicate interference links. Transmit power P and channel gain G are illustrated.

4.4 Proposed scheduling strategy

We assume that UE data rate averaged over time is the primary index of QoS in our study case. User fairness is another important network performance index, which takes into account service latency. Therefore PFS can well address the performance metrics in pure cellular network. By introducing D2D mode, we expect that total capacity is increased by frequency reuse, and overall user throughputs are improved. As stated previously, we want to check the maximum offloading capability of D2D and we would like to let D2D UEs reuse as many resources as possible as long as macro transmissions are not impaired. That is to say, D2D UEs and macro UEs need to be treated differently, the conventional PFS in pure network is no more suitable to meet our goal of hybrid network scheduling.

When a D2D link is sharing the same resources with a DL UE, their receiving SINR γ_D and γ_C can be formulated as:

$$\gamma_D = \frac{P_D \cdot G_D}{P_C \cdot G_{cd} + N_o} \qquad \gamma_C = \frac{P_C \cdot G_C}{P_D \cdot G_{dc} + N_o} \tag{4.1}$$

where G_D (resp. G_C) denotes the D2D channel gain (resp. the cellular channel gain), G_{cd} (resp. G_{dc}) is the interference channel gain from cellular transmission to D2D (resp. from D2D to cellular transmission). P_D (resp. P_C) denotes the D2D transmit power (resp. the eNB transmit power to the DL UE). N_o is the noise level.

It is illustrated in Figure4.1, with UE_{Dt} and UE_{Dt} denoting respectively D2D UE transmitter and receiver, and UE_C denoting cellular UE.

It can be seen that DL UEs at the cell center are generally more suitable for resource sharing as they have more robust DL channel (larger G_C) than those at the cell edge. On the other hand, the further the DL UE is separated from the D2D transmitter, the smaller interference (smaller G_{dc}) it receives. When there are many D2D pairs in a cell, due to D2D user diversity, there are chances that a DL UE is separated from some D2D transmitters. Whereas if there are very few D2D pairs in a cell, it is highly possible that a DL UE finds itself close to all the D2D transmitters and thus might suffer from severe interference if sharing resources with D2D links. Therefore DL UEs which is far from eNB or close to all the D2D transmitters are unlikely to share resources with any D2D links. In order to preserve the basic transmission of these DL UEs, some DL spectrum might need to be reserved for DL use only. In D2D scheduling, we propose an optimization criteria which maximizes D2D reused spectrum with the constraint of DL rate threshold.

However above all, eNB as a central coordinator should be able to eliminate inefficient D2D transmission. As mentioned in 4.4.1, decision of applying D2D mode or UL/DL mode for potential D2D traffic could be made at the initial stage of transmission, or dynamically during resource allocation phase. Generally DL UE diversity in a cell is high enough, and chances of finding a set of DL UEs which are relatively isolated from a specific D2D link are not small. If DL UE diversity can be fully exploited in resource allocation, that is to say, if there is no problem of scheduling the most suitable DL UEs for resource sharing with D2D pair, then the efficient mode depends more on D2D link quality than on the choice of DL UE for resource sharing. In addition, D2D channels are in slow fading, which leads to a stead choice of D2D mode over the time. Therefore we have reason to decide the transmission mode at the initial stage, and fix the mode during all the transmission time. However, even if D2D mode is estimated to be more efficient than UL/DL mode at the initial stage, it can be actually less efficient than UL/DL mode due to, for example, resource sharing with improper macro UEs. Normally this is the job of scheduler to manage interference and ensure efficient D2D mode transmission. In practice, if D2D links go bad for a period, handover to UL/DL mode is always possible. In our scheduling algorithm, however, dynamic backup solution which allows flexible switch between D2D and UL/DL mode is not included. Instead of avoiding interference by falling back to UL/DL mode, our purpose is to try to fulfill interference management task and ensure efficient D2D mode transmission by resource allocation and power control techniques.

As stated in 4.3, we study the most challenging case where cellular network is highly overloaded by resource consuming local traffic. It challenges not only resource management in scheduler, but also signaling overhead in network. In order to keep signaling overhead reasonable, we propose that D2D links are scheduled in a semi-persistent way. This choice can be justified by the large size of buffered D2D traffic and slow-fading characteristics of D2D channels. Semi-persistent scheduling means that resources of a D2D pair will be kept unchanged for a period of time. Whereas dynamic scheduling is assumed for DL UEs. In this way, semi-persistent D2D scheduling implies that D2D is scheduled prior to DL UEs. Number of resources available to D2D users should be adjusted in semi-persistent scheduling moment in order to meet the constraint of DL rate threshold.

For simplicity, this thesis considers only the case that resources can be reused only once between DL and D2D transmission. Different D2D links within the same cell use orthogonal resources. As D2D is scheduled before DL UEs, interference management depends mainly on resource allocation and power control to DL UEs. The idea is that eNB exploits DL user diversity in a cell to schedule mutually isolated DL and D2D transmission on the same resources.

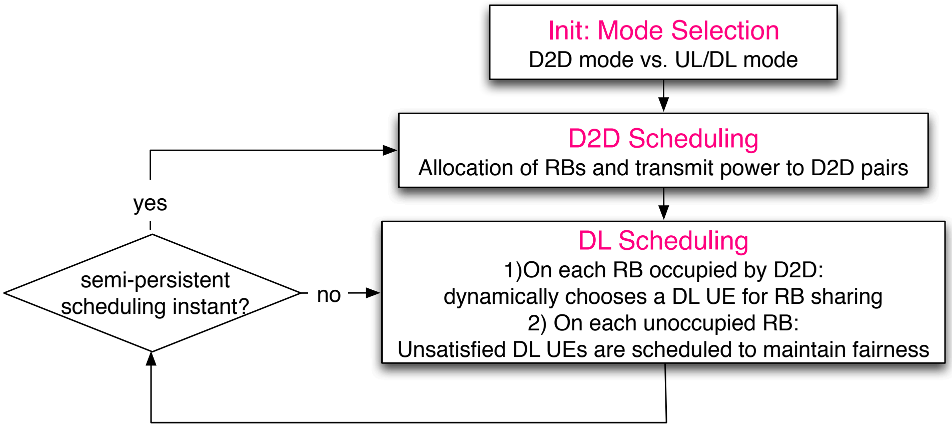


Figure 4.2 — Semi-persistent scheduling procedure in eNB

Our scheduling strategy include three parts (Figure5): Mode selection at initial stage, allocation of resource and power to D2D links at each semi-persistent scheduling instant and allocation of resource and power to DL UEs at each time slot (TTI).

4.4.1 Mode selection

It is at the initial stage that eNB decide whether local traffic will go in direct D2D mode or be relayed by eNB in UL/DL mode. The decision is based on comparison of estimated RB consumption in each mode. The mode which consumes less RBs is more efficient and will be selected. Estimation of RB consumption is calculated by following steps.

- Calculate achievable SNR assuming maximum transmit power.
- Find corresponding rate in MCS mapping table.
- Calculate required RB number based on required service rate.

If required RB number in D2D mode is less than the sum RB number consumed in UL/DL mode, then D2D mode is selected.

4.4.2 D2D scheduling

D2D RB pattern is decided in semi-persistent scheduling instants, same scheduling period for all D2D links is assumed. The main objective is to favor frequency reuse with limited impact on DL rate. Therefore we let D2D UEs take as many resources as possible as long as a DL rate threshold is reached. This puts the constraint on the total number of RBs that can be occupied by D2Ds. We would also like to maintain certain fairness among D2D UEs. The fairness can be adjusted centrally by eNB by deciding the number of RBs for each D2D. D2D resource allocation can therefore be decomposed into two steps:

- Calculate the total number of RBs that can be occupied by D2D data communications according to DL rate constraints.
- Calculate the number of RBs to each D2D pair according to D2D fairness.

As explained previously in this section, DL UEs, which are not suitable for RB reuse (i.e. cell-edge UEs), require unoccupied resources to maintain their rate. Therefore we propose that adjustment of total D2D bandwidth depends on the minimum rate of all DL UEs. If the threshold is attained, total D2D bandwidth can be increased, otherwise it should be decreased. This threshold can be set to, for example, the minimum DL rate that can be guaranteed by pure cellular network.

RBs that can be occupied by D2D data Communications are then allocated to each D2D pair. In our study, we propose that the division of RBs among D2D pairs takes into consideration both D2D user fairness and frequency channel selectivity. The algorithm is described as follows:

- Number of RB for each D2D pair is decided by a D2D fairness factor.
- Once RB number for each D2D pair is decided, a frequency selective allocation algorithm is applied:
  - Estimate SINR in each RB and sort RBs in SINR order for each D2D pair.
  - D2D is scheduled in round-robin order until each D2D fulfills its designated RB number.
  - Scheduled D2D takes RB in its own SINR order (take RB which has highest SINR first).

In our study, we assume that the smallest allocation unit is 1 RB. We do not assume the constraint of continuous RBs assignment, that is to say, multiple RBs allocated to one UE can be discontinuous. However, we do assume that D2D transmit power per RB should be identical on multiple RBs allocated to the same D2D UE. In addition, a total power constraint is assumed for UE.

As stated previously, we aim at coordinating interference by resource allocation and power optimization techniques instead of avoiding interference by switching back to UL/DL mode. Therefore D2D transmit power should guarantee basic D2D transmission.

Joint power optimization of DL transmission and D2D transmission reusing the same resources is optimal, but is at the cost of complexity and signaling overhead. In our study, we propose that D2D transmit power is also semi-persistently assigned, right after the D2D resource allocation. We impose a minimum D2D SINR constraint γ_{Dmin} and a maximum DL transmit power constraint P_{Cmax}, in addition to the maximum D2D power constraint P_{Dmax}. Required D2D transmit power is defined in a way that the minimum D2D rate can be attained even under the maximum DL transmit power in resource sharing scheme. On a specific RB, G_D and G_{cd} are known, required D2D transmit power can thus be calculated as:

$$P_D = \gamma_{Dmin} \cdot \frac{(P_{Cmax} \cdot G_{cd} + N_o)}{G_D} \tag{4.2}$$

Suppose that the number of RBs allocated to a D2D pair is l_D, maximum required D2D transmit power over the allocated set of RBs is $P_{D'}$, D2D transmit power per RB for this D2D pair can be defined as:

$$P_D = min\left\{\frac{P_{Dmax}}{l_D}, \quad P_{D'}\right\} \tag{4.3}$$

4.4.3 DL scheduling

As D2D transmission occupy RBs first, interference management becomes the key task of DL scheduling. The main technique is to exploit DL UE diversity in the cell so that mutual isolated DL and D2D transmission are scheduled on the same RB. It is actually a user selection algorithm. The DL UE which is most suitable for resource sharing with a D2D pair will be selected to reuse the RB occupied by this D2D link. On the other hand, on unoccupied resources, DL UEs that are not suitable for reuse should be given priority so that their data rates are maintained. Therefore we propose that RBs that are occupied by D2D transmissions are scheduled first and DL resource allocation on occupied and unoccupied RBs use different criteria. On occupied RBs, maximizing aggregate rate of DL and D2D UEs is prioritized, whereas on unoccupied RBs, DL UE fairness is the main consideration. We use "modified PFS criterion" in scheduling occupied RBs and "conventional PFS criterion" in scheduling unoccupied RBs. In the following, the conventional PFS criterion is firstly introduced, and then the modified PFS criterion is explained.

I. The conventional PFS criterion

As it is well known, the conventional PFS criterion schedules a user when its instantaneous channel quality is high relative to its own average channel condition over time. Suppose that the number of DL UEs is K and the number of RBs is L, conventional PFS criterion applied on RB l is:

$$\hat{k} = \arg\max_{k=1,\ldots,K} \frac{R_{lk}}{\bar{r}_k(t)} \tag{4.4}$$

where R_{lk} denotes the rate of DL UE k if it is scheduled on RB l. $\bar{r}_k(t)$ stands for the average rate of DL UE k over a time window, and is recursively computed at each TTI:

$$\bar{r}_k(t) = (1 - \frac{1}{t_c}) \cdot \bar{r}_k(t-1) + \frac{1}{t_c} \cdot r_k(t) \tag{4.5}$$

where t_c is the time window length over which fairness is imposed and $r_k(t)$ is the accumulated throughput of user k throughout all the RBs at TTI t:

$$r_k(t) = \sum_{l=1}^{L} R_{lk} \cdot \chi_{lk} \tag{4.6}$$

where χ_{lk} indicates whether RB l is allocated to user k or not, with $\chi_{lk} \in \{0, 1\}$.

By adjusting time window length t_c, the PFS criterion can flexibly balance between maximizing throughput and UE fairness. A large time window t_c tends to maximize the total average throughput. In fact, in the limit of a very long time window, PFS and maximum-rate constant-power scheduling result in the same allocation of resources. Whereas for small t_c, the PFS tends towards a round-robin scheduling of users. As the conventional PFS criterion in scheduling unoccupied RBs is to address the DL UE fairness problem, a relative small t_c will be adopted.

II. The modified PFS criterion

On occupied RBs, the main gain that is to achieve through scheduling is the spectral efficiency gain. As in conventional PFS, a large time window t_c tends to maximize the total average throughput, a little modification can make PFS work for our purpose. The modified PFS criterion can be formulated as follows:

$$\hat{k} = \arg\max_{k=1,\ldots,K} \frac{R_{lj} + R_{lk}}{\bar{r}_k(t)} \tag{4.7}$$

where R_{lj} denotes rate of D2D UE j already scheduled on RB l during the D2D semi-persistent scheduling phase. A DL UE is scheduled in a RB when the instantaneous aggregate rate in this RB is high relative to this DL UE's own average rate over a measurement time window. A relative large t_c will be adopted.

It should be noted that although the modified PFS criterion is introduced after the conventional one, occupied RBs are actually scheduled before unoccupied RBs in our proposed DL scheduling algorithm.

On occupied RBs, we aim to optimize DL transmit power according to a maximizing aggregate rate criterion. We further impose unified constraints of maximum DL transmit power and minimum D2D rate. Another practical constraint is the highest rate confined by MCS. The optimal transmit power for each DL is calculated on RB basis before DL user selection equation (4.7). That is to say, R_{lk} in 4.7 is rate of UE k on RB l with optimized DL transmit power.

If taking the Shannon capacity expression to calculate rate, we can formulate the DL power optimization problem as follows:

$$\hat{P}_D = \arg\max \left[\ln(1 + \frac{P_D \cdot G_D}{P_C \cdot G_{cd} + N_o}) + \ln(1 + \frac{P_C \cdot G_C}{P_D \cdot G_{dc} + N_o}) \right] \tag{4.8}$$

submitted to four constraints: 1) maximum DL transmit power P_{Dmax} 2) minimum D2D SINR γ_{Dmin} 3) maximum required DL SINR γ_{Cmax} which is sufficient to attain the maximum rate offered by MCS 4) similarly, maximum required D2D SINR γ_{Dmax}

The objective function (4.8) is known as non-convex [Tadrous et al., 2011], and is of high complexity when linear form constraints are added. A suboptimal solution is to pre-configure multiple transmit power levels, and search through them to find the best power level which verifies all the constraints and gives the maximum aggregate rate.

For simplicity, maximum DL transmit power is applied on unoccupied RBs.

4.4.4 The originality of proposed scheduling strategy

In order to manage intra-cell interference resulted from spectrum reuse by D2D, we propose a scheduler combining techniques of resource allocation, power allocation and mode selection. Decisions are made centrally by base station.

The proposed scheduling strategy has performance metrics targeting global user satisfaction. Global user satisfaction usually requires well-balanced spectral efficiency and user fairness. We propose performance metrics based on proportional fairness criteria, which balance flexibly between maximizing system throughput and maintaining cellular user fairness.

The proposed scheduling algorithm is a general algorithm targeting arbitrary network layout. It has no constraints on D2D numbers or D2D distances. The total bandwidths that can be occupied by D2D communication submit to a cellular UE rate constraint. In this way, cellular data communications are protected even in a dense D2D deployment. Poor D2D links (eg. D2D links of long distance), are prevented from being scheduled in D2D mode by a mode selection algorithm.

The proposed scheduling strategy has low complexity due to separate optimization of D2D and cellular transmissions. The signalling overhead is also reduced due to low D2D scheduling cycle.

4.5 Conclusion

In this chapter, main issues in coordinated in-band D2D scheduling is firstly analyzed in section 4.2. Different approaches and their interest are compared. How these issues are addressed in literature studies is also introduced.

Section 4.3 describes the hybrid scenario that we study, and presents objectives that we aim to achieve through scheduling. In a word, we study a macro cell overloaded by local traffic and our objective is to check the maximum offloading capability of D2D. We concentrate on the interference scenario where frequency resources are allowed to be reused only once between one D2D and DL transmission.

Suggested scheduling strategies are described in section 4.4 Mode selection between D2D and traditional UL/DL modes is implemented at the initial stage of transmission. Dynamic switch between D2D and UL/DL mode is not integrated in our scheduling algorithm because the main purpose is to check the interference control capability provided by resource and power allocation techniques in managing the coexistence of D2D and DL transmissions.

We propose semi-persistent D2D scheduling for the purpose of reducing signaling overhead in the cellular system. On the other side, scheduling D2D and DL separately also reduces the complexity of optimization problem. Our D2D resource allocation strategies try to fulfill multiple tasks. First of all, we aim to maximize RB number reused by D2Ds while guaranteeing a minimum DL rate. Secondly, resource allocation among D2D UEs takes into consideration both user fairness and frequency channel selectivity. D2D transmit power is optimized after D2D resource allocation. The objective is to guarantee a minimum D2D rate under the worst interference circumstance (maximum DL transmit power).

DL UEs is scheduled dynamically. User diversity in DL scheduling is the key to mitigate mutual interference between DL and D2D. We propose that RBs occupied by

D2D is scheduled in the first stage. We suggest a modified PFS criterion to select DL UEs in a way that the aggregate rate of DL UE and D2D on one RB is prioritized. RBs unoccupied by D2D is scheduled in the second stage, with the purpose to compensate DL UEs which did not attain satisfied rate in the previous stage of RB allocation. The applied criterion is conventional PFS with the emphasis on the DL UE fairness.

On occupied RBs, DL transmit power is optimized on RB basis before DL UE selection. The criterion is maximizing aggregate rate under power and rate constraints. We suggest a suboptimal solution with moderate complexity. For simplicity, maximum DL transmit power is applied on unoccupied RBs.

CHAPTER 5 System Simulation

5.1 Overview

In this chapter, a general description of evaluation methodology is firstly introduced in Section 5.2. Radio access requirements, and corresponding evaluation approaches are presented. System simulation is the most important approach for multi-link evaluations in a network. Two essential elements in the system simulation: channel models and link-to-system mapping are detailed. In Section 5.3, scheduling method proposed in Chapter 4 for a hybrid cellular and D2D network is examined by system-level simulation. Choices of deployment scenario, network layout, parameters and assumptions are firstly detailed. Performance metrics, mainly the per user average throughputs and the system spectral efficiency are simulated in different settings. The analysis of the simulation results is followed by a summary and discussion.

5.2 Evaluation Methodology

5.2.1 Introduction to Radio Access Requirements

International Mobile Telecommunications-Advanced (IMT-Advanced) are requirements set by the International Telecommunication Union (ITU) in 2008, to address evolving user needs of advanced mobile services and Internet access service offered by mobile and fixed networks. IMT-Advanced systems support low to high mobility applications and a wide range of data rates in accordance with user and service demands in multiple user environments. IMT-Advanced has also capabilities for high-quality multimedia applications within a wide range of services and platforms providing a significant improvement in performance and quality of service. The key features of IMT-Advanced are:

- a high degree of commonality of functionality worldwide while retaining the flexibility to support a wide range of services and applications in a cost efficient manner;
- compatibility of services within IMT and with fixed networks;
- capability of interworking with other radio access systems;

- high-quality mobile services;
- user equipment suitable for worldwide use;
- user-friendly applications, services and equipment;
- worldwide roaming capability;
- enhanced peak data rates to support advanced services and applications (100 Mbit/s for high mobility and 1 Gbit/s for low mobility were established as targets for research).

The ITU Radiocommunication Sector (ITU-R) called for submission of candidate Radio Interface Technologies (RITs) fulfilling the ITU-R's requirements for IMT-Advanced. In response to the call for proposals from ITU-R, 3GPP TSG RAN identified targets and potential techniques for further advancement of LTE, specified as LTE-Advanced (LTE Release 10 and beyond), which was approved by ITU-R in 2010 as IMT-Advanced RIT.

Some of the 3GPP targets for LTE-Advanced exceed the IMT-Advanced requirements as LTE Releases 8 and 9 already satisfy to a large extent the requirements set by ITU-R for the IMT-Advanced designation. In addition, 3GPP set requirements on backward compatibility with earlier releases of LTE network which allows operators to continue serving existing LTE customers while their network equipment is progressively upgraded. Requirements on spectrum deployment and flexibility, coexistence with legacy Radio Access Technologies (RATs), and complexity and service support were also defined [TR3,].

Report ITU-R M.2135 [M.2, 2009] provides guidelines for both the procedure and the criteria to be used in evaluating IMT-Advanced RITs or Sets of RITs (SRITs) for a number of test environments and deployment scenarios for evaluation. Evaluation criteria and corresponding high level assessment methods are summarised in Table 5.1.

- Simulation approach includes system and link-level simulations. System simulation shall be based on the network layout defined in Report ITU-R M.2135 [M.2, 2009].
- Analytical approach uses a straight forward calculation based on the definition in Report ITU-R M.2134 [M.2, 2008].
- Inspection is done by reviewing the functionality and parameterisation of the proposal.

These methodologies serve as a baseline for evaluating continuous enhancements in LTE-Advanced.

Table 5.1 — Evaluation criteria and methods

Characteristic for evaluation	**Method**
Cell spectral efficiency	Simulation (system level)
Peak spectral efficiency	Analytical
Bandwidth	Inspection
Cell edge user spectral efficiency	Simulation (system level)
Control plane latency	Analytical
User plane latency	Analytical
Mobility	Simulation (system and link level)
Intra- and inter-frequency handover interruption time	Analytical
Inter-system handover	Inspection
VoIP capacity	Simulation (system level)
Deployment possible in at least one of the identified IMT bands	Inspection
Channel bandwidth scalability	Inspection
Support for a wide range of services	Inspection

5.2.2 System simulation principles

Multi-cell system level simulations are to be used for evaluating the IMT-Advanced requirements cell spectral efficiency, cell edge user throughput, VoIP capacity and mobility. System simulations deal with multiple links in multiple cells/sectors. Performance metrics such as throughput and delay are gathered statistically over a large number of independent simulation runs, called 'drops', where a 'drop' is defined as one simulation run over a certain time period. During a drop (or snapshot or channel segment), the large-scale parameters are fixed (e.g. shadow fading, pathloss, and angular spreads), but the channel undergoes fast fading according to the motion of the terminals, resulting in varying small-scale parameters (e.g. the changing phases of the rays). While simple models might be adequate to evaluate the performance of individual radio links, more complex models are needed to evaluate the overall system-level reliability and suitability of specific technologies.

Link-level simulations might be adequate to evaluate the performance of individual radio links and allow for the investigation of issues such as Multiple-Input Multiple-Output (MIMO) gains, Adaptive Modulation and Coding (AMC) feedback, modeling of channel encoding and decoding, developing receiver structures. However it is not possible to reflect the effects of network-related issues such as cell planning, scheduling, mobility handling or interference management with such simple link-level simulation. System-level simulations are needed to evaluate the overall system-level reliability and suitability of specific technologies. As the network size grows, it is not feasible to model all aspects of every link explicitly. Especially the coding and decoding of the signal require high computational resources and are typically modeled by a link to system level mapping [Brueninghaus et al., 2005]. In system-level simulations the physical layer is abstracted by simplified models that capture its essential characteristics with high accuracy and low complexity. General system-level simulation takes the following steps.

Table 5.2 — Selected deployment scenarios for evaluation and the channel models

Test environment	Base coverage urban	Microcellular	Indoor	High speed
Deployment scenario	Urban macro-cell scenario	Urban micro-cell scenario	Indoor hotspot scenario	Rural macro-cell scenario
Channel model	UMa Urban macro (LoS, NLoS)	UMi Urban micro (LoS, NLoS, Outdoor-to-indoor)	InH Indoor hotspot (LoS, NLoS)	RMa Rural macro (LoS, NLoS)

- Choose a deployment scenario, define network layout and evaluation configuration
- Generate active mobile terminals in the scenario and corresponding channel parameters for each link between base station and UE.
- Calculate channel state information
- Execute radio resource management (handover, link adaptation, scheduling, power control, etc.)
- Calculate SINR for each link
- Map SINR to block error rate and determine if data packets were successfully received
- Collect statistics

5.2.2.1 Test environment and channel models

Test environments are the most basic factor to be considered in the evaluation process. The reference models are used to estimate the critical aspects, such as the spectrum, coverage and power efficiencies. IMT-Advanced evaluation guideline has defined four test environments and corresponding deployment scenarios and channel models that shall be used for each test environment, shown in Table 5.2.

The test environments have been chosen such that typical and different deployments are modelled and a wide range of performance and critical questions in system design can be investigated in a wide range of environments.

For evaluation of radio access technologies in the four selected test environments, a set of reliable and measurement-based channel models are needed. Channel models have to be accurate as radio propagation has a significant impact on the performance evaluation of wireless systems when choosing modulation and coding, in multi antenna system design, in the selection of channel estimation method, channel equalization and other baseband algorithm design, as well as network planning. It is necessary to use common and uniform channel models for evaluation, comparison, and selection of technologies.

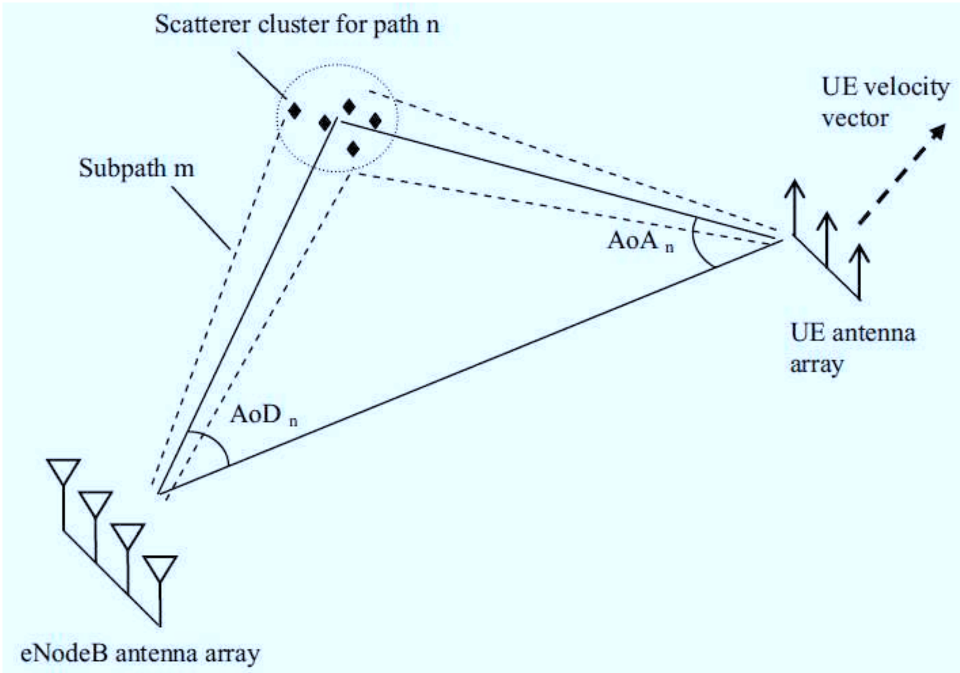


Figure 5.1 — Geometry for generating spatial parameters for base station and UE

Geometry-based stochastic channel models have been developed for system level evaluations of multi-link models. The channel parameters are determined stochastically, based on statistical distributions extracted from channel measurement. The distributions are defined for, e.g., delay spread, delay values, angle spread, shadow fading, and cross-polarisation ratio. The directions of the rays, rather than the locations of the scatterers are specified. Channel realizations are generated by summing contributions of rays (plane waves) with specific small-scale parameters like delay, power, angle-of-arrival (AoA) and angle-of-departure (AoD). Geometry-based modelling of the radio channel enables separation of propagation parameters and antennas. Antenna geometries and radiation patterns can be defined properly by the user of the model, independent of propagation parameters. Different scenarios are modelled by using the same approach, but different parameters. Therefore the geometry-based stochastic channel models allows creating of multiple double directional radio channels with arbitrary antenna configurations for an unlimited number of propagation environment.

The IST-WINNER Phase II channel model [L. Hentila and Alatossava., 2007] forms the basis for the ITU IMT-Advanced models. A Matlab implementation is developed and channel coefficients are generated by a step-wise procedure illustrated in Figure 5.2.

5.2.2.2 Link-to-System Mapping

Simulating the physical layer links between multiple eNBs and UEs in a network can be computationally prohibitive. Therefore system level simulator uses physical layer (PHY) abstraction to predict link layer performance in a computational simple way. The role of PHY abstraction method in OFDM system is to predict the coded block

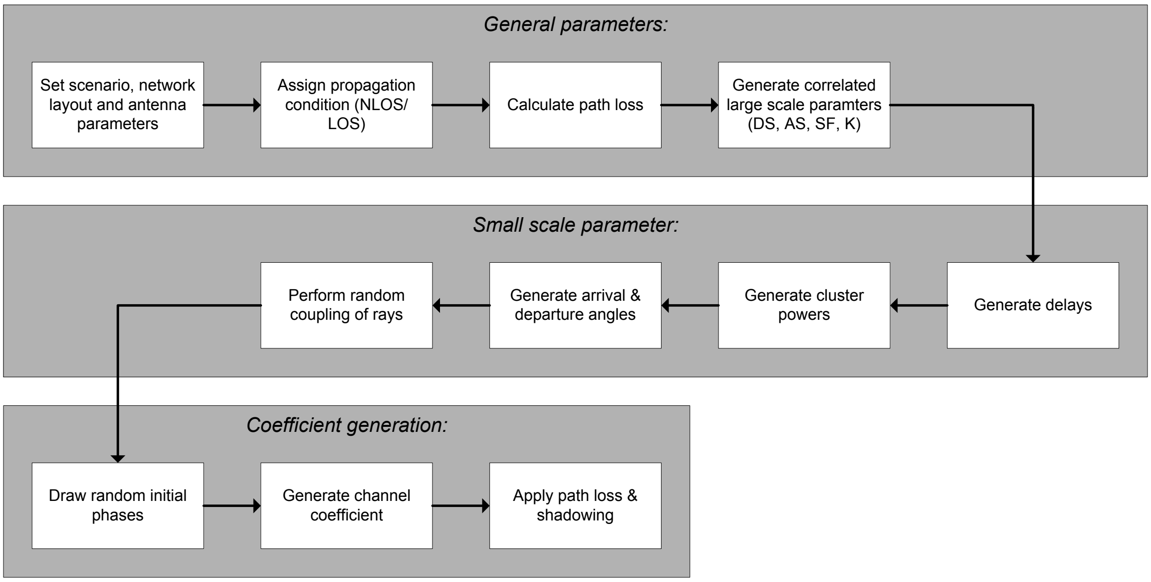


Figure 5.2 — Channel coefficient generation procedure

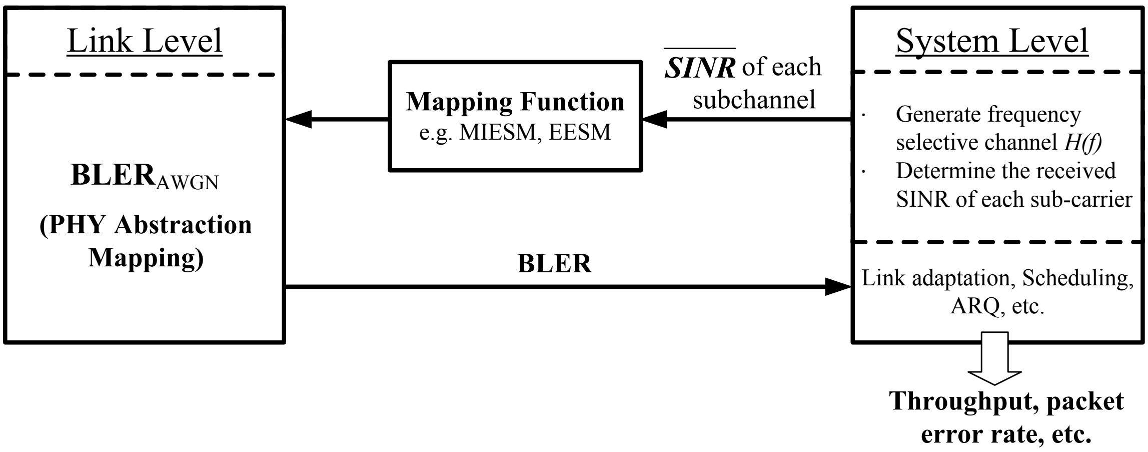


Figure 5.3 — PHY link-to-system mapping procedure

error rate (BLER) for a given received channel realization across the OFDM subcarriers used to transmit the coded forward error correction (FEC) block. The input to the PHY abstraction mapping is the post-processing SINR values at the input to the FEC decoder.

However, as the link level BLER curves are generated assuming a frequency flat AWGN channel response at given SINR, the set of received SINR values need to be converted to a single effective SINR, $SINR_{eff}$, which can then be mapped onto the link level curves to determine the resulting BLER. This mapping is termed effective SINR mapping (ESM), shown in Figure 5.3.

In general, the mathematical function of ESM PHY abstraction methods can be

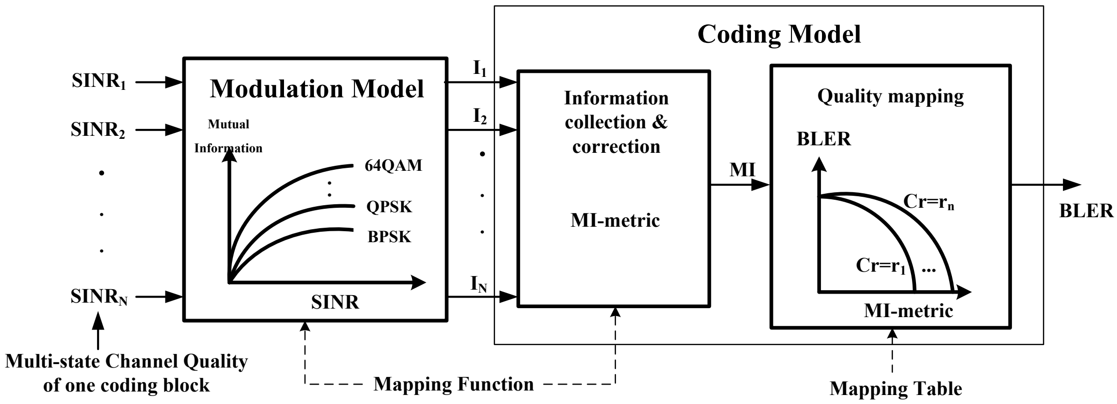


Figure 5.4 — Computational procedure for MIESM method

described as follows:

$$SINR_{eff} = \Phi^{-1}\left\{\frac{1}{N}\sum_{n=1}^{N}\Phi(SINR_n)\right\} \tag{5.1}$$

where $SINR_{eff}$ is the effective SINR, $SINR_n$ is the SINR in the n_{th} sub-carrier, N is the number of sub-carriers used in an OFDM system and $\Phi(\bullet)$ is an invertible function.

There are several ESM approaches, using different functions to map the set of SINR values to a single number. Examples include mean instantaneous capacity [28]-[30], exponential-effective SINR Mapping (EESM, [31], [33]-[35]) and Mutual Information Effective SINR Mapping (MIESM, [36], [37]). MIESM is by far the most accurate mapping method for OFDM system.A block diagram for the MIESM approaches is shown in Figure 5.4.

Given a set of N received encoder symbol SINRs from the system level simulation, denoted as $SINR_1$, $SINR_2$, $SINR_3$, $\cdots$, $SINR_N$, a mutual information metric is computed. Based on the computed MI-metric an equivalent SINR is obtained and used to look-up the BLER.

5.3 System-level simulation for D2D data Communications

We apply system-level simulation to a multi-user scenario in order to examine performances of scheduling methods that we proposed in Chapter 4 for a hybrid cellular and D2D network. The objective is to leverage D2D mode transmission to offload heavy local traffic from cellular networks in a resource-limited scenario. The proposed scheduling methods aim to achieve high system throughput while guaranteeing an overall satisfying per UE throughput. D2D offloading effect can be shown by comparing performances of hybrid cellular and D2D networks with pure cellular networks where only UL/DL mode is allowed.

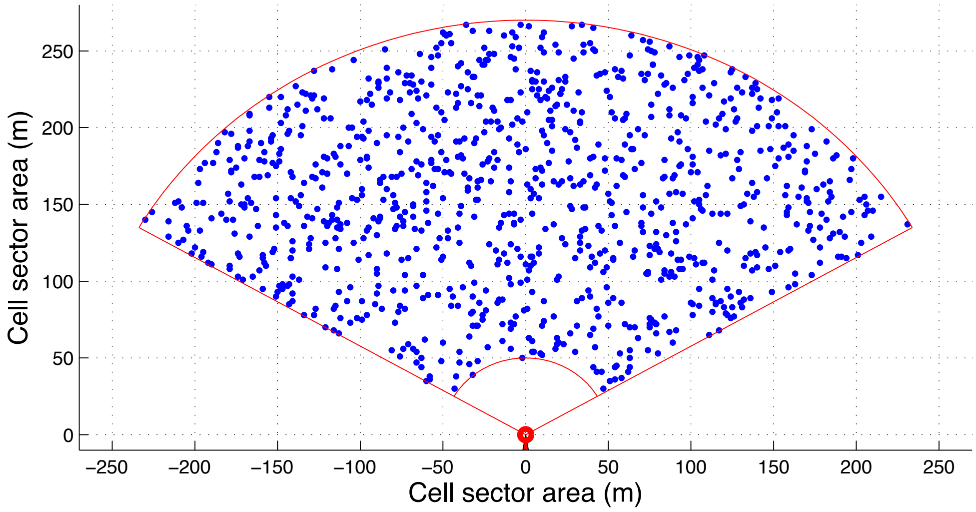


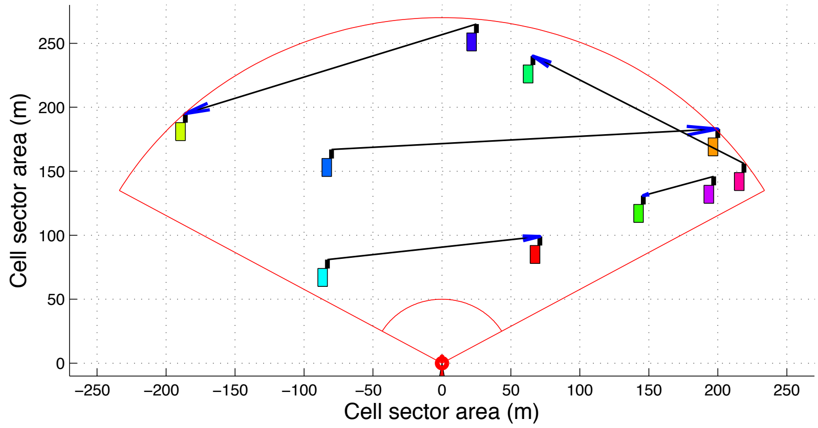
Figure 5.5 — Uniformly distributed UE positions with Geometry-based stochastic modeling

5.3.1 Deployment scenario, network layout, parameters and assumptions

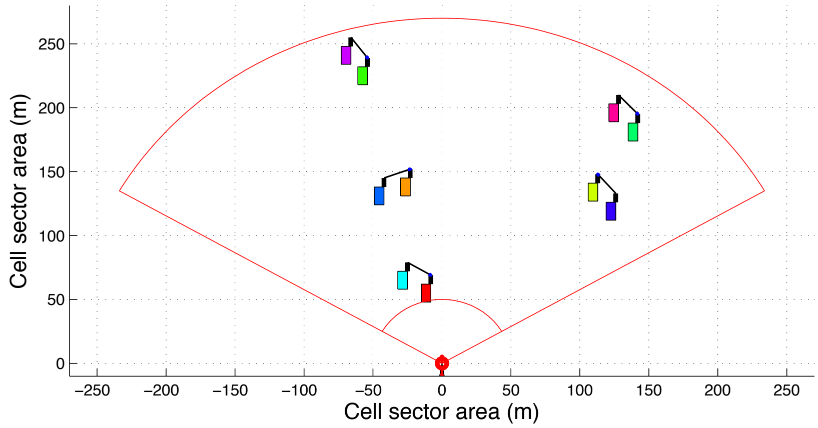
We assume an urban macro-cell deployment scenario and apply urban macro channel model defined by ITU (ITU UMa) for macro transmissions between eNB and UEs. WINNER PHASE II channel model is used for system simulation. D2D channel model is not defined by ITU and is not implemented in WINNER PHASE II channel model. Here we use urban micro channel model (ITU UMi) for D2D link.

However links of different scenario are generated independently with WINNER PHASE II channel model implementation and are not correlated, which might be different from the real case. In reality, for example, a link from an eNB to a UE and a link from a proximate UE to this same target UE might have correlated large scale parameters such as shadowing correlation as both links might experience same obstacles located around the target UE. This thesis focus on intra-interference management and constrains the network layout to a single sector of a three-sector LTE hexagonal macro cell. Performance statistics are collected over a large number of independent drops, and in each drop UEs are generated randomly. In principle, UEs positions should be uniformly distributed in order that over several runs, statistics of UE positions can basically cover the whole sector area (with scenario-specific transmission range constraints recommended by ITU). Figure5.5 illustrates 1000 uniformly distributed UEs covering a predefined macro sector area (minimum range 50m and maximum range 270m)

In our study, two different layout settings are configured for performance comparison: random D2D distance setting and fixed D2D distance setting. In the former setting, D2D transmitters and receivers are generated onto the sector area and paired randomly. While in the latter setting, each D2D receiver is firstly generated onto the sector area with uniformly distributed rules, and a corresponding D2D transmitter is generated af-



(a) a snapshot of 5 D2D pairs in random D2D distance setting



(b) a snapshot of 5 D2D pairs in 20 m D2D distance setting

Figure 5.6 — Random and fixed D2D distance settings

terwards with a fixed D2D range. Figure5.6a (resp. Figure5.6b) presents a snapshot in network layout with random D2D distance setting (resp. fixed D2D distance setting).

The cumulative distribution function (CDF) of D2D distance in random D2D distance setting is shown in Figure 5.7. A 10-meter minimum distance constraint in ITU UMi channel model is respected.

Important simulation parameters are listed in Table 5.3, more detailed channel model parameters can be found in [WIN, 2008].

5.3.2 Simulation results

Channel characteristics

The output of channel coefficients from WINNER PHASE II channel model is affected by four elementary elements:

- propagation path-loss,

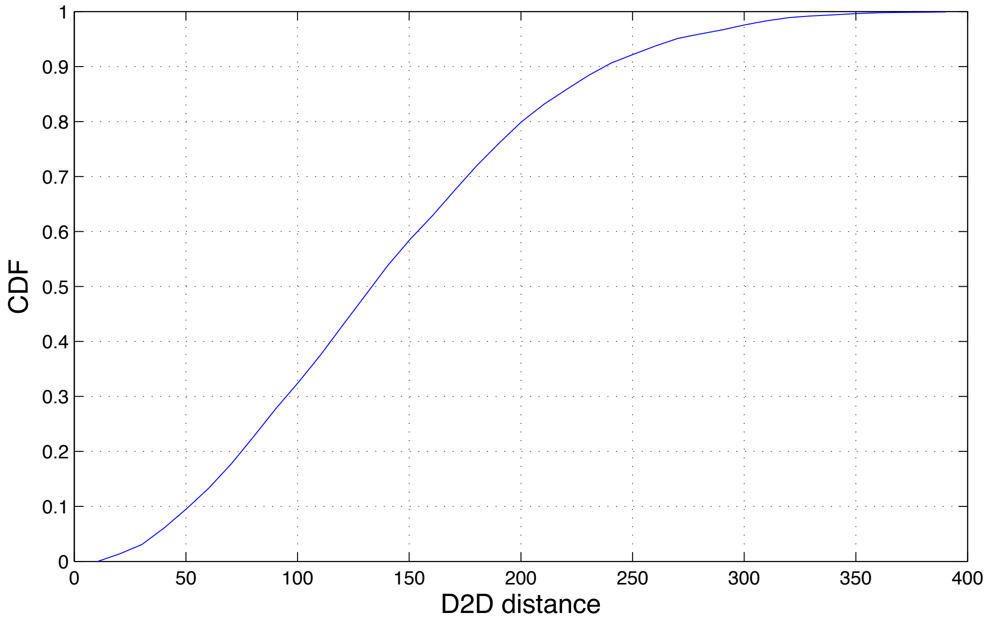


Figure 5.7 — CDF of D2D range in random D2D distance setting

- shadow (slow, or 'large-scale') fading
- multipath (fast, or 'small-scale') fading
- antenna configuration

Path loss models for the various propagation scenarios used here are given in [M.2, 2009]. Although path loss values increase in direct proportion to transmission distance, final channel coefficients are not, due to fading deviation and different antenna configuration in different transmitters/receivers. The log-normal standard deviation parameter is scenario-dependent, and is also given in [M.2, 2009]. Channel gains of a specific transmission distance might vary ± 20dB or more. Figure 5.8 illustrates the CDF of D2D channel gain in 20 m D2D distance setting and in random D2D range setting.

It can be seen that one D2D UE has buffered data for a target D2D UE in the same sector do not necessarily have good D2D channel condition. Poor D2D links with small channel gains might also occur due to large D2D distance and/or fading. In our proposition, they are taken into consideration by a mode selection mechanism and a resource sharing strategy.

Mode selection influence

We name a pair of UE transmitter and receiver as a potential D2D pair when the UE transmitter has buffered data for a target D2D UE in proximity. It is therefore possible to be scheduled in D2D mode according to mode selection criteria. The proposed mode selection criterion is based on comparison of spectral efficiency in D2D mode and in UL/DL mode, and can be described by the following algorithm:

Table 5.3 — Simulation Parameters

System Parameters	
Center Frequency	2GHz
DL Bandwidth	5MHz(25PRBs)
Inter-site distance	500m
Mobile velocity	3km/h
Pathloss model	NLoS
Target packet error rate	10%
Antenna Parameters	
Max Tx Power	eNB:43dBm, UE:24dBm
Antenna configuration	SISO
Maximum antenna gain	eNB:17dBi, UE:0dBi
Antenna height	eNB:25m, UE:1.5m
Noise Figure	7dB
Thermal noise PSD	-174dBm/Hz
Receiver interference PSD	-170dBm/Hz
Shadow fading Parameters	
D2D lognormal std deviation	4dB
DL lognormal std deviation	6dB
DL penetration loss std deviation	5dB
Others	
Simulation duration	0.2s (200TTIs) per drop
Semi-persistent scheduling period	0.02s(20TTIs)
Fairness window length in mPFS	6
Fairness window length in PFS	2
Traffic model	full buffer
Highest MCS	4.5bps/Hz
DL channel model	ITU UMa
D2D channel model	ITU UMi

Algorithm 1 Mode selection algorithm

$N_{diff} = N_{D2D} - (N_{UL} + N_{DL})$
if $N_{diff} > 0$ **then**
  UL/DL mode is selected
else
  D2D mode is selected
end if

where N_{D2D}, N_{UL} and N_{DL} present respectively the number of RB required by D2D link, UL, and DL, calculated by the method proposed in Chapter 4. D2D mode is chosen as long as estimated RB consumption in D2D mode is less than in UL/DL mode. In Table 5.4, percentages of D2D mode being chosen for potential D2D pairs are listed. Three different distance settings are compared, in each setting, 3000 potential D2D pairs are analyzed as a statistical base. It can be seen that when D2D distance is

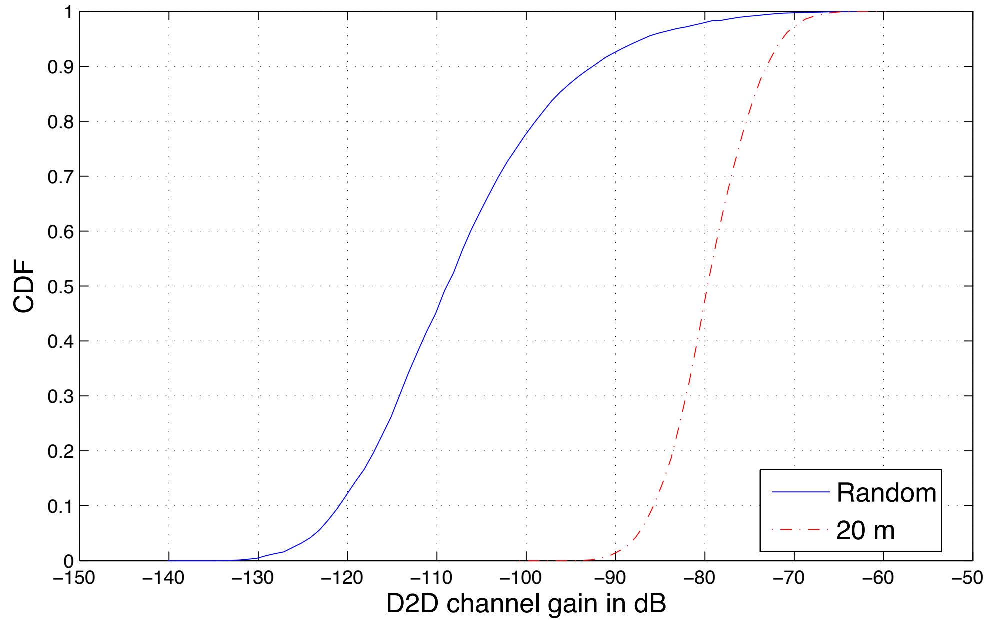


Figure 5.8 — CDF of D2D channel gain in random D2D distance setting and 20 m D2D distance setting

Table 5.4 — Mode selection results

	20m distance	random distance	200m distance
D2D mode (%)	100%	90%	80%

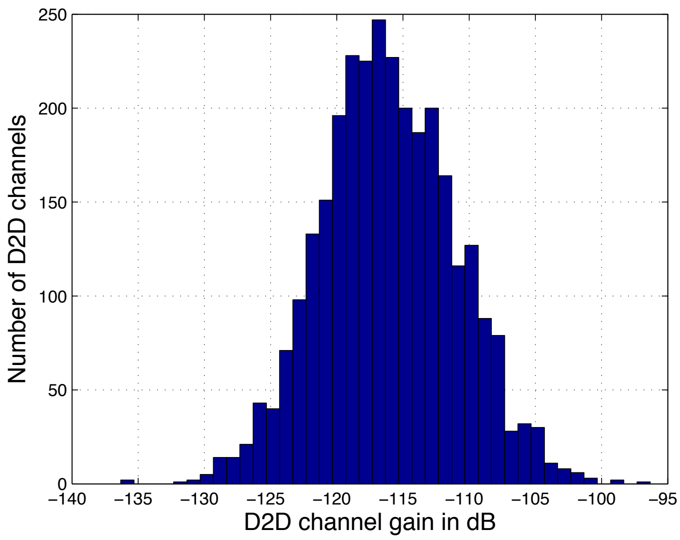
short (20 m), D2D channel is usually good, and potential D2D pair is almost always scheduled in D2D mode. Whereas with the increase of D2D distance, poor D2D channel might occur, and the potential D2D pair is likely to be scheduled in UL/DL mode.

In Figure 5.9, histogram shows the distribution of D2D channel gains before and after mode selection. In Figure 6a, 3000 D2D channels are counted, whereas in Figure6b, only D2D channels that are finally scheduled in D2D mode are counted. It can be seen that in most of the cases when D2D channel gains are below -120 dB, UL/DL mode is chosen.

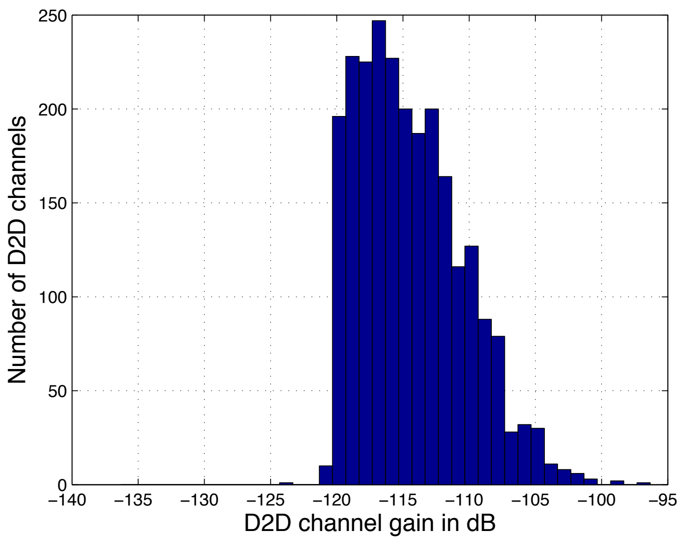
Per user average throughput

The proposed scheduler is designed to work with arbitrary number of D2D pairs in a cell. However in the following analysis, we fix the number of potential D2D UE pairs in the network setting in order to facilitate the comparison.

We firstly examine a sector with 5 potential D2D UE pairs and other 10 macro DL UEs. We investigate both 20 m D2D distance setting and random D2D distance setting. According to analysis of mode selection influence, we know that in 20 m D2D distance setting, near 100% potential D2D pairs are scheduled in D2D mode due to short-distance good channel conditions, while in random D2D distance setting, the rate of being scheduled in D2D mode is 90%. Potential D2D pairs that are not scheduled in D2D mode will use conventional UL/DL mode and their performances are classified



(a) histogram of D2D channel gains before mode selection



(b) histogram of D2D channel gains after mode selection

Figure 5.9 — histogram of D2D channel gains before and after mode selection in a 200 m D2D distance setting

as performances of macro UL/DL transmission. That is to say, in the sector, x UEs ($0 \leq x \leq 5$) will receive data from D2D UE transmitters directly, while the other $15 - x$ UEs will receive data from eNB. We assume the same number of potential D2D UE pairs and macro DL UEs when analyzing random D2D distance setting and 20 m D2D distance setting, and therefore the congestion in random D2D distance setting is statistically more severe than in 20 m D2D distance setting.

In Figure 5.10 per user throughput statistics are analyzed.UEs receiving data from D2D UE transmitters and from eNB are analyzed separately. Comparing to pure cellular network containing 15 DL UEs, a 2.7 fold gain in D2D UE throughput and 1.5

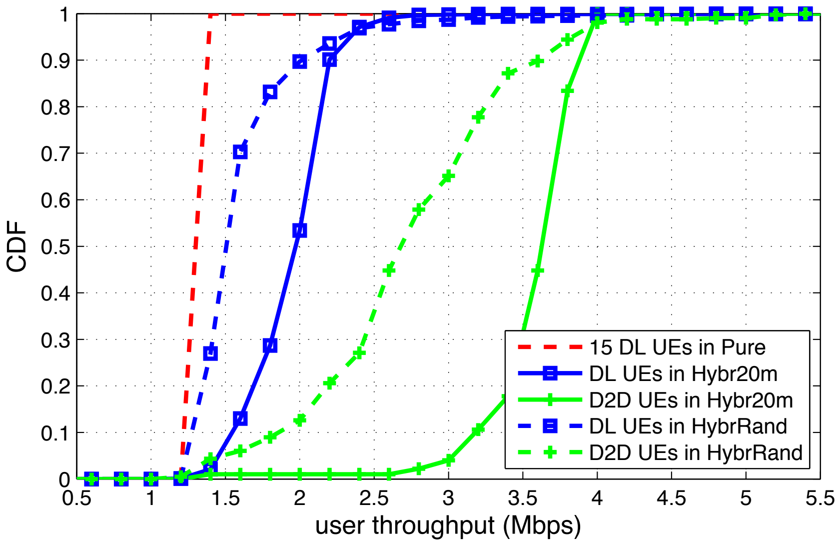


Figure 5.10 — User throughput CDF, 5 potential D2D pairs

fold gain in DL UE throughput are observed at 50% CDF level in hybrid network with 20 m D2D distance setting. The difference between D2D UE throughput and DL UE throughput in hybrid network is explained by the resource allocation strategy: D2Ds are allowed to take as many resources as possible under the constraint of a DL rate threshold. This simulation uses an estimated average DL UE rate in pure cellular network as threshold. It can be seen from the figure that the poorest DL rate in hybrid network is about the same as the targeted threshold value while the overall UE throughput (especially D2D UE throughput) is largely improved. This threshold value can be altered for different scheduling purposes.

As shown in Figure5.8 before, in random D2D distance setting, D2D channel gains are in average much degraded (about 30dB lower at 50% CDF level) comparing to 20 m D2D distance setting. In addition, some potential D2D UEs are actually scheduled in UL/DL mode and split the system bandwidth orthogonally with other macro UEs. Due to these two reasons, both D2D UE throughput gain and DL UE throughput gain in random D2D distance setting are lower (about 25% lower) than that in 20m distance setting. However, they are still considerably higher comparing to pure cellular network.

A denser sector with 10 potential D2D UE pairs and other 10 macro DL UEs is examined as well. User throughput at 50% CDF level in pure cellular network containing 20 DL UEs is only about 1.1 Mbps due to severe congestion, while in hybrid network with 20 m D2D distance setting a 2.0 fold gain in average per user throughput is achieved (Figure 5.11). In random D2D distance setting, 1.65 fold gain in D2D UE throughput and 1.2 fold gain in DL UE throughput have been observed at 50% CDF level.

The above performances are achieved under the condition that full Channel State Information at the Transmitter (CSIT) is available at eNB. However, feeding back channel gains of all transmission links in a cell to eNB is impractical. In particular, frequency-dependent channel gains of interference channels between UEs are difficult

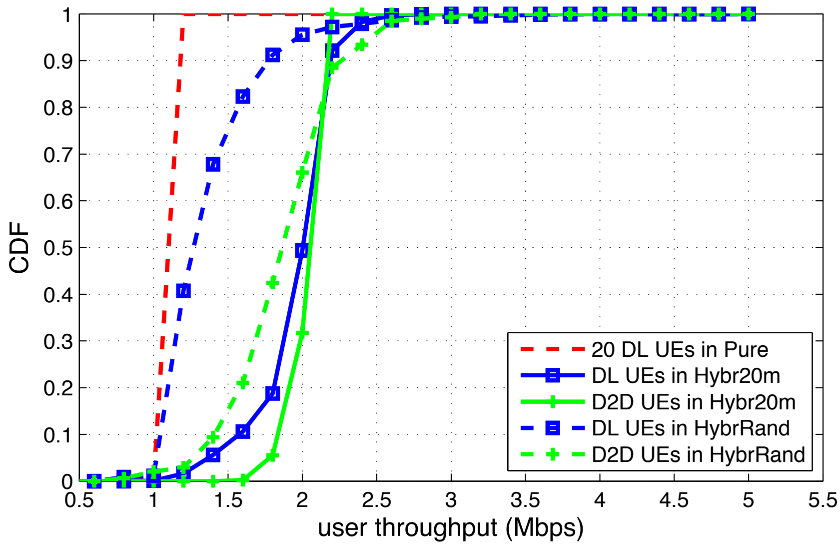


Figure 5.11 — User throughput CDF, 10 potential D2D pairs

to be obtained. We assume that only average channel gain of UE-UE interference channels are known at eNB, which can be estimated based on beacon signals for example. Performances that can be achieved by the scheduler with reduced CSIT are analyzed in a sector with 5 potential D2D UE pairs in 20 m D2D distance setting and other 10 macro DL UEs. Comparing to full CSIT case (Figure5.12), DL UE throughputs degrades 12% at 0.5 CDF level, while influence to D2D UE throughputs is negligible. The reason is that the inaccuracy in UE-to-UE interference channel estimation might result in suboptimal resource sharing, for example, a DL UE which is close to the D2D UE transmitter is chosen for resource sharing with the D2D link. For the DL UE that is scheduled in the same resource as the D2D link, underestimation of interference level from the D2D transmitter might result in insufficient DL power allocation, and therefore cause DL throughput degradation.

Cell spectral efficiency

Spectral efficiency gain is examined in Table 5.5. When D2D distance is fixed to 20m, with full CSIT, the spectral efficiency gain is almost doubled, which is close to the full spectral reuse efficiency (9bps/Hz). As is already analyzed, D2D channels in random distance setting are generally much weaker than those in 20 m D2D distance setting. When the D2D channel weakens, the sum rate in reused RBs becomes interference-limited. Therefore spectral efficiency gain in random distance setting is lower than that in 20 m D2D distance setting. In our scheduling, exclusive resources serve to maintain rates for certain DL UEs that are not suitable for resource sharing with existent D2D transmissions. With the increase of D2D pairs in a cell, the probability of finding a suitable D2D link for resource sharing becomes higher for an individual DL UE. Due to this D2D UE diversity, the number of DL UEs that need exclusive resources diminishes, this explains the higher spectral efficiency gain in maximum 10 D2D case than in maximum 5 D2D case. By assuming reduced CSIT, spectral efficiency gain has a 11% degradation in random D2D distance setting and a 4% degradation in

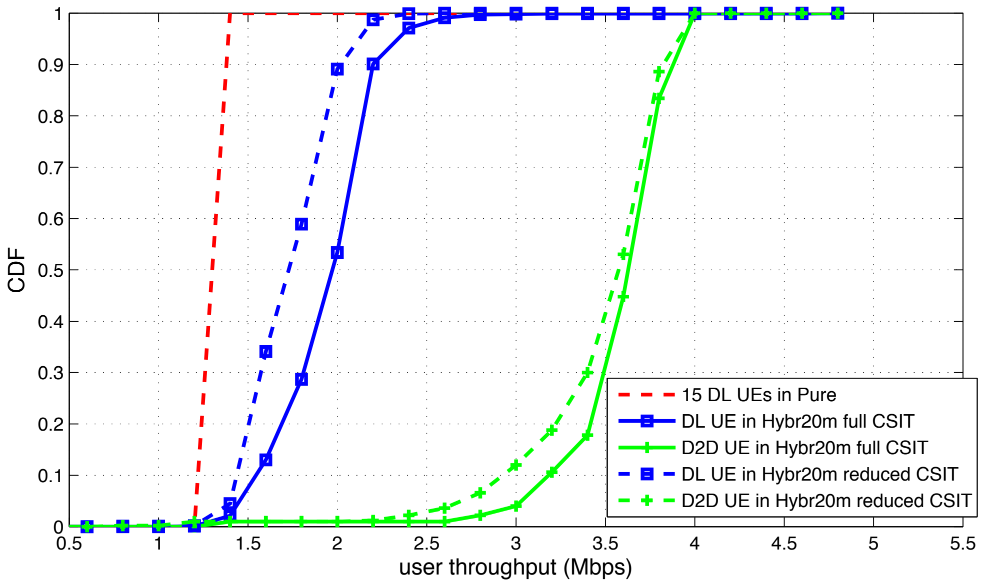


Figure 5.12 — Comparison of full and reduced CSIT

Table 5.5 — Spectral efficiency gain comparison

Measurements	**Pure Cellular**	**Hybrid random D**	**Hybrid D=20m**
5 potential D2Ds, full CSIT (bps/Hz)	4.5	6.4	8.2
10 potential D2Ds full CSIT (bps/Hz)	4.5	6.8	8.7
5 potential D2Ds, reduced CSIT (bps/Hz)	4.5	5.3	7.9

20 m D2D distance setting, comparing to that under full CSIT assumption.

Fairness

Maintaining a maximum fairness among UEs is not our scheduling objective. On the contrary, in order to maximize spectral efficiency, D2Ds are allowed to take as many resources as possible under the constraint of a DL rate threshold. That is to say, D2D UEs could have much higher throughputs than DL UEs in the case that the number of D2D UEs in a cell is sparse comparing to DL UEs. For example, Figure 5.10 shows that in a sector containing 5 potential D2D links and 10 other DL UEs, D2D UE throughput at 0.5 CDF level is about 1.8 fold of DL UE throughput in 20 m D2D distance setting. The DL fairness factor, however, is maintained in a way that the worst DL UE throughput is about the same as that in pure cellular network.

5.3.3 Summary and discussion

To evaluate the scheduler proposed in Chapter 4, system-level simulation is executed for a multi-link network model. We use the WINNER Phase II channel model, which is a geometry-based stochastic channel model. Performance metrics such as per UE throughput and spectral efficiency of the hybrid cellular and D2D network are evaluated in FDD DL spectrum. The simulation layout is constrained to a single sector of a three-sectored urban macro cell.

The proposed scheduler is designed to work with arbitrary D2D distance and arbitrary number of D2D pairs in a cell. However, for the analysis purpose, two D2D distance settings: fixed D2D distance setting and random D2D distance setting, and two user number settings: medium-density and high-density D2D deployments are simulated. In fixed D2D distance setting, D2D receivers are firstly generated randomly in the sector area. Then for each D2D receiver, a D2D transmitter is generated with fixed distance to the D2D receiver. In random D2D distance setting, D2D UEs are generated randomly in the sector area, and then paired randomly.

When generating D2D UEs, it is the number of potential D2D pairs that is fixed. The medium-density D2D deployment contains 5 potential D2D pairs and 10 other DL UEs while the high-density D2D deployment contains 10 potential D2D pairs and 10 other DL UEs. Potential D2D pairs designate a pair of source and sink UE in proximity. With mode selection algorithm, certain potential D2D pairs are finally scheduled in UL/DL mode, acting as traditional UL and DL UEs, orthogonally sharing the UL and DL band with other macro UEs. If a potential D2D pair is scheduled in UL/DL mode, then the UE receiver is classified as DL UE and its performances are classified as DL UE performances in the simulation results.

The proposed mode selection algorithm chooses between D2D mode and UL/DL mode, which is estimated to have higher spectral efficiency. Therefore the criteria depends on channel gains between the transmitter UE and the receiver UE, as well as UL channel gains between the transmitter UE and the eNB, and DL channel gains between the eNB and the receiver UE. The mode selection result shows high dependence on channel gains between the transmitter UE and the receiver UE. The comparison of D2D channel gains of D2D pairs being selected by mode selection algorithm and channel gains of all potential D2D pairs before mode selection shows that the proposed mode selection algorithm prevents pairs of source and sink UEs with poor D2D channels (mostly below -120 dB) from using D2D mode.

In mode selection algorithm, the estimated spectral efficiency of a D2D link is calculated by required data rate dividing minimum bandwidth that is needed to support the required data rate under the D2D channel condition. The real spectral efficiency on D2D pairs occupied bandwidths can be higher due to resource sharing with DL UEs, with interference well controlled. Simulation results show that when D2D distances are small, in a 20 m D2D distance setting, D2D mode is always selected, and the spectral efficiency is almost doubled comparing to that in pure cellular network. In addition, the hybrid network achieves almost the highest spectral efficiency that can be offered by the reusing scheme. The highest spectral efficiency with the designated reusing scheme can only be attained when D2D transmissions share the whole DL bandwidth, and both D2D and DL transmit with the highest rate that can be supported by the highest MCS. It strongly proofs that the proposed scheduler successfully mitigates the intra-cell interference between D2D UEs and DL UEs reusing the same resources.

In random D2D distance setting, channel gains are usually much lower (-30 dB lower in average) than that in 20 m D2D distance setting, but 90% of the potential

D2D pairs are still scheduled in D2D mode according to the mode selection criteria. The spectral efficiency has more than 1.4 fold gain comparing to pure cellular network.

In the proposed scheduling strategy, D2D links are scheduled semi-persistently, and DL UEs are scheduled dynamically to reuse the same resources as D2D pairs. Therefore, the more D2D pairs existent in a cell, the easier for a specific DL UE to find suitable D2D pairs for resource sharing. Therefore in high-density D2D deployment, the spectral efficiency gain can be higher than in medium-density D2D deployment due to D2D UE diversity.

Optimizing spectral efficiency is the main target for the purpose of offloading. On the other hand, however, we desire that improvements in overall UE throughputs can be achieved. In other words, we desire that average per user data throughputs in the hybrid system get commonly ameliorative comparing to those in the pure cellular network. Criteria based on PFS are used to scheduling DL UEs in order to flexibly achieve the balance between spectral efficiency and DL UE fairness. In addition, a constraint to protect the lowest DL rate is applied when scheduling D2D UE. D2Ds are allowed to take as many resources as possible as long as a minimum DL rate requirement is attained. In the simulation, this minimum DL rate threshold is defined as the estimated lowest DL rate in pure cellular network. The simulation results demonstrate that this value is well targeted and both DL and D2D UE per user data throughputs are basically much higher than this threshold. Comparing to per user data throughputs in pure cellular network, in the hybrid system with 20 m D2D distance setting and medium-density D2D deployment, a 2.7 fold gain is observed in D2D per user data throughputs in average and a 1.5 fold gain is observed in DL per user data throughputs. D2D per user data throughputs are especially high due to the ambitious D2D resource allocation strategy.

In a high-density D2D deployment, local traffics between proximate UEs, if not scheduled in D2D mode, are highly resource consuming and might congest the cellular network. Through D2D mode offloading, DL congestion is largely alleviated. As a result, about 2-fold gain is observed in both DL and D2D per user data throughputs in 20 m D2D distance setting.

As explained before, D2D links with short range usually have high D2D channel gains, and performance gains resulted from D2D mode transmission are prominent. With the increase of D2D distance, the D2D channels degrade, the possibility of a potential D2D pair being scheduled in D2D mode decreases, and mutual interference augments in resource sharing scheme. Therefore D2D offloading effect is less remarkable in random D2D distance setting than in 20 m D2D distance setting. In medium-density D2D deployment, both D2D and DL UE throughput gain in average are about 25% lower than that in 20 m D2D distance setting. In high-density D2D deployment, DL UE throughput gain in average is about 37% lower than that in 20 m D2D distance setting and D2D UE throughput gain in average is about 14% lower than that in 20 m D2D distance setting.

The centralized interference coordination is sensitive to the availability of CSI at eNB, whereas interference channels between UEs are usually difficult to measure and feedback overhead can be prohibitive. When replacing full CSIT by mean channel gain information for all the interference channels from D2D transmitters to DL UEs, a 12% degradation in DL per user data throughput in average is observed, while influence to D2D per user data throughput is negligible.

To conclude, the system-level simulation results demonstrate that traffics originated between proximate UEs can be successfully offloaded from cellular network by applying in-band D2D mode transmission. The spectral efficiency gain mainly results from the frequency reuse between D2D and DL transmissions. The combined coordination techniques of mode selection, resource allocation and power control successfully optimize the aggregate throughput in the frequency reuse scheme. The proposed scheduling method not only achieves high spectral efficiency gain, but also guarantees an overall improvement in per user data throughput.

CHAPTER 6 Conclusion

Integrating D2D into LTE-Advanced networks is a promising method to support ever-increasing demand of proximity-based social/commercial services and applications. The objective of this work has been the analysis, design, development and evaluation of a hybrid D2D cellular system.

This thesis begins by a brief introduction to the research interests on D2D technologies in next-generation wireless communication systems, as well as to the academic research history and existent D2D technologies in other wireless standards.

Chapter 2 is concerned with background survey of D2D technologies and standardization process of LTE D2D. Potential usages, opportunities and risks of this new network architecture are analyzed. The contributions include:

- An informative survey of existent widely used D2D technologies in other wireless standards and a detailed comparison of usage cases, market prospects, network structure, PHY/MAC characteristics, etc.
- A thorough literature review of coexistent D2D and cellular networks and a presentation of D2D features in LTE standardization process.
- An analysis of LTE D2D potential usages, general functions that need to be provided, and implementation challenges.

Chapter 3 investigates physical and MAC characteristics that are required to support LTE D2D. Its contributions include:

- An introduction to current LTE physical and MAC specifications, especially those related to our consideration of D2D discovery and communication design.
- Identification of design requirements and choices to enable devices in LTE to discover each other directly over the air.
- Identification of design requirements and choices to enable devices in LTE to communicate to each other directly and to enable the LTE network to control the D2D data Communications under its coverage.

In Chapter 4, a centralized scheduling strategy in eNB is proposed to coordinate the D2D and cellular data transmissions in the same FDD downlink band. The contributions include:

- An analysis of issues in coordinating in-band D2D data transmission underlaying LTE network, in addition to literature reviews.
- A global consideration of both D2D and cellular users in performance metrics but separability in optimization for D2D and cellular users. Overall per user average throughput gain is targeted with low complexity.
- An innovative scheduling strategy with no constraint on D2D range and D2D number in the network layout, which allows calibration under more general assumptions. D2D is semi-persistently scheduled so that signaling overhead is reduced.

Chapter 5 introduces evaluation methodology and presents simulation results of in-band D2D transmission coordinated by the scheduling strategy proposed in Chapter 4. Its contributions include:

- An introduction to evaluation methodology, including radio access requirements, ITU guidelines for evaluation procedure and criteria, system simulation principles, and channel models.
- System-level performance calibration of D2D data communication in LTE FDD downlink spectrum.
- A demonstration that the hybrid system with proposed centralized scheduling method largely outperforms the pure cellular system in terms of system spectral efficiency and overall user throughputs.

The key achievement in this work has been the feasibility analysis in physical and MAC layer functions to support direct D2D discovery and direct D2D data Communication underlaying LTE networks, the design of a centralized scheduling strategy in eNB to coordinate intra-cell interference resulted from in-band D2D communication, and performance calibration of D2D data communication in LTE FDD downlink spectrum via system-level simulation. The initial tests demonstrate considerable performance advantages of direct D2D data transmission replacing conventional UL/DL mode transmission for local traffic between proximate UEs.

At the moment this thesis is being concluded, the physical and MAC layer specification for LTE D2D is under discussion in 3GPP RAN1 group. To complete the design of physical and MAC layer for LTE D2D, a lot of aspects are to be studied in details: D2D channel models, evaluation requirements, channel access method, synchronization mechanism, discovery beacon design, random access procedure, discovery procedure, resource use, frame structure, control signaling and reference signal design, etc.

The proposed scheduler works well under the ideal full CSIT assumption. Imperfection of channel information, however, due to measurement accuracy, quantization loss, feedback delay, etc., may deteriorate scheduling efficiency and should be analyzed by simulation.

Interference scenario in the case of D2D operating in FDD uplink spectrum is different from that in the case of D2D operating in FDD downlink spectrum. Therefore interference coordination methods differ in theses two cases. Potential performance gains in uplink reuse case are to be evaluated on the purpose of comparison with downlink case and eventually contribute to the decision of D2D resource use.

Performances of D2D transmission are evaluated under the assumption that each D2D pair locates in the same sector. In reality, the D2D transmitter and receiver might locate in neighbor sectors/cells, and therefore more advanced inter-cell interference cancellation techniques might be required, requiring joint scheduling between different sectors/cells. Enhancements to scheduling method should be identified and performance gains, as well as complexity and delays, should be analyzed.

Résumé de la thèse

Le concept des transmissions Device-to-Device (D2D) basées sur le réseau LTE-Advanced (Figure 1) repose sur le fait que la transmission des signaux d'un équipement utilisateur (UE) puisse être reçu depuis un autre équipement utilisateur sans utiliser l'infrastructure cellulaire (eNB, HeNB, etc). Intégrer le service D2D au sein de la norme LTE-Advanced est une méthode prometteuse pour répondre à la demande toujours croissante des services et applications basés sur la proximité. Cette thèse a pour objectif l'analyse, la conception, le développement et l'évaluation d'un réseau hybride avec la technologie D2D et les communications cellulaires.

Dans le chapitre 2, nous avons effectué l'état de l'art des technologies D2D. Premièrement, nous avons présenté et comparé quatre technologies D2D du type out-band : Bluetooth, ZigBee, NFC, Wi-Fi Direct. Ensuite, nous avons examiné les études bibliographiques réalisées sur la coexistence entre la technologie D2D et les réseaux cellulaires. Enfin, nous avons analysé les intérêts et les défis provenant de l'apport des capacités de la technologies D2D au réseau LTE-Advanced. Aussi, nous avons introduit le processus de standardisation 3GPP de la technologie LTE D2D.

Le chapitre 3 a pour objectif d'identifier les options de conception et les meilleures solutions pour les couches physique et MAC. Ceci a pour but de faire en sorte que les équipements utilisateurs puissent se détecter et communiquer directement à travers l'air, mais aussi que le réseau LTE puisse diriger et contrôler les détections et les communications D2D. Les spécifications clés des couches physiques et MAC du réseau LTE

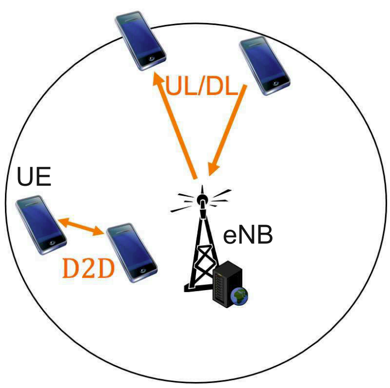


Figure 1 — Transmission D2D VS. Transmission UL/DL

sont tout d'abord examinées. Les modifications et améliorations de LTE qui permettent d'incorporer les capacités liés à la technologie D2D sont ensuite recherchées. Les discussions ont porté sur les quatre aspects suivants :

1. Considération générale sur l'utilisation des ressources D2D

   Afin que l'équipement utilisateur puisse supporter les transmissions D2D, nous avons étudié les modifications nécessaires sur la conception RF, ce qui pose des contraintes liées à l'utilisation des ressources D2D dans les systèmes TDD et FDD. Nous avons comparé les avantages et désavantages dans le cas des transmissions D2D via l'utilisation des ressources dédiées, et dans le cas où celles-ci utilisent le chevauchement des ressources avec les réseaux cellulaires.

2. Choix de synchronisation

   La synchronisation est déterminante pour l'efficacité de la transmission. Nous avons mis en évidence les avantages de la communication synchronisée et nous avons proposé que le canal et la procédure D2D soient utilisées dès que celles-ci sont possible. Nous avons analysé les techniques possibles pour réaliser un système D2D synchronisé, et nous avons proposé que l'équipement utilisateur D2D puisse se synchroniser constamment à un nœud de référence pour tirer parti de l'efficacité des transmissions synchronisés. Nous avons aussi évoqué les points pertinents tels que le nœud de référence, la structure du signal de synchronisation et la consommation énergétique.

3. Conception de la structure du signal de détection D2D, du multiplexage de ressources dédiées à la détection, et de la procédure de détection

   Pour réaliser la détection D2D, deux fonctions sont essentielles : la détection de proximité et d'identité. Nous avons proposé que les signaux de détection D2D soient composés tout d'abord d'une séquence de voie balise, qui est utilisée pour la détection de proximité, et la synchronisation, et ensuite du message contenant l'identité et les informations de service. Cette structure fonctionne aussi bien avec et sans couverture de réseau. Nous avons comparé différentes méthodes de multiplexage des ressources dédiées à la détection. Et nous avons proposé (Figure 2) de réserver les ressources uplink de LTE qui seront utilisées périodiquement pour la détection D2D. Les ressources dédiées à la détection D2D consistent à une continuité de sous-trames dans lesquelles PUSCH n'apparaît pas (multiplexage temporel avec PUSCH), et dans ces sous-trames dédiées à la détection, les liens D2D sont multiplexés en fréquence. Enfin, nous avons proposé une procédure de détection sous contrôle de réseau (Figure 3).

4. Techniques de coordination d'interférences pour les communications de données D2D utilisant les ressources en chevauchement avec les transmissions cellulaires

   L'utilisation des ressources en chevauchement est préféré pour les communications de données D2D afin de permettre une meilleure utilisation des bandes du spectre sous licence. Nous avons étudié le problème de l'interférence due à l'effet "proche-lointain" qui peut être causé par l'utilisation des ressources en chevauchement.

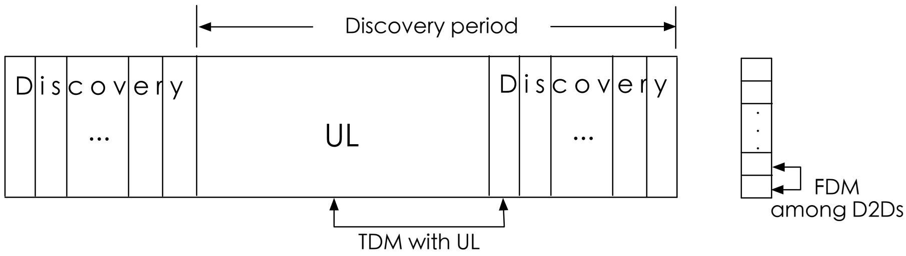


Figure 2 — La structure de ressources dédiées à la détection

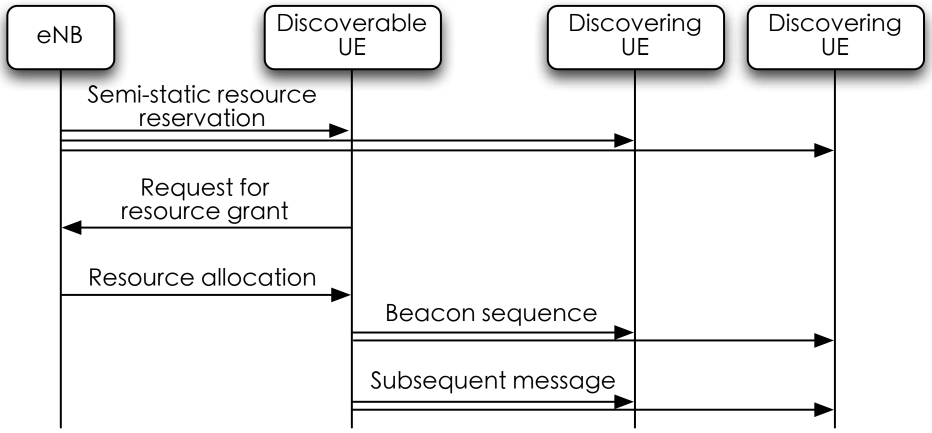


Figure 3 — La procédure de détection sous contrôle de réseau

Quatre techniques ont été avancé pour permettre la coordination d'une communication hybride D2D et cellulaire, et pour parvenir à réutiliser les ressources efficacement. La coordination de trois différents niveaux de centralisation est discuté, à savoir une centralisation totale, partielle, ou une distribution. Pour les communications de données D2D, nous avons proposé une stratégie d'allocation des ressources, caractérisée par le niveau de centralisation, qui dépend du déploiement D2D (Figure 4).

Dans le chapitre 4, nous avons introduit une stratégie de planification centralisée dans eNB pour coordonner les transmissions D2D sous couverture. Les études bibliographiques sur la coordination des ressources D2D "in-band" ont tout d'abord été analysées. Puis, nous avons établi des considérations importantes sur la planification. Différentes approches avec leurs intérêts propres sont comparées. Ensuite, nous avons décris le scénario et les objectifs de planification. Nous avons proposé une planification combinant des techniques d'allocation de ressource, d'énergie, et de sélection de mode. Ces décisions sont faites de manière centralisé par les stations de base.

La procédure complète de planification est illustrée par le diagramme suivant (Figure 5). Initialement, le mode utilisant le plus efficacement les ressources est sélectionné pour transmettre le trafic local. A chaque instant "semi-persistant" de planification, les liens D2D sont replanifiés et le nombre de ressources disponibles pour les utilisateurs D2D est ajusté afin de satisfaire le débit DL. A chaque slot temporel, les utilisateurs DL sont planifiés dynamiquement. Le principal objectif de l'allocation des ressources

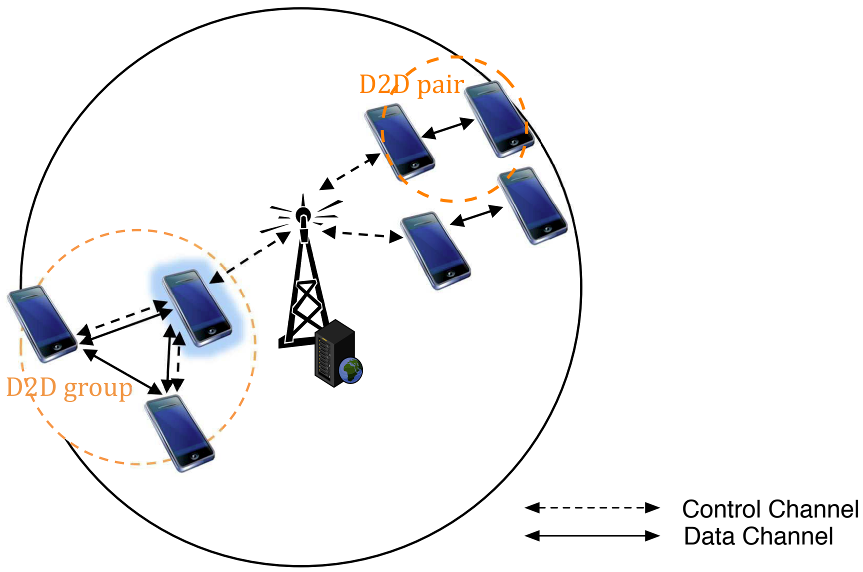


Figure 4 — L'allocation des ressources avec niveaux de centralisation partielle ou de centralisation totale

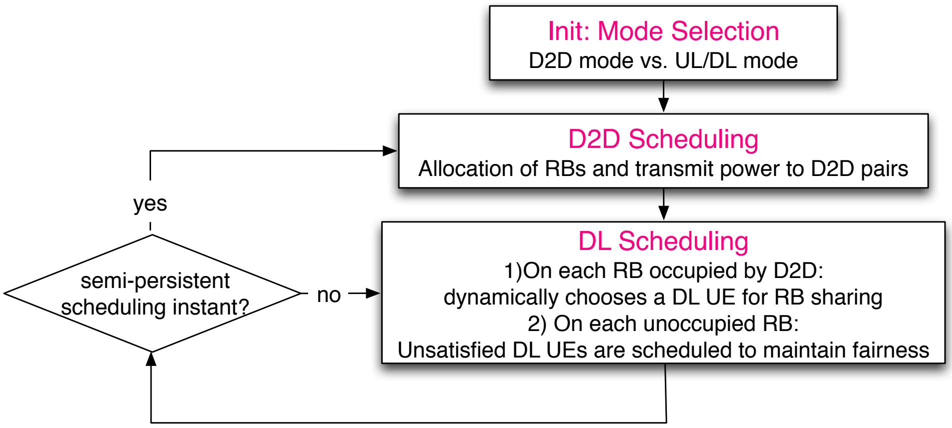


Figure 5 — La procédure de planification semi-persistant dans eNB

DL est la gestion des interférences, et l'optimisation des gains de débit du système. Le principe consiste à tirer parti de la diversité des utilisateurs dans une cellule pour réutiliser les ressources afin de maximiser le débit additif sur les RBs occupés par D2D. Cependant, pour les RBs inocupés, l'équité est la principale considération pour satisfaire l'ensemble des utilisateurs cellulaires.

La mesure de performance de la stratégie de planification proposée vise la satisfaction de l'ensemble des utilisateurs. Un bon équilibre entre l'efficacité spectrale et l'équité parmi les utilisateurs est nécessaire pour garantir la satisfaction globale des utilisateurs. Nous avons proposé une mesure de la performance basée sur des critères d'équité proportionnelle, qui permettent de jouer sur l'optimisation du débit du système, et sur la conservation de l'équité parmi les utilisateurs.

L'algorithme de planification proposée est un algorithme général pouvant gérer une structure arbitraire de réseau. Celui-ci n'a pas de contrainte particulière sur les dis-

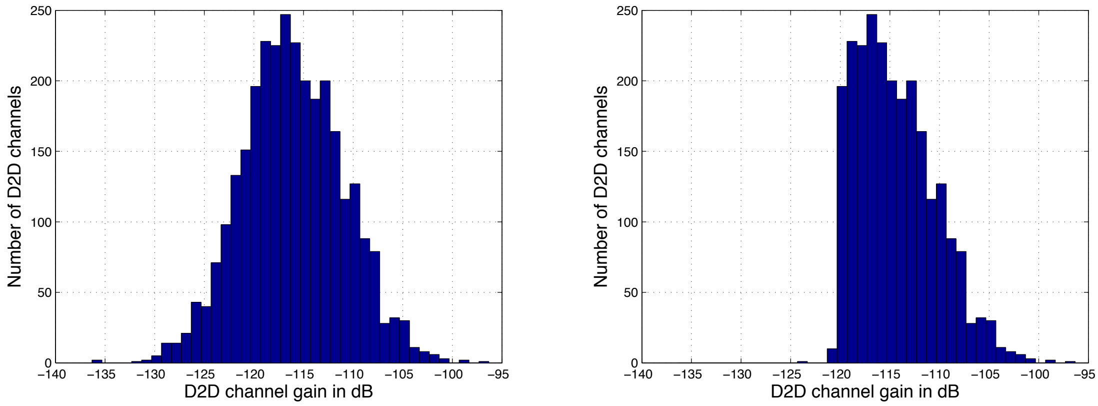


Figure 6 — L'histogramme des gains de canaux D2D avant (gauche) et apès (droit) la sélection de mode

tances D2D ou les nombres de paires D2D. La bande passante totale pouvant être occupée par les communications D2D est contrainte par le débit minimal de l'équipement utilisateur cellulaire. De cette façon, les communications de données cellulaires sont protégées même en cas d'une présence massive des communications de données D2D. Le mode D2D n'est pas choisi pour les liens D2D de faible qualité (par exemple les liens D2D de longue distance) grâce à un mode sélectif de l'algorithme.

La stratégie de planification proposée est de faible complexité. Cela est dû au fait d'avoir séparé l'optimisation des transmissions D2D des transmissions cellulaires. Le coût de signalisation est aussi réduit grâce au faible cycle de planification.

Le chapitre 5 évalue la planification proposée au chapitre précédent à travers une simulation au niveau système dans un modèle de réseau multi-liens. Nous avons tout d'abord décrit la méthodologie générale d'évaluation. Les approches de la simulation au niveau système, et les modèles des canaux sont présentés. Aussi, nous avons détaillé nos choix de scénarios de déploiement, la structure du réseau, ses paramètres et hypothèses faites. Les mesures de performances telles que le débit moyen par UE et l'efficacité spectrale d'un réseau cellulaire hybride D2D sont évalués via un spectre FDD DL.

La comparaison des gains de canaux entre les paires D2D sélectionnées par l'algorithme de sélection de mode et l'ensemble des potentielles paires D2D avant la sélection de mode montre que l'algorithme de sélection de mode proposée empêche les paires d'émetteur/récepteur de faible qualité (en dessous de -120dB) d'utiliser le mode D2D (Figure 6).

Les résultats des simulations montre que lorsqu'on impose une distance D2D fixée à 20 mètres, le mode D2D est toujours sélectionné car les liens de qualité D2D sont satisfaisants. L'efficacité spectrale est presque doublée en comparaison avec un pur réseau cellulaire. Cela prouve que le spectre cellulaire est efficacement réutilisé par les communications D2D. En augmentant la distance D2D, la qualité des liens D2D se dégrade, ce qui devient moins avantageux pour la réutilisation des ressources. Cependant, l'efficacité spectrale du réseau hybride est toujours beaucoup plus élevée que celle d'un pur réseau cellulaire. L'augmentation de l'efficacité spectrale signifie que la planifica-

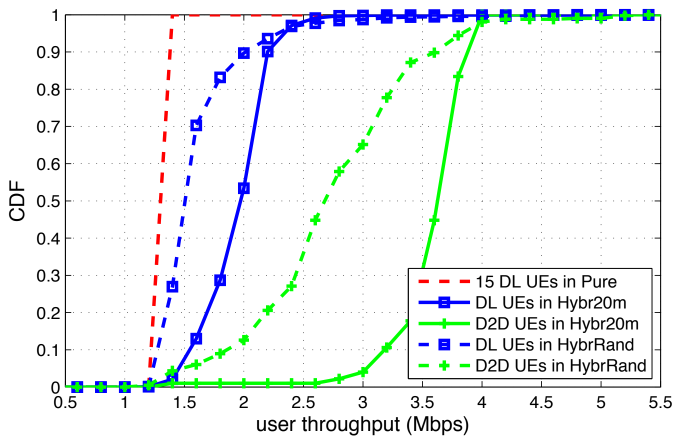


Figure 7 — CDF de débit moyen par utilisateur, 5 potentielles pairs D2D

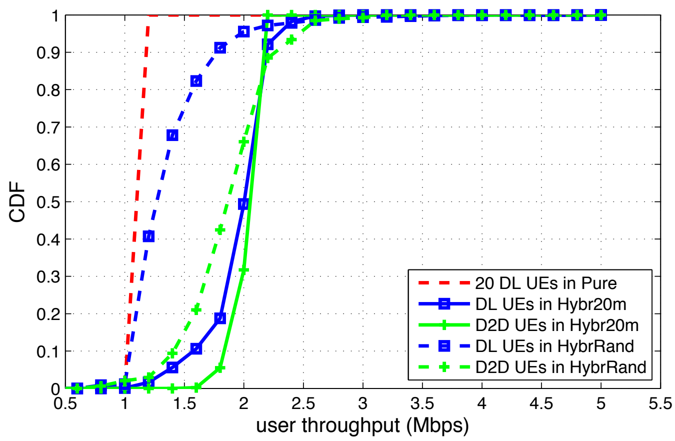


Figure 8 — CDF de débit moyen par utilisateur, 10 potentielles pairs D2D

tion proposée a réduit les interférences intra-cellulaire provenant de la réutilisation des ressources D2D, et qu'elle a aussi réduit le trafic présent sur le réseau cellulaire.

Le débit moyen par utilisateur est un autre indicateur clé de performance pour évaluer la planification car il reflète la satisfaction globale de l'utilisateur. Nous avons effectué des simulations sur deux configurations différentes: celle d'un trafic D2D moyennement chargé (Figure 7), et celle avec un trafic élevé (Figure 8). Dans les deux cas, les statistiques (présentées par CDF) montrent que le débit global de l'utilisateur est plus élevé dans un réseau hybride intégrant le mode D2D que dans un pur réseau cellulaire. Le débit minimum DL s'est bien trouvé être au dessus du seuil prédéfini. Cela prouve que l'augmentation de l'efficacité spectrale ne sacrifie pas le débit moyen d'un certain nombre d'utilisateur. La planification proposée permet donc d'atteindre la satisfaction de l'ensemble des utilisateurs.

Nous avons tout d'abord lancé la simulation en supposant une connaissance totale du CSIT, cela signifie qu'en pratique les mesures des canaux doivent être renvoyées à la station de base à temps. Nous avons ensuite comparé avec les résultats de la simulation obtenue en supposant une connaissance réduite du CSIT. Dans ce dernier cas, seul les

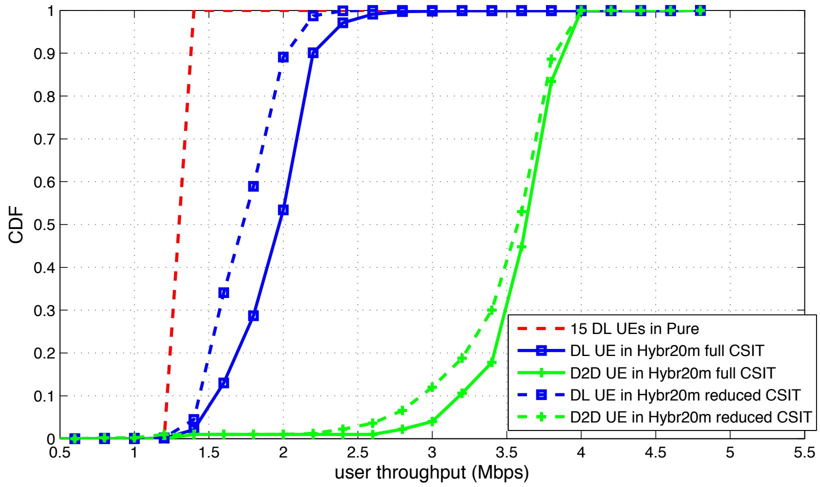


Figure 9 — Comparaison entre le cas d'une connaissance totale du CSIT et le cas d'une connaissance réduite du CSIT

gains moyen des canaux interférences UE-UE sont connus par la station de base. Bien que l'influence du débit moyen de données D2D par utilisateur est négligeable, une diminution du débit moyen de données DL par utilisateur est observé (Figure 9), cela signifie que la planification centralisé est sensible à la disponibilité de CSI à la station de base.

Bibliography

[TR2,] 3gpp technical report 22.803, feasibility study for proximity services (prose). Technical report, www.3gpp.org.

[TR3,] 3gpp technical report 36.913, requirements for further advancements for evolved universal terrestrial radio access (e-utra) (lte-advanced). Technical report, www.3gpp.org.

[ABI, a] Bluetoothâs role in the internet of everything , 2013 report. www.abiresearch.com/research/service/bluetooth/.

[ABI, b] Nfc market data , 2012 report. www.abiresearch.com/research/service/nfc/.

[M.2, 2008] (2008). *ITU-R M.2134, Requirements related to technical performance for IMT-Advanced radio interface(s).*

[WIN, 2008] (2008). *WINNER II Public Deliverable D1.1.2 WINNER II channel models.*

[M.2, 2009] (2009). *ITU-R M.2135, Guidelines for evaluation of radio interface technologies for IMT-Advanced.*

[WIN, 2009] (2009). *WINNER+ Public Deliverable D1.3 Innovative concepts in Peer-to-Peer and Network Coding.*

[Adachi T, 1998] Adachi T, Nakagawa, M. (1998). A study on channel usage in a cellular ad-hoc united communication system for operational robots. *communications, IEICE transactions on*, 81(7):1500–1507.

[Bhatia et al., 2006] Bhatia, R., Bhatia, E., Li, L. E., Luo, H., Ramjee, R., and Sanjoy, P. (2006). Icam: Integrated cellular and ad-hoc multicast. *IEEE Transactions on Mobile Computing*, 5:1004–1015.

[Brueninghaus et al., 2005] Brueninghaus, K., Astely, D., Salzer, T., Visuri, S., Alexiou, A., Karger, S., and Seraji, G.-A. (2005). Link performance models for system level simulations of broadband radio access systems. In *Personal, Indoor and Mobile Radio Communications, 2005. PIMRC 2005. IEEE 16th International Symposium on*, volume 4, pages 2306–2311 Vol. 4.

[Chen et al., 2012] Chen, R., Liao, X., Zhu, S., and Liang, Z. (2012). Capacity analysis of device-to-device resource reusing modes for cellular networks. In *Communication, Networks and Satellite (ComNetSat), 2012 IEEE International Conference on*, pages 64–68.

[Chiussi and Sivaraman, 1998] Chiussi, F. and Sivaraman, V. (1998). Achieving high utilization in guaranteed services networks using early-deadline-first scheduling. In *Quality of Service, 1998. (IWQoS 98) 1998 Sixth International Workshop on*, pages 209–217.

[Doppler et al., 2009] Doppler, K., Rinne, M., Wijting, C., Ribeiro, C., and Hugl, K. (2009). Device-to-device communication as an underlay to lte-advanced networks. *Communications Magazine, IEEE*, 47(12):42–49.

[Doppler et al., 2010] Doppler, K., Yu, C.-H., Ribeiro, C., and Janis, P. (2010). Mode selection for device-to-device communication underlaying an lte-advanced network. In *Wireless Communications and Networking Conference (WCNC), 2010 IEEE*, pages 1–6.

[Huang et al., 2008] Huang, K., Chen, Y., Chen, B., Yang, X., and Lau, V. (2008). Overlaid cellular and mobile ad hoc networks. In *Communication Systems, 2008. ICCS 2008. 11th IEEE Singapore International Conference on*, pages 1560–1564.

[Huang et al., 2009] Huang, K., Lau, V., and Chen, Y. (2009). Spectrum sharing between cellular and mobile ad hoc networks: transmission-capacity trade-off. *Selected Areas in Communications, IEEE Journal on*, 27(7):1256–1267.

[Islam et al., 2007] Islam, H., Liang, Y.-C., and Hoang, A. T. (2007). Distributed power and admission control for cognitive radio networks using antenna arrays. In *New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on*, pages 250–253.

[J. E. Korneluk and Rodrigues,] J. E. Korneluk, S. E. Dubin, W. A. P. and Rodrigues, A. Swithcing a call from a network assisted communication mode to a direct communication mode.

[Janis et al., 2009] Janis, P., Koivunen, V., Ribeiro, C., Korhonen, J., Doppler, K., and Hugl, K. (2009). Interference-aware resource allocation for device-to-device radio underlaying cellular networks. In *Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th*, pages 1–5.

[Kim et al., 2008] Kim, D. I., Le, L. B., and Hossain, E. (2008). Joint rate and power allocation for cognitive radios in dynamic spectrum access environment. *Wireless Communications, IEEE Transactions on*, 7(12):5517–5527.

[L. Hentila and Alatossava., 2007] L. Hentila, P. Kyosti, M. K. M. N. and Alatossava., M. (2007). *MATLAB implementation of the WINNER Phase II Channel Model ver1.1.*

[L. Sun and Jia,] L. Sun, N. Ma, J. C. and Jia, Q. Distance dependent direct mode peer-to-peer communication establish in a tdd cdma network.

[Law et al., 2010] Law, L., Pelechrinis, K., Krishnamurthy, S., and Faloutsos, M. (2010). Downlink capacity of hybrid cellular ad hoc networks. *Networking, IEEE/ACM Transactions on*, 18(1):243–256.

[Le and Hossain, 2008] Le, L. B. and Hossain, E. (2008). Resource allocation for spectrum underlay in cognitive radio networks. *Wireless Communications, IEEE Transactions on*, 7(12):5306–5315.

[Li et al., 2008] Li, X. J., Seet, B.-C., and Chong, P. H. J. (2008). Multihop cellular networks: Technology and economics. *Comput. Netw.*, 52(9):1825–1837.

[Liu et al., 2012] Liu, P., Hu, C., Peng, T., Qian, R., and Wang, W. (2012). Admission and power control for device-to-device links with quality of service protection in spectrum sharing hybrid network. In *Personal Indoor and Mobile Radio Communications (PIMRC), 2012 IEEE 23rd International Symposium on*, pages 1192–1197.

[Luo et al., 2003] Luo, H., Ramjee, R., Ramjee, R., Sinha, P., Li, L. E., and Lu, S. (2003). Ucan: A unified cellular and ad-hoc network architecture. In *In Proceedings of ACM MOBICOM*, pages 353–367.

[Menon et al., 2005] Menon, R., Buehrer, R., and Reed, J. (2005). Outage probability based comparison of underlay and overlay spectrum sharing techniques. In *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*, pages 101–109.

[Norlund et al., 2004] Norlund, K., Ottosson, T., and Brunstrom, A. (2004). Fairness measures for best effort traffic in wireless networks. In *Personal, Indoor and Mobile Radio Communications, 2004. PIMRC 2004. 15th IEEE International Symposium on*, volume 4, pages 2953–2957 Vol.4.

[Papadogiannis et al., 2009] Papadogiannis, A., Saadani, A., and Hardouin, E. (2009). Exploiting dynamic relays with limited overhead in cellular systems. In *GLOBECOM Workshops, 2009 IEEE*, pages 1–6.

[Pokhariyal et al., 2006] Pokhariyal, A., Kolding, T., and Mogensen, P. (2006). Performance of downlink frequency domain packet scheduling for the utran long term evolution. In *Personal, Indoor and Mobile Radio Communications, 2006 IEEE 17th International Symposium on*, pages 1–5.

[Raghothaman et al., 2011] Raghothaman, B., Sternberg, G., Kaur, S., Pragada, R., Deng, T., and Vanganuru, K. (2011). System architecture for a cellular network with cooperative mobile relay. In *Vehicular Technology Conference (VTC Fall), 2011 IEEE*, pages 1–5.

[Sankaranarayanan et al., 2005] Sankaranarayanan, S., Papadimitratos, P., and Mishra, A. (2005). Enhancing wireless spectrum utilization with a cellular-ad hoc overlay architecture. In *Military Communications Conference, 2005. MILCOM 2005. IEEE*, pages 405–412 Vol. 1.

[Stefania Sesia, 2011] Stefania Sesia, Issam Toufik, M. B. (2011). *LTE - The UMTS Long Term Evolution: From Theory to Practice, 2nd Edition*. Wiley.

[Tadrous et al., 2011] Tadrous, J., Sultan, A., and Nafie, M. (2011). Admission and power control for spectrum sharing cognitive radio networks. *Wireless Communications, IEEE Transactions on*, 10(6):1945–1955.

[Tadrous et al., 2010] Tadrous, J., Sultan, A., Nafie, M., and El-Keyi, A. (2010). Power control for constrained throughput maximization in spectrum shared networks. In *Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE*, pages 1–6.

[Xing et al., 2007] Xing, Y., Mathur, C., Haleem, M., Chandramouli, R., and Subbalakshmi, K. P. (2007). Dynamic spectrum access with qos and interference temperature constraints. *Mobile Computing, IEEE Transactions on*, 6(4):423–433.

[Xu and Wang, 2012] Xu, S. and Wang, H. (2012). Transmission mode selection and communication establishment in the hybrid device-to-device and cellular networks. In *Ubiquitous and Future Networks (ICUFN), 2012 Fourth International Conference on*, pages 156–161.

[Xu et al., 2010] Xu, S., Wang, H., Chen, T., Huang, Q., and Peng, T. (2010). Effective interference cancellation scheme for device-to-device communication underlaying cellular networks. In *Vehicular Technology Conference Fall (VTC 2010-Fall), 2010 IEEE 72nd*, pages 1–5.

[Yu et al., 2009] Yu, C.-H., Tirkkonen, O., Doppler, K., and Ribeiro, C. (2009). Power optimization of device-to-device communication underlaying cellular communication. In *Communications, 2009. ICC '09. IEEE International Conference on*, pages 1–5.

[Zhao and Todd, 2006] Zhao, D. and Todd, T. (2006). Cellular cdma capacity with out-of-band multihop relaying. *Mobile Computing, IEEE Transactions on*, 5(2):170–178.

[Zhou and Yang,] Zhou, J. and Yang, Y. R. Parcels: Pervasive ad-hoc relaying for cellular systems.