Next-Generation Cellular Technologies for Sensor Networking

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Abstract

Device-to-Device (D2D) and Massive Machine Communication (MMC) are believed to be cornerstones in next generation cellular technologies. With D2D enabled in Long Term Evolution Advanced (LTE-A) networks, devices in physical proximity are able to discover each other and communicate via a direct path using licensed LTE spectrums. As a method to increase spectrum utilisation, extend cellular coverage, and offload backhaul traffic, D2D has been proposed in 3rd Generation Partnership Project (3GPP) LTE-A, but mainly to address Public Safety communications. Combining with LTE-A D2D, networks with massive number of machine type communications, such as wireless sensor network, introduces a paradigm shift and opens up new opportunities for proximity-based services.

Based on 3GPP standardised channel models, this thesis simulates and analyses D2D message exchanges between two sensor nodes and the maximum communication range obtained under different environments with receiver diversity. Also, a novel distributed resource allocation method is proposed for the clustered sensor network. D2D will introduce a new interference source to regular cellular users. Through a comparison between three power control approaches under two distributed resource allocation methods, this thesis analyses interference not only among the clustered sensor nodes, but also between sensor nodes and cellular users, and proposes a feasible power control mechanism for a sensor network with relatively stable topology. Furthermore, mobility support for D2D is studied and solutions are proposed for the control plane and the user plane. An optimised Coordinated Multi Point (CoMP) scheme is proposed to support D2D soft handover and reduce the signalling overhead for clustered sensor network. Performance comparison between the original CoMP and the optimised one is also presented.

With the inherent synchronisation, security and high speed features of LTE-A network, the use of D2D for sensor networking is promising a bright prospect.

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Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Student's Signature:

Date: 27/05/2016

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List of Abbreviations

3GPP	3rd Generation Partnership Project
CH	Cluster Head
CM	Cubic Metric
CN	Core Network
CoMP	Coordinated Multi Point
CP	Control Plane
CQI	Channel Quality Indicator
CSI	Channel State Information
CUE	Cellular User Equipment
D2D	Device-to-Device
DPS	Dynamic Point Selection
DRX	Discontinuous Reception
DUE	D2D User Equipment
eNB	Evolved Node B
E2E	End-to-End
EPA	Extended Pedestrian A model
EPC	Evolved Packet Core
EVA	Extended Vehicular A model
EVM	Error Vector Magnitude
FDD	Frequency Division Duplexing
FPC	Fractional Path Loss Compensation
IBE	In-Band Emission
ICI	Inter-Cell Interference
ICIC	Inter-Cell Interference Coordination
ISI	Inter-Symbol Interference
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
MAC	Medium Access Control
MCL	Maximum Coupling Loss

MCS	Modulation and Coding Scheme
ME	Mobile Equipment
MIB	Master Information Block
MMC	Massive Machine Communication
MTC	Machine Type Communication
OFDM	Orthogonal Frequency Division Multiplex
PA	Power Amplifier
PAPR	Peak to Average Power Ratio
PBCH	Physical Broadcast Channel
PC	Power Control
PDSCH	Physical Downlink Share Channel
PL	Path Loss
PRB	Physical Resource Blocks
ProSe	Proximity Services
PS	Public Safety
PUSCH	Physical Uplink Shared Channel
QoS	Quality of Service
RA	Resource Allocation
RB	Resource Block
RNC	Radio Network Control
RRC	Radio Resource Control
RRM	Radio Resource Management
RSRP	Reference Signal Received Power
S1AP	S1 Application Protocol
SDN	Software Defined Network
SIMO	Single Input Multiple Output
SINR	Signal-to-Interference-and-Noise-Ratio
SISO	Single Input Single Output
TDD	Time Division Duplexing
TDM	Time Division Multiplexing

TPC	Transmit Power Control
TTT	Time-to-Trigger
UP	User Plane
USIM	Universal Subscriber Identity Module
WSN	Wireless Sensor Network
X2AP	X2 Application Protocol

Chapter 1 – Introduction

With inventions of the Internet, mobile broadband network and smart phones, demands for communication and sharing of data anytime and anywhere are explosively large. Due to the everlasting demand for more devices to be connected and higher network speed, the fifth generation (5G) cellular network is expected to be much more dynamic and densely deployed than today's wireless networks. Driven by diverse factors, researchers are seeking for new paradigms to revolutionise the traditional cellular networks. Device-to-Device (D2D) is believed to be a cornerstone in next generation cellular technologies not only by academic researchers but also by standard organisations [1]–[9].

D2D opens up new opportunities for proximity-based services, such as public safety, local data transfer etc. Furthermore, D2D may bring benefits such as increased spectrum utilisation, extended cellular coverage and reduced backhaul demand. However, the main focus of this new technology is on the efficient support of human-oriented services and user equipment (UEs). Whilst these services offer high data rates, they can support only relatively low number of simultaneous connections. On the other hand, Massive Machine Communications (MMC) can support a massive number of connections between communicating machines, but typically they offer only low data-rate services [10].

How we live and work has been changed and will continue to be changed by mobile communication. The early generation of cellular network, which is voice-centric, has evolved into the current data-centric fourth generation (4G) network known as Long Term Evolution Advanced (LTE-A). This development trend will continue for both human and machine-type communications, leading to the next generation 5G network.

In contrast to current 4G network, 5G network will be more powerful and flexible for new usage scenarios to meet technical objectives as follow [4][6]:

- 1000 times higher mobile data volume per area;
- 10 to 100 times higher typical user data rate;
- 10 to 100 times higher number of connected devices;
- 10 times longer battery life for low power devices;
- 5 times reduced End-to-End (E2E) latency.

LTE-Advanced (LTE-A) D2D and MMC are seen as cornerstones to achieve these ambitious targets. LTE-A D2D communication allows two or more nearby devices to communicate with each other in the licensed cellular bandwidth without Core Network (CN) involvement in the data path. The term "device" here refers to the UE, e.g. a cell phone, or other device in Human-to-Human (H2H) communications as well as in Machine-to-Machine (M2M) communications without the involvement of human activities. It is obviously a new paradigm compared to the conventional cellular architecture, where the data has to route through the base station, which is referred to as Evolved Node B (eNB) in LTE systems.

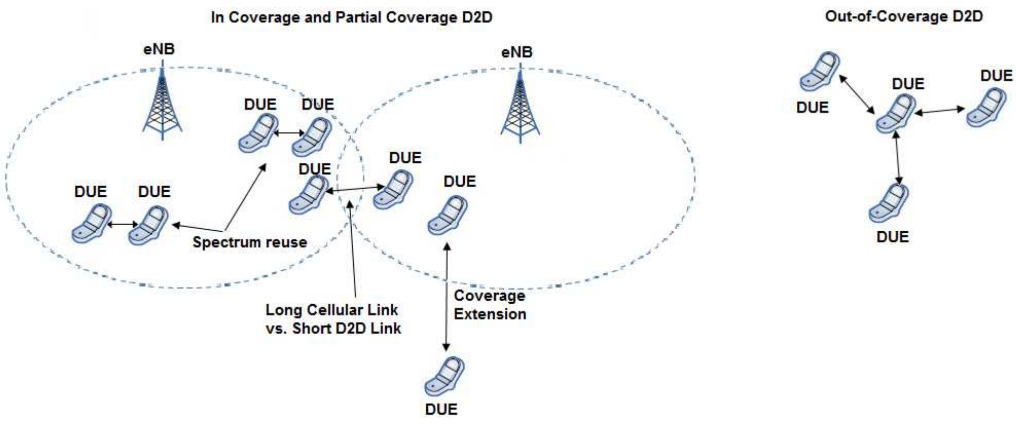


Figure 1. LTE-A D2D concepts and usage

An illustration of LTE-A D2D concepts and usage can be found in Figure 1. From a technical perspective, multiple benefits are provided by exploiting the proximity of communicating devices. First, cellular coverage could be extended via UE-to-UE relaying for partial coverage scenario; second, high data rate and low E2E delay could be enjoyed by D2D UEs (DUEs) due to the direct communication; third, compared to normal downlink/uplink cellular communication, radio resource utilisation is improved. Other benefits may be envisioned as well, such as to offload cellular traffic, and to alleviate signal congestion by switching from an infrastructure path to a direct path.

From an economic perspective, even though the commercial applications are not the focus in LTE Rel.12 [11], D2D still would create new business opportunities. For example, social networking among friends, advertising nearby shops, finding an available parking lot in a shopping mall, and automatic data collection from a group of sensors. In particular, potential D2D use cases have been identified in [1].

Actually, the concept of D2D is not new. The most widely known D2D technologies are Bluetooth, Wi-Fi and ZigBee. However, they operate in un-licensed bands, and the interference is uncontrollable. In addition, switching between different technologies is not an integral part of cellular networks and could impact user experience, e.g. both Bluetooth and Wi-Fi require manual pairing. Furthermore, the speed and communication range of those technologies are limited compared with LTE-A D2D [8]. Moreover, they cannot provide the security and quality of service (QoS) guarantee which cellular network does. Last but not least, cellular operators cannot make profits from conventional D2D technologies as they work without the involvement of the operators. A detailed comparison of different D2D technologies is provided in Table 1 below.

Recently, with the emerging context-aware applications and services in smart phones that are envisioned as valuable add-ins, and also with the fast growth of M2M applications, the wireless operators' attitude towards D2D is changing. Unwilling to lose the rising D2D market, cellular operators and telecommunication equipment providers are exploring the possibilities of introducing D2D into mobile networks. A wireless technology called FlashLinQ, a synchronous OFDM-based peer-to-peer wireless network, is proposed in [12]. As early as 2011, the 3rd Generation Partnership Project (3GPP) started studying the radio aspects of LTE-A D2D discovery and communication with the term Proximity Services (ProSe), and now D2D is introduced as a part of LTE-A in 3GPP Release 12 with a new term Sidelink for public safety [13][14][15].

With the nature of cellular network, LTE-A D2D users work under a synchronous network, leading to energy saving. Inherent security is provided and QoS guaranteed. Application service providers can also leverage on the high security and QoS, as well as other features such as low E2E latency for their application end-users. For example, LTE-A D2D can be used in vehicle-to-vehicle (V2V) applications because of the strict delay requirement in traffic safety. In particular, for collision avoidance systems, it will be essential to have very low E2E delay.

For the rest of the discussion, unless otherwise specified, the term “D2D” will refer to LTE-A Device-to-Device.

Table 1. Comparison of various D2D technologies

D2D Technologies	**LTE D2D**	**Wi-Fi Direct**	**NFC**	**ZigBee**	**Bluetooth**
Standardisation	3GPP LTE-A	802.11	ISO 13157	802.15.4	Bluetooth SIG
Working Frequency	Licensed Bands for LTE	2.4/ 5 GHz	13.56 MHz	869/915 MHz, 2.4 GHz	2.4 GHz
Max. Transmission Distance	1000m	200m	0.2m	10-100m	10-100m
Max. Data Rate	1 Gb/s	500 Mb/s	424 kp/s	250 kp/s	24 Mb/s
Application	Offload traffic, Public safety, Context Sharing, Local Advertising, Cellular relay	Context Sharing, Group Gaming, Device Connection	Contactless payment, Bluetooth and Wi-Fi Connections	Home Entertainment and Control, Environmental Monitoring	Object Exchange, Peripherals Connection
Infrastructure	In licensed bands	In un-licensed bands			

1.1 Problem statements and research motivations

Introducing D2D poses plenty of open challenges and risks to the traditional cellular architecture, which is centred on the base station. Research on D2D implementation with cellular communications in practice is still in its infancy. From a technical point of view, issues such as security, radio resource management (RRM), interference management, new D2D channel models, signalling protocols design, multi-cell environments and mobility support are open research questions. New technology introduces new functions, but also new challenges in software or hardware and requires new protocols and standards, which add complexity into existing network infrastructures and increase processing burden to the system.

There are also marketing challenges to compete with traditional cost-free D2D techniques. A dilemma that operators need to address is how they control and charge for D2D services. It is possible that some users, if charged for D2D services, may turn to traditional non cellular D2D methods, which are free but have lower speed and less security. Therefore, the operators must answer the “pay for what” question before they can push forward the operator-controlled D2D technology, which requires extensive analysis of usage cases and business models. Also FDD-

D2D devices need an additional Uplink (UL) receiver, which increase the cost and complexity of D2D equipment modules.

1.2 Thesis objectives, scope and contributions

Considering the LTE eNB capacity, which normally has hundreds of active users at the same time per eNB, this thesis explores the use of LTE-A D2D technology in sensor networking, which involves a massive number of nodes and is energy sensitive in general.

The main objectives of this thesis are:

1) Analysing the maximum possible D2D communication range;
2) Exploring various D2D radio resource allocation methods for sensor networking;
3) Addressing the new interference modes in D2D introduced by sensor networking;
4) Examining the feasibility of providing mobility support for D2D.

The scope of the thesis includes using 3GPP standardised D2D channel models to simulate D2D direct communication between two DUEs in order to determine the maximum communication range. It also includes performance comparison of D2D direct discovery by various resource allocation mechanisms. Furthermore, interference management, power control for group D2D nodes under single eNB, and D2D handover in both control plane (CP) and user plane (UP), are involved.

The key contributions of the thesis are:

1) Investigated the maximum possible communication range between D2D end users (DUEs) under 3GPP channel models (outdoor-outdoor, outdoor-indoor, indoor-indoor) using the Maximum Coupling Loss (MCL) calculation method and D2D link simulation method. This knowledge can be useful for the pragmatic deployment of DUEs.

2) Proposed a new resource allocation (RA) method for D2D discovery with both time and frequency hopping. The proposed method is shown to achieve higher discovery rate over that of current 3GPP RA mechanisms.

3) Proposed a joint power control and resource allocation method to increase resource utilisation while mitigating the intereference problem for the sensor nodes in a mixed cellular UEs (CUEs) and D2D UEs (DUEs) environment. Three power control schemes and two resource allocation methods are considered.

4) Proposed a Coordinated Multi Point (CoMP) based method with reduced signalling overhead to implement a seamless D2D handover caused by DUE’s mobility.

1.3 Thesis structure

This thesis has 8 chapters, each of which includes a number of sub-chapters. The purpose of each chapter is summarised with a short description as follows:

Chapter 1, titled "*Introduction*", provides an overview of the next generation cellular network and device-to-device technology. Furthermore, it lists the encountered problems and research opportunities. Thesis objectives and contributions are specified in this chapter as well.

Chapter 2, titled "*Background*", presents LTE basic concepts and D2D design structure and aspects; and describes cellular technology for wireless sensor network in sub section 2.3.

Chapter 3, titled "*Literature review*", surveys a variety of technology aspects about D2D, including clustering, maximum communication range, radio resource allocation, interference and power control, mobility support and using D2D for sensor network.

Chapter 4, titled "*D2D communication range under 3GPP channel models*", uses 3GPP D2D channel models to simulate D2D communication under various environments in order to get the max D2D communication range. It presents and compares results from two simulation approaches.

Chapter 5, titled "*D2D radio resource allocation*", focuses on the resource allocation mechanisms for clustered sensor network. It proposes a novel resource allocation method and compares its performance with an existing allocation approach.

Chapter 6, titled "*D2D interference management and power control*", considers joint resource allocation and power control under two RRC states of cluster head, simulates and presents results to find a feasible trade-off to mitigate interference and to save energy.

Chapter 7, titled "*Mobility support for D2D*", proposes to implement coordinated multi point (CoMP) for seamless D2D handover and suggests optimised mechanisms to reduce signal overhead and enable un-interrupted data flow during handover.

Chapter 8, titled "Conclusion and future works", concludes the thesis and lists the future research directions.

A reference list and relevant source code are appended at the end of this thesis.

Chapter 2 – Background

In this chapter, basic LTE-A knowledge and concepts will be introduced, such as radio frame, sub-frame, resource block (RB), radio resource management, power control, mobility management and Coordinated Multi Point (CoMP). Basic LTE-A D2D concepts, proposed architecture and signalling design aspects are also included.

2.1 Long Term Evolution Advanced (LTE-A)

Long Term Evolution, commonly known as 4G LTE, is a mobile communication standard developed by 3GPP for wireless high speed data communications technology. It is a development of 3G UMTS and HSPA standards and specified first in its release 8 series. As the early versions of LTE (Rel.8, Rel.9), marketed as 4G network, does not satisfy the technical requirements, 3GPP has adopted its new LTE-A standard. The main differences with other wireless technologies are listed in Table 2 as below.

Table 2. Comparison of LTE-A with other cellular technologies

Cellular technologies	**WCDMA (UMTS)**	**HSPA HSDPA / HSUPA**	**HSPA+**	**LTE**	**LTE ADVANCED**
Max downlink speed (bps)	384 k	14 M	28 M	100M	1G
Max uplink speed (bps)	128 k	5.7 M	11 M	50 M	500 M
Latency round trip time approx.	150 ms	100 ms	50ms (max)	~10 ms	less than 5 ms
3GPP releases	Rel 99/4	Rel 5 / 6	Rel 7	Rel 8	Rel 10
Approx. years of initial roll out	2003 / 4	2005 / 6 HSDPA 2007 / 8 HSUPA	2008 / 9	2009 / 10	2014 / 15
Access methodology	CDMA	CDMA	CDMA	OFDMA (DL) SC-FDMA (UL)	OFDMA (DL) SC-FDMA (UL)

There are a number of key technologies employed or will be employed in LTE-A to achieve those ambitious targets.

- Orthogonal Frequency Division Multiplex (OFDM), along with Orthogonal Frequency Division Multiple Access (OFDMA) for downlink (DL) and Single Frequency Division Multiple Access (SC-FDMA) for uplink (UL).
- Multiple Input Multiple Output (MIMO)
- Carrier Aggregation (CA)
- Coordinated Multi Point (CoMP)
- LTE Relaying
- Device to Device (D2D)

2.1.1 Frame structure

In order to maintain system synchronisation and manage varying types of information that are carried between eNB and UEs, LTE system has a defined frame and sub-frame structure. There are two types of LTE frame structure: Type 1 used for Frequency Division Duplexing (FDD) mode and Type 2 used for Time Division Duplexing (TDD) mode. However, only Type 1 frame structure will be considered in this thesis.

A typical LTE frame has an overall length of 10ms, in which there are 10 sub-frames of 1ms each, and each sub-frame is further divided into two slots of 0.5ms each. In every slot, there are either 6 or 7 OFDM symbols, depending on the Cyclic Prefix (CP) length. Frames carry system information, sub-frames facilitate resource allocation, and slots are useful for synchronisation. Figure 2 illustrates the FDD frame structure.

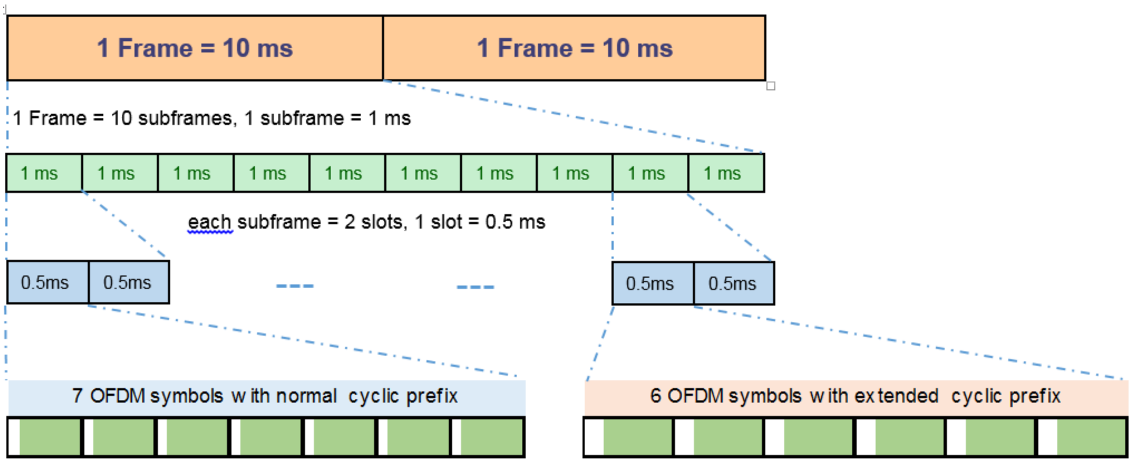


Figure 2. LTE FDD Frame Structure

In LTE, radio resources are allocated in unit of Resource Block (RB). A RB is defined as a group of resource elements corresponding to 12 subcarriers or 180 kHz in the frequency domain and one 0.5ms slot in the time domain. For instance, there are 600 usable subcarriers and 50 RBs in a 10MHz spectrum bandwidth system.

2.1.2 General concepts and procedures

- A LTE UE must perform certain steps before it can transmit/receive data. These steps, including cell search and selection, derivation of system information and random access, are known as LTE initial access procedure. UE scans and extracts cell ID and cell group ID from the primary and secondary synchronisation signal respectively, multiple cells may be in the list, then decode cell specific reference signals based on Channel Quality Indicator (CQI) to decide to camp on a particular cell. After cell selection, UE receives the Master Information Block (MIB) from Physical Broadcast Channel (PBCH) and System Information Block Type1 (SIB1) from Physical Downlink Share Channel (PDSCH), then UE gets the scheduling information about other SIBs from PDSCH.
- A LTE UE can switch between two RRC layer states like below:

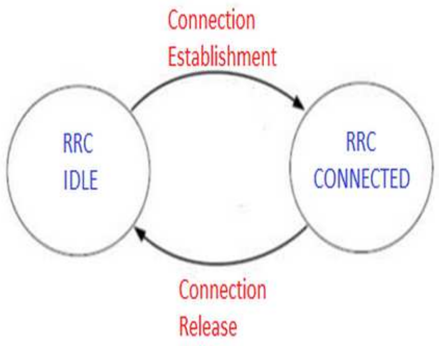


Figure 3. RRC State Switching

Under the RRC_Idle state, UE is registered and known in Evolved Packet Core (EPC), has IP address but is not known in eNB; receives system information broadcasted by eNB; receives and responds to paging message; performs serving and neighbour cells measurement and cell (re-)selection; a UE specific DRX (discontinues reception) cycle can be configured to enable power savings;

In the RRC_Connected state, UE is known to both EPC and eNB; besides the tasks in idle, UE also provides channel quality feedback information; monitors control channels associated with shared data channel to determine if data is scheduled or not.

2.1.3 Radio resource management

The purpose of radio resource management (RRM) is to utilise the limited frequency spectrum resources and maximize the system spectral efficiency as much as possible and provide mechanisms that enable LTE to meet radio resource related requirements, such as fairness.

The LTE RRM functions located in eNB is responding to establish, maintain and release radio bearers; to manage the radio resources in connection with idle or connected mode mobility; to dynamically allocate/de-allocate resources to user and control plane; to keep the inter-cell interference (ICI) under control; to achieve load balancing of distribution of the traffic load over multiple cells, etc. The schemes for RRM can be generally classified into centralised, decentralised and hybrid approaches.

2.1.4 Interference management and power control

As previously mentioned, radio resources in LTE are allocated in units of Physical Resource Blocks (PRBs). Interference occurs when one or more PRBs assigned to a user in a cell edge is used by other users in the neighbouring cells in the 1:1 frequency re-use system. Interference within a cell is less of a concern due to the orthogonality of the subcarriers in the cell. Cyclic Prefix (CP) is the overhead added to the signal to combat Inter-Symbol Interference (ISI). To minimize inter-cell interference (ICI), LTE develops a variety of schemes, such as static partial and soft frequency reuse schemes, also the mechanisms like Inter-Cell Interference Coordination (ICIC), enhanced ICIC (eICIC) and CoMP, to mitigate ICI.

Power control in LTE refers to setting output power of eNB in downlink and mobile in uplink to improve system coverage, to reduce power consumption and to mitigate inter-cell interference. In the downlink, eNB often transmits with a constant maximum power, this strategy guarantees the maximized UE received power. In the uplink, open-loop (signal strength measurement done by UE) and closed-loop (Transmit Power Control (TPC) commands generated by eNB in downlink control signalling to UE) power control mechanisms are used. Two UE specific TPC commands can be used, Accumulative TPC commands and Absolute TPC commands, to allow UE to adjust its transmission power.

The following is an example of the setting of UE transmit power for a Physical Uplink Shared Channel (PUSCH) transmission from 3GPP 36.213 [16].

$$P_{\mathrm{PUSCH}} = \min\begin{Bmatrix} P_{\mathrm{CMAX}}, \\ 10\log_{10} M_{\mathrm{PUSCH}} + P_{\mathrm{O\_PUSCH}} + \alpha \cdot PL + \Delta_{\mathrm{TF}} + f_c \end{Bmatrix} \text{ [dBm]} \quad (2.1)$$

where:

P_{CMAX} is the configured maximum UE transmit power for serving cell;

M_{PUSCH} is the bandwidth of PUSCH resource assignment expressed in number of resource blocks;

$P_{\mathrm{O\_PUSCH}}$ is a base power level used to control the SNR target;

α is the path loss (PL) compensation factor in range of $\{0, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1\}$;

PL is the downlink path loss estimate calculated in the UE;

Δ_{TF} is the current modulation and coding scheme (MCS) dependent component;

f_c represents the explicit transmit power control (TPC) commands.

2.1.5 Mobility management

While handover controls the mobility of UE in connected state, cell reselection controls the same in idle state [17].

It is UE who is in control of cell reselection. Waking up at the end of every DRX cycle, UE measures the signal of its serving cell to compare the specified threshold to decide triggering cell reselection or not. When the reselection criterion is satisfied for a certain period of time (those parameters are from SIB3/4), the UE selects the best satisfying cell and attaches to it.

While UE is in connected state, the location of UE is known at the cell level, mobility management in LTE is achieved by handover procedure, which is a network-controlled UE-assisted process. UE measures the signal strength (Reference Signal Receiving Power (RSRP)) of the serving and neighbour eNBs periodically. When two conditions are fulfilled the HO is initiated: the signal strength of target cell is greater than that of serving cell plus a certain hysteresis value; this condition lasts at least for the specified Time-to-Trigger (TTT) parameter. As the Radio Network Control (RNC) was cancelled in LTE, hard handover technology is adopted in 3GPP LTE system, which means UE must terminate the existing connection with serving eNB first then establish a new session with the target cell. A brief HO process is shown as in Figure 4, the HO starts on T2 and HO is executed during the time interval (T3-T2), which equals 0.2s. A critical time (5s) after T3 is necessary to evaluate ping-pong occurrences.

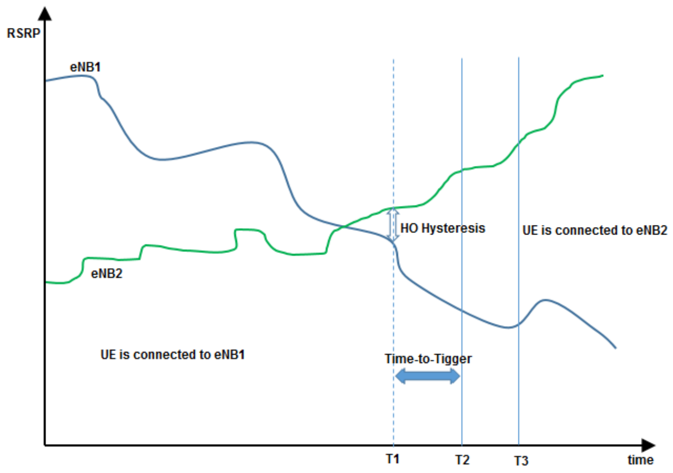


Figure 4. LTE Handover trigger illustration

The HO Control-Plane handling procedure can be found below:

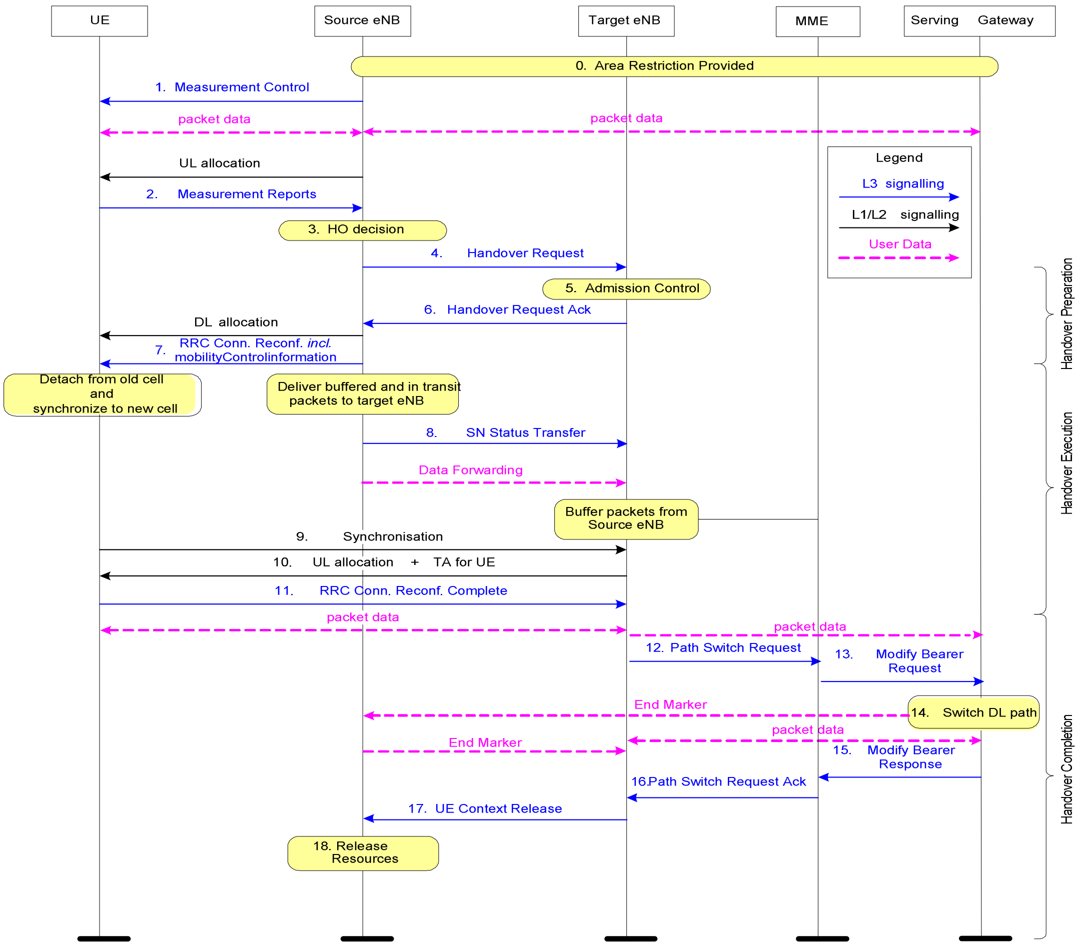


Figure 5. LTE HO Control-Plane procedure

For User-Plane, the following principles are taken into account to avoid data loss during HO:

1) During HO preparation, U-plane tunnels can be established between source and target eNBs;

2) During HO execution, data can be forwarded from source eNB to the target eNB;

3) During HO completion, the target eNB informs EPC to switch the U-plane.

The HO interruption time defined by 3GPP is that "the time between end of the last TTI containing the RRC command on the old PDSCH and the time the UE starts transmission of the new PRACH, excluding the RRC procedure delay." The time should be less than $T_{interrupt} = T_{search} + T_{IU} + 20\ ms$. where: T_{search} is the time to search the target cell, T_{search} = 0 ms if the target cell is known and T_{search} = 80 ms if the target cell is unknown; T_{IU} is the interruption uncertainty in acquiring the first PRACH of target cell, which can be up to 30 ms. So the interruption time is in the range of 20ms to 130ms.

2.1.6 Coordinated multi point (CoMP)

Introduced in 3GPP Rel.11 specifications, CoMP mainly aims to improve network performance at cell edges [18]. In CoMP, a number of transmit (TX) points provide coordinated transmission in DL and a number of receive (RX) points provide coordinated reception in the UL. CoMP can be done in a number of ways and the major categories are listed as below:

In Dynamic Point Selection (DPS), UE data is available at multiple TX-points within a coordinating set but it is only scheduled and transmitted from one TX-point each subframe with varying channel conditions, especially at a cell edge.

In Joint Transmission (JT), UE data is transmitted from multiple TX-points simultaneously on the same frequency in the same subframe.

To achieve either of these modes, highly detailed feedback is required on the channel properties in a fast manner so that the changes can be made; also additional radio resources for signalling is required.

2.2 LTE-A Device-to-Device (D2D)

Based on spectrum sharing or not, D2D can be classified into underlay D2D (both DUEs and CUEs share the same cellular spectrum) and overlay D2D (dedicated radio resources for DUEs and CUEs) [9]. The term Proximity-based Services (ProSe) is used in 3GPP series documents to describe the services for UEs being in proximity to each other, which include the following functions: ProSe Direct Discovery (open and restricted); ProSe Direct Communication (one-one, one-many) and ECP-level ProSe Discovery [1][11]. Sidelink is used for ProSe direct communication and direct discovery between DUEs [13].

It is assumed that one UE can switch between cellular mode or D2D mode to enhance the overall system performance. The cellular mode is the conventional one where UE communicates with another UE through eNB; in D2D mode, UE will use the direct traffic link – Sidelink - to transceive data with another UE.

There are two assumptions about D2D service [13]:

1) DUE does not need to scan all the configured “interesting frequency” simultaneously;
2) Normal cellular traffic has higher priority than D2D services, like the voice service has higher priority than data service in mobile networks.

2.2.1 Use of uplink spectrum

LTE uplink (UL) resource is reused by D2D, because UL is underutilised compared to downlink (DL). Moreover, for UL resources, the interfered device is the eNB, which is more robust and controllable in management.

D2D signal related performances, Cubic Metric (CM) and Peak to Average Power Ratio (PAPR), have been evaluated for SC-FDM and OFDM on both UE transmitter and receiver [2]. It is shown that both CM and PAPR of OFDM are significantly higher than SC-FDMA, which results in higher Error Vector Magnitude (EVM) and In-Band Emission (IBE) on average for the same Power Amplifier (PA). Agreed in the standards, D2D operates in uplink spectrum and all data carrying physical channels use SC-FDMA.

2.2.2 Network architecture and protocols

New interfaces and new functions for implementation of D2D are specified in [1]: they are PC3 interface between DUE and the ProSe Function, and the PC5 interface between DUEs; also there is a logical ProSe function for Proximity services and ProSe Application Server to storage and map ProSe User/Application/Function IDs. The proposed high level reference model of D2D discovery and communication can be found below:

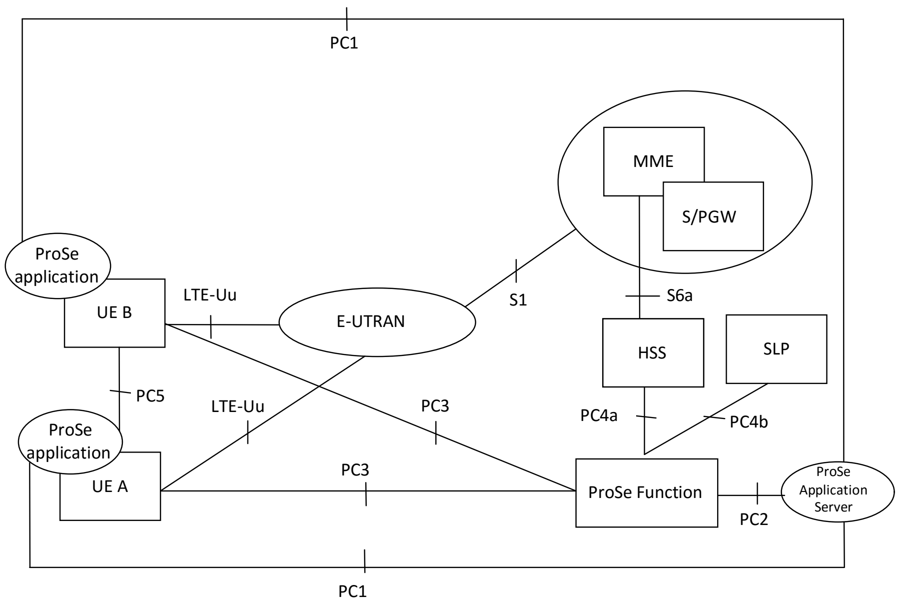


Figure 6. D2D Reference Architecture from 3GPP

2.2.3 Signalling design aspects

The signalling design aspects for D2D are presented in [2], such as the discovery bit and modulation. D2D transceiver uses half duplex, meaning DUE either transmits discovery signal or receives discovery signals from other DUEs within the assigned D2D resources. Discovery transmissions transmit a MAC PDU by using Physical Uplink Share Channel (PUSCH) structure with CRC inserted, Turbo channel coding, rate matching, scrambling, precoding and Demodulation Reference Signal (DMRS). And the last symbol serves as a guard period to mitigate Inter Symbol Interference (ISI).

For D2D discovery, it is suggested to use a reserved resource by Qualcomm [19] and 3GPP [2]. In order to find UEs in proximity, UEs have to transmit and receive for discovery signals periodically, which in turn means that periodic uplink resources have to be reserved. This is illustrated with an example below (Figure 7) where 64 contiguous uplink sub-frames have reserved for discovery in every 10 seconds, which is only 0.64% of uplink radio resources. The period with one reserved D2D discovery resources is named “discovery period” and the sub-frames reserved for discovery resources are named “discovery sub-frames”. Time Division Multiplexing (TDM) is used for D2D discovery and cellular resources.

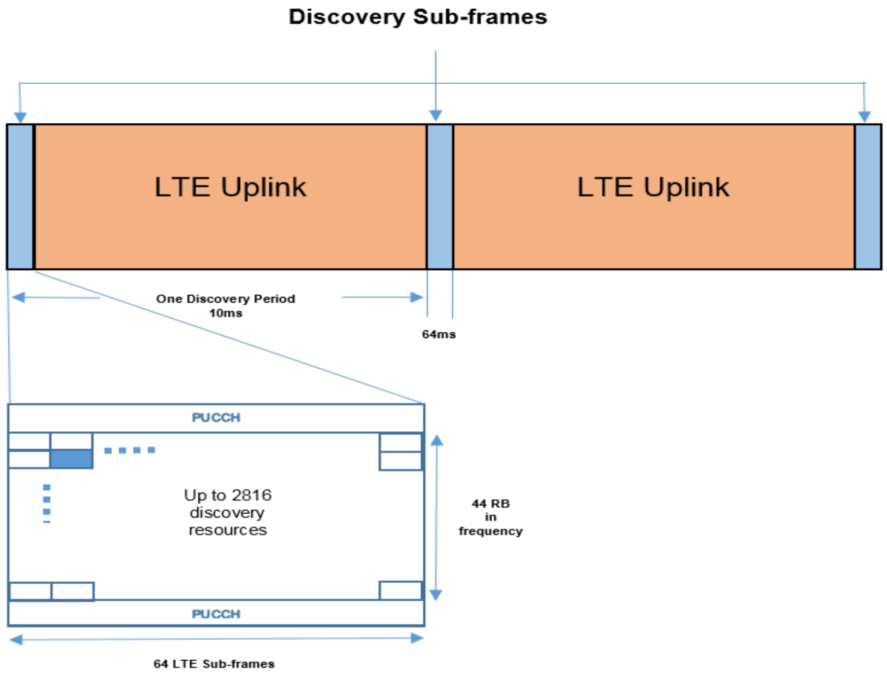


Figure 7. D2D Discovery Period and Discovery Resources

One D2D resource block occupies 12 sub-carriers in frequency domain and two slots in time domain as depicted in Figure 8, in other words, one D2D RB is equal to two LTE RBs.

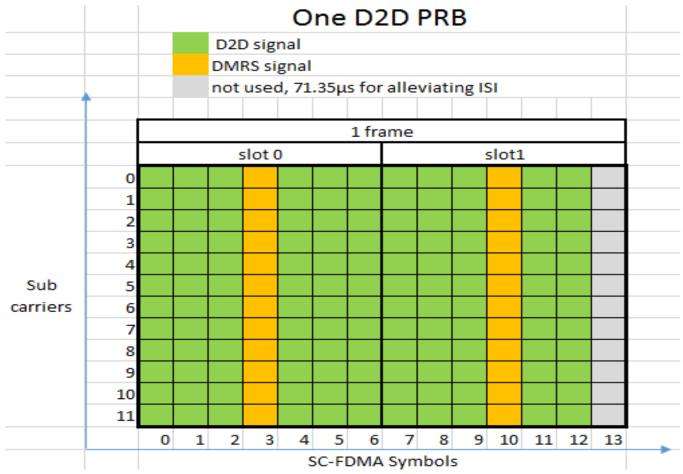


Figure 8. D2D Signal Slot structure and physical resources

2.2.4 Synchronisation

D2D works in a synchronous network with licensed spectrum, which provides significant advantages such as coordinated resource allocation. Besides the current LTE signals and channels for synchronisation, 3GPP defines new synchronous signals and channels for D2D services [2]. Two types of D2D synchronisation signal are introduced - Primary D2D Synchronisation Signal (PD2DSS) and Secondary D2D Synchronisation Signal (SD2DSS). They will be carried on Physical D2D Synchronisation Channel (PD2DSCH). D2D synchronisation signal (D2DSS) should be transmitted by a D2D synchronisation Source, which is an eNB or a DUE. In the D2DSS, the identity and/or type of D2D Synchronisation Source is included.

When DUEs scan and select the D2D Synchronisation Source, the priority from high to low sequence is eNB, UE in-coverage then UE out-of-coverage.

2.2.5 Authorisation and security

The authorisation for D2D determines whether the UE is authorised to use ProSe discovery announcing or monitoring or both, and to use ProSe communication in a PLMN. It can be pre-configured in UE or acquired from ProSe Function over the PC3 interface [11]. The pre-configured information may be stored in the Mobile Equipment (ME) or in the Universal Subscriber Identity Module (USIM), values in USIM should take precedence. When using the secondary method, both authorisation and configuration parameters are provided by ProSe Function.

The security aspects and security flows for discovery and communication are specified in 3GPP TS 33.303 [20]. For group members, a shared security key is used to encrypt/retrieve data for this group.

2.3 Wireless sensor network

Wireless Sensor Network (WSN) is composed of numerous sensor devices, also known as motes, each of which equipped with a micro-controller, a number of sensors and a wireless transceiver, has the capability of sensing the surrounding environment, collecting and processing sensed data and communicating with its neighbours by wireless transmission in order to accomplish certain tasks. The related applications range from military and civilian surveillance to tracking systems, from environmental and structural monitoring to home automation, from agriculture and industrial control to health care [21][22].

Based on different standards, those applications can be categorized into:

- Low-Rate Data Collection, the first and still the majority of existing scenarios for WSN, typically characterised by periodic monitoring and simple scalar data (discrete data) per measurement;
- High-Rate Data Collection;
- On-Demand Data Collection, where data collection is usually triggered on-demand, and typically involves a persistent data storage on the node or within network in order to allow later retrieval of data;
- Event-Driven, by which pre-defined events or classified events are detected and carried out on-node processing.

The main characteristics of a WSN include:

- Power consumption constraints for nodes using batteries or energy harvesting
- Ability to cope with node failures (resilience)
- Mobility of nodes
- Heterogeneity of nodes
- Scalability to large scale of deployment
- Ability to withstand harsh environmental conditions
- Ease of use.

2.3.1 Clustering

Clustering is manifested to be an effective approach to provide data aggregation and to utilise the limited energy of sensor nodes for a large WSN [23]. In a clustered network, some sensors are elected as cluster heads (CHs) and they aggregate data from their respective nodes, then forward it to a central station. Various clustering schemes have been studied in areas such as cluster formation, CH selection, residual energy and hop distance. There are still several challenges for existing clustering algorithms: limited energy of sensor nodes; secure communication; synchronisation; and fault tolerance management.

2.3.2 Mobility management

Research about mobility in WSN can be classified into physical and architectural aspects [24]. The studies about mobile element, sink node or sensor node, and types of movement, which includes random, pre-defined and controlled, are referred to the physical part; WSN mobility handled at protocol level, at medium access control (MAC) layer or at the network layer, and the entity that handles the mobility procedures belong to architectural aspect.

A common factor of researches into the physical aspect is that they approach from an application perspective without considering the complexity of architectural implementation. Several approaches are proposed for WSN mobility support at the MAC layer, such as the sensor MAC (S-MAC), mobile S-MAC and adaptive mobility MAC etc. Among those MAC proposals, many are simulation based and it is apparent that many issues are still open. On the other hand, network layer mobility is the subject of most research, Mobile IP (MIP), proxy MIPv6 and mobile SCTP are part of mobility solutions at network layer. However, most of the mobility solutions suffer intense signalling.

2.3.3 Cellular technologies for Wireless sensor networking

In recent years, cellular participatory sensing applications have received substantial attention, mainly because of the ubiquitous presence of smart phones and the high data handling capability of cellular networks. The idea of using cellular technologies in WSN to support M2M communications is presented in [25], in which cellular UEs acting as both gateways and sensor nodes are proposed and a better system performance has been observed by simulation. However, technical challenges like authorisation of the sensor nodes in the cellular side and time coordination schemes for the converged architecture need further study. With the introduction of LTE D2D, the use of cellular technologies in sensor networking is certainly expected to increase.

Chapter 3 – Literature review

As a new paradigm to revolutionise the traditional cellular communication, D2D communication in LTE-A system has been widely studied by academia, industry and standardisation organisations. The results showed that D2D has advantages in improving cellular coverage, spectral efficiency, energy saving, throughput and E2E delay. However, this new communication mode also introduces complications in terms of interference control, radio resource management, and so on.

3.1 LTE-A D2D clustering and relaying

To introduce massive nodes into cellular network, the first thing needed to be considered is the cellular network capacity, in other words, how many users can be supported in one cell, as the supportable active users per cell is limited. So the idea of grouping nodes that operate the same application or within the same area is proposed; also clustering has been proven to be an effective approach in providing scalable data operations in WSNs [23]. In such clustered networks, some nodes are preconfigured/selected by eNB (centralised mode), elected autonomously (decentralised mode), or selected based on a mix of information from both eNB and nodes (hybrid mode), as Cluster Heads (CHs). A CH takes on tasks such as data aggregation and forwarding, organising and relaying the cluster schedule, on behalf of other nodes in the cluster.

D2D, which is capable of operating in both under and outside of network coverage, has attracted much interest for use in Public Safety (PS) and in the commercial field. Authors in [26][27] studied clustering schemes for integrating D2D into cellular network under partial/no network coverage and using LTE random access radio resources for M2M networks.

It is commonly accepted to adopt clustering and relaying functions in massive machine type communications (MMC). Combining D2D with MMC will introduce more challenges such as CHs selection, cluster formation/re-formation, energy consumption and resource management, etc. Existing cluster algorithms need to be modified to adapt to this new technology. However, the clustering mechanism itself is not the main focus of this thesis.

3.2 LTE-A D2D communication range

As D2D is a proximity based service, one critical criterion is the maximum communication range between D2D end users. The main stream of current literature focuses on fields such as radio resource management, spectrum efficiency, interference, and power control, assuming the D2D communication range from a few metres to 1000 metres [8]. Some papers even use distance as a criteria to select communication modes (cellular mode or D2D mode) [28], or just used simple channel models to determine the maximum D2D communication range.

The coverage probabilities of a D2D-enabled cellular system were analysed in [29] with consideration of both uplink and downlink transmissions. From an analysis of coverage probability of cellular mode and D2D mode between two UEs, the authors established a relationship between these two probabilities, and between the maximum DUEs communication distance and the load of base station (eNB). The results showed that maximum D2D range will increase with higher intensity of base stations, which leads to a lower coverage probability for cellular mode. However, only a simple path loss exponent was used for the channel model and receiver characteristics were not considered in obtaining these results.

3.3 LTE-A D2D radio resource allocation

Despite the promising advantages with the introduction of D2D into LTE cellular infrastructure, such as increasing spectrum utilisation and offloading cellular traffic, D2D also poses new challenges to existing radio resource management on fully realising the potential reuse gain and alleviating the interference to legacy cellular users.

The RRM schemes and resource allocation methods in 3GPP serial documents [30][15][2] focus on handheld UEs or just a few pairs of UEs where eNB is the coordinator or controller in the conventional way. Distributed radio allocation methodologies have been suggested by some papers [31][32][33]. With the aim to minimise the overall power consumption in cellular system, authors in [31] developed a single-cell distributed resource allocation algorithm and compared its performance with that of the centralised algorithm using numerical analysis. Based on coalitional game theory, a distributed resource management scheme was developed in [32] to solve the problems of mode selection and spectrum utilisation. The numerical simulation results showed that with the proposed scheme, the overall achievable rate of system is improved. Another distributed resource allocation method using message passing approach was proposed in [33] for relay-assisted D2D communication. The results revealed that the network performance can be improved significantly with a relatively small increase in end-to-end delay.

In [34], a persistent location-based radio resource allocation scheme for each cell was proposed as shown in Figure 9, in which cell coverage was divided into several zones and special sub-frequencies (RBs) were assigned to each zone. This approach aims to reduce signalling overhead as the full CSI knowledge between eNB and DUEs can be eliminated so that it can be used in E2E latency sensitive services like V2V communications. However, this method requires huge amounts of careful network planning, and leads to reduced spatial efficiency as one particular set of frequencies used by one zone cannot be used by its neighbouring zones. Furthermore, the DUEs need to report their position information and obtain the configuration of new RB set for each zone, which will add new signalling overheads between DUEs and eNB.

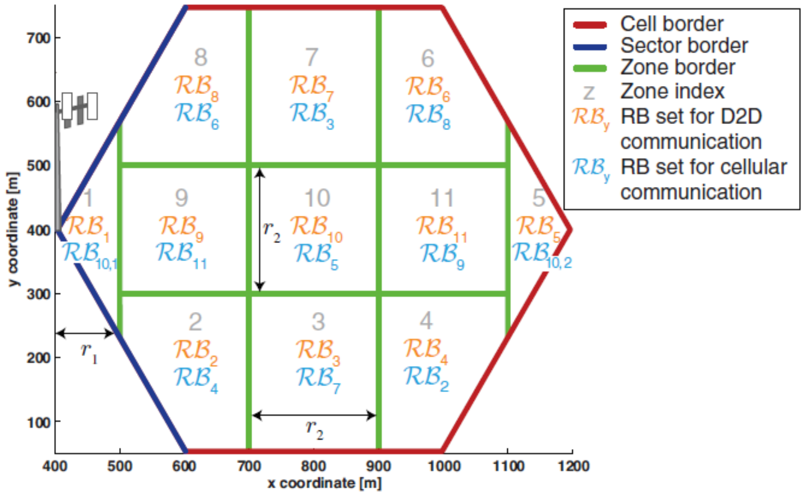


Figure 9. Example of zone design and resource assignment for a single sector [34]

3.4 LTE-A D2D interference and power control

While D2D discovery uses reserved resources, the idea of D2D communication sharing radio resources with cellular users is suggested by main stream literature in order to maximise the spectrum efficiency [9]. However, this will introduce new interference problems between the CUEs and DUEs as well as amongst DUEs that share the same resource pool, while there is no interference between CUEs under the same eNB as in conventional LTE.

Figures 10 to 12 demonstrate those newly introduced interferences under a single eNB. Figure 10 mainly shows the interference from cellular users to DUEs. CUE1 and CUE2 are normal cellular users and when they transmit data to eNB, they may influence the received signal when DUE1 is receiving data from other DUEs (red lines). In Figure 11, the interference from D2D is depicted, in which the eNB suffers disturbance from a DUE transmitter when it receives signal/data from CUEs. However, the LTE fractional power control (FPC) can be applied to D2D communication, which will efficiently suppress this type of interference according to the existing study. For a group of DUEs sharing the resource pool, potential interferences from other members are marked as red dash lines in Figure 12 when more than one member use the same radio resource.

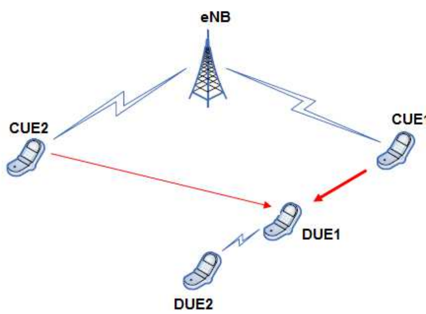


Figure 10. Interference from cellular to D2D

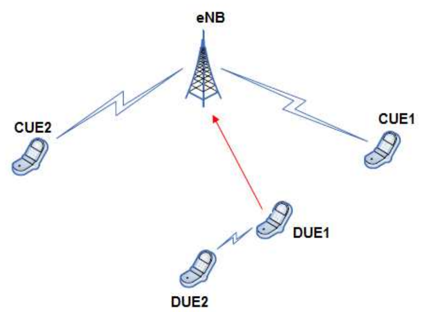


Figure 11. Interference from D2D to cellular

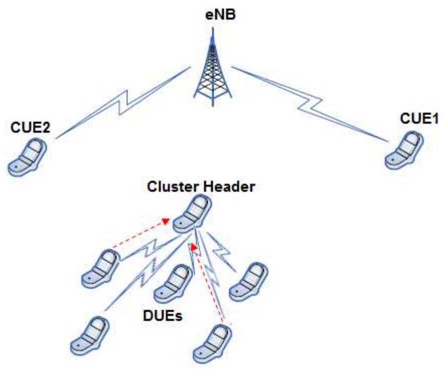


Figure 12. Interference among a clustered DUEs

Interference and power control are part of RRM and a large amounts of research has been done in this area; various interference avoidance/cancellation mechanisms have been studied and reported. Two interference avoidance mechanisms - interference tracing approach to address the interference from cellular to D2D, and the tolerable interference broadcasting approach to solve the reverse interference - were proposed in [35]. However, both approaches will increase the processing workload of either UEs or BS, and incur signalling overheads by broadcasting the calculated interference list.

The interference from cellular users to DUEs is addressed in [36], in which eNB broadcasts the D2D configuration information, including time and frequency information, and CUEs listen and report the SINR from DUEs periodically. If the SINR value decreases to below a predefined threshold, then eNB will update and re-broadcast the resource to reduce the interference experienced by DUEs. This proposed procedure and mechanism may suit a few DUEs' system. However, the CUEs' signalling overhead will increase under a huge number of DUEs.

Power control plays a vital role in interference management and is widely used in current wireless systems. A comparison of LTE power control for D2D has been studied [37]. Performances of four power control methods, namely fixed transmit power, fixed SINR target, open loop path loss compensation and closed loop schemes, have been evaluated by numerical simulation. The results suggest that the LTE power control algorithms work well for D2D communications.

Centralised and distributed on-off power control algorithms were developed in [38], in which the centralised power control is aimed to ensure that the cellular users have sufficient coverage probability by limiting the interference from DUEs when eNB is able to obtain the channel state information (CSI) from CUEs, while the distributed power control aimed to maximise the sum rate of the D2D links. Multiple antennas and joint work across the resource allocation and power control need to be investigated in future work.

3.5 Mobility support for LTE-A D2D

When D2D users move from one cell's coverage to another, it will trigger cell reselect (no session) or Handover (HO, with communication session or on-going data stream). In 3GPP documents, on-going D2D data session is not addressed for ProSe service. The documents only mentioned that a “ProSe authorized” indication should be included in the S1 Application Protocol (S1AP) or X2 Application Protocol (X2AP) Handover Request message [1] to indicate that the UE is ProSe-enabled and authorised to use D2D services based on the subscription data.

Mobility support is still an open issue though a few papers have studied it. For example in [39], D2D HO procedure is proposed for “cellular controlled” D2D communications. The brief idea is that whenever the HO is triggered by network or D2D pair, just as in normal cellular HO, HO request and reply messages are exchanged between target and source eNB with D2D identifier, allocation of radio resources, etc. If the HO criteria is met, both D2D nodes in the pair are handed over to the target base station. However, this method is only suitable when both D2D nodes in the pair move and can be covered by target eNB. HO will fail if one of the pair is far away from the target cell as the signal quality is inadequate for it. Furthermore, this work does not mention how to handle the on-going D2D data session.

A similar method is also reported in [40]: similarly, network assisted D2D is assumed, and optimised resource utilisation, minimised interference amongst DUEs and CUEs, and more robust mobility support are the targets. Two solutions are proposed: D2D-aware handover solution and D2D-triggered handover solution. The first solution is the same as in [39]: to delay the HO process and to wait until the signal quality of target eNB is able to fulfil the control condition for both D2D pair. The second solution aims to cluster DUEs in order to reduce signalling overhead due to inter-eNB exchange. When a new DUE wants to join an existing group, the cell which controls the majority of the members will check whether the new DUE can be handled by itself or by same eNB. If not, the new DUE will be redirected to other cells in same eNB or another eNB. Also they suggest the D2D HO and regular cellular handover could be executed separately, which actually adds to the eNB signalling burden. From these works, we can see that they focused mainly on the signalling part.

In [41], another network-assisted D2D HO method is proposed. The main idea is when HO is triggered by one DUE (master), it measures and passes the neighbour cells information to its counterpart DUE (Slave), which also measures the signals from its neighbour list and reports result to the master. Then the master chooses the candidate with minimum difference in signal strength like RSRP with that of slave. In general, the involved DUEs will exchange their target cell list with signal measurement and agree upon the selection of the best suitable candidate for HO. If no suitable target cell can be found by DUEs, e.g. under an extreme condition, the master will initiate mode switching request to core network, which will be similar to the normal cellular HO. Furthermore, both of the DUEs should be under the same cell before and after handover.

The authors of [42] proposed D2D communication HO to a relay node (eNB or another UE in proximity). When DUEs link quality is worse than a pre-defined value, one DUE senses the link quality with its peer, measures the channel quality with neighbouring devices and choose one as the relay device, transmits a handover request to this relay device in order to start HO, and receives a handover complete message including resource allocation. Then it performs D2D communication with its peer via the relay device. This mechanism assumes DUEs and the potential relay device are powerful with the functions like device search, channel quality measurement, resource allocation, data buffering etc. Also, this method will add burden to the signalling as it requests transmission of the reference signal from/to the neighbouring devices and DUE pairs as well.

Introducing CoMP into LTE is a new trend to implement soft-handover [43]. However, in [44], the authors mainly use CoMP in D2D to mitigate intra/inter cell interference, and evaluated both the spectral and energy efficiency of system and traffic offload from core network.

3.6 LTE-A D2D for wireless sensor network

Convergence of cellular network and sensor network is attracting interests from researchers and organisations. As described in [25], the cellular technologies can enable higher layer control to prolong the network lifetime of WSN, improve system performance and provide QoS for WSN services.

In addition to the features of LTE-A such as synchronisation, security and licensed spectrum, D2D offers a solution with the potential to solve the problems of conventional cellular systems by improving spectrum efficiency, offloading infrastructural traffic and improving energy efficiency, is proposed to integrate with wireless sensor networks [45][46].

A hierarchal D2D architecture with a centralised software-defined network (SDN) controller is proposed in [45], which targets possible public safety scenarios where the controller processes and stores data from WSNs.

Leveraging on LTE capabilities of increasing network lifetime and high transfer rate, a heuristic approach for data gathering between D2D enabled sensor nodes and aerial vehicles is proposed in [46]. The author evaluated the time for delivering data collected in WSN in the presence of mobile elements.

In general, both D2D studies and its convergence with WSN are still in their infancy. Plenty of research and analysis are still needed.

Chapter 4 – D2D communication range under 3GPP channel models

To determine the maximum D2D communication range, channel mode selection is a key element. Nevertheless, introducing D2D into cellular network poses more complexity in D2D channel modelling. The major differences between the characteristics of D2D channel and those of traditional cellular link can be categorised as below [2][47][48]:

- Dual Mobility: both transmitter and receiver might be moving whereas only one is moving in a traditional cellular link;
- Low height antennas: both transmitter and receiver have low elevation antennas in D2D, whereas eNB is located at higher position in traditional cellular link.

This thesis mainly uses the channel models in 3GPP [2] to investigate the maximum D2D communication range under different scenarios (outdoor-to-outdoor (O2O), outdoor-to-indoor (O2I) and indoor-to-indoor (I2I)). These scenarios are for typical urban macro-cell. More information about the channel model can be found in [2][49]. Details of the channel model parameters are given below in Table 3.

Table 3. Channel models used for D2D simulation

	Outdoor to Outdoor (O2O)	Outdoor to Indoor (O2I)	Indoor to Indoor (I2I)
Pathloss	$PL_{LOS}(d) = 20\log_{10}(d)+46.4+20\log_{10}(fc/5.0)$; $PL_{NLOS}(d) = (44.9-6.55\log_{10}(h_{BS}))\log10(d)+5.83\log_{10}(h_{BS})+14.78+34.97\log10(fc)$ Where: d is distance between UEs in metre; fc is the working frequency; h_{BS} = 1.5m	$PL_{LOS}(d) = PL_{O2O}(d_{out} + d_{in}) + 20.0 + 0.5*d_{in}$ $PL_{NLOS}(d) = PL_{O2O}(d_{out} + d_{in}) + 20.0 + 0.5*d_{in} - 0.8*h_{MS}$ Where: PL_{O2O} is the pathloss of outdoor to outdoor d_{in}=1.5m and d_{out}=d-d_{in} for virtual indoor UEs h_{MS} = 1.5m	$PL_{LOS}(d)$= 89.5 + 16.9log10(d) $PL_{NLOS}(d)$= 147.4+43.3log10(d) Where: d is distance between UEs in km and penetration loss = 40 dB
LOS Probability	$P_{LOS} = \min(18/d,1)\cdot(1-\exp(-d/36))+\exp(-d/36)$	$P_{LOS} = \begin{cases} 1, & d \le 18 \\ \exp\left(-\left(\frac{d-18}{27}\right)\right), & 18 < d < 37 \\ 0.5, & d \ge 37 \end{cases}$	$P_{LOS} = \begin{cases} 1, & d \le 18 \\ \exp\left(-\left(\frac{d-18}{27}\right)\right), & 18 < d < 37 \\ 0.5, & d \ge 37 \end{cases}$
Shadowing standard deviation	7 dB log-normal	7 dB log-normal	UEs are in same building: LOS: 3 dB log-normal NLOS: 4 dB log-normal UEs are in different building: 10 dB log-normal
Shadowing correlation	i.i.d.		
Fast Fading	ITU-R IMT [49] (Annex 1.3.2) UMi LOS and NLOS	ITU-R IMT [49] (Annex 1.3.2) UMi O2I	ITU-R IMT [49] (Annex 1.3.2) InH LOS and NLOS
Delay Profile used in link simulation	Extended Vehicular A model (EVA) [50]	Extended Vehicular A model (EVA) [50]	Extended Pedestrian A model (EPA) [50]

4.1 Simulation environment

Maximum Coupling Loss (MCL) calculations method and D2D link simulation method are used. The results will provide a guide for the pragmatic DUEs deployment.

For MCL method, the total pathloss between two DUEs is given by

$$PL_{total} = PL_{LOS}*P_{LOS} + PL_{NLOS} * (1-P_{LOS}) + Shadowing + Fast\ Fading \quad (4.1)$$

Also, based on the UE transmitter and receiver characteristics in LTE **Error! Reference source not found.**, the UE maximum output power is 23 dBm, and the minimum reference sensitivity power level for QPSK is -94 dBm in a 10 MHz channel bandwidth system. Thus, the maximum allowed pathloss is 117dB. Using this value as threshold, MCL method calculates the maximum D2D communication range by increasing the distance of DUEs step by step, and the results will be presented in Section 4.2.

For D2D link simulation method, a D2D discovery message is generated by using MATLAB™, which is then transmitted through LTE fading channel and is received by another DUE to decoded the signal. Measuring the signal strength of the received signal can easily determine the maximum transmission distance by increasing the distance step by step. Also, the receiver diversity is considered and the performances are compared between single and two receive antenna(s). The steps of simulation can be found below:

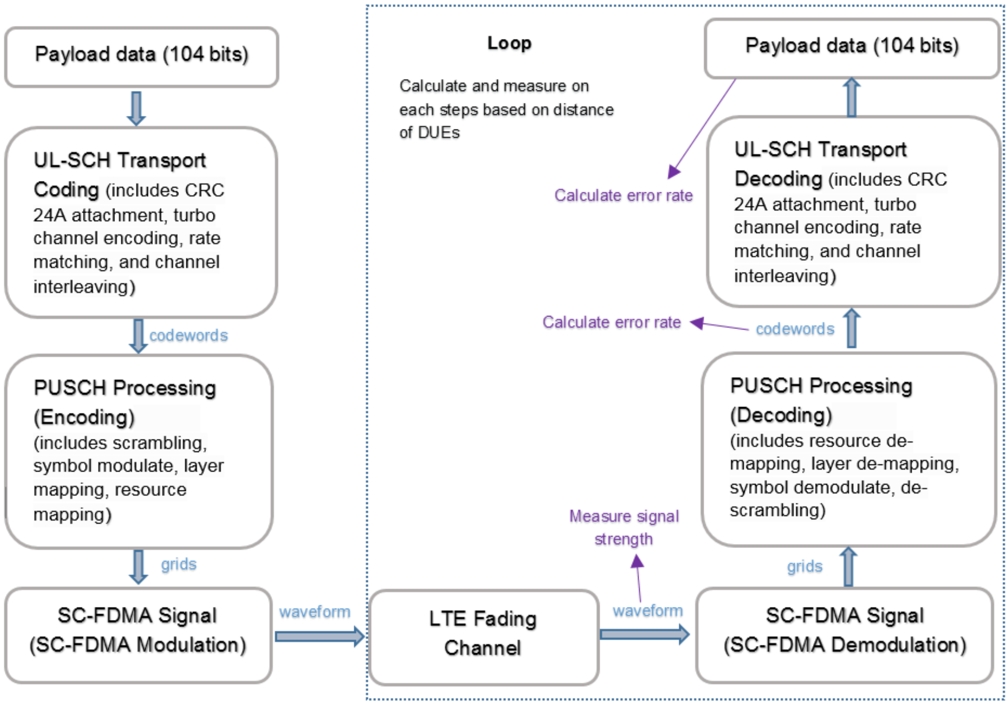


Figure 13. D2D Link simulation steps

A workstation running Windows 7 with Intel Core i5 CPU, 8GB RAM and MATLAB™ version 2015b with LTE system toolbox are used for this simulation, as well as for the rest of the simulation work done in this thesis.

4.2 Results and discussion

Below are the results of different scenarios (outdoor-to-outdoor, outdoor-to-indoor and indoor-to-indoor) with two simulation methods. The MCL method is based on pathloss, fading calculation and probability of outage; while the D2D link simulation method is simulating a D2D message and measuring the received signal strength by using MATLAB™. Results of MCL are shown below:

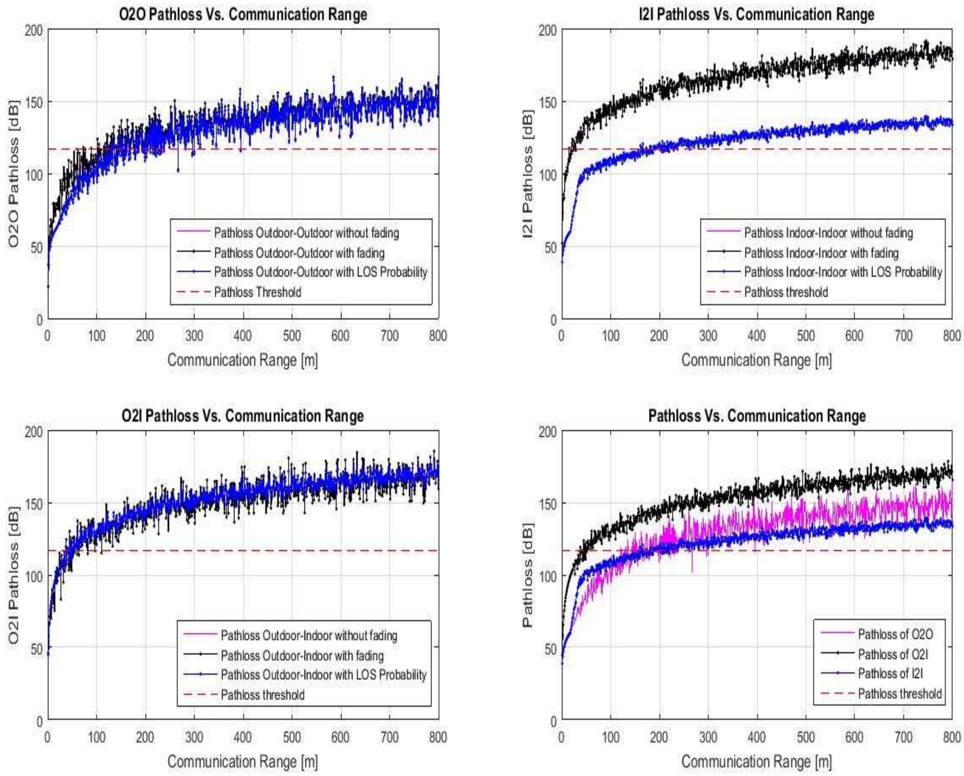


Figure 14. D2D communication range under different scenarios (output power 23dBm)

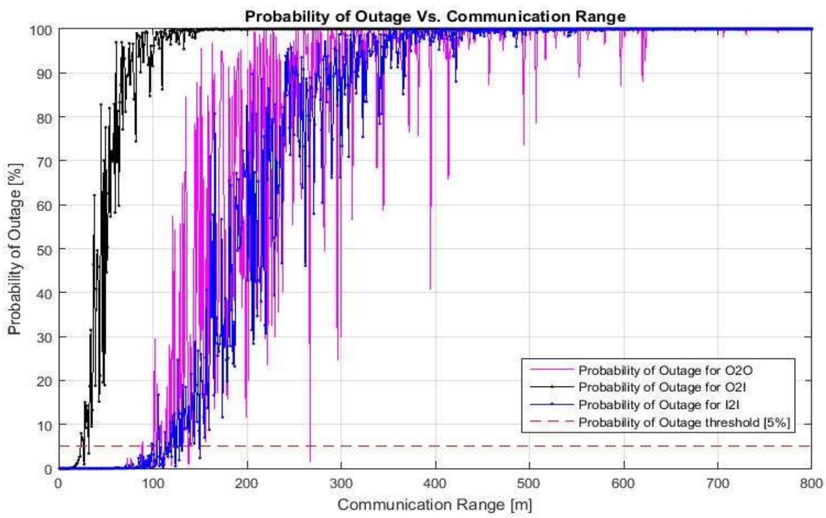


Figure 15. D2D communication range under different scenarios (with probability of outage)

Figure 14 shows that the maximum D2D communication range for O2O is about 230 metres, around 220 metres for I2I environment and an estimated 60 metres for the O2I scenario, which is the worst circumstance for D2D communication. All these results are based on the maximum UE output power, which is 23dBm.

In the wireless system, the received power at any given distance with log-normally distributed shadowing showed some probability of falling below the minimum received power level. Outage probability is defined as the probability of the received power at a given distance falling below the minimum power level. Figure 15 depicts the maximum D2D communication range under various scenarios with 5% probability of outage, from which it can be seen that the range of O2O and I2I are similar and can reach to about 130 metres, while that of O2I is further shortened to around 30 metres only.

Compared with the MCL method, which is based on pathloss and fading without considering receiver characteristics, D2D link simulation produces a whole D2D message process between a transmitter and a receiver. Also, the receiver's characteristics are taken into account; the results are listed below.

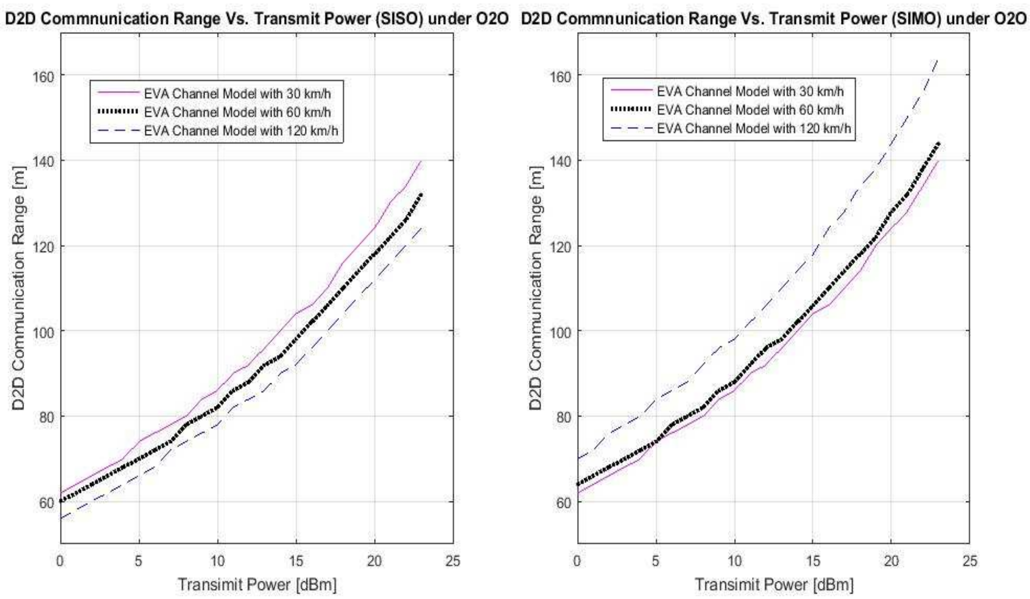


Figure 16. Max D2D communication range with receiver diversity_ O2O

It is observed from Figure 16 that with the same output power 23dBm, the maximum D2D communication range for single transmit and single receive antenna DUE is about 140, 130 and 125 metres under relative velocity 30, 60 and 120 km/h respectively, whereas it is around 140, 145 and 165 for a single transmit and dual receive antennas DUE.

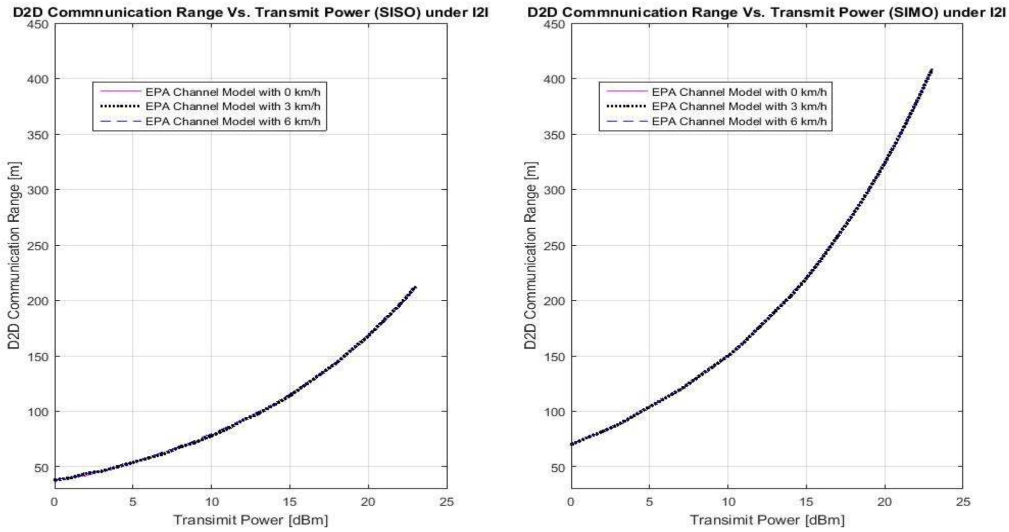


Figure 17. Max D2D communication range with receiver diversity _ I2I

Figure 17 illustrates how two receive antennas affect D2D communication range under the low speed environment. However, speed impact can be ignored in this scenario. For a single transmit and single receive antenna DUE, the maximum communication range is about 210 metres with maximum output power. For a single transmit and double receive antenna DUE, the maximum communication range is almost double to reach 410 metres.

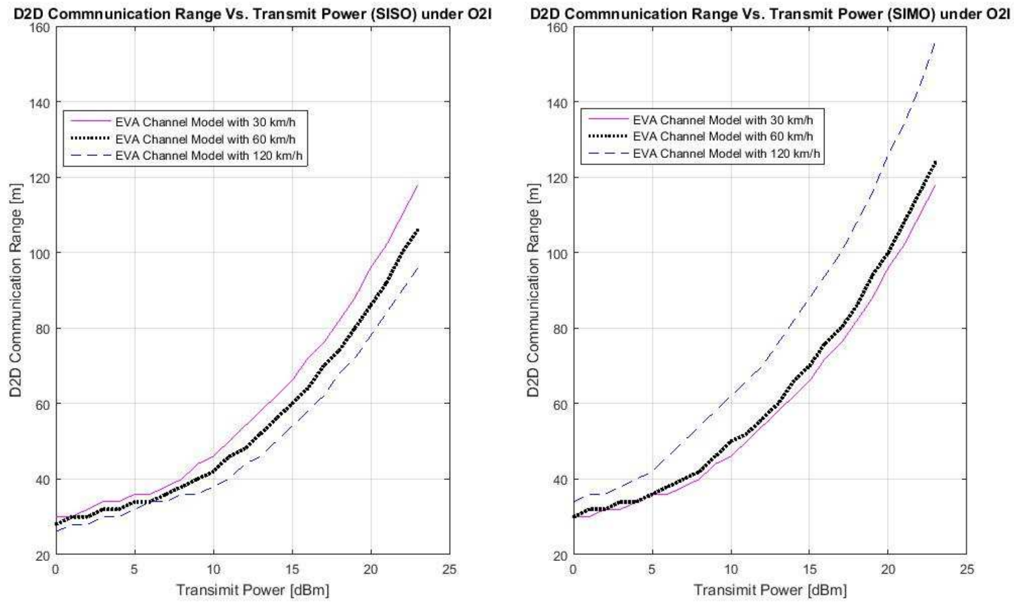


Figure 18. Max D2D communication range with receiver diversity _ O2I

The same phenomenon in Figure 16 can be seen in Figure 18 as they use the same delay profile. With output power 23dBm, for example, the maximum communication for Single Input Single Output (SISO) is about 120, 105 and 95 metres and that of Single Input Multiple Output (SIMO) is approximately 120, 125 and 155 metres under different speeds.

From Figure 16 to Figure 18, it is obvious that multiple antennas improve the signal quality and extend the communication coverage significantly under I2I scenario, while speed impacts the communication range for single/multiple antenna(s) in a reverse way for O2O and O2I scenarios. This is because different delay profiles are used for different scenarios.

Chapter 5 – D2D radio resource allocation

5.1 Clustering design for D2D massive machine communication

Combining the LTE-A D2D concept with Massive Machine Communication (MMC), this thesis provides a feasible solution for massive machine type communications in current cellular networks by raising the cluster/group concept (static or dynamic depending on the application, service or geographic location) in order to maintain a reasonable signalling overhead even for a large number of sensor nodes.

Though the cluster idea has already been presented by some authors [26], [27], there are some improvements/differences. One or several so called cluster heads (CHs) with special capabilities take over some functions of the network, such as synchronisation, authentication and resource management when necessary. If network coverage is fully or partially available, the CHs can be smoothly integrated into the infrastructure, relay control plane (CP) and user plane (UP) between network and cluster members to implement synchronisation, service authentication, resource management and payload transmission/receiving. When network coverage is unavailable (out of coverage), the CHs take over most of the functionalities of the network and control the resource utilisation for a group of devices by using pre-configuration/dynamic setting, such as acting as DHCP server to allocate IP to each member or allocating radio resource to members.

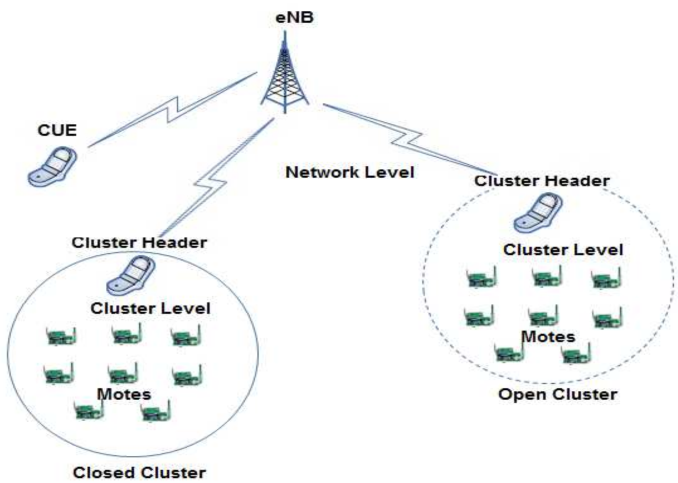


Figure 19. Cluster of MMC and Two Levels resource assignment

Furthermore, a cluster can be open/public cluster or closed/private cluster, based on the application/data type or geographic position. For open-cluster, the data of group members can be accessed by anyone with D2D enabled in a certain vicinity, such as advertisement clips sharing in a stadium or shopping mall, temperature and humidity report when one user passes by a special area, etc.. For closed cluster, confidential data can only be accessed by authorised users, such as in commercial or military applications.

Also, the assignment of resources is organised in two levels as shown in Figure 19. On the network level where the D2D relevant resources for discovery and communication are assigned by the network (eNB) to each cluster heads. On the cluster level, where each CH uses its respective set of resources to allocate radio resource to the individual sensor motes within the cluster. The two-level assignment of resources (network and cluster levels) allows maintaining a reasonable signalling overhead between CHs and eNB even for massive machine type communication like sensor networking.

To enable close control and profit from this new service, this CH function should be applied from operators, who can release a licence with a certain client number based on the D2D resource configuration or application type, which makes it easy to control access to licensed spectrum by D2D terminals and helps to mitigate any potential interference between D2D services and normal cellular services.

The same D2D radio resources can be re-used for different clusters if their geographic locations are far enough from each other as shown in Figure 19. Cluster of MMC and Two Levels resource assignment, which improves the spectrum efficiency. To implement this solution, determining the maximum D2D communication range is a vital issue.

5.2 Proposed resource allocation for clustered sensor network

Wireless radio resource allocation is a vital part of RRM. Combined with power control, a competent radio allocation algorithm can be achieved, which helps to alleviate interference, improve spectrum efficiency and extend battery lifetime. As mentioned previously, a variety of resource allocation methods have been suggested by standard organisations and academic researchers. Nevertheless, those mechanisms either are not very suited to, or are not efficient for a scenario with a swarm of sensor motes.

A novel radio resource allocation mechanism is proposed for clustered sensor networks, in which a modified LTE hopping type 1 in frequency zone, and a novel hopping algorithm based on member ID in time zone are combined together. The equations for resource allocation in time and frequency domains are listed below:

$$i^{drid} = (floor(mID / dridsPerSubframe) + mID) \bmod DrSubF \quad (5.1)$$

$$j^{drid} = (mID \bmod dridsPerSubframe + dridsPerSubframe/N\_Hop) \bmod dridsPerSubframe \quad (5.2)$$

where

drid: Discovery radio block id;

$i^{drid:}$ *Discovery RB on time domain (subframe);*

j^{drid} *: Discovery RB on frequency domain;*

mID: Mote cluster member ID;

dridsPerSubframe: Number of Discovery RB per subframe, e.g. 44 RBs for 10MHz bandwidth, should be even for hopping;

DrSubF: Number of Discovery subframe per discovery period, e.g. 64 subframes reserved for discovery in a 10s period;

N_Hop: number of hopping in frequency, e.g. 2 or 4.

It should be noted that equation (5.1) is for a member's position in time domain, while equation (5.2) is for its position in frequency domain. The latter is a modified form of LTE frequency hopping type 1 in which the constant hopping offset is replaced by the result of a modulo operation that varies with individual member ID.

The idea of the proposed radio RA mechanism is described as follows: Due to the half duplex nature of most transceiver designs, a D2D UE or a sensor node enabled D2D cannot receive and decode the D2D message when it is transmitting. For a group of nodes with D2D enabled, a pool of reserved radio resource is assigned to them to firstly discover each other, and then communicate with each other. One DUE transmits D2D message using two PRBs, 12 subcarriers in frequency and one subframe, and receives or monitors D2D messages from other members within this discovery resource pool. Because of synchronisation of LTE system, there are always chances when two or more DUEs use the same subframe, i.e. using the same time slot to transmit, and thus they cannot discover each other in this discovery period. They can "see" mutually until they use different subframe in next discovery period, assuming each of the DUEs has a temporary list to record who has been discovered. Thus, avoiding transmission collision and detecting all nodes under the use of such half duplex transceivers is the goal of the proposed RA algorithm, in which the nodes in the same subframe (time) will hop based on their member IDs in the next discovery period. The rate of discovery or discovery rate is defined as the ratio of discovered nodes to the total number of discoverable nodes in one discovery period, which is a key performance indicator of how efficient the resource allocation mechanism is.

Below is an example of resource allocation for 100 sensor motes with 352 RBs (22*16) pool under each D2D discovery period. The circle represents the RB for D2D transmission, 1 means group member 1 occupies RBID 3 on subframe 0 to transmit its D2D message, and 22 means member 22 takes RBID 24 on subframe 0, for instance. And in the first discovery period, for example, member ID 1 does not discover members 2 to 22 as they sent messages out at the same time even though they use different frequency.

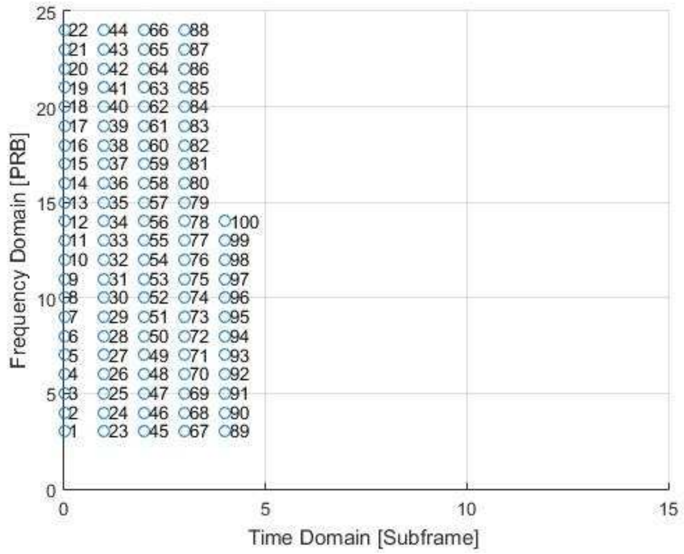


Figure 20. The resource block allocation_ first round

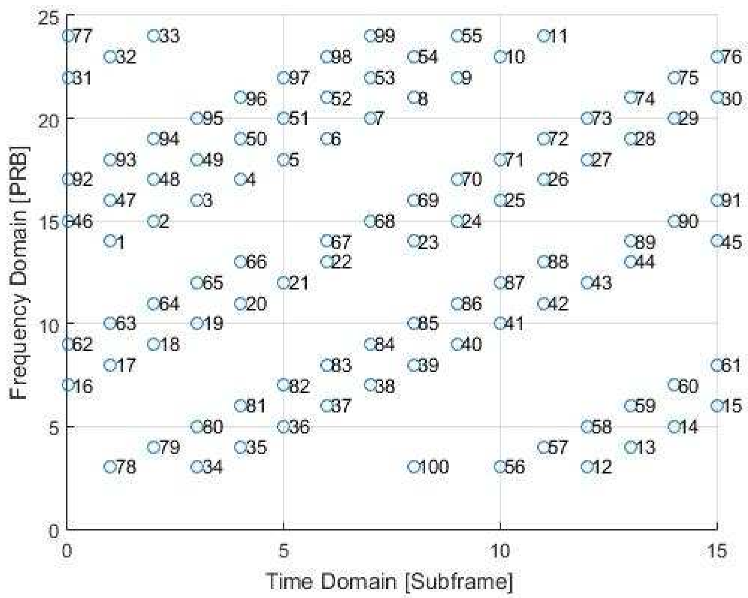


Figure 21. The resource block allocation_ second round

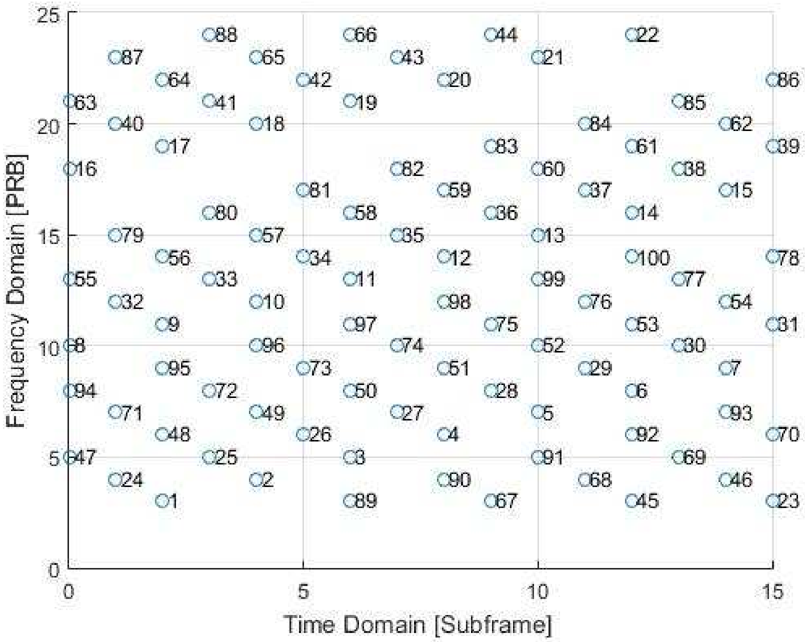


Figure 22. The resource block allocation_ third round

In the secondary discovery period or round (as shown in Figure 21), member 1 takes RBID 14 on subframe 1, while member 2 picks RBID 15 on subframe 2, and other members choose their resources using the same pattern. Now member 1 can detect those who took the same subframe in the first round as they are in different subframes during this discovery period.

In the third discovery period (Figure 22), member 1 hops to RBID 3 on subframe 2, but member 2 jumps to RBID 4 on subframe 4, and the subframe (time) gap between them will increase in the following round as well.

5.3 Simulation environment

MATLAB™ is used to simulate a group of sensor nodes in a cluster to determine how many of them can be detected by a CH in each discovery period. Then performances are compared between random selection (based on random uniform discrete distribution), and the proposed resource allocation mechanisms based on 1/3, 2/3 and full capacity of the resource pool to evaluate the suggested algorithm. The following assumptions have been made:

- The reserved radio resource for D2D discovery is 44*64=2816 RBs per discovery period;
- The CH is located in the centre of the group sensors, all of which are within its maximum communication range;
- The CH has the capability to decode received messages if there is no conflict between their transmissions;
- The CH will drop any message(s) if two or more sensors use the same PRB;
- The CH has the capability to record which sensors have been detected in each discovery period;
- Also, when node transmits discovery message (announce), it does not receive this or other message (monitor) due to the half-duplex nature of its transceiver.

5.4 Results and discussion

Below are the results comparisons between two resource allocation mechanisms on different resource capacity levels. It is clear that the performance of the proposed RA method surpasses that of the random RA method dramatically. Also, it can be seen that the performance of random RA stays downward when the number of nodes increases, while that of the proposed RA maintains a stable performance at a high level.

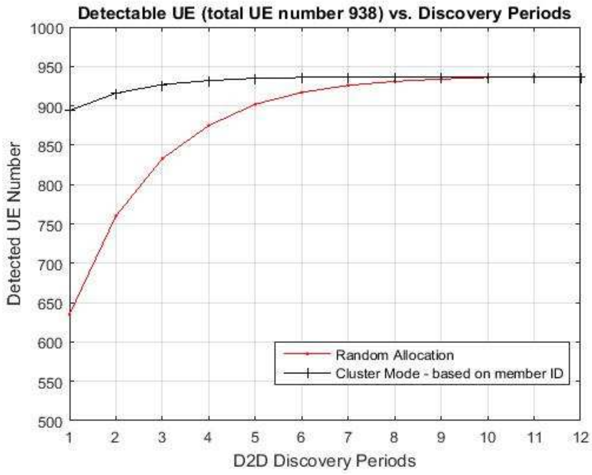


Figure 23. Performance comparison of resource allocation methods (1/3 capacity)

On the 1/3 resource capacity level, there are 938 nodes, including the CH, for a total 2816 RBs resource pool. From the result of random RA shown in Figure 23, the accumulative discovery rate increases dramatically for the first five discovery periods, then slows to reach a plateau. The discovery rate rises from 72.3% in the first discovery period to 98.7% and 99.6% in the seventh and eighth period, respectively. In this one third resource usage level, all sensors are discovered on the 10^{th} discovery period by random RA method.

In stark contrast, the discovery rate of the proposal cluster RA maintains stable and significantly surpasses that of the random RA from very beginning. It reaches 95.3% in the first discovery round and goes up to 98.8% in third period and 99.4 in the fourth period. All sensors were detected by the 8^{th} discovery period.

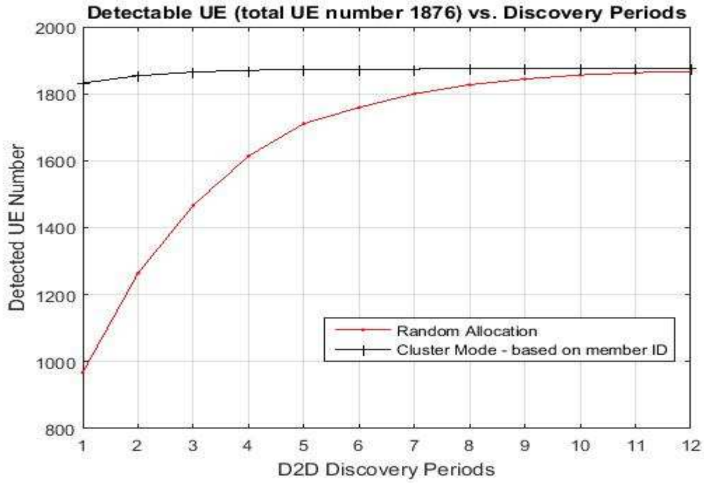


Figure 24. Performance comparison of resource allocation methods (2/3 capacity)

In the second tested level, there are 1876 sensors, which is equal to 2/3 of capacity for the same radio resource pool. Similar discovery performance trends are received for both RA methods as depicted in Figure 24 with minor differences in both of them.

For random RA, the discovery rate of the first discovery period is 50.3%, which is far below the performance in the previous node configuration. The rate climbs rapidly to 95.1% and 96.5% on seventh and eighth discovery periods respectively, but only reaches 99.3% after 12 discovery periods. Only after 16 consecutive discovery periods, can all nodes be fully detected.

The proposed RA once again outperforms the random RA. It starts as high as 97.7% in the first discovery period and exceeds 99% on third period to 99.4%. On the fourth round, the discovery rate achieves 99.7%. 100% nodes discovered by the 8^{th} discovery period, which is the same as that achieved in the scenario with fewer sensors.

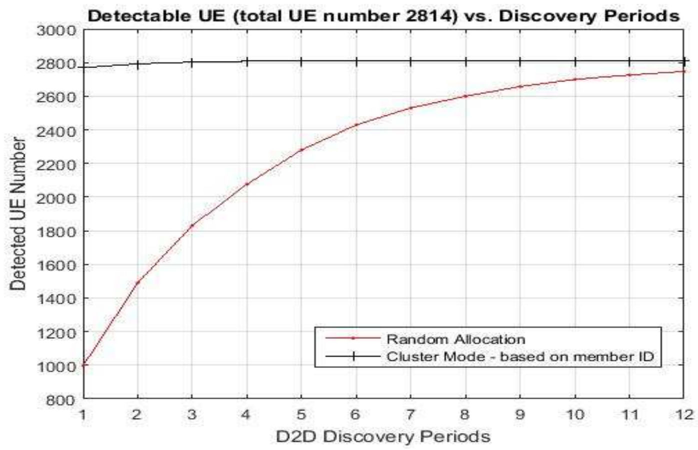


Figure 25. Performance comparison of resource allocation methods (fully capacity)

With the full capacity configuration, which is 2816 sensors for 2816 available radio resource blocks, the performance of random RA is worse compared with those in less crowded scenarios, even though it maintains an uphill trend throughout (Figure 25). Only 36.5% of the sensors are discovered in the first discovery period, 90.6% in seventh round and 93.0% in eighth round.

Random RA method can only detect up to 97.8% after 12 discovery periods. 100% detection is only accomplished on the 24th discovery round.

Under the same configuration, the gap between these two RA approaches becomes even wider. An incredible 98.4% of all sensors can be detected in the first discovery period, and that reaches 99.6% in the third round and 99.8% in the fourth period. All but one are discovered in the 8th discovery period, which is the only difference from the previous configuration for this resource allocation approach. Hence, full capacity configuration is not recommended, but leave at least two RBs for redundancy. With such a setting, 2814 nodes for the same pool, 100% discovery rate can be achieved on 8th discovery period as with previous scenarios.

In summary, it is worth noting that the performance of the new proposed RA approach can significantly outperform the random RA mechanism regardless of the resource pool utilisation. Furthermore, the more crowded a cluster is, the more efficient is the performance. If 100% nodes discovery is adopted as the performance target, the new allocation approach can reduce discovery time by 50% under 2/3 utilisation of the resource pool, and up to 67% under full utilisation of the resource pool compared with that of the random selection RA.

Chapter 6 – D2D interference management and power control

6.1 Joint resource allocation and power control for clustered sensor network

As mentioned in Section 3.4, introducing D2D into current LTE systems can cause potential interference issues if radio resource for communication is shared between DUEs and CUEs. This is because D2D supports UE under RRC idle status, where eNB cannot schedule radio resource dynamically according to instant feedback from UE. Even when DUEs are in RRC connected status, there are also latency problems if the scheduled radio resource is used by a group of DUEs, such as for a sensor network.

In order to implement D2D service to sensor network, grouping/clustering sensor nodes for the purpose of signalling overhead reduction and energy saving is recommended. Together with staying in RRC idle status and LTE Discontinuous Reception (DRX), maximum power saving is achieved for the sensor cluster members. For the cluster heads, which performs additional tasks, there are two possibilities for requesting radio resources from eNB and assigning them to its cluster members, depending on its RRC status.

When the CH requests D2D resource for communication under RRC connected status, eNB will dynamically assign a corresponding pool to it according to the channel status feedback. In this way, there is no interference between the CUEs and the CH, and also between the CH's group members. However, the CH may suffer interference from its group members if two or more of them use the same PRBs to transmit data, as illustrated in Figure 12.

When the CH is under RRC idle status, whether it is under coverage or out of coverage, the D2D resource pool for communication can be allocated by eNB, such as by broadcasting when the CH was first attached to this eNB, or can be pre-configured by operator. In this method, besides the latent interference from its cluster members, the CH may be influenced by other CUEs, as shown in Figure 10.

To mitigate new interference modes, this thesis proposes a joint resource allocation and power control approach. Two resource allocation methods: the proposed RA method mentioned in Chapter 5 and random RA are evaluated under the effects of three power control strategeies: fixed transmit power, fixed SINR target and fractional power control (FPC) for open loop control. The objective is to determine the best combination to mitigate the interference in an energy efficient way.

Closed loop power control is excluded from this thesis because of some less-than desired characteristics of their mechanisms. The UE adjusts the uplink transmit power in accordance with a correction value, also known as transmit power control (TPC) command, transmitted by the eNB. The eNB estimates the SINR of the received signal and compares it with a pre-configured target value. If the estimated value is below the SINR target, a TPC command is transmitted to UE to request an increase in the transmitter power. Otherwise the TPC command will request to decrease its power. By this, the UE can change its output power dynamically. However, this mechanism requires feedback from the receiver and the transmitter needs to stay in active state, i.e. it is infeasible from the bandwidth and energy cost perspectives for a CH to provide such a feedback to each member of its cluster, with the cluster members keeping active all the time. Furthermore, it was recently reported in [51] that Open Loop Power Control (OLPC) exhibited higher power efficiency than Closed Loop Power Control (CLPC) in D2D communication, and thus our focus on OLPC in this thesis.

6.2 Simulation environment

Similar to the methodology used in Section 5.3, a group of sensor nodes, including one CH, are simulated by MATLAB™ under two scenarios:

The first simulation condition is that the CH is under RRC connected state and other cluster members are under RRC idle, in order to reduce energy consumption and signalling overhead. Besides awaking to broadcast the discovery message periodically, the sensor nodes awake only by on-demand, such as when the CH requests data from them, or by a pre-set time trigger. They select the radio resource for communication from the CH according to the RA mechanism used. On the other hand, the CH requests resource pool from eNB dynamically when needed, depending on its channel condition, according to the two levels resource assignment explained in Section 5. In this situation, CH only suffers from intra-group interference from the cluster members. Simulation settings, including power control methods and resource allocation approaches for this scenario, are listed in Table 4.

Table 4. Simulation settings of joint power control and resource allocation for clustered sensor network

Power Control	Fixed transmit power, no power control (No PC)
	Fixed SINR target
	Fractional power control (FPC) for open loop control
Resource Allocation Method	Uniform random selection
	Proposed cluster resource allocation

The sensor nodes are distributed with a Poisson distribution in a circle with CH in the centre. The CH discovers these sensor nodes and requests data from them. Each sensor chooses its own resource block to push data to CH using random selection RA or the proposed RA method. Unlike the discovery process, the CH does not need to occupy resources in a communication pool. It just needs to monitor/receive incoming data from its cluster members in communication stage. In other words, it saves one subframe's radio resources in communication resource pool. In order to simplify and clearly show the result, a small resource pool, 16 subframes in time domain with 12 RB in frequency domain, is simulated with 90% occupation, which is 173 nodes in this group. 1000 repetitions have been executed for each simulation to evaluate the possibility of interference; also various power control methods are used to measure the received SINR level. For fixed transmit power, 5 values (0, 5, 10, 15, and 23 dBm) are used; for the fixed SINR target power control method, it fully utilises the LTE path loss compensation capability by setting α = 1 and P_0

= β_{tgt} + P_{IN}, where β_{tgt} is a predefined SINR target and P_{IN} is the interference plus noise power. P_{IN} could be assumed as a fixed value for simplicity in practice. Four SINR values are used in the fix SINR power control. For open loop power control, the equation for sensor transmit power can be expressed as below:

$$P_{DUE} = \min (P_{MAX}, P_0 + \alpha \cdot PL + 3) \text{ [dBm]} \quad (6.1)$$

For the second simulation condition, on the contrary, the CH is under RRC idle state. The resource pool for D2D communication is either assigned by eNB when CH attaches to it or from pre-configuration, which is static and the useful signal received by CH may be influenced by both cluster members and other regular cellular users. The setting of simulation for this scenario is the same as previous scenario shown in Table 4.

Different from the first scenario, the simulation under this scenario needs to consider eNB and normal cellular users. Thus herein, a single sector with a 500 metres radius and 200 active cellular users dropped randomly under its coverage is simulated. Each of the CUEs occupies 6 PRBs for UL, which can reach up to 6Mbps using 64QAM and 4.5Mbps even with 25% overhead. To compare with the first simulation, the resource pool for communication and the size of cluster are same as the first scenario. Furthermore, in order to evaluate the influence of CUEs, various settings of resource pool for D2D and different occupied RRBs for CUEs are simulated. More detailed parameters for both simulation scenarios are listed below in Table 5. Simulation parameters:

Table 5. Simulation parameters for interference and power control

Parameter	***Value***
Channel Model	Outdoor-to-outdoor [2]
System Bandwidth	10 MHz
Carrier Frequency	1.8 Ghz
Noise Figure	9 dB
Sensor Max Tx Power, P_{MAX}	23 dBm
Sensor Fixed Tx Power	[0 5 10 15 23] dBm
Fixed SINR Target, β_{tgt}	[0 5 10 15] dB
P_{IN}	-110 dBm
P_0	[-35 -55 -75 -95] dBm
α	[0.4 0.6 0.8]
Number of RB per D2D node	2
Resource Pool for D2D	16 subframe * 12 RB
Cluster Member Number	173 (90% of resource pool)
Cellular UEs	200
Number of RB per CUE	6
Cluster Radius	100 metres
Cell Radius	500 metres
Number of Iterations	1000

6.3 Results and discussion

First, the random selection RA method is used. An example of sensor nodes distribution and interference of the CH can be seen below in Figure 26.

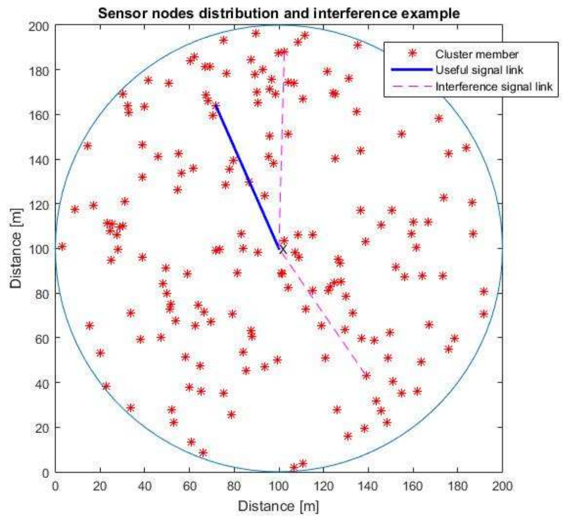


Figure 26. Sensor nodes distribution and CH interference example (random selection)

The black mark "X" means the location of the CH, which is in the centre of a group Poisson distributed nodes. The blue solid line stands for the desired data link from one node, and the dotted red lines represent other nodes sending their data using the same PRB at the same time, which is harmful to CH in receiving useful data.

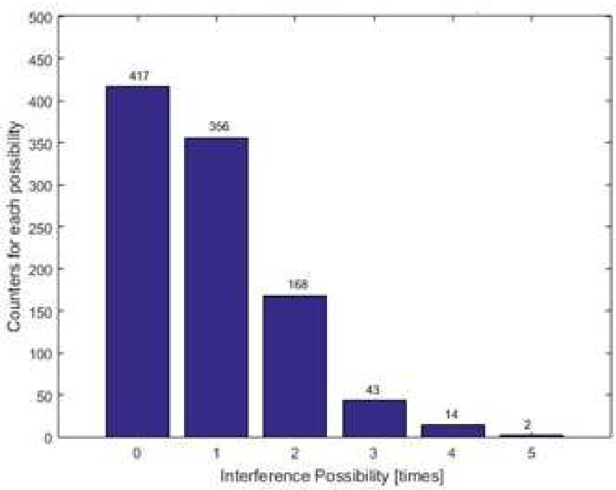


Figure 27. Histogram of CH interference probability (random selection)

The possibility of interference suffered by the CH is evaluated by executing the simulation 1000 times. The statistics for each of the possibilities can be seen in Figure 27. When the CH receives data from one of its group members, there is a more than 58% possibility that it will suffer interference from one or more members by using random selection. This 58% comes from the proportion of possibility with one or more interference sources, which is (356+168+43+14+2)/1000. Within this 58%, one interferring source accounts for most of it (356 times), while three or more interfering sources accounts for about 6%. Only about 41% of probability is achieved without any interference. It is thus proved, in another way, that the efficiency of random selection RA method for a group of members is low and the interference issue cannot be ignored.

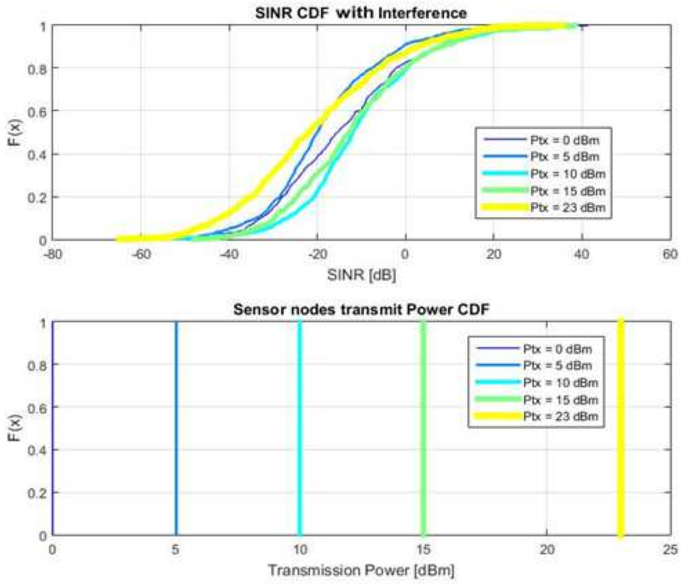


Figure 28. SINR CDF chart with fixed transmit power (random selection)

From Figure 28 - result of sensor nodes transmitting with fixed output power - it can be seen that around 80% of SINR is below 0 dB, regardless of the transmit power. Under the assumption that the CH could decode the data from its group member when the SINR is above 0 dB, the CH may decode properly only 20 per cent when there is interference. Fixed power control may control the power consumption of the sensor nodes, but it does not contribute too much to interference control in this scenario.

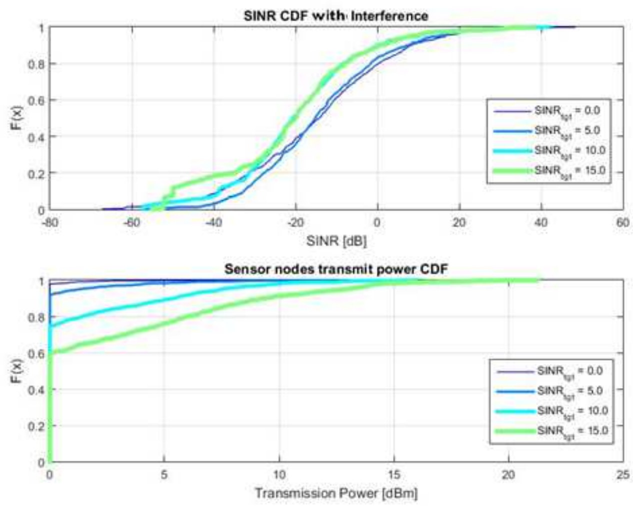
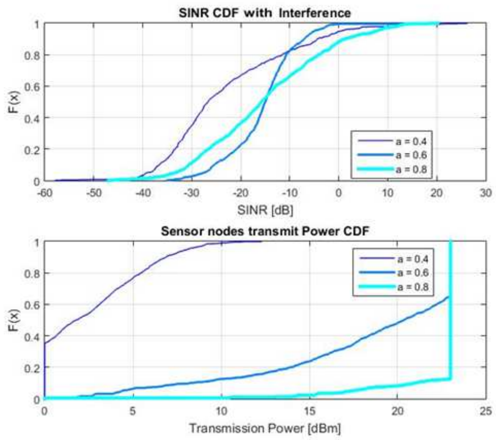
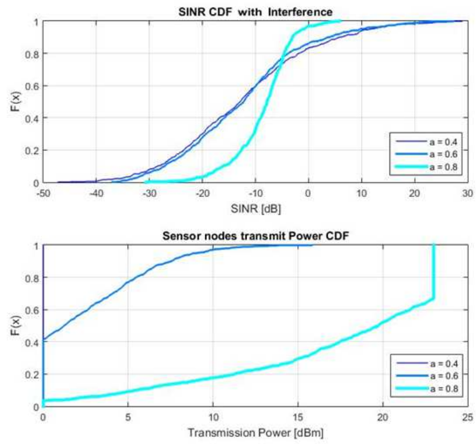


Figure 29. SINR CDF chart with fixed SINR target power control (random selection)

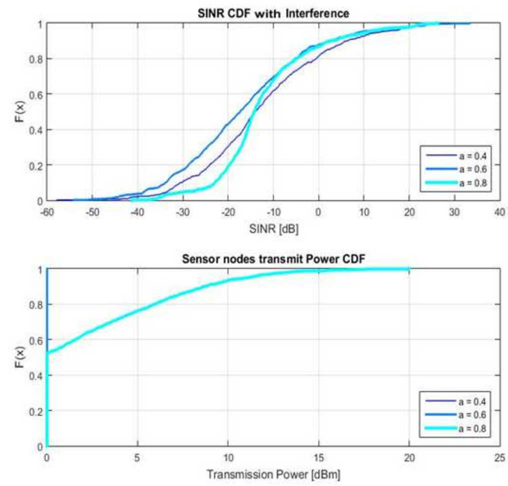
The result of fixed SINR target power control is shown in Figure 29, where a SINR trend similar to that of Figure 28 shows up when interference occurs. Approximately 80% probability of the SINR value is below 0 dB, independent of the different SINR values used. For the output power of sensor nodes, it maintains at 0 dBm most of time and may increase to the maximum output power of 23 dBm very quickly. This is particularly obvious for situations with a small SINR target. With a large SINR target, such as 15 dB, the output power of sensor nodes is 0 dBm for 60% possibility and close to 90% is below 10 dBm.



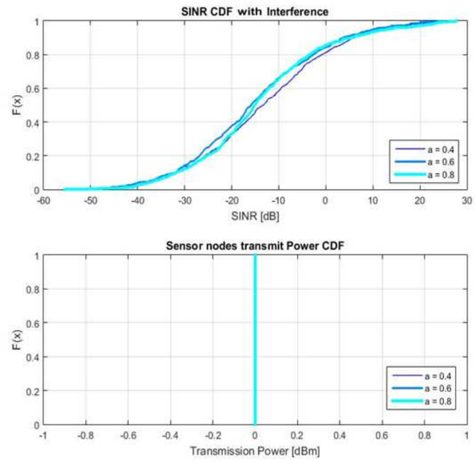
(a) P_0 = -35 dBm



(b) P_0 = -55 dBm



(c) P_0 = -75 dBm



(d) P_0 = -95 dBm

Figure 30. SINR CDF chart with open loop power control (random selection)

For open loop power control with a variety of initial output power P0, Figure 30 shows the SINR CDF graph when there is interference and distribution of node output power level with different path loss compensation factor α. Here we can see that the SINR distribution with P_0 equalling -35dBm is the worst, as shown in (a), in which the SINR is below 0 dB with > 90% probability. SINR curves for other situations are similar: all are below 0 dB with 80% probability. For the output power level of sensor nodes, the differences between various P_0, even those for different α with same P_0 are quite outstanding. When P_0 is -35dBm, below 40% of node output power distribution is 0 dBm and most are below 10 dBm with α = 0.4. For α = 0.8 under the same situation, the output power is 23 dBm with over 90% probability. When P_0 is -55dBm, node output power distribution maintains at 0 dBm with α = 0.4. For α = 0.6 and 0.8, the output power distributions are similar with those of α = 0.4 and 0.6, respectively, under a P_0 of -35dBm. With the decrease of P_0, the output power of those sensor nodes tends to 0 dBm inevitably with all values of the path loss compensation factor α, as shown Figure 30 (c) and (d).

From the above results of random selection RA method, it is clear that from the interference perspective, the three power control methods for such an environment with a group of sensor nodes are not effective. Whilst power control mechanisms can be used to conserve energy, the communication range will be impacted when the output power reduces. A way of mending this flaw and to improve the performance is by using a re-transmission algorithm, whereby the CH compares the received data with its known node list after the first communication period, then requests those nodes whose data were missed in the first round to transmit data again. However, this method requires another D2D communication pool applied from CH to eNB and nodes whose data are missed are kept awake to send data again, costing additional energy and adds delay to the CH data gathering process.

Next, the performance of the proposed RA method under the same power control mechanisms is evaluated. The same number of sensor nodes is distributed in the same way within a 100-metre radius circle. A snapshot of the node distribution and interference can be seen in Figure 31.

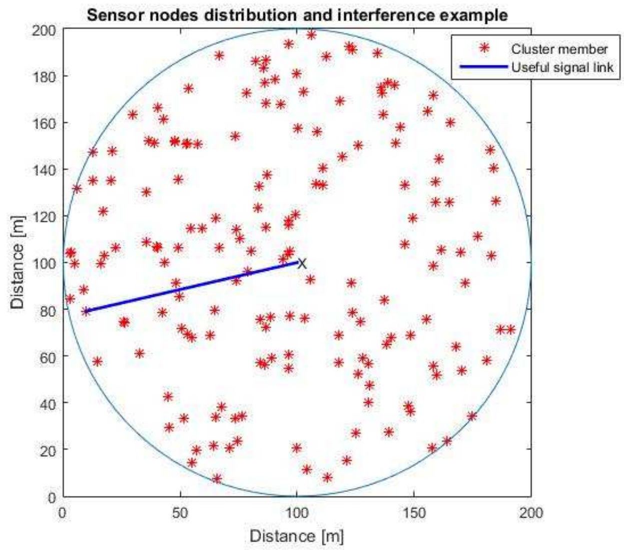


Figure 31. Sensor nodes distribution and CH interference example (proposed RA)

The result is similar to that of random selection RA: the solid blue line represents the desired data signal, but the difference between the two RA methods is that there is no interference by using the proposed RA method, as the group members use their own PRBs corresponding to their member IDs. Also, the CH does not need to use the communication pool to send/announce D2D messages but only requires to receive/monitor D2D signal from its members. Thus, the CH can receive data from all its cluster members in the first communication period as long as the size of cluster is less than size of the resource pool. The histogram graph of interference probability is shown below:

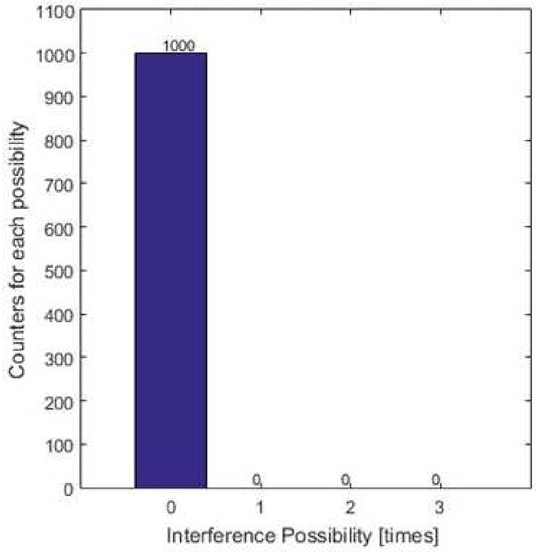


Figure 32. Histogram of CH interference probability (proposed RA)

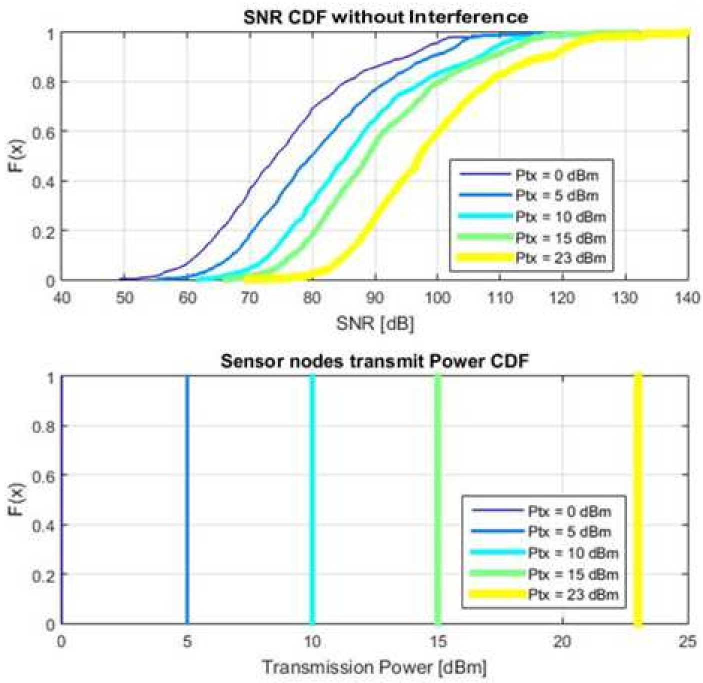


Figure 33. SINR CDF chart with fixed transmit power (proposed RA)

Comparable results can be found with other power control approaches, even when the transmit power of sensor node is changing with different power control algorithsms. Independently of the output power, the received signal with SNR > 50 dB can guarantee the CH to decode data from its received signal, as shown in Figure 34 and Figure 35.

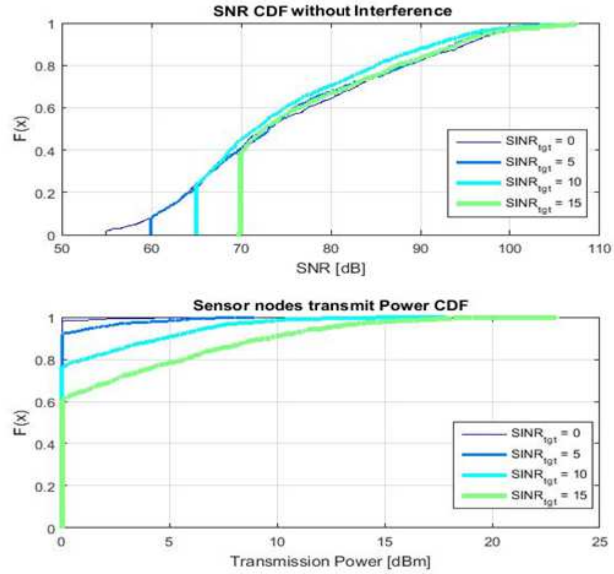
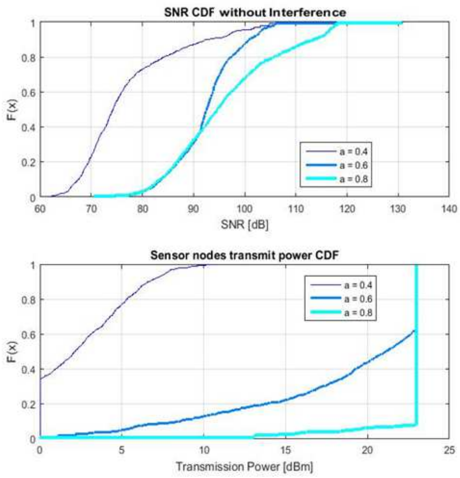
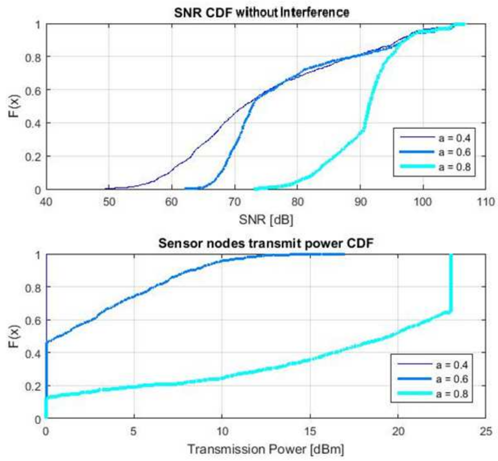


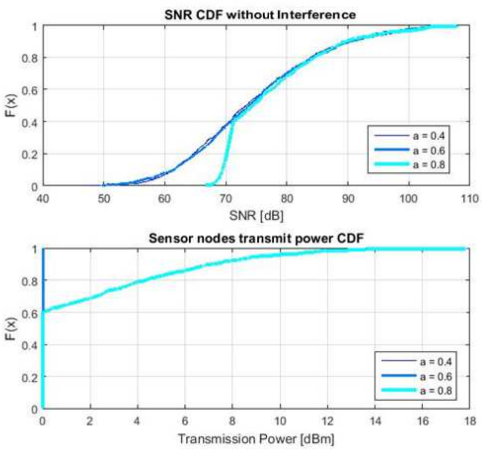
Figure 34. SNR CDF chart with fixed SINR target power control (proposed RA)



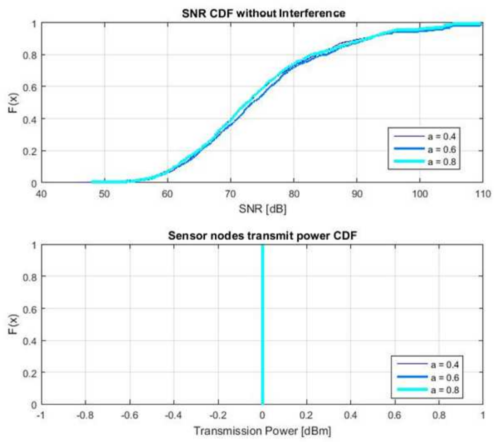
(a) P_0 = -35 dBm



(b) P_0 = -55 dBm



(c) P_0 = -75 dBm



(d) P_0 = -95 dBm

Figure 35. SNR CDF chart with open loop power control (proposed RA)

Now evaluate the results when the CH is under RRC idle state, in which the resource pool for the grouped sensor nodes is static and may be used by other normal cellular users, i.e. it is shared with other CUEs. An example of distribution and interference suffered by the CH is illustrated by Figure 36, from which we can see that the fan shaped area is the cell's coverage and the red dotted circle area is the CH's communication range. There are two jamming sources, one is from a sensor node and another is from a CUE while it is receiving data from one of its member. In the same way as previous distribution examples, the solid blue line represents the desired data transmitted from one of sensor nodes and dotted red lines represent the interferring signals.

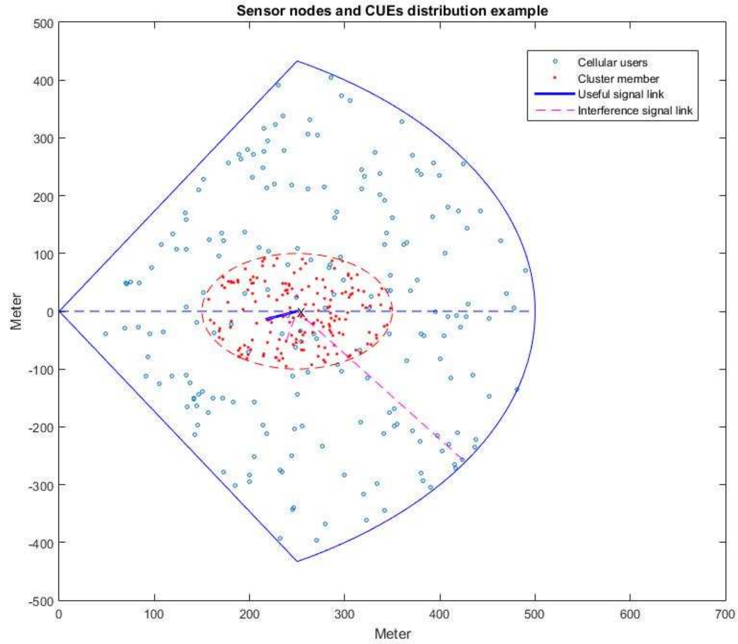


Figure 36. CUEs and sensor nodes distribution and CH interference example (random selection)

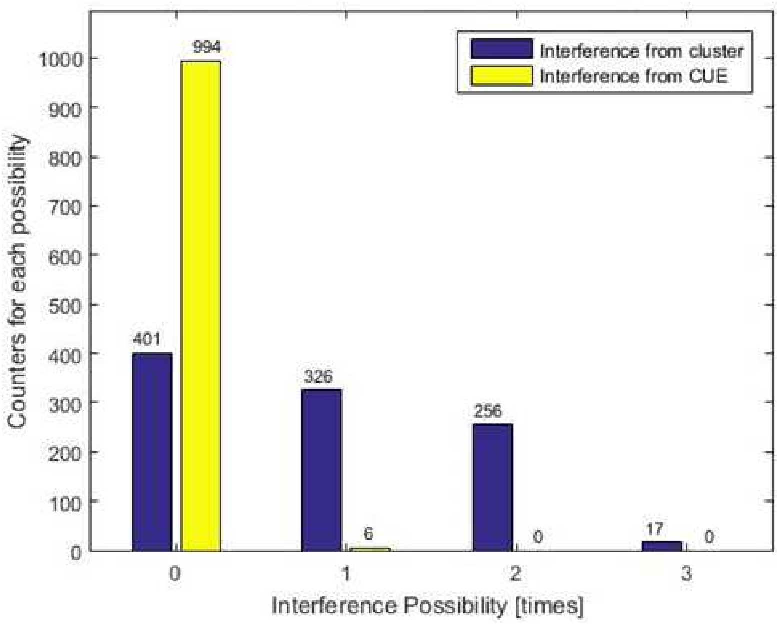


*Figure 37. Histogram of CH interference probability (random selection) with a 16*12 pool*

Figure 37 shows the interference probabilities for the CH from both its cluster members and the CUEs within a 1-second period. With the same size of resource pool assigned to the same size of cluster as in previous scenario and an additional 200 cellular users, each of which takes 6 PRBs, the result reveals that the main interference sources are still its members, which is about 60%. The probability of interference from the active CUEs is a mere 0.6% under the situation where the assigned D2D resource pool only accounts for 0.4% of the total available PUSCH radio resource in a 1 second time frame.

From the SINR distribution with fixed power control and interruption from CUEs as shown in Figure 38, it is clear that the SINR below 0 dB is more than 90%, which is higher than that of interference just from a cluster member situation. In this case, it is more difficult for the CH to decode the received data as there are interferences from both its cluster members and around CUEs.

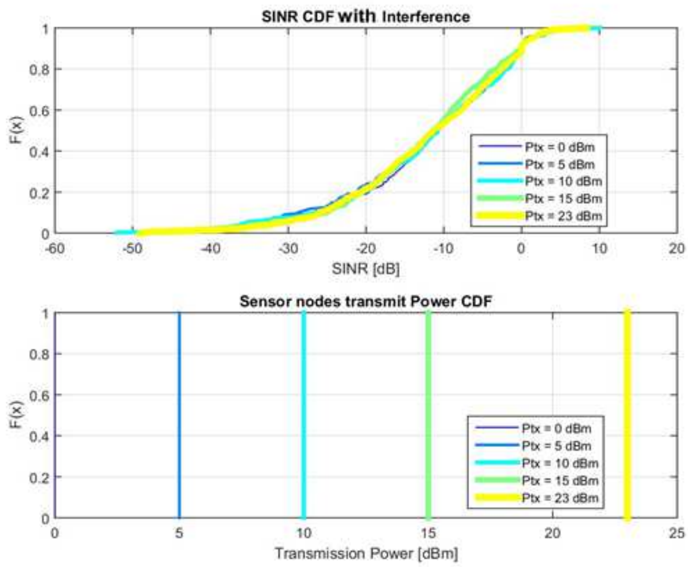


Figure 38. SINR (CUE and DUE) CDF chart with fixed transmit power (random selection)

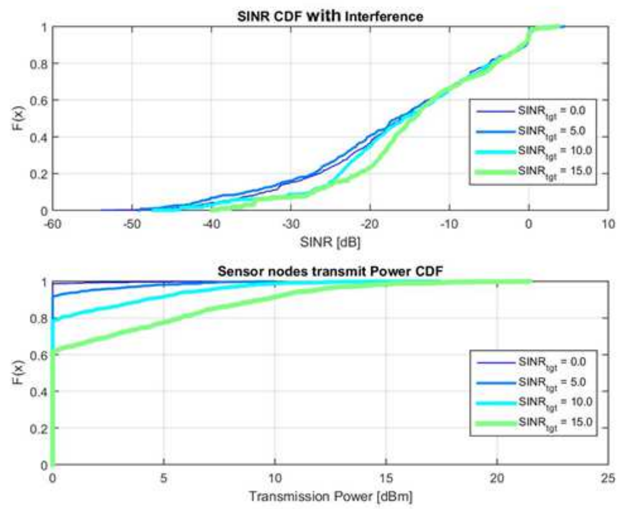
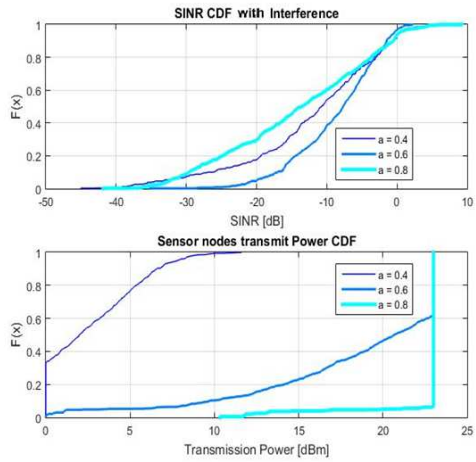


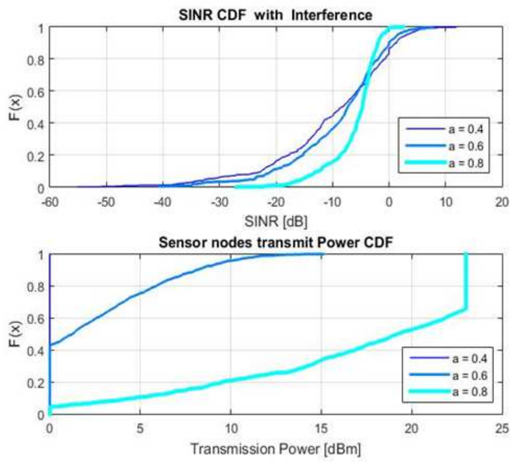
Figure 39. SINR (CUE and DUE) CDF chart with fixed SINR target power control (random selection)

Figure 39 shows the SINR distribution with SINR target power control with CUE interference, from which we can see the transmit power of sensor nodes has the same trend compared with Figure 29, which is without interference from CUEs. Nevertheless, the SINR has a worse result as more than 90% is below 0 dB.

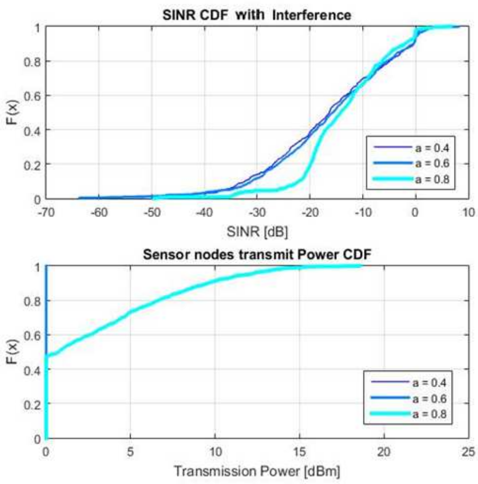
Similar trends can be observed with open loop power control as well. Even when the transmit power is the same as that of previous scenario, the interference from CUE worsens the SINR distribution of the CH. Details can be seen in Figure 40.



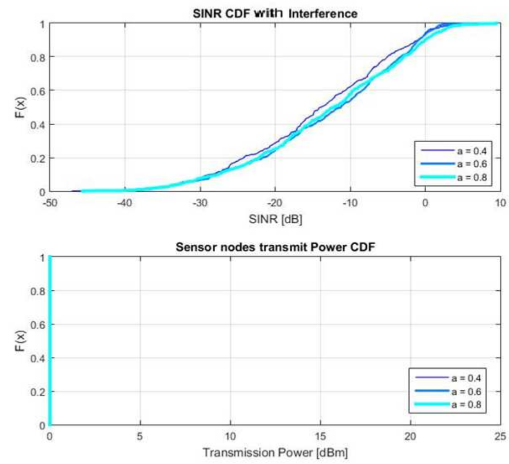
(a) P_0 = -35 dBm



(b) P_0 = -55 dBm



(c) P_0 = -75 dBm



(d) P_0 = -95 dBm

Figure 40. SINR (CUE and DUE) CDF chart with open loop power control (random selection)

To evaluate the impact of the size of resource pool assigned for D2D usage, more configurations are considered. In a 10 MHz bandwidth LTE system, if the assigned pool for D2D increases to 16 sub-frame in time domain and 44 RB in frequency domain, which is 1.6% of available PUSCH resource - with the assumption that the occupation rate of D2D resource pool is still 90% and the same number of CUEs and their resource blocks for uplink, the interference probability can be seen in Figure 41. We can see the interference probability from the cluster members is maintaining at the same level, while that of CUEs jumps to 1.8%.

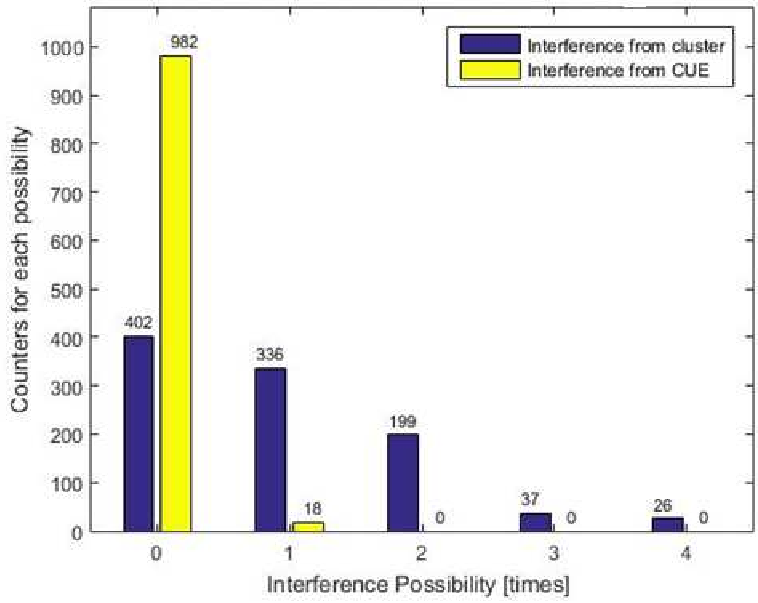


*Figure 41. Histogram of interference probability (random selection) with a 16*44 pool*

If more resource is assigned to D2D users, such as a 64*44 pool and 2534 nodes (90% of resource occupation), which is 6.4% of available PUSCH resource within 1 second, with the same setting for CUEs, the result is disclosed in Figure 42 as approximately 3% interference probability from CUEs. The interference tendency of these results is not unexpected, as the more resources are used by DUEs, the higher is the interference risk from CUEs.

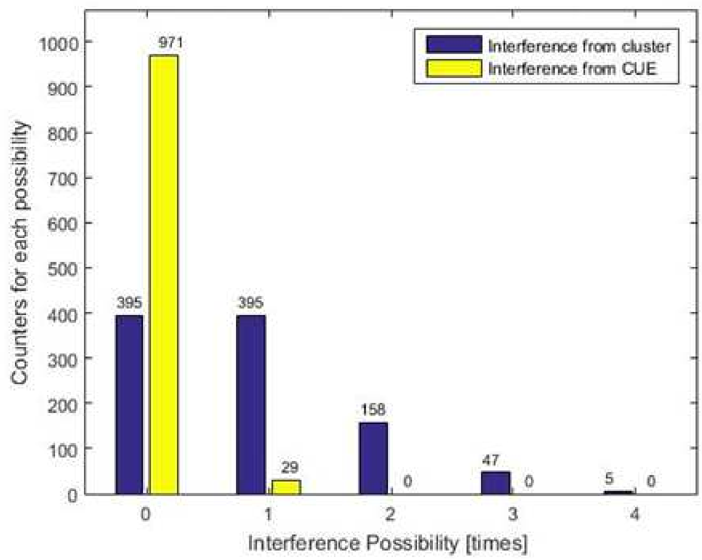


*Figure 42. Histogram of interference probability (random selection) with a 64*44 pool*

Now let us go back to the proposed RA method, when the D2D communication resource pool is shared by CUEs. Distribution and interference example is shown in Figure 43. As there is no intra-cluster interference, the only jamming source are the CUEs, as marked in the dotted red line.

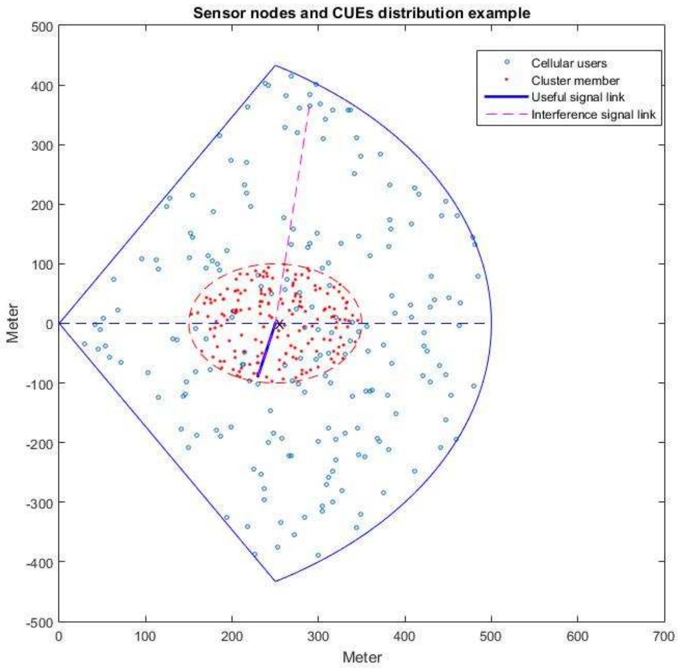


Figure 43. CUEs and Sensor nodes distribution and CH interference example (proposed RA)

The interference probability shown in Figure 44 is a bit different from that of random selection. It shows 1.3% of probability of interference from CUEs when using the proposed RA approach, while it is only 0.6% when the cluster member randomly selects from resource pool. This is because of the high D2D resource utilisation by the group members, whereas there are still a number of non-occupied resource blocks in the pool when using random selection method, which is the reason for high intra-cluster interference.

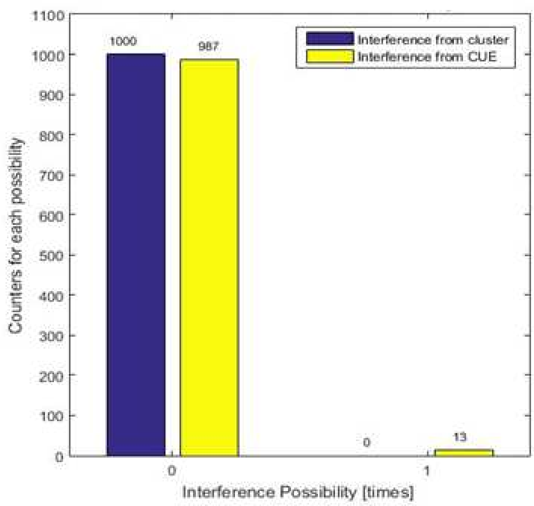


*Figure 44. Histogram of interference probability (proposed RA) with a 16*12 pool*

With the possibility of interference from CUEs, the SINR distribution graph under this test environment is shown in Figure 45. We can see that there is still about 30% of chance that the SINR is below 0 dB when sensor nodes transmit power is 0 dBm, and over 10% probability the SINR is 0 dB when cluster members transmit with 5 dBm output power.

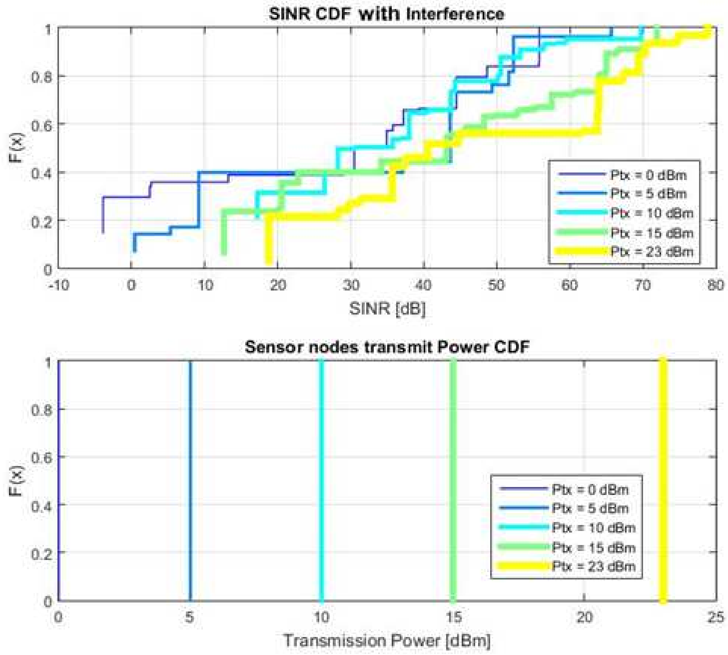


Figure 45. SINR (CUE) CDF chart with fixed transmit power (proposed RA)

When using fixed SINR target power control for the sensor members, the SINR of received signal is shown in Figure 46. As the sensor output power is mostly at 0 dBm when the SINR targets are set to 0 and 10 dB, there is still about 30% chance that the received SINR is below 0 dB with those targets.

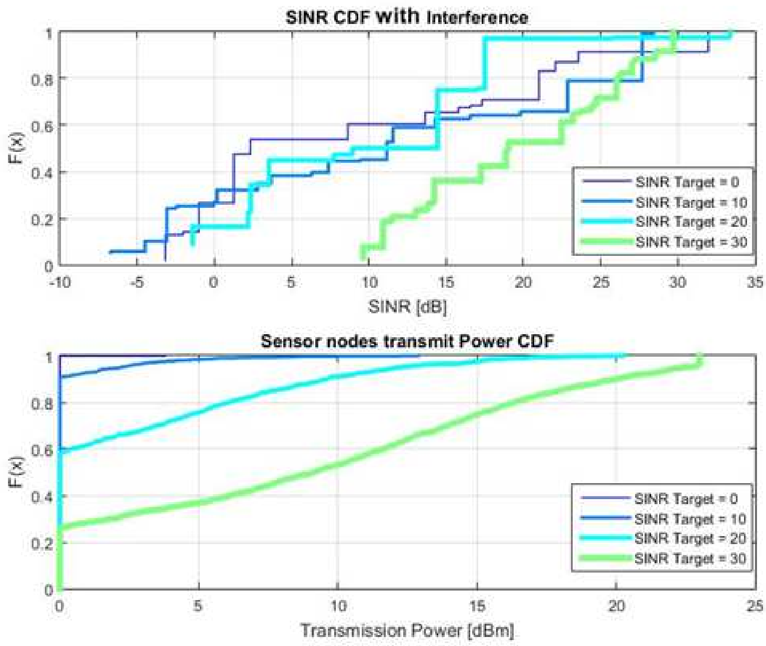
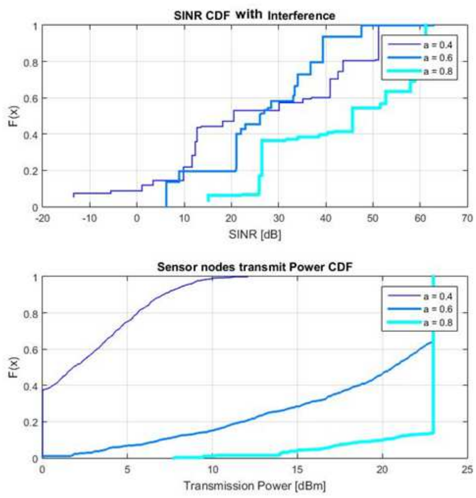
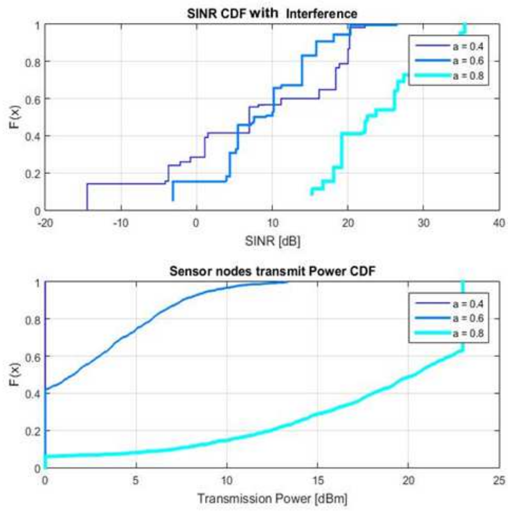


Figure 46. SINR (CUE) CDF chart with fixed SINR target power control (proposed RA)

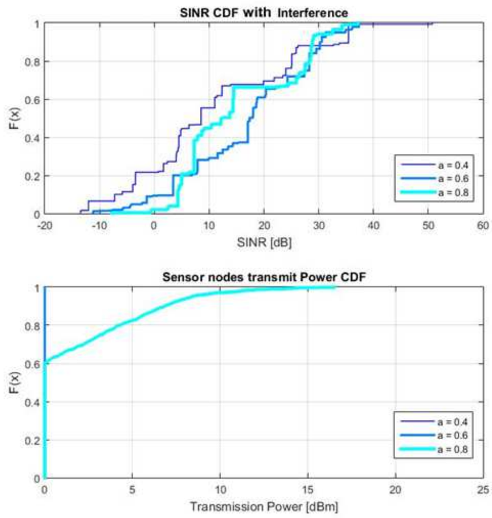
When fractional power control is used, the results can be found in Figure 47. With the initial power P_0 decreasing from -35 dBm to -95 dBm, the sensor nodes transmit power tends to 0 dBm and the chance of SINR from CUEs is close to the result of fixed output power equalling to 0 dBm.



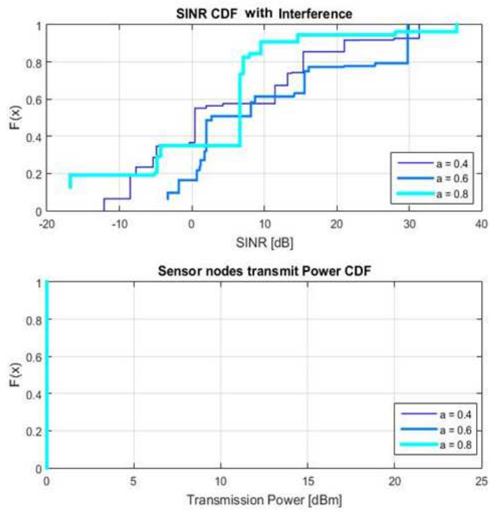
(a) P_0 = -35 dBm



(b) P_0 = -55 dBm



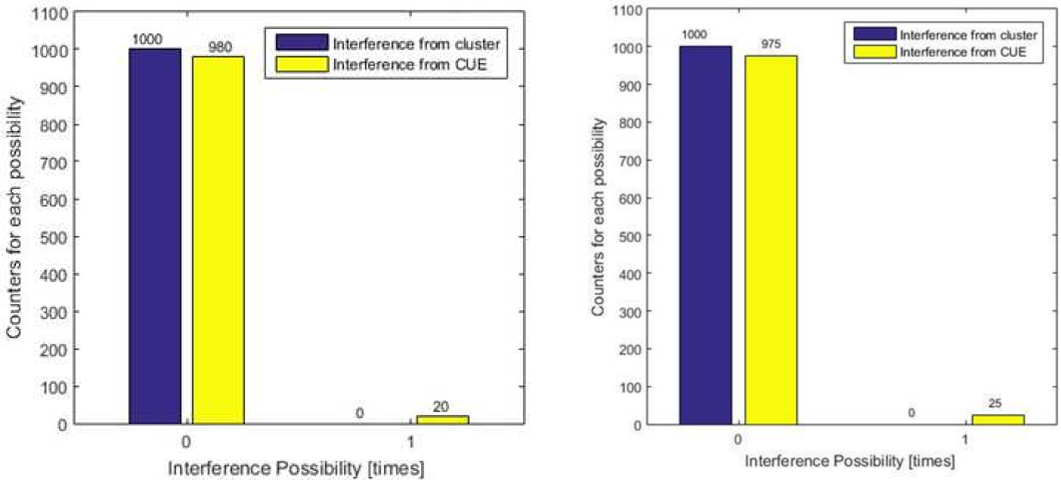
(c) P_0 = -75 dBm



(d) P_0 = -95 dBm

Figure 47. SINR (CUE) CDF chart with open loop power control (proposed RA)

Here the same resource pool setting as when using random selection is simulated to evaluate the interference probability under the proposed RA. Results are shown in Figure 48, from which it can be seen that with a smaller size of resource pool assigned for D2D usage, the interference from CUEs is increasing. The probability can reach up to 2% and 2.5% when the D2D resource pool accounts for 1.6% and 6.4%, respectively, of the total resource (based on 1 second). It is a similar level as that of using random resource selection method in the previous simulation.



(a) 16*44 resource pool (b) 64*44 resource pool

Figure 48. Histogram of interference probability (proposed RA)

Through these results from random RA, it is clear that the intra-cluster interference rather than interference from CUEs is the main interference source. This is true even when there are more CUEs than DUEs operating in the same space (see Table 5). However, by using the proposed RA method, in which the cluster members choose their resource blocks based on their member ID, the intra-cluster interference can be eliminated as long as the size of cluster is equal to or less than the size of the resource pool. CUEs do interfere with DUEs when D2D communication resource pool is shared with them, but this side effect can be mitigated either by reserving D2D resource pool or by increasing the DUE's transmit power, which will increase the communication range and consume more energy as a consequence. Power control for a group of nodes is complex: fixed power for all cluster member is simple but will not be energy efficient. Fixed SINR target power control and open loop power control need to choose the target value or initial power P_0 and α more elaborately, and the nodes need to measure the signal strength to compensate the pathloss between them and the CH.

A multi-layer fixed power control method is suggested for a group of relatively static sensor nodes, as illustrated in Figure 49. Based on the results in Chapter 4, for example, the output power in the inner circle could be set to 5 dBm and the communication range can reach 100 metres on this transmit power under indoor-to-indoor environment. The transmit power for those located in the middle circle (with radius 200 metres) can be set to 15 dBm, while those in the far circle can be configured with maximum output power. In this way, compared with maximum transmit power for the whole group, nodes in the inner circle and middle circle can save around 98%, and 84% of energy, respectively. The advantages of this power configuration are simplicity and effective. However, it may only suit sensor network topologies that are relatively static, which is the case in many real-life deployments.

Also, sensor network operators could define more layers to sub-divide the communication range and set their own power levels depending on actual environment, such that they could guarantee sufficient communication distance while minimising energy consumption.

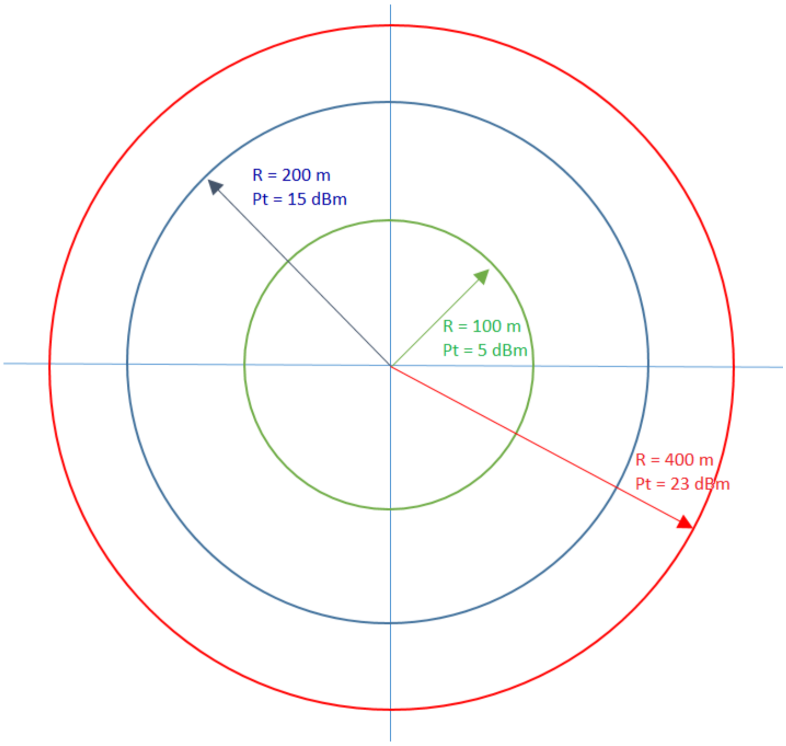


Figure 49. Suggested multi-layer fixed power method for group DUEs (e.g. I2I scenario)

Chapter 7 – Mobility support for D2D

As discussed in Section 3.5, the current proposals for D2D handover have mainly focused on the signalling procedure with little attention paid to the data exchange during HO. D2D is different from conventional cellular communications as the data (user plane) are exchanged between UEs directly. In normal LTE HO process, data (UP) can be buffered by the target eNB until the new traffic link is established between UE and the target eNB. In the D2D situation, however, where to buffer the data or how to keep an on-going data session is more challenging.

7.1 Proposed mobility support for D2D

As D2D service should be supported under both RRC_idle and RRC_connected states, mobility support of D2D must consider DUEs under those two conditions.

In RRC_idle state:

- In the case of a simple D2D session between DUEs, in which a D2D channel is established between DUEs but there is no on-going data transmission: UE should still follow the normal cell reselection procedure and attaches to the new cell to obtain new resource configuration and establish D2D session with its previous D2D partners if they are still in proximity.
- In the case of an on-going D2D data session, the same signalling procedure above may be used with additional priciples for user plane. In order to achieve a seamless user experience of D2D data session, the following two principles should be followed:
  1) A list of frequencies at which DUEs can operate in LTE-A network should be pre-configured into the DUEs. It is the UE (not target eNB) who decides which frequency should be used for the D2D user plane after HO.
  2) UE has the capability to check data packet segments and a decision to use the new radio resource depends on whether or not the data session has finished.

In RRC_connected state:

- If it is only a simple D2D session between DUEs with no on-going data transmission: the DUE should follow the normal HO process (S1 HO or X2 HO) with some modifications. HO_Request and HO_RequestAck messages should include the D2D session relevant information in order to resume it after HO. The DUE scans neighbour cells in edge area and initialises the D2D session setup process with its D2D neighbours by using the new resource configuration after moving into the target cell. The original signalling session will be replaced by the new session after HO is finished.
- If there is an on-going D2D data session, here are some proposals for both the control plane and user plane:
  1) Switch to cellular mode when D2D HO is triggered and follow the regular LTE HO process with signalling modifications for D2D session and the eNB buffer D2D data, then re-establish D2D session (if still in the D2D communication range). This way the on-going data session will be maintained, and we can call it mode selection D2D soft-

HO. A brief illustration of traffic link under this handover is described in Figure 50. D2D traffic link with mode selection soft handover, in which the DUEs move from their initial positions marked with “o” under D2D mode. With the distance between them increasing, they switch to cellular mode once they are beyond the D2D communication range and the data goes through eNBs during this situation. As long as the data stream keeps running, they would switch back to D2D mode once they are again within communication range.

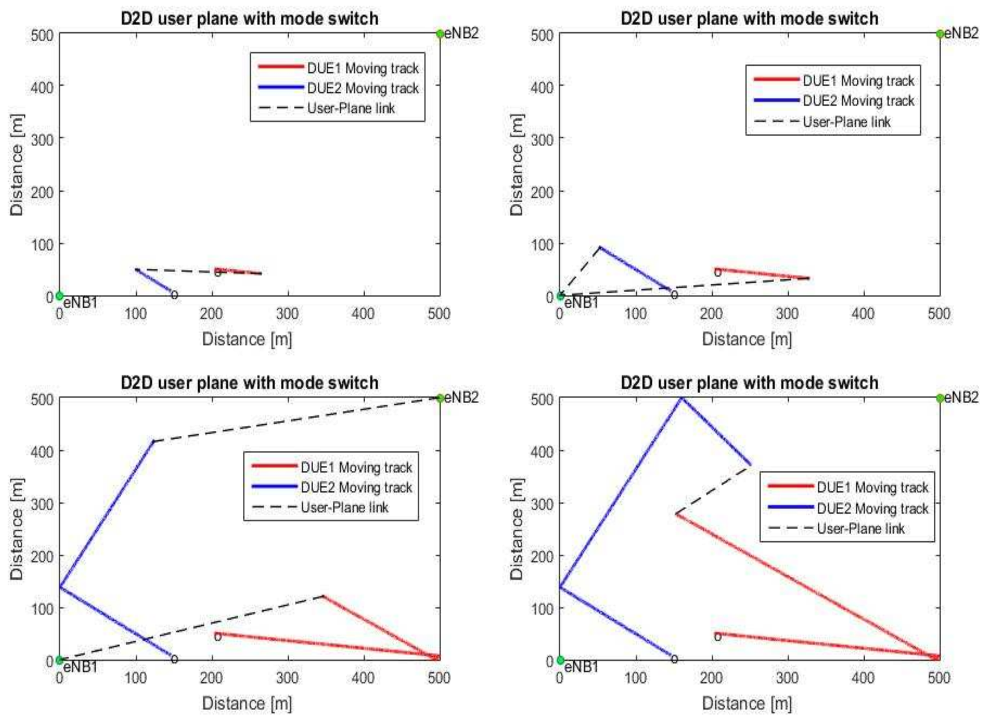


Figure 50. D2D traffic link with mode selection soft handover

2) When HO is triggered, DUE stops the current data transmission, measures and selects the most suitable target eNB/cell and initialises the normal D2D setup session process with its counterpart DUE (if still in D2D communication range) and re-starts the data session. For this approach, we refer it as D2D hard-HO;
3) By using Coordinated Multi Point (CoMP) technology to achieve D2D soft-handover: in cell edge coverage, DUE can obtain the D2D radio resources configuration from multi cells/eNBs dynamically depends on its channel status. With this technology, transmission points - eNBs - will be switched dynamically and DUE will receive the new radio resource smoothly to continue its D2D communication. For this approach, we refer it as D2D soft-HO.

Furthermore, an optimised CoMP process to reduce the signalling overhead is proposed. The optimised CoMP can be briefly explained as follows (Figure 51): when T2_1 is shorter than T1_1, the transmission point is unchanged; when T2_2 is longer than T1_2 but the next T2_3 is shorter than T1_3, still no switching occurs; when T2_4 is equal or larger than T1_4 and the consecutive T2_5 is longer than T1_5, which meets the switching criterion, the transmission point is switched to eNB2.

T1_x here represents the time when UE remains with eNB1 as the signal quality is better, while T2_x represents the time when UE switches to eNB2 when the signal quality from eNB1 becomes worse. Although only a two-cell environment is illustrated here, this approach can be applied to multi-cell scenarios as well.

This optimised CoMP algorithm is not only based on the reported CQI value for signal quality, but also based on the duration of CQI. The principal theory is that the eNBs still measure and check the reported CQI values from DUE subframe by subframe, but delay switching the transmission point until two or more consecutive durations of equal or higher CQI from target cell have occurred (as depicted in Figure 51).

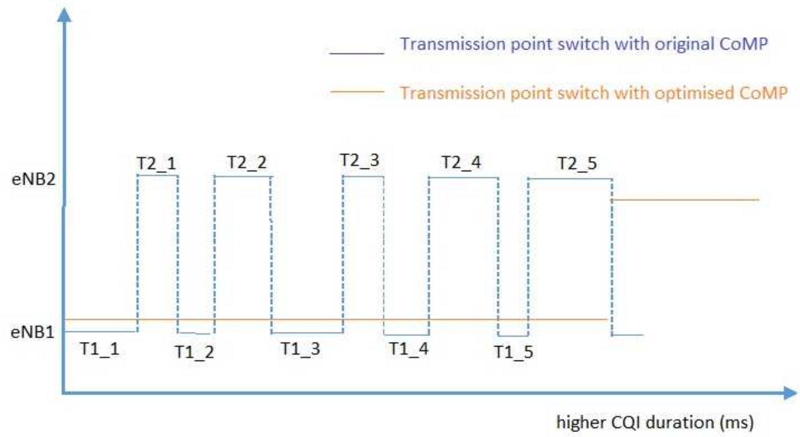


Figure 51. Optimised CoMP illustration

Even though plausible solutions for user plane D2D HO are discussed briefly in this thesis, the control plan is still the pre-conditional element, i.e. since the setting up or maintaining of a traffic channel is a pre-requisite for any data exchange during D2D handover, it should be given higher priority over the user plane, and thus our focus on a CoMP based solution.

7.2 Simulation environment

The D2D discovery radio resource configuration is provided by SIB19 and the communication resource configuration is provided by SIB18 [15]. Also, because SIB messages are carried by PDSCH, receiving the resource configuration via PDSCH message is the pre-condition to maintain an on-going D2D data session when DUE is in cell edge area.

It is a hot topic to use CoMP to implement LTE soft-handover. This thesis suggests using CoMP to fulfil D2D mobility support when DUEs are under RRC_connected state; and proposes an optimised CoMP to accomplish signalling overhead reduction. The simulation uses CoMP Dynamic Point Selection (DPS) for D2D resource configuration signal transmission under a two-eNB environment based on Channel Quality Indicator (CQI) reported from the moving DUE, as shown in Figure 52.

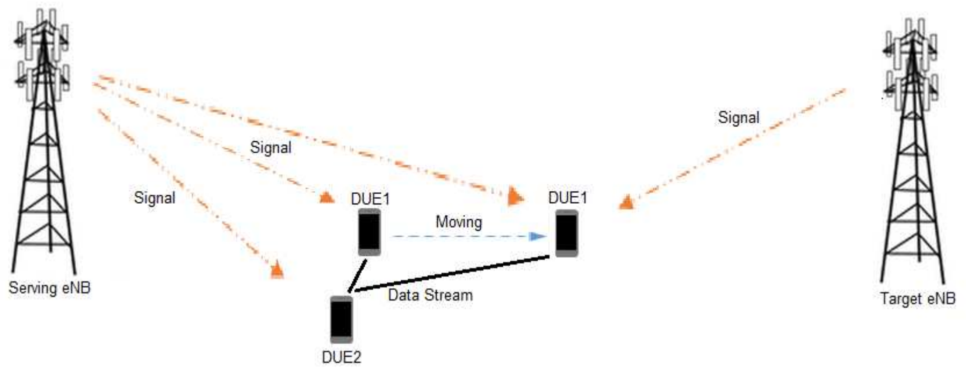


Figure 52. D2D mobility support simulation

Initially, both DUEs are under one serving cell – eNB1, and one moves towards eNB2 while there is an on-going data session between the two DUEs. On each subframe, SNR from both eNBs is checked by the moving DUE1. The eNB transmission contains cell-specific reference signal (CSI-RS), synchronising signal, and the resource configuration for D2D. The signal is generated and modulated, then sent through a fading channel. DUE1 receives the signal and demodulates it, then calculates CSI feedback. System selects the transmission point (eNB) and the modulation and coding schemes using the CQI reported by DUE1. The transmission point can be changed on a subframe basis to take advantage of instantaneous channel conditions. Detailed parameters used in this simulation are listed below:

Table 6. Simulation parameters for CoMP

Parameters	***Value***
Channel Model	Outdoor-to-outdoor [2]
System Bandwidth	10 MHz
Carrier Frequency	1.8 Ghz (LTE Band 3 for NZ)
Noise Figure	9 dB
eNB Transmit Power	38 dBm
eNB Minimum Receive Sensitivity Level	-93.5 dBM
eNB Communication Range	500 metres
DUE Transmit Power	23 dBm
DUE Movement Speed (Relative)	120 km/h

7.3 Results and discussion

To easily trigger a handover and show the result more clearly, firstly DUE1 is simulated to move only vertically across the cell edge. Also, because of the proximal nature of D2D communication, the movement distance is limited to 150 metres in order to ensure that the DUE1 is still in the communication range of DUE2. The movement track is shown in Figure 53.

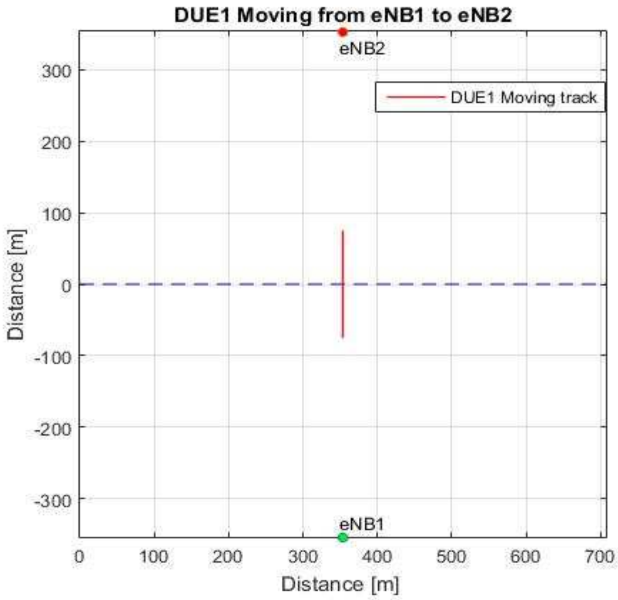


Figure 53. DUE1 movement track

The red line in the above graph represents the movement track of DUE1, which is from eNB1 to eNB2 with a speed of 120 Km/H. With this speed, it takes 4500ms to travel through the distance of 150 metres. The corresponding dynamic transmission point selection using CoMP is shown in Figure 54.

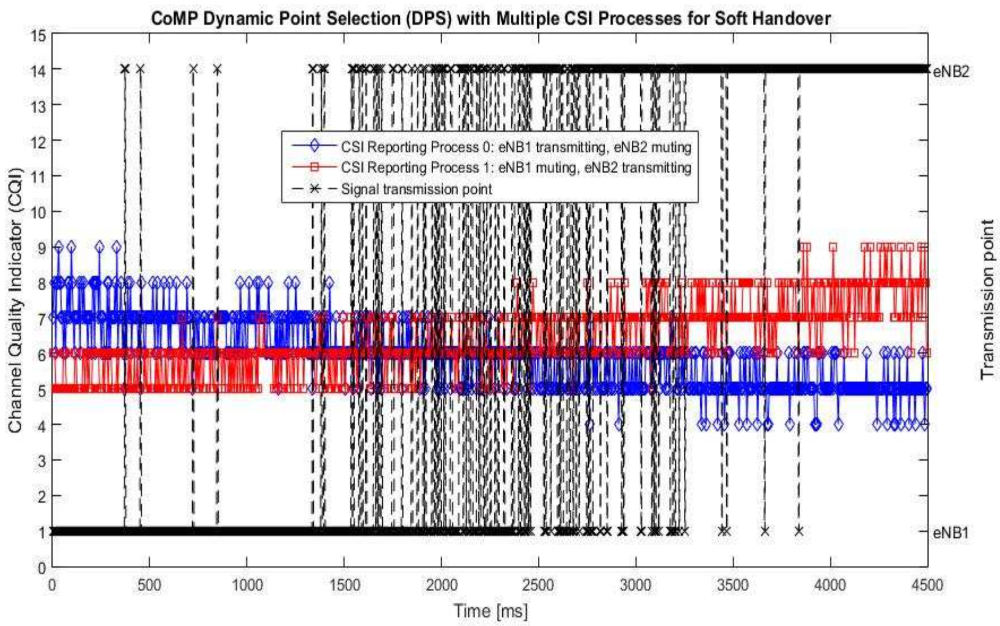


Figure 54. CoMP dynamic point selection supporting D2D soft handover

The blue line with a diamond shape is the CQI value reported by DUE1 from eNB1, and the red line with a square represents CQI value from eNB2. When the CQI from eNB2 is equal or higher than that of eNB1, which means the channel quality from eNB2 is better than eNB1, the DUE1 chooses eNB2 as the new transmission point and receives resource configuration from it, and vice versa. The black dotted line with a star symbol stands for the transmission point switching between eNB1 and eNB2. From the result, we can see that the transmission point switches between two eNBs instantly according to the CQI value, which guarantees the soft handover during the cell edge coverage. Unlike the traditional LTE inter-eNB handover, in which the service will stop and re-establish after HO finishes, the service is uninterrupted by using CoMP. However, it is obvious that the amount of switching between two eNBs is huge.

In other words, the amount of signalling exchanges with the two eNBs is enormous, as DUE1 needs to obtain new radio configuration from the target cell whenever it hands over to it. From this result, there are 157 times of switching during that period. To improve spectrum effciency and reduce signalling overhead, an optimised CoMP is proposed. The result of this mechanism is shown in Figure 55, from which it is noted that the switching frequency of transmission point is reduced to only 7 times, which translates into a 95% savings of signalling overhead when HO occurs.

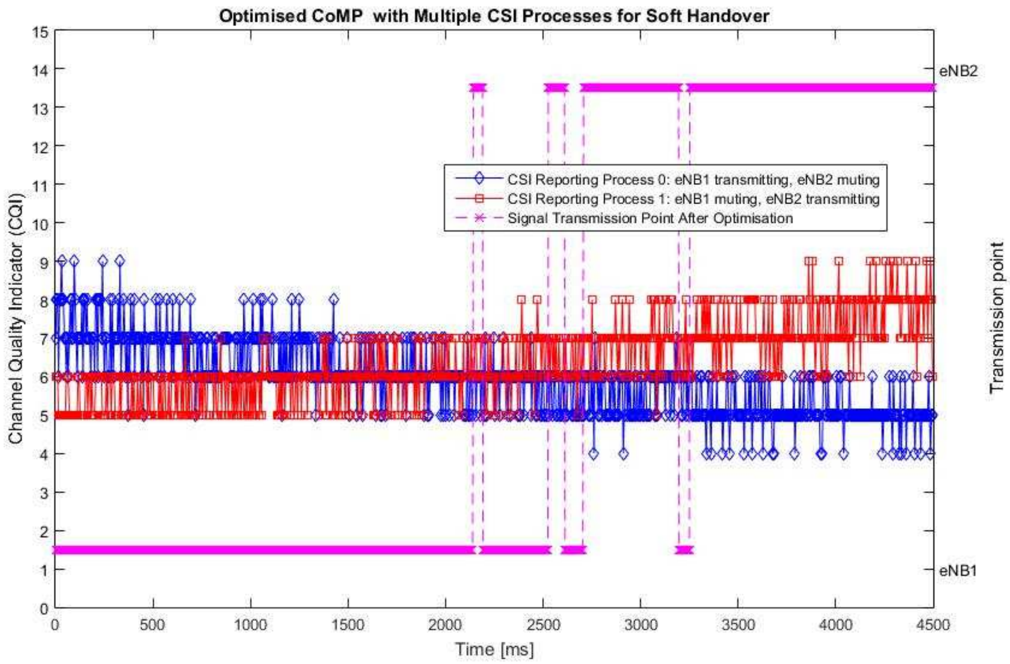


Figure 55. Optimised CoMP supporting D2D soft handover (2 consecutive periods)

Furthermore, when more consecutive periods are considered, the frequency of transmission point switching and resulting signalling overhead can be further reduced. Figure 56. Optimised CoMP supporting D2D soft handover (3 consecutive periods) shows an example with three consecutive periods, from which it is clear that the switching frequency is reduced, resulting in a signalling overhead reduction of up to 97% compared with the original CoMP scheme. Since almost 100% savings in signalling overhead can be already achieved with 3 consecutive periods, no further increase in the consecutive periods may be necessary. Even though optimised CoMP will introduce some HO delay, it will not impact the D2D communication due to the DPS mechanism of the CoMP as mentioned in Chapter 7.1.

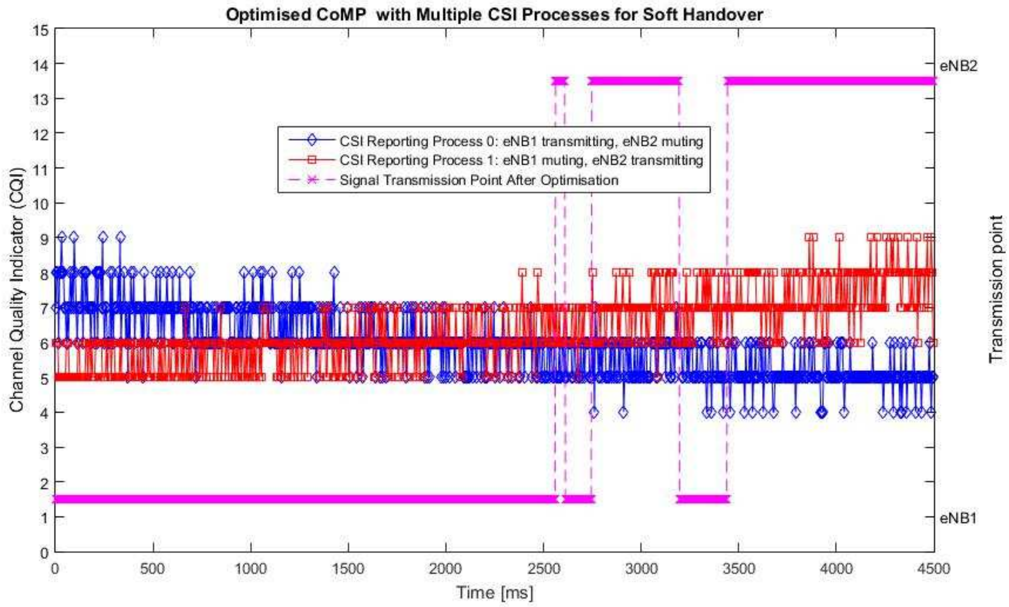


Figure 56. Optimised CoMP supporting D2D soft handover (3 consecutive periods)

In order to evaluate the performance of the proposed optimised CoMP mechanism, three other typical movement scenarios are simulated; the movement tracks are shown in Figure 57.

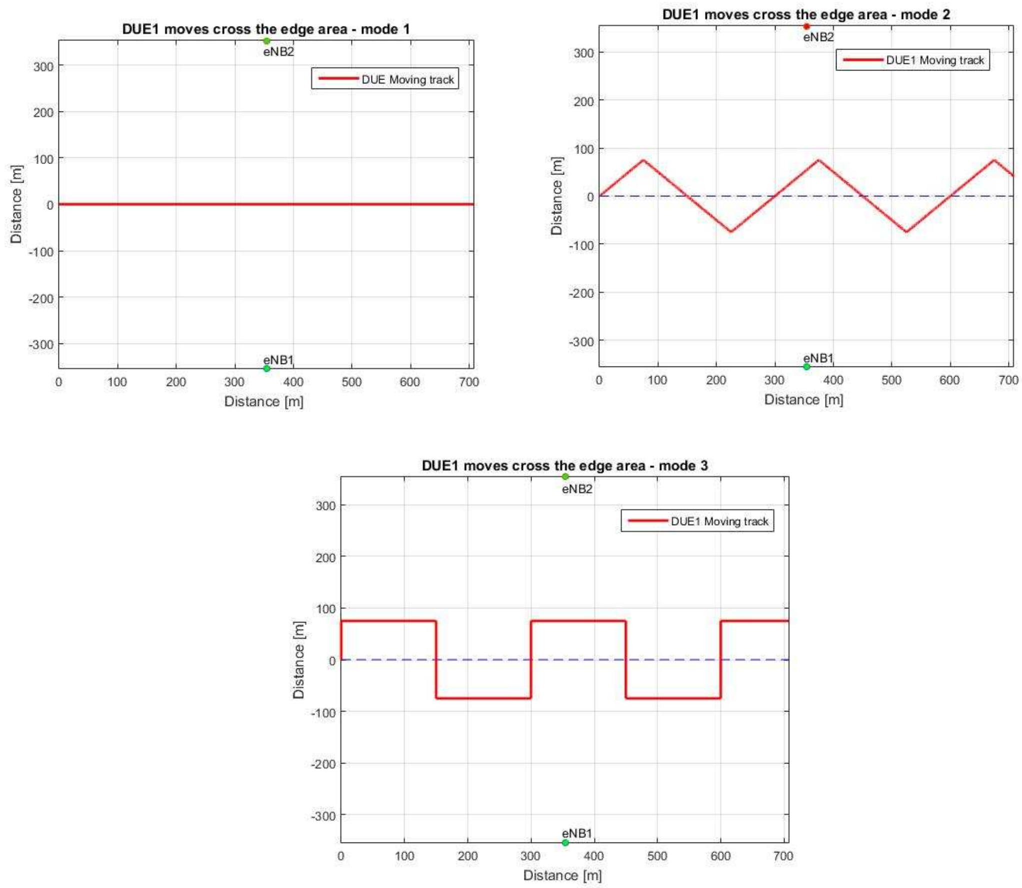


Figure 57. DUE1 moves across the cell edge area with three modes

The results of these three scenarios with original CoMP are hard to identify as there is an enormous amount of transmission point shifts, which 'black out' the whole figure. Thus, for better clarity, only the results with optimised CoMP scheme are displayed.

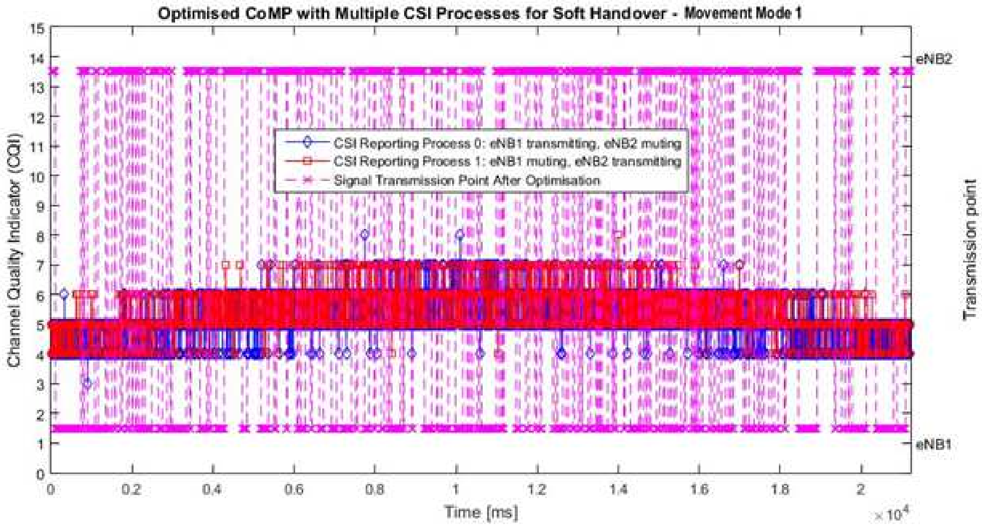


Figure 58. Optimised CoMP supporting D2D soft handover (Movement mode 1 with 2 consecutive periods)

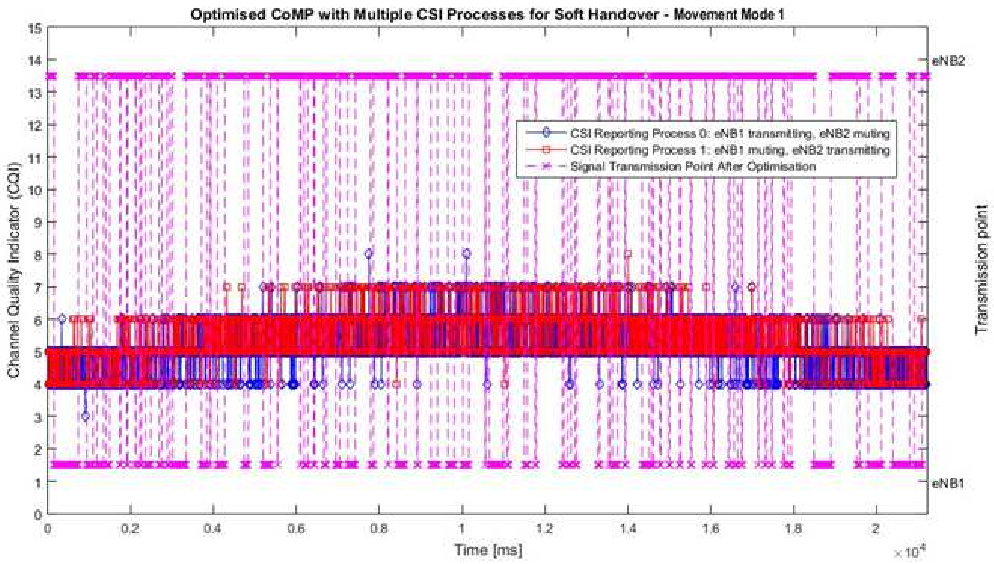


Figure 59. Optimised CoMP supporting D2D soft handover (Movement mode 1 with 3 consecutive periods)

The results from movement mode 1 are depicted in Figure 58 and Figure 59, from which we can see that the more consecutive periods are used as the threshold, the less number of handovers is triggered. When using two successive periods with better signal quality from target cell as the handover trigger, there are still 194 switches between two eNBs, while there are 128 switches if three consecutive periods are adopted, saving about 90.3%, and 93.6% respectively, compared with that of the original CoMP process, in which there are 1998 times of switching from one eNB to another in a 21-second period.

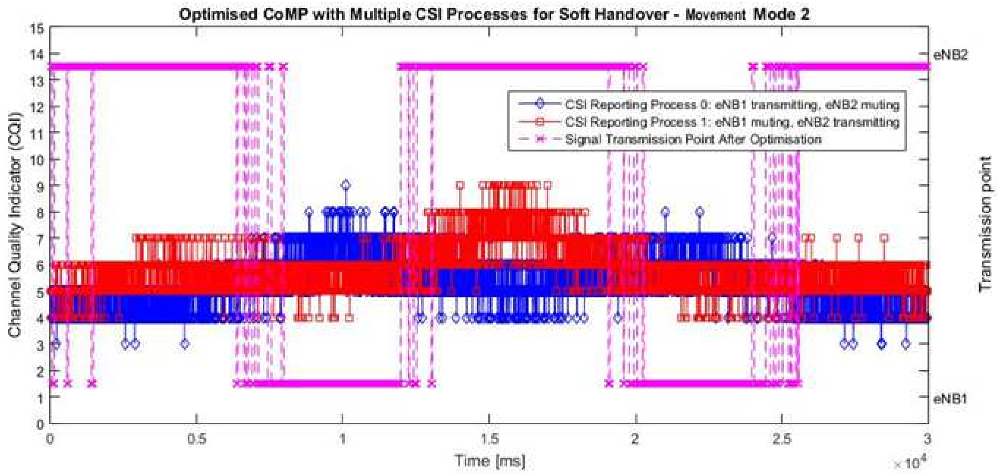


Figure 60. Optimised CoMP supporting D2D soft handover (Movement mode 2 with 2 consecutive periods)

Figure 60 shows the result of optimised transmission point selection with better signal quality from target cell in two successive periods. Comparing with the result of the original CoMP, which has 1503 times of eNB switching during a 30 seconds time slot, this optimised CoMP only has 52 times of handover between two eNBs, reducing the signalling overhead by up to 96.5%.

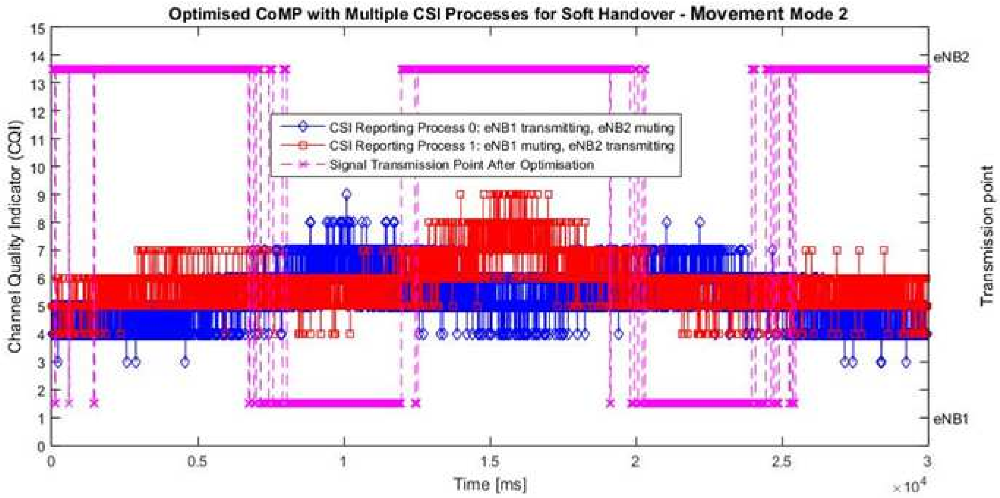


Figure 61. Optimised CoMP supporting D2D soft handover (Movement mode 2 with 3 consecutive periods)

Figure 61 depicts the result for HO with 3 continuous periods with better target cell signal, from which it is clear that the HO times is further reduced to 36 times, or a saving of 97.6% in signalling overhead compared with the original CoMP.

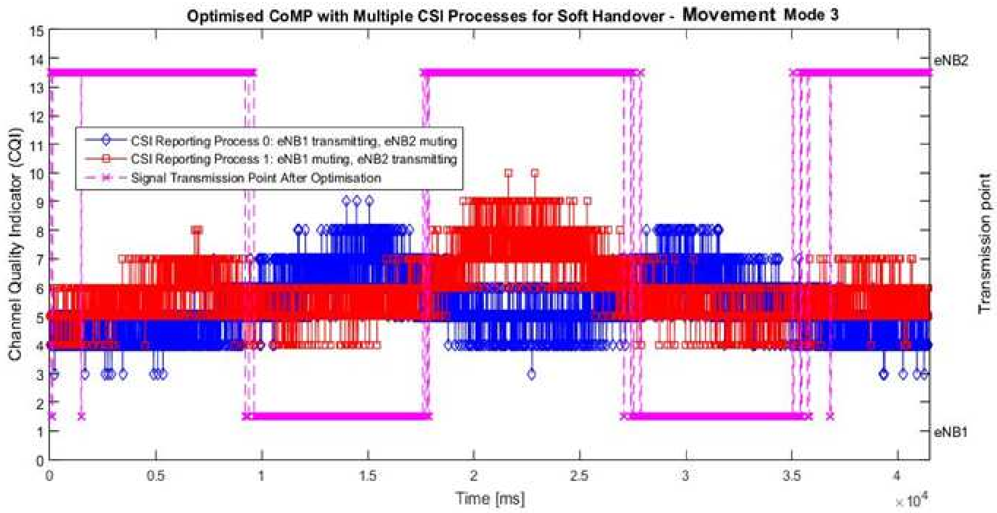


Figure 62. Optimised CoMP supporting D2D soft handover (Movement mode 3 with 2 consecutive periods)

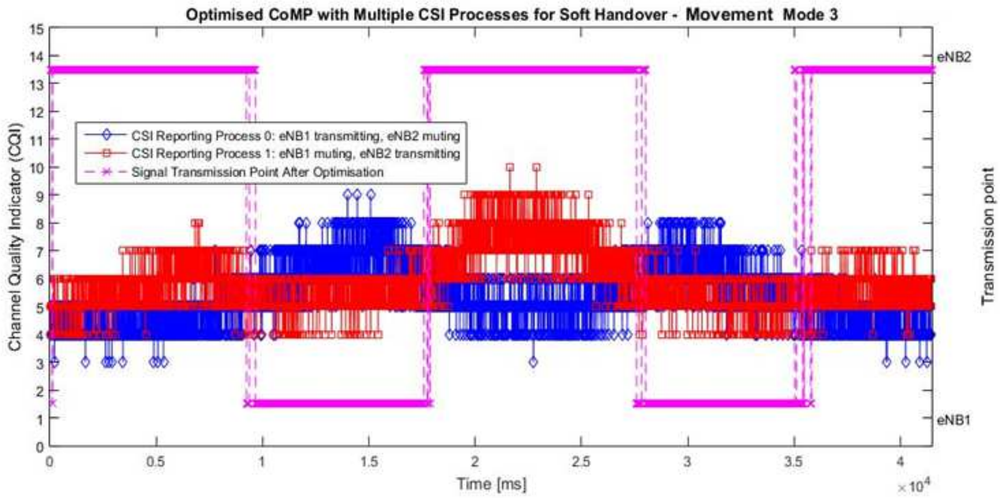


Figure 63. Optimised CoMP supporting D2D soft handover (Movement mode 3 with 3 consecutive periods)

Figure 62 and Figure 63 represent the result with movement mode 3. Similar to the results from movement mode 2, the more consecutive periods considered, the less number of handovers is triggered, resulting in lower signalling overhead. Within the 41472 ms of movement, there are 28 switches between two eNBs with 2 consecutive periods as handover threshold, and 20 switches with 3 consecutive periods, translating into a signalling overhead of only 2.4% and 1.7%, respectively, of the original COMP, in which there are 1180 switches within the same movement duration.

Chapter 8 – Conclusion and future works

In this thesis, the next generation of cellular technologies, LTE-A D2D and MMC, are jointly investigated to support wireless sensor networking.

Beginning with 3GPP channel models, the maximum D2D communication range under various environments is simulated and analysed with receiver diversity. The results show that channel environment impacts the communication range significantly and the configuration of SIMO improves the received signal quality remarkably. As a result, the use of multiple receive antennas extends the D2D communication range, the effectiveness of which depends on the channel scenarios.

For a large sensor network, clustering is suggested in order to utilise spectrum more efficiently. Also, a novel radio resource allocation algorithm is proposed for the clustered sensor network. Compared with random RA mechanism, the performance of the proposed RA is overwhelming.

Introducing D2D into LTE-A network will present new interference scenarios between DUEs and CUEs. For clustered sensor nodes, the intra-cluster interference is particularly severe if an inappropriate RA scheme is used. Unlike the existing literature, this thesis simulates interference experienced by the CH in both RRC_idle and RRC_connected states under different power control algorithms. Results reveal the intra-cluster interference can be eliminated by using the proposed RA method, while the disturbance from cellular users may be avoided by reserving D2D radio resource or restricting the D2D resource pool depending on spectrum strategy.

Finally, D2D mobility support is studied in both control plane and user plane. An optimised CoMP scheme is proposed to implement soft handover for moving DUE under RRC_connected state. Performance of the optimised scheme is compared with that of the original COMP, and the results show the optimised scheme has substantial potential in reducing the signalling overhead.

Future work may include the setup of a testbed with D2D enabled UEs, in order to measure the maximum D2D communication range in reality. For mobility support for D2D, there is a need for further investigation on how the optimised CoMP scheme affects handover delay and how different optimisation strategies apply to different operating scenarios, with the aim of achieving a balance trade-off between signalling overhead reduction and handover delay. Also, the clustering and CH selection algorithms proposed in current literature may need to be adapted to suit the specific characteristics and requirements of LTE-A D2D.

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Appendix

MATLAB scripts and saved results for this research are included in a DVD disk enclosed in this thesis.

The files included in the DVD disk are listed as follow:

Cluster_Dist_Cluster RA_Share.m	# Sensor nodes distribution example using proposed RA with CUEs
Cluster_Dist_Random_Share.m	# Sensor nodes distribution example using random RA with CUEs
CoMP for D2D.m	# CoMP for D2D mobility support
Consecutive Periods _ Optimised CoMP.m	# Proposed optimised mechanism for CoMP
Create_eNB.m	
Create_UE.m	
D2D_Cluster_SINR_Cluster RA_fixPower.m	# Proposed RA with fix power control
D2D_Cluster_SINR_Cluster RA_FixPower_Share.m	# Proposed RA with fix power control, share here means with CUEs
D2D_Cluster_SINR_Cluster RA_FPC.m	
D2D_Cluster_SINR_Cluster RA_FPC_Share.m	
D2D_Cluster_SINR_Cluster RA_tarSINR.m	
D2D_Cluster_SINR_Cluster RA_tarSINR_Share.m	
D2D_Cluster_SINR_Random.m	
D2D_Cluster_SINR_Random_FixPower.m	# Random selecion RA with fix power control
D2D_Cluster_SINR_Random_FixPower_Share.m	# Random selecion RA with fix power control, share here means with CUEs
D2D_Cluster_SINR_Random_FPC.m	
D2D_Cluster_SINR_Random_FPC_share.m	
D2D_Cluster_SINR_Random_tarSINR.m	
D2D_Cluster_SINR_Random_tarSINR_Share.m	
D2D_Traffic_Link.m	# D2D mobility support U_plane
D2D_Traffic_Link.mat	# D2D mobility support U_plane, saved result
dB2lin.m	
Doppler_Shift.m	
lin2dBm.m	
Max_Distance_I2I.m	# D2D link simulation for indoor-to-indoor environment with SIMO
Max_Distance_O2I.m	# D2D link simulation for outdoor-to-indoor environment with SIMO
Max_Distance_O2O.m	# D2D link simulation for outdoor-to-outdoor environment with SIMO
Max_dis_I2I_SIMO.mat	# saved result
Max_dis_I2I_SISO.mat	
Max_dis_O2I_SISM.mat	
Max_dis_O2O_SIMO.mat	
Max_dis_O2O_SISM.mat	
Move_Flat.m	# Movement track mode _ 3
Move_Flat.mat	
Move_Flat100m.mat	
Move_Flat_CoMP.m	# CoMP for Movement track mode _ 3
Move_Hori.m	# Movement track mode _ 1
Move_Hori.mat	
Move_Hori_CoMP.m	# CoMP for Movement track mode _ 1
Move_Vert.m	# Movement track mode _ vertical
Move_Vert_CoMP.m	# CoMP for Movement track mode _ vertical
Move_Vert_CoMP.mat	
Move_Zip.m	# Movement track mode _ 2
Move_Zip.mat	
Move_Zip_CoMP.m	# CoMP for Movement track mode _ 2
N_detect_random_1000.mat	
N_detect_random_2000.mat	
N_detect_random_4000.mat	
N_detect_random_500.mat	
Pathloss_Compare.m	# Maximum Coupling Loss method
Qz.m	
Resource Allocation _ Cluster.m	# Proposed RA
Resource Allocation _ Random.m	# Random selection RA
Resource_Allocation_100nodes.m	# Proposed RA with 100 nodes for example
Tx.m	