DESIGN OF M2M COMMUNICATIONS OVER CELLULAR NETWORKS WITH LOCALIZATION-ASSISTED POWER CONTROL AND COMMUNICATION MODE SELECTION MECHANISM

SREE KRISHNA DAS

MILITARY INSTITUTE OF SCIENCE AND TECHNOLOGY

2020

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SREE KRISHNA DAS

(BSc Engg., MU)

A THESIS SUBMITTED
FOR THE DEGREE OF MASTER OF SCIENCE IN
ELECTRICAL, ELECTRONIC AND COMMUNICATION ENGINEERING

DEPARTMENT OF
ELECTRICAL, ELECTRONIC AND COMMUNICATION ENGINEERING
MILITARY INSTITUTE OF SCIENCE AND TECHNOLOGY

2020

APPROVAL CERTIFICATE

The thesis titled **"DESIGN OF M2M COMMUNICATIONS OVER CELLULAR NETWORKS WITH LOCALIZATION-ASSISTED POWER CONTROL AND COMMUNICATION MODE SELECTION MECHANISM",** submitted by **Sree Krishna Das,** Student No- 101316130032, Session: Oct/ 2013 has been accepted as satisfactory in partial fulfillment of the requirements for the degree of Master of Science in Electrical, Electronic and Communication Engineering on 15 July 2020.

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Dedicated to my beloved parents and my wife

ABSTRACT

The location information of an unknown machine (UM) is crucial in machine-to-machine (M2M) communications for several perspectives, such as energy efficiency (EE) and spectrum efficiency (SE). Integration of location information of UMs in designing power control and communication mode selection is the key feature of this thesis. A time difference of arrival (TDOA) using weighted least square (WLS) algorithm based localization architecture for M2M communications over cellular networks is proposed.

A location-aware resource blocks (RBs) allocation policy and communication mode selection mechanism for M2M communication is proposed. The system performance improves if the mode selection mechanism can be applied before transferring data which results in enhancement of throughput and reduces traffic burden. Later, a location-aware communication mode selection based power control mechanism for reducing interference in M2M communications is extended. Resource allocation between the M2M user equipment (MUE) and cellular user equipment (CUE) that share the channels in both orthogonal and non-orthogonal ways are analyzed for different modes. A water filling algorithm and Lagrange decomposition scheme based power optimization process is adopted in the proposed mechanism. Therefore, the proposed mechanism allocates the proper optimal transmit power for each UE.

A MATLAB based simulation platform is developed for thoroughly investigating the performance of the localization architecture and proposed mechanisms. Performance of the proposed architecture and mechanism are evaluated in terms of root mean square error (RMSE), channel utilization, per-user throughput and per-user EE. Simulation results show that the randomly distributed AMs provide better localization accuracy compared with AMs placed in a fixed pattern. A comparison and feasibility study of the proposed mode selection scheme is also presented demonstrating better performance compared to the direct mode and indirect mode. Our investigation using the direct mode communication reduces the traffic burden on the cellular BSs compared to the other modes. Besides, the orthogonal resource sharing scheme based proposed mechanism achieves superior system performance compared to the non-orthogonal resource sharing scheme based proposed mechanism. This also suggests that localization assisted communication mode selection and power control mechanism might be a better choice for M2M communications, which is crucial for future cellular networks.

ACKNOWLEDGEMENTS

I express deep sincere gratitude from the bottom of my heart to the Almighty God for bestowing me with the blessings to perform this work.

Foremost, I would like to express my indebtedness and sincere respect to my supervisor Dr. Md. Farhad Hossain, Professor, Department of Electrical and Electronic Engineering (EEE), Bangladesh University of Engineering and Technology (BUET), Dhaka-1205, Bangladesh, for his continuous support in completing my research. It is his wise knowledge, motivation, patience and guidance, which made it possible to complete my thesis.

I would be pleased to extend my sincere thanks to all of my course teachers and staffs of EECE department, MIST for their cordial help and excellent support for successful completion of my research works.

Finally, my deepest gratitude goes to my parents and especially my wife, whose unconditional love and inspiration has kept me patient to endure the hard work and complete this thesis.

SREE KRISHNA DAS

Military Institute of Science and Technology

Dhaka, Bangladesh

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LIST OF SYMBOLS

Symbols	Description
B	The allocated bandwidth of the considerable RBs
c_1	The reciprocal of drain efficiency for the PA of direct mode user
c_2	The reciprocal of drain efficiency for the PA of indirect mode user
d	M2M pair distance
d_{th}	Mode selection threshold distance
d_i	Distance between the BS and UE
d_d	Distance between M2M pair
d_{tr}	Distance from other M2M transmitters to M2M receiver
d_{nr}	Distance from the CUE to M2M receiver
d_{mr}	Distance from the MUE to the CUE receiver
I_d^m	Interference from the MUE to the CUE receiver
I_m^d	Interference from other M2M transmitters to M2M receiver
I_n^i	Interference from the CUE to M2M receiver
I_T	Total interference is originated in the proposed mechanism
I_{th}	Threshold interference
K	Orthogonal frequency sub-band
K_d	Number of user pairs with direct modes
K_i	Number of user pairs with indirect modes
$L_m^{OS,d}$	Orthogonal resource sharing scheme based Lagrangian dual function for the direct mode user
$L_m^{NOS,d}$	Non-orthogonal resource sharing scheme based Lagrangian function for the direct mode user
$L_n^{OS,i}$	Orthogonal resource sharing scheme based Lagrangian dual function for the indirect mode user

Symbols	Description
$L_n^{NOS,i}$	Non-orthogonal resource sharing scheme based Lagrangian function for the indirect mode user
M	m^{th} MUE
M_d	Number of direct mode users
M_T	Total number of UEs in the proposed network
N	n^{th} CUE
N_i	Number of indirect mode users
N_o	Power spectral density of the AWGN
P_r	Received power of UE
P_t	Transmit power of UE
$P_{c,m}^d$	Total circuit power consumption of the m^{th} MUE
$P_{c,n}^i$	Total circuit power consumption of the n^{th} CUE
P_m^d	Transmit power of the m^{th} MUE
$P_{m'}^d$	Transmission power of the co-tier interference link from the other MUE transmitter to the MUE receiver
P_n^i	Transmit power of the n^{th} CUE
P_t^d	Total power consumption of the direct mode user
P_t^i	Total power consumption of the indirect mode user
$P_{\max}^{OS,d}$	Maximum transmission power of the orthogonal resource sharing scheme based direct mode UE
$P_{\max}^{OS,i}$	Maximum transmission power of the orthogonal resource sharing scheme based indirect mode UE
$P_{m,d}^{OS^*}$	Orthogonal resource sharing scheme based optimal power allocation of the m^{th} MUE
$P_{n,i}^{OS^*}$	Orthogonal resource sharing scheme based optimal power allocation of the n^{th} CUE
$P_{m,d}^{NOS^*}$	Non-orthogonal resource sharing scheme based optimal power allocation of the m^{th} MUE

Symbols	Description
$P_{n,i}^{NOS^*}$	Non-orthogonal resource sharing scheme based optimal power allocation of the n^{th} CUE
P_T	Total power consumption of the proposed mechanism
q_m^d	Orthogonal resource sharing scheme based EE for the direct mode UE
q_n^i	Orthogonal resource sharing scheme based EE for the indirect mode UE
$R_{d,m}$	Achievable data rate for m^{th} MUE
$R_{d,m}^{OS}$	Orthogonal resource sharing ways based achievable data rate for m^{th} MUE
$R_{d,m}^{NOS}$	Non-orthogonal resource sharing ways based achievable data rate for m^{th} MUE
$R_{d,m}^{OS,\min}$	Minimum required data rate of the orthogonal resource sharing scheme based direct mode user
$R_{i,n}^{OS,\min}$	Minimum required data rate of the orthogonal resource sharing scheme based indirect mode user
$R_{i,n}$	Achievable data rate for n^{th} CUE
$R_{i,n}^{OS}$	Orthogonal resource sharing ways based achievable data rate for n^{th} CUE
$R_{i,n}^{NOS}$	Non-orthogonal resource sharing ways based achievable data rate for n^{th} CUE
$R_{d,m}^{NOS,\min}$	Minimum required data rate of the non-orthogonal resource sharing ways based achievable data rate for m^{th} CUE
$R_{i,n}^{NOS,\min}$	Minimum required data rate of the non-orthogonal resource sharing ways based achievable data rate for n^{th} CUE
R_d^T	Total data rate of direct mode
R_p	Per-user throughput
R_i^T	Total data rate of indirect mode

Symbols	Description
R_T	Total Throughput
t	Time iteration index
U_{EE}	Per-user EE
(x_k, y_k)	Actual coordinates of the UM
X_σ	Log-normally distributed shadow fading
$(\hat{x}_k, \hat{y}_k)$	Estimated coordinate of the UM
$\eta_{m,k}$	TOA measurement noise
$\sigma^2_{m,k}$	Zero-mean and variance
γ_{th}	Mode selection threshold SINR
γ_d	Direct mode SINR
γ_i	Indirect mode SINR
$\gamma_{d,m}$	Received SINR at the m^{th} MUE
$\gamma^{OS}_{d,m}$	Orthogonal resource sharing scheme based received SINR at the m^{th} MUE
$\gamma^{NOS}_{d,m}$	Non-orthogonal resource sharing scheme based received SINR at the m^{th} MUE
$\gamma_{i,n}$	Received SINR at the n^{th} CUE
$\gamma^{OS}_{i,n}$	Orthogonal resource sharing ways based received SINR at the n^{th} CUE
$\gamma^{NOS}_{i,n}$	Non-orthogonal resource sharing ways based received SINR at the n^{th} CUE
α	The PL exponent
η_{EE}	Total EE
$\lambda^{OS,d}_m$	Orthogonal resource sharing scheme based Lagrange multiplier of the direct mode UE for transmission power constraint
$\lambda^{OS,i}_n$	Orthogonal resource sharing scheme based Lagrange multiplier of the indirect mode UE for transmission power constraint
$\lambda^{NOS,d}_m$	Non-orthogonal resource sharing scheme based Lagrange multiplier of the direct mode UE for interference constraint

Symbols	Description
$\lambda_n^{NOS,i}$	Non-orthogonal resource sharing scheme based Lagrange multiplier of the indirect mode UE for interference constraint
$\mu_m^{OS,d}$	Orthogonal resource sharing scheme based Lagrange multiplier of the direct mode UE for data rate constraint
$\mu_n^{OS,i}$	Orthogonal resource sharing scheme based Lagrange multiplier of the indirect mode UE for data rate constraint
$\mu_m^{NOS,d}$	Non-orthogonal resource sharing scheme based Lagrange multiplier of the direct mode UE for data rate constraint
$\mu_n^{NOS,i}$	Non-orthogonal resource sharing scheme based Lagrange multiplier of the indirect mode UE for data rate constraint
$v_m^{OS,d}$, $v_n^{OS,i}$, $v_{OS,d}^m$ and $v_{OS,i}^n$	Orthogonal resource sharing scheme based positive step sizes
$v_m^{NOS,d}$, $v_n^{NOS,i}$, $v_{NOS,d}^m$ and $v_{NOS,i}^n$	Non-orthogonal resource sharing scheme based positive step sizes

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LIST OF ABBREVIATIONS

Abbreviations	Description
3GPP	Third generation partnership project
1G	First generation
2G	Second generation
3G	Third generation
4G	Fourth generation
5G	Fifth generation
2D	Two dimensional
AMs	Anchor machines
AP	Access point
AOA	Angle of arrival
AWGN	Additive white Gaussian noise
BSs	Base stations
CM2M	Cognitive M2M communication
CAPEX	Capital expenditure
CDMA	Code division multiple access
CDF	Cumulative distribution function
CUE	Cellular user equipment
CR	Cognitive radio
CRAN	Cloud radio access network
CSI	Channel state information
dB	Decibel
dBm	Decibel-milliwatts
EE	Energy efficiency
eNB	Evolved node B
FDD	Frequency division duplexing

Abbreviations	Description
FDMA	Frequency division multiple access
GPS	Global positioning system
IEEE	Institute of Electrical and Electronics Engineers
IoTs	Internet of things
KKT	Karush-Kuhn-Tucker
KPI	Key performance indicators
LIPA	Local IP access
LTE	Long-term-evolution
LTE-A	Long-term-evolution advanced
M2M communication	Machine-to-machine communication
MEC	Mobile edge computing
MIMO	Multiple input multiple output
METIS	Mobile and wireless communication enablers for twenty-twenty (2020) information society
MUE	M2M user equipment
Mmwave	Millimeter wave
mmWave-NOMA	Millimeter wave non-orthogonal multiple access
MTC	Machine type communication
NLOS	Non-line of sight
NOMA	Non-orthogonal multiple access
NOS Scheme	Non-orthogonal resource sharing scheme
OFDMA	Orthogonal frequency division multiple access
OPEX	Operating expenditure
OS scheme	Orthogonal resource sharing scheme
PA	Power Amplifier
PL	Path loss
PRB	Physical resource block
QoS	Quality of service

Abbreviations	Description
RAN	Radio access network
RAT	Radio access technology
RBs	Resource blocks
RSSI	Received signal strength indicator
RSS	Received signal strength
RF	Radio frequency
RFID	Radio frequency identification
RMSE	Root mean square error
SDN	Software defined network
SE	Spectrum efficiency
SIC	Successive interference cancellation
SINR	Signal to interference plus noise ratio
TDOA	Time difference of arrival
TDD	Time division duplexing
TDMA	Time division multiple access
TOA	Time of arrival
UAV	Unmanned aerial vehicle
UE	User equipment
UDN	Ultra dense network
V2V	Vehicle-vehicle communication
WLS	Weighted least square

CHAPTER 1

INTRODUCTION OF M2M COMMUNICATIONS

1.1 Machine-to-Machine (M2M) Communications over Cellular Networks

In fourth-generation (4G) cellular communication, long-term-evolution advanced (LTE-A) is already implemented and used in various countries [1-2]. LTE-A improves network capacity by implementing a number of efficient methods, such as carrier aggregation [1-2], coordinated multipoint (CoMP) [3], multiple-input multiple-output (MIMO) [2-3], cooperative relays [3] and heterogeneous networking [1-3]. The network performance targets that LTE-A aims to achieve peak data rate of one gigabyte per second in the traditional cellular downlink and five hundred megabyte per second in the traditional cellular uplink, mobility up to three hundred fifty kilometer per hour and less than fifty mille-second latency [3]. However, these performance targets would not be able to provide the tremendous growth of fifth-generation (5G) mobile data network [3].

Compared with the 4G cellular networks, the 5G cellular networks are predicted to provide one thousand times the network capacity, twenty-five times the average system throughput, five times the traffic delay reduction and one hundred times the linked UEs with ten times longer battery life [1], [4], [9-10]. Hence, more efficient techniques are required to reduce the power consumption and efficient load balancing for 5G cellular network. The user equipment (UE) rise in demand for data applications, existing cellular networks have been experiencing an exponential enhancement in data volume. This ever enhancing user data traffic gives huge pressure on the existing cellular network infrastructure. However, the existing cellular network infrastructure cannot provide the expected per-user data rate. Therefore, the existing cellular 4G networks demand new architectures, methodologies, and technologies (see Fig. 1.1).

Machine-to-machine (M2M) communication is one of such paradigms that appears to be a promising component in 5G cellular technologies. Therefore, M2M communication satisfy the increasing demands of per-user data rate and reduce power consumption where devices

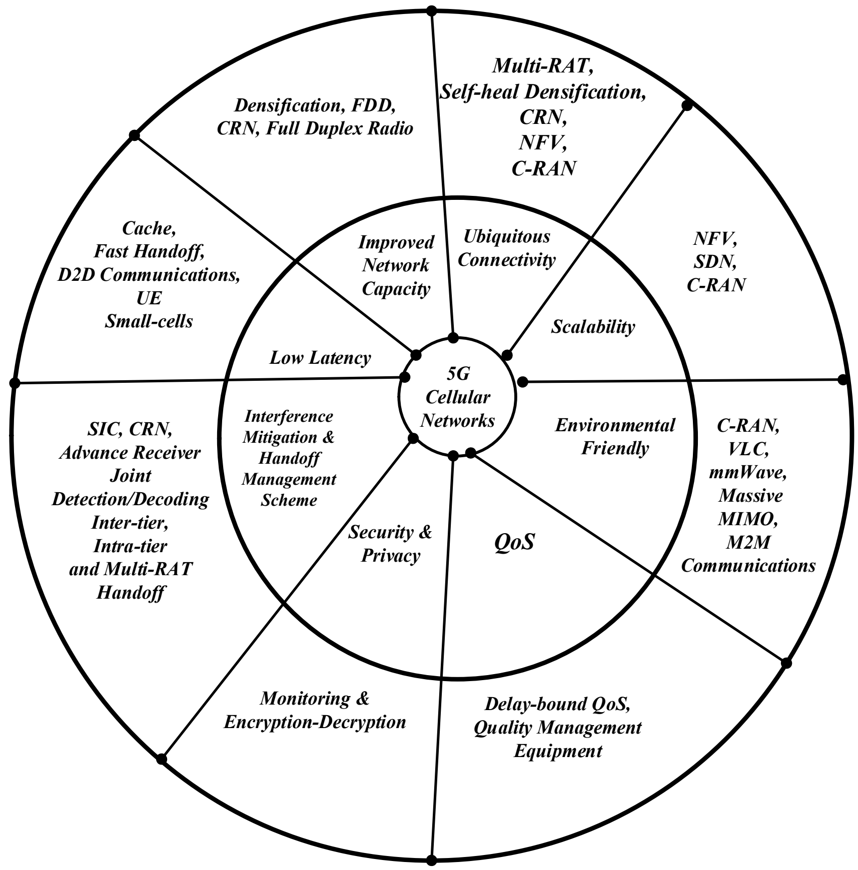


Fig. 1.1: Necessities and proposed solutions for the improvement of 5G cellular networks [11].

can directly exchange data without using any cellular network infrastructure [1-3]. With the billions of UEs, everything will be linked and form the Internet of Things (IoT), that facilitates a further useful and intelligent world [4]. Furthermore, efficient M2M communications are essential in numerous IoT applications. Therefore, M2M communications are currently being considered to enable the realization of the IoT deprived of the human intervention [4]. Moreover, it is significant for enhancing the coverage area, reducing the energy consumption, reducing the traffic delay and extending the battery lifetime of UEs [5-6], which has drawn much research attention in recent years. Furthermore, M2M communication is crucial for numerous circumstances, such as natural disasters, intelligent transportation systems, smart healthcare systems and public safety systems [4], [7-9]. To achieve the aforementioned benefits, M2M communication is deemed as a key technology to unlock the potential in the 5G cellular networks. Therefore, the third-generation partnership project (3GPP) planed M2M communication as a research topic for release 15, 16 and further [2], [10-12].

Given all these promising advantages, incorporation of location information of unknown machines (UMs) in designing power control and communication mode selection is the key feature of this research. The objective of this thesis is to propose localization architecture, communication mode selection and power control mechanisms aiming at tackling some of the challenges of M2M communication over cellular networks, as well as validating the potential of M2M technology.

1.2 Location-Aware M2M Communications

Localization is essential for numerous reasons, such as mitigation of interference, spectrum efficiency (SE) and energy efficiency (EE). Localization is one of the crucial technologies in cellular networks, then it provides many location-aware based M2M applications. In M2M communications, determining UMs location is a critical task. The problem of localization is the process of finding location information of UM. To localize a M2M communication over cellular network in the global coordinate system, some special node should be aware of their locations which are called anchor machines (AMs). Other UEs, which are usually called UMs, calculate their locations by using special localization algorithm. UM localization process can be classified as [13-14]

- range based and
- range free.

Range-based localization approach means that distances between UEs are estimated by using some physical properties of communication signals, i.e., received signal strength indicator (RSSI), time of arrival (ToA), time difference of arrival (TDOA) and angle of arrival (AOA) [13-14].

Range free localization approaches estimate the UM information without using the distance or angle information. Range based localization approach is better than the range free localization approach for higher localization accuracy [15-16]. The accuracy of TOA and TDOA based localization schemes is better than that of RSSI and AOA based localization approach [17-18]. However, the distance between two neighboring UEs is first estimated, for example, by using the TOA measurements. On the other hand, radio frequency received signal strength (RSS) measurements are commonly used to estimate range, but the accuracy of this scheme is poor even in the best of conditions. On the other hand, AOA scheme uses angle information from AMs and ignore the interconnectivity among the neighboring UEs. However, AOA-based localization approaches require special antenna which are computationally costly. The TOA based localization scheme requires knowledge of the transmission time of the received signal from the transmitter which is not necessary for TDOA-based localization technique [19]. TDOA based localization approach is provided the accurate estimation of UM location.

On the other hand, LTE Release 12, M2M communication is deemed a candidate technology for neighbor discovery. In 5G, neighbor discovery technique can provide low transmit powers and extremely low latency [20-21]. Moreover, AM position information assisted to develop efficient TDOA based localization architecture for achieving higher localization accuracy. Integration of location information of UMs in designing power control and communication mode selection is the crucial feature of this thesis.

1.3 Research Motivations

In recent years, M2M communications have been widely studied as a promising technique to enhance both spectral efficiency (SE) and energy efficiency (EE) in cellular networks [1-4]. To achieve those benefits, localization of UM in M2M communications is crucial for several perspectives, such as power control to mitigate interference, improve EE and reduce traffic burden on the BSs by using M2M direct communications [3].

Localization techniques can be classified into two types, such as range based and range free [13-15]. Range based provides better performance compared to range free in terms of localization accuracy [16-19]. The main challenge of range based localization approach is the need for precise synchronization among AMs and UMs. However, range based TDOA method is not needed synchronization between AMs and UMs. Therefore, range based TDOA method is widely applied for finding the unknown source locations [17-18].

Several mode selection schemes taking into account the quality of both M2M and cellular links were proposed for M2M communications [21-23]. Proper M2M mode selection can improve the system performance. In [23-25], a practical energy-efficient mode switching scheme based on a M2M direct link gain threshold has been recommended to rise system performance like throughput and EE. However, this method can require a substantial amount of feedback, which increases the signaling overhead. The current cellular BS is responsible for the radio RB allocation process. This type of radio RB allocation enhances the overload at the cellular BS side, resulting in the increment of the traffic burden. Therefore, a location-aware communication mode selection and location-aware mode selection based RB allocation strategy is applied for improving the system performance and reducing the traffic burden in M2M communication.

On the other hand, Zhang *et al.* [7] proposed the power control scheme that adjusts the transmit power of UE to mitigate the cross-tier interference. Moreover, authors in [25-26], has proposed two power control schemes, such as centralized and distributed power control scheme which can manage the interference, but increases the signaling overhead in the cellular network. Furthermore, a power control based interference mitigation scheme was proposed in [26-28] and [28-31], which reduced the network performance of the M2M communication for UE situated far away from the BS while requiring higher transmission power. However, the main drawbacks of the existing power control schemes are the excessive or insufficient transmission power of UE. To overcome the aforementioned problem, the design of localization assisted power control mechanism for mitigating the co-tier and cross-tier interference is of superior significance.

1.4 Research Objectives

The main objectives of this thesis can be summarized as below

a. To propose a TDOA based localization architecture for M2M communications over cellular networks

b. To develop TDOA based localization assisted power control techniques for mitigating interference and improving EE

c. To implement localization assisted communication mode selection techniques to reduce traffic burden on the cellular BSs

d. To analyze simulation platforms and evaluate the performance of the proposed localization architectures and the communication mode selection mechanisms under a wide range of network settings

e. To investigate the impact of various network parameters, such as per-user throughput, per-user EE, mode selection threshold SINR, mode selection threshold distance, density of machines and transmit power on the proposed mechanism performance

f. To compare the proposed mechanism with the existing counterparts in terms of various parameters for determining their feasibility to be used in practice.

1.5 Thesis Contributions

The main contribution of this research is to integrate of location information of UMs in designing power control and communication mode selection mechanism for M2M communications with the aims to improve the network throughput, EE and reduce the traffic burden. First, a localization architecture for estimating the UM locations using TDOA based technique is proposed. It is inferred that localization of UMs before data transfer might improve the performance of these techniques. The key contributions of this thesis are summarized as follows

i) Proposed a TDOA scheme using WLS algorithm based localization architecture for M2M communications over cellular networks. Performance of the proposed localization architecture is investigated in terms of root mean square error (RMSE). Simulation results show that the randomly distributed AMs can provide better performance compared with AMs placed in a fixed pattern in terms of localization accuracy.

ii) Develops a location-aware resource block (RB) allocation policy and communication mode selection mechanism for M2M communications over cellular networks. Then, the communication mode selection technique includes the generalized expressions of SINR, throughput and channel utilization etc. Therefore, the proposed mechanism is evaluated in terms of SINR, per-user throughput and channel utilization.

iii) Extended the proposed mechanism implements a novel location-aware communication mode selection based power control mechanism for mitigating interference in M2M communications over cellular networks. Resource allocation between the MUEs and CUEs that share the channels in both orthogonal and non-orthogonal ways are analyzed for different modes. A water filling algorithm and

Lagrange decomposition scheme based power optimization process is adopted in the proposed mechanism. We derive the per-user EE, which is a performance metric for the assessment of the proposed scheme. The performance of the proposed mechanism is evaluated under various changing parameters, such as the number of UEs, mode selection threshold distance and transmission power etc. Simulation results show that the proposed mechanism mitigates the interference and thus provides the higher throughput as well as higher EE in the proposed network.

1.6 Organization of the Thesis

Chapter 2 provides essential background on the basics of M2M communications including its applications, a comparative study on the existing cellular network architecture and a summary of design challenges. A comprehensive literature survey on the existing M2M communication classifying them into different approaches is also presented.

Chapter 3 describes the localization architecture for M2M communications over cellular networks.

In chapter 4, proposed a location-aware communication mode selection mechanism and the proposed mechanism based RBs allocation strategy for M2M communications over cellular networks.

Chapter 5 focuses on location-aware communication mode selection based power control mechanism for mitigating the interference in M2M communication over cellular networks.

Chapter 6 concludes the thesis and extensions of the future plan of proposed localization architecture assisted power control and communication mode selection mechanism.

CHAPTER 2

M2M COMMUNICATIONS: BACKGROUNDS AND RESEARCH TRENDS

2.1 Introduction

This chapter describes the basic concepts of M2M communications including 5G cellular network architectures and typical applications. Challenges in designing localization-assisted mode selection and power control mechanism for M2M communications are then discussed. Then a brief overview of the existing mode selection and power control mechanism for M2M communications is given. The chapter is finally concluded by presenting a brief discussion on the state-of-the-art research on the localization assisted M2M communications.

2.2 Evolution of Wireless Communications

During the years, the capacity of UE data traffic has raised at a fast speed and measureable studies expect that the rapid growth will remain in forthcoming as illustrated in Figure 2.1. Concretely, every novel generation of wireless networks is familiarized every ten years, from the first generation (1G) in 1980, second generation (2G) in 1991, third generation (3G) in 1998, fourth generation (4G) in 2008 and the expected fifth generation (5G) will be established in 2020. The development of cellular network is shown in Fig. 2.2 and LTE and LTE-Advanced (LTE-A) systems is operated in several countries. Currently, we are on the edge of change into a situation of completely linked society where high capacity is needed, but incremental fluctuations in the present systems and technologies are not enough to make this transition [30] major variations are desirable to handle upcoming non-homogeneous

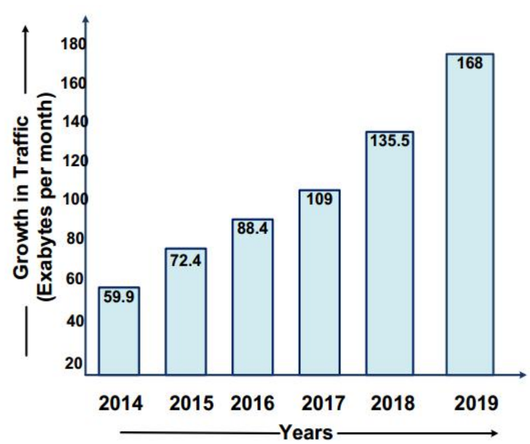


Fig. 2.1: Mobile data traffic growth prediction [30].

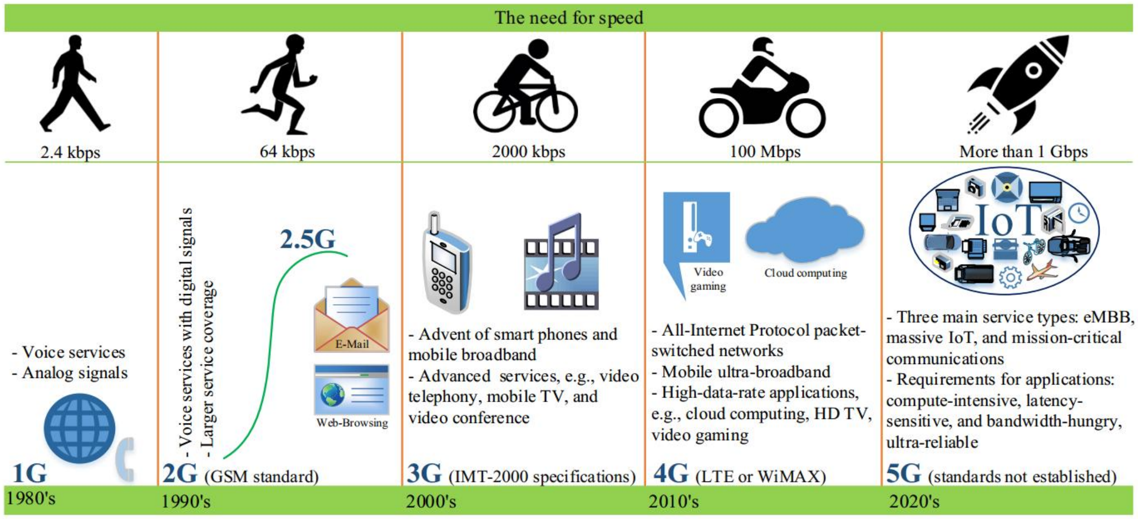


Fig. 2.2: Evolution of Wireless Communications [37].

cellular networks as well as novel tendency in user manners and applications, such as exalted quality video streaming and amplified authenticity. Therefore, debates of a novel standard have taken place in academia and industry so as to conceive the necessities and possible requirements and possible use cases for upcoming networks, denoted to as the 5G. The precise meaning of 5G is not yet lucid, however it wants to take into account a wider range of various characteristics. Consequently, adamant key performance indicators (KPIs) and close-fitting necessities have been proposed so as to manage upper UE data volumes, reduce traffic delay and rise the number of connected UEs, although at the tantamount time rising EE and SE [29-37].

2.3 Basics of M2M Communications

M2M communication is envisioned to be a key technology for 5G wireless network to offload network traffic and enable new proximity based services [1]. M2M communication commonly refers to the communication between two or more devices directly, i.e. single hop communication without any need of infrastructure or BS, while for the existing cellular network user-to-user communication is two hop communication via the BS.

There are numerous ideas, design standards, and scenarios that have been proposed for 5G; some of them, if implemented, will bring fundamental challenges at the new network design.

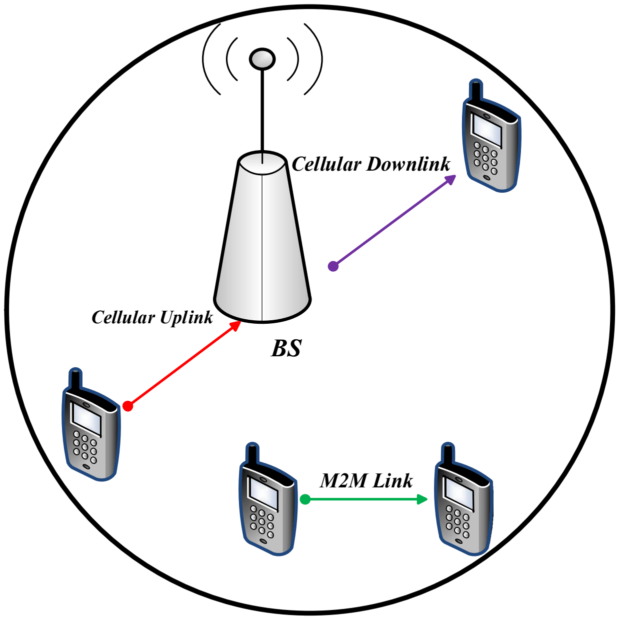


Fig. 2.3: M2M communications in a cellular system.

One example of such proposed technologies is M2M communications will change the nature of conventional network design. Integration of M2M communication in cellular networks is demonstrated in Fig. 2.3. Depending on network condition, M2M pair works in two modes, such as direct and indirect mode.

2.3.1 Direct mode based M2M communications

The UEs communicate directly with other UEs in a pair if they are close to each other. This way of data transmission process is denoted as the direct mode [9-10]. The use of direct mode based M2M communications provides lower transmit power and reduces traffic delay compared to traditional cellular communication [2], [20]. Due to the above facilitates, direct mode provides more benefit for short range communications [15]. However, the direct mode based M2M communication needs half of the physical resource block (PRB) compared to the indirect mode communication. Therefore, direct mode communication usually provides the double spectral efficiency per M2M link.

2.3.2 Indirect mode based M2M communications

For long-distance M2M communications, channel condition turns weak and data transmission occurs using the cellular BSs [10]. This type of data transmission process is called the indirect mode [10]. Moreover, the indirect mode is normally treated as traditional cellular communication. Indirect mode offers better system performance for longer distance among M2M pairs. On the other hand, direct mode and indirect mode communication work upon unlicensed and licensed radio spectrum, respectively. Unlicensed spectrum utilization in cellular network is a key technique to satisfy the massive user traffic demand [3]. The utilization of unlicensed spectrum not only mitigates the interference but also improves the user data rate [3].

To provide the best performance to the end users in terms of QoS, the M2M communication will be able to provide a number of services to end users as well as proximity awareness. The M2M communication can achieve four types of gains [38-43], such as proximity gain, hop gain, reuse gain and pairing gain. M2M communication can probably develop the network performance.

2.4 Wireless Channel Models

Wireless communication operates through the air interface. In wireless communication, radio propagation refers to the behavior of electromagnetic waves when they are propagated from transmitter to receiver. Radio propagation environment in wireless communication is very dynamic and unpredictable compared to that in wired communication because of the characteristic of wireless channel. The signal transmitted over wireless channels are affected by three basic propagation mechanisms: reflection, diffraction and scattering. Furthermore, there is a special phenomenon in a wireless channel which is called fading. Fading refers to the variation of the signal amplitude over time and frequency, which can be classified into large scale fading and small scale fading. In the next section, a brief description of the wireless channel models for M2M communications are described.

2.4.1 Link model for M2M communications

The link model denotes the propagation loss that happens when the signal moves from one UE to another UE. Let d be the M2M pair distance in meters. Received power $P_r\,(dBm)$ of a UE located at a distance d from its serving cellular BS can be written as [33-34]

$$P_r(dBm) = P_t - PL(dB) + X_\sigma \tag{2.1}$$

where P_t is the transmit power of UE in dBm and $PL\ (dB)$ is the total path-loss (PL) in dB. Whereas X_σ denotes the log-normally distributed shadow fading of random variable with a mean zero and standard deviation equivalent to σ dB. The PL model for direct mode based M2M communication can be expressed as [36]

$$PL(dB) = 148 + 40\log_{10}(d_d) \tag{2.2}$$

where d_d is the distance between M2M pair in meters. The M2M pair PL model for indirect mode based M2M communication is stated as [36]

$$PL(dB) = 128.1 + 37.6\log_{10}(d_i) \tag{2.3}$$

where d_i is the distance among the BS and UE in meters.

2.5 Key 5G Candidates for M2M Technologies

5G is a crucial enabler for IoT by providing a platform to connect a massive number of UEs. Deployment of these networks will be emerged between 2020 and 2030.

Table 2.1: Key 5G wireless communication systems requirements compared to 4G (5G Infrastructure Association, 2015) [37]

Figure of benefit	5G prerequisite	Analogy with 4G
Peak data rate	Ten Gbps	Approximately one hundred times higher
Mobile data volume	Ten Tbps/km^2	Approximately one thousand times higher
End-to-end latency	Less than one milli-second	Twenty five times lower
Number of UEs	one M/km^2	
Number of human-oriented terminals	More than 50 billion	
Number of IoT terminals	More than one trillion	
Energy consumption		90% less
Reliability	99.999%	99.99%
Peak mobility support	≥500 km/h	

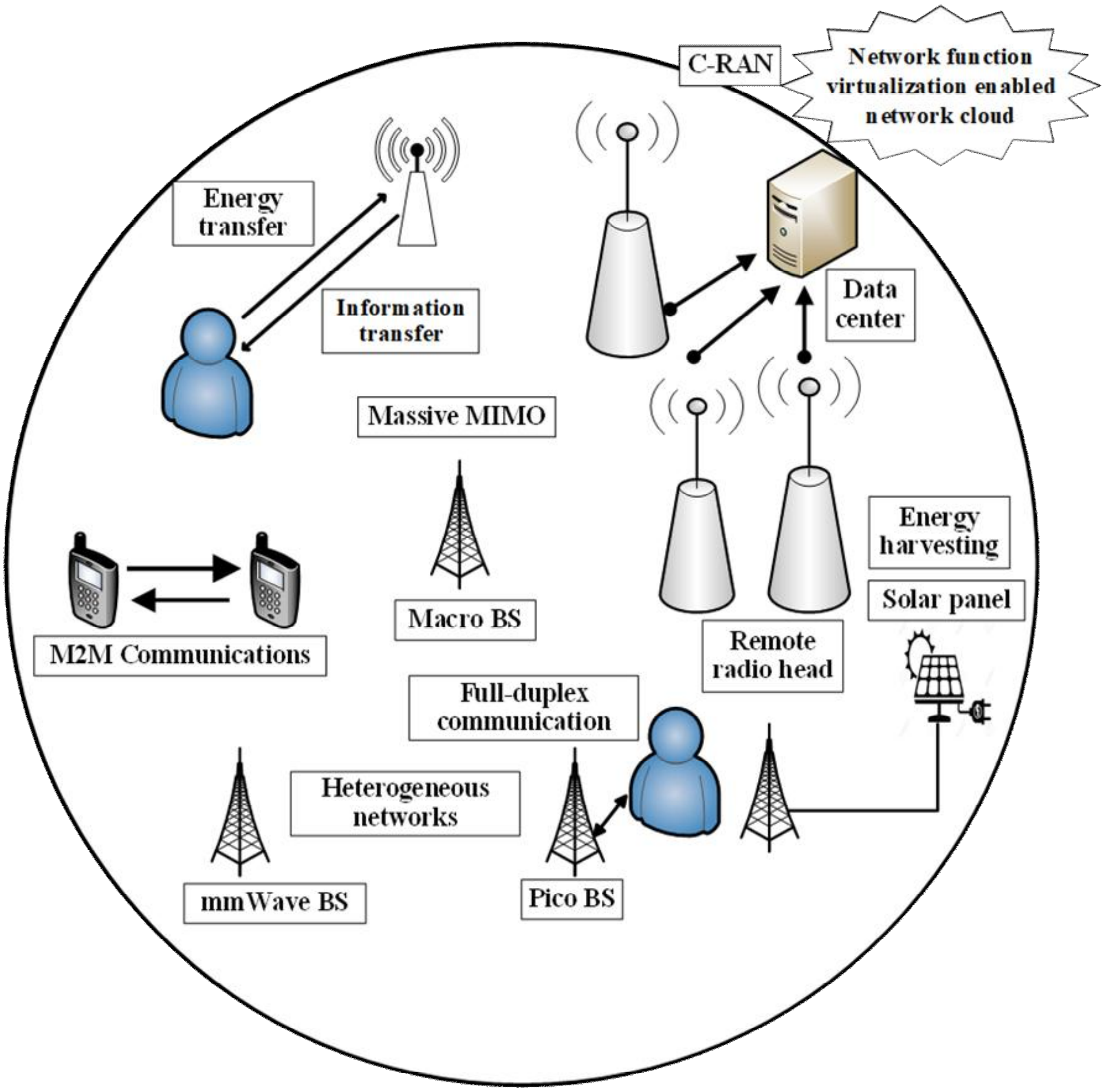


Fig. 2.4: General 5G cellular network architecture [11], [31-32].

Some key technologies are: ultra-dense networks (UDN), massive MIMO, millimeter wave (mmWave), cloud radio access networks (C-RAN) [44], non-orthogonal multiple access (NOMA), mobile edge computing (MEC) [47], wireless caching, hand over, cognitive radio (CR), cognitive M2M communication (CM2M), network coding, wireless caching and full duplex communication, etc. Figure 2.4 demonstrates the enabling technologies and probable aims for 5G. Table 2.1 provides the estimated facilitates of 5G mobile network. We briefly describe the M2M technology and how it contributes to the requirements of 5G.

2.6 Configurations of M2M Communications

There are different configurations of the M2M networks discussed below

- ***Network-controlled M2M communication:*** The BS and the core network controls the signalling setup and thereafter RB allocation for both CUEs and M2M pairs. The centralized control can result in efficient interference management and RB allocation.

- ***Self-organized M2M communication:*** This configuration is distributed in nature. M2M users sense the spectrum holes, collect channel state information (CSI) and possible interferences much like CR and communicate in a self-organizing way to other M2M pairs. Thus, it reduces signalling overhead but may create instability due to lack of centralized control.

- ***Network-assisted M2M communication:*** In this scenario, the BS only allocates resources to the M2M users and thereafter users communicate between themselves in a self-organizing way. This method has low signalling overhead and also partial centralized control to avoid communication chaos, but security can be a potential issue.

- ***Localization-assisted M2M communication:*** In this scenario, the integration of location information of UM is needed for mode selection and power control in M2M communications. This scheme is efficient localization assisted power control and mode selection techniques leading to enhance network performance.

2.7 Challenges in Designing M2M Communications over Cellular Networks

This section gives an overview of the main challenges in the integration of UMs location assisted M2M communications over cellular networks.

2.7.1 Localization techniques

Localization is a fundamental problem in M2M communications, as UM location information is essential for several perspectives, such as tracking, quality of service (QoS) and EE. In addition, localization is significantly essential for reliable estimation of M2M location-based applications in 5G cellular networks for their several benefits, such as, e-health care, smart metering, remote monitoring and controlling applications etc. [4]. M2M localization architecture depend on various parameters such as, range difference, transmitted or received power, sending or receiving time and the number of AMs etc. Localization method can be classified into two groups: range-based approach and range-free approach. Range free localization approaches estimate UM coordinates using connectivity information between AMs without ranging (i.e., distance or angle) information [14]. Then, UMs compute their locations based on the received beacon locations, the hop count from the corresponding beacon and the average distance per hop [5]. Range free localization approach is economical due to lower power consumption than range based localization approach [15].

There are many localization techniques using radio signals. Also a localization algorithm is proposed for finding the machine location in cellular networks. The TOA, AOA, TDOA and RSSI methods are known as range based localization methods [16-17]. TOA is the time for a signal to go from the transmitter to the receiver. It is observed that in the absence of timing errors, TOA method can be applied to determine the machine location [18]. In addition, the distance between two neighboring machines are first estimated, for examples, by using TOA measurements. RSSI estimates the distance among two machines based on the energy level of AMs and UM. RSSI method suffers from localization problem because of multipath fading of signal for M2M communications and decreasing the accuracy of localization [12]. In this thesis [12], TDOA method is applied to address the problem. TDOA measurement is more suitable for localization and exhibits improved performance than other range based localization methods. The key idea of TDOA based localization architecture is to determine the location of UM by evaluating the difference in arrival time of the signal at spatially separated from AMs [18].

The estimation performance of those schemes are subject to vary due to the non-line of sight (NLOS) environment. The improved TDOA method for reducing the errors in the NLOS environment is proposed in this thesis. TDOA based localization architecture for estimating the UM in M2M communication is of high significance.

2.7.2 Neighbor discovery and synchronization

Neighbor discovery and synchronization are binary significant initial steps in establishing reliable M2M links [2]. Neighbor UE discovery means of asynchronous scan or search mechanisms using the beacon series. In this technique, M2M communications is originated independently, and MUEs can manage with RBs allocation and power allocation. However, this discovery is main problem of lack of synchronization. To overcome the problem of lack of synchronization, an UM information estimation is crucial for neighbor discovery.

When M2M communications are incorporated with the aid of the cellular network, the synchronization of the M2M discovery can improve the network performance. However, in this case, new location-aware discovery signals needs to be designed and introduced in to the existing cellular procedures. M2M synchronization can also be integrated in 5G which the location of UMs information can provide the user performance.

A planned UE discovery is considered as a promising technology for 5G [48]. The real-time UE discovery to minimize communication delay and improve discovery performance.

2.7.3 Communication mode selection mechanism

The number of UEs are expected to enhance radically in future 5G mobile cellular network, with a guess of more than 50 billion connected UEs by 2021 [31]. Consequently, the amount of traffic on the network has been explosively growing and decreasing the "end-user of QoS" [42]. The performance of M2M communication is practically limited due to the large distance between M2M pairs in the network [45]. To overcome these issues, it is crucial to explore the communication mode selection mechanism in existing cellular network infrastructure.

Different mode choosing techniques taking into account the quality of both direct and indirect links have proposed to lessen interference and reduce traffic burden caused by M2M communications [48-49]. Instead, the author's in [50] proposed mode choosing frameworks which have taken the random UE locations into account and analyzed the consequent cellular network performance using stochastic geometry. Moreover, the authors studied a cellular network where the cellular BSs can manage the interference among direct and indirect mode based M2M communications based on the CSI [50-53]. However, this method can require a substantial amount of feedback, which increases the signaling overhead. In [52-53] authors focus on a distance-dependent communication mode choosing scheme in M2M communication. In spite of its significance, unfortunately, the investigation of the possible M2M pair distance is still absent.

It is inferred that the selection of mode before data transfer can improve the system performance like throughput, spectrum utilization and energy efficiency (EE).

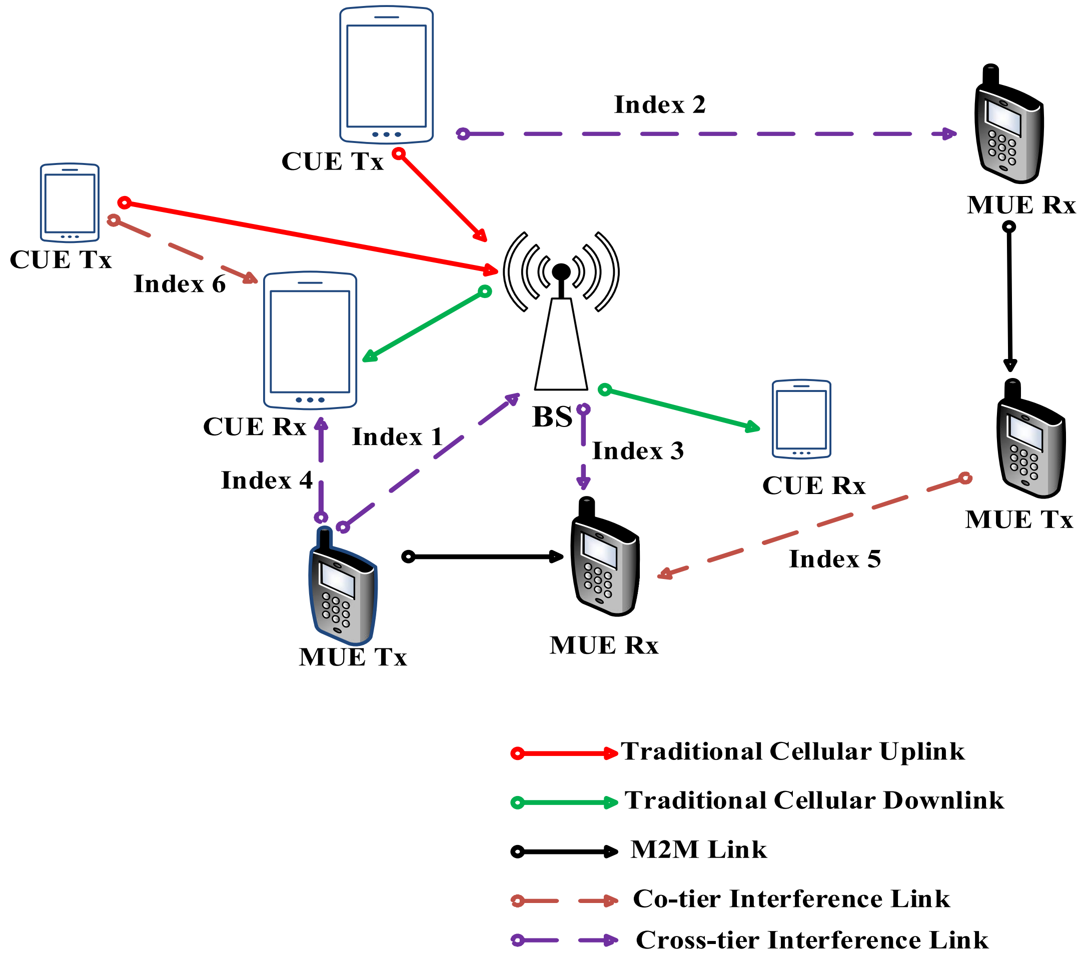
Communication mode selection mechanism of deciding that the M2M pair will work in one of the two modes, such as direct or indirect mode based on the network condition. The mobile UEs can communicate using the direct mode is called the MUE. When the UEs communicate using the cellular BS is called as the CUE. Direct mode communication cannot only develop the per-user data rate but also minimize the power consumption of UE [2]. As a result, direct mode UE reduces the interference. Besides, direct mode communication can offload the traffic from the cellular network, which can substantially reduce the traffic burden on the cellular BSs compared to other modes. However, the direct mode based M2M communication needs half of the physical resource block (PRB) compared to the indirect mode communication [2]. Therefore, direct mode communication provides the double spectral efficiency per M2M link usually. If the UEs are remote from each other, indirect mode communication provides better system performance compared to the direct mode communication. Furthermore, direct mode and indirect mode communication work upon unlicensed and licensed frequency spectrum, respectively. The unlicensed frequency bands in primary markets are various hundred megahertz (MHz) [11]. Thus, unlicensed frequency spectrum utilization in cellular networks is a key technique to satisfy the massive user traffic demand. The utilization of unlicensed frequency spectrum not only alleviates the interference but also develops the user data rate in the wireless network. To further improve the system performance, a location-aware communication mode selection mechanism can be applied in M2M communications.

2.7.4 Interference management

Interference management is a major issue in 5G where M2M communications can reuse the same RBs. In the situation, the channel utilization among users in the same cells and various cells adds co-tier interference and cross-tier interference, respectively [53-58]. In fact, the interference link can strongly affect the system performance. However, interference can be mitigated through mode selection, RB allocation policy, power control mechanism [58-64]. Power control mechanism is considered as a promising technique to mitigate the interference.

Types of interference in two-tiered network architecture:

Interference can be classified into M2M communications over cellular network architecture, such as co-tier and cross-tier interference. All the possible interference scenarios are represented in Fig. 2.5.



Index	Aggressor	Victim	Interference Type
1	MUE Transmitter (Tx)	BS	Cross-tier
2	CUE Tx	MUE Receiver (Rx)	Cross-tier
3	BS	MUE Rx	Cross-tier
4	MUE Tx	CUE Rx	Cross-tier
5	MUE Tx	MUE Rx	Co-tier
6	CUE Tx	CUE Rx	Co-tier

Fig. 2.5: All possible interference scenario for M2M communication over cellular network [53].

2.7.4.1 Co-tier interference

This type of interference is produced between UEs which belong to the same tier in the proposed network. Co-tier interference occurs between M2M users and another M2M user in the same tier [53-57]. In orthogonal frequency division multiple access (OFDMA) systems, the co-tier interference is caused when the same RBs are allocated to multiple MUEs.

Furthermore, the co-tier interference can be mitigated through proper RBSs allocation policy and power control mechanism [53-56].

2.7.4.2 Cross-tier interference

This type of interference is produced between UEs which belong to different tiers. In this type of interference, the source of interference and the victim of interference are different depending on the spectrum reuse (uplink/downlink).

2.7.5 Resource blocks (RBs) allocation strategy

Radio RBs allocation strategy among direct and indirect mode is also essential to be taken into account. Proper RB allocation strategy is another way to lessen the interference for cellular networks. Meanwhile, how to choose the proper communication mode and utilize the radio resource capably are still open questions. However, the current cellular BS is responsible for the radio RB allocation process. This type of radio RB allocation process enhances the overload at the cellular BS side, resulting the increment of the traffic burden [65-66].

Therefore, RB allocation strategy becomes a key plan for implementing the mode selection mechanism based M2M communications. A location-aware communication mode selection mechanism based RB allocation strategy can be applied in M2M communications.

Resource allocation for M2M communication can be mainly classified into two categories.

- ***Direct mode based M2M communication:*** In this scenario, M2M pairs share same channels as the CUEs, thus causing potential interference to CUEs. However, interference avoidance technique can improve the spectral efficiency in the cellular networks.

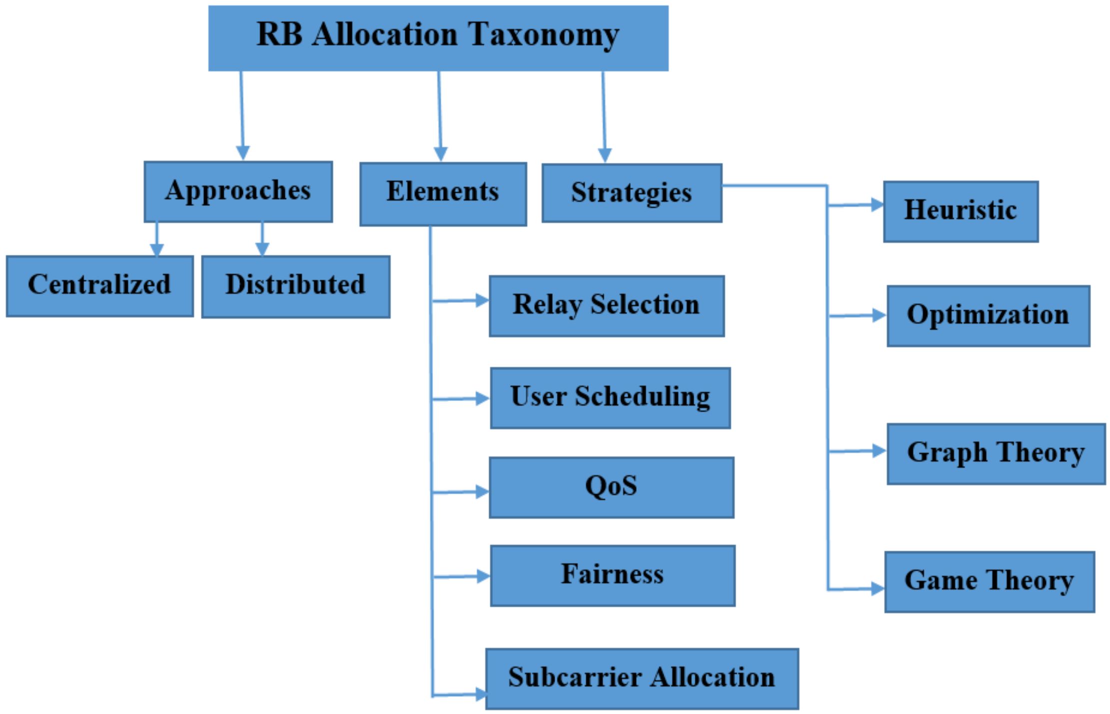


Fig. 2.6: Classification for the RBs allocation policy.

- ***Indirect mode based M2M Communication:*** In this scenario, allocated channels to the CUEs and M2M pairs are orthogonal, thus eliminates any possibility of interference. However, in terms of spectral efficiency no gain is achieved.

On the other hand, a taxonomy for the RBs allocation strategy in M2M communication over cellular network is provided [67-76]. Fig. 2.6 provides the adopted taxonomy in detail. However, with increased occupancy of ISM bands, efficient RBs allocation scheme becomes crucial for avoiding congestion, collision issues, and intersystem interference.

2.7.6 Power control mechanism

SE and EE are crucial for designing future 5G mobile cellular networks. Besides, EE is crucial for UEs due to their confined battery capacity [77-80]. By minimizing the power consumption of UE we can develop their EE. Thus, to fulfil user data rate demand, EE strikes a balance among the user data rate and the power consumption of UE [78]. However, M2M communications can increase the SE and EE of mobile cellular networks using the advantage of the proximity, reuse and hop gains [81-84]. M2M communication over cellular network imposes several technical challenges in terms of interference mitigation. As a result, interference mitigation will be a key challenge in the future 5G mobile cellular network. On the other hand, one primary topic of M2M communication is how to efficiently share the radio spectrum among MUEs and CUEs, as they share the same radio spectrum which generates the interference. MUEs can share the radio spectrum with the CUEs and vice versa in orthogonal or non-orthogonal ways. Thus, the non-orthogonal resource sharing scheme provides better system performance compared to the orthogonal resource sharing scheme [65-71]. However, the non-orthogonal resource sharing scheme makes strong interference. Interference in cellular networks can be classified into two types, such as cross-tier and co-tier interference [75]. Co-tier interference is generated between M2M pairs that are situated in the same tier. Otherwise, cross-tier interference is generated between M2M pairs that are situated in various tiers in the cellular network. Besides, the M2M pairs in nearby proximity suffer from strong co-tier interference because multiple MUEs can share the same frequency simultaneously. Otherwise, CUEs and MUEs share the same radio spectrum which suffers heavy cross-tier interference. Furthermore, the aforementioned interference severely decreases the system performance on the M2M link. Thus, mitigating the cross and co-tier interference is crucial for the QoS user [82-83]. In [85-87], energy efficient RBs allocation and power control scheme to maximize the network performance for M2M communication is proposed. However, the above authors have focused on how to optimize the network capacity and neglect the power consumption of UE. On the other hand, Gu *et al.* [81], proposed the power control scheme that adjusts the transmit power of UE to mitigate the cross-tier interference. Moreover, authors in [79-81], proposed two power control schemes, such as centralized and distributed power control scheme which can manage the interference, but increases the signalling overhead in the cellular network. Furthermore, a power control based interference mitigation scheme was proposed in [79] and [82], which reduced the network performance of the M2M communication for UE far away from the BS while requiring higher transmission power. However, the main drawbacks of the existing power control schemes are the excessive or insufficient transmission power of UE. Therefore, the communication mode selection and power control mechanism can reduce the cross-tier and co-tier interference. To further improve the system performance, a location-aware power control mechanism for M2M communications over cellular network is of extreme significance.

2.8 Conclusion

In this chapter we provide a comprehensive review of cellular evolution towards 5G networks. An introduction to the architecture, applications and design challenges of M2M communications has been presented in this chapter. This chapter also have briefly discussed the type of existing key 5G enabling technologies for cellular networks with a particular focus on the M2M communications. At the end of the chapter, a thorough discussion on the current research on the designing of M2M communications over cellular network with localization-assisted communication mode selection and power control mechanism has been presented.

CHAPTER 3

TDOA BASED LOCALIZATION ARCHITECTURE

3.1 Introduction

This chapter presents a TDOA based localization architecture for M2M communications over cellular networks. A weighted least square (WLS) based algorithm is adopted in the proposed localization architecture. The algorithm estimates the location of UM using the TDOA from the location information of AMs. The proposed localization architecture is evaluated in terms of RMSE.

3.2 Principles of Time Domain Localization Approaches

Time domain positioning approaches require accurately measuring the signal propagation time from a transmitter to a target receiver. Then main stream approaches are presented in this section.

3.2.1 Time of arrival (TOA) based localization approach

Time domain positioning approaches require accurately measuring the signal propagation time from a transmitter to a target receiver. Then main stream approaches are presented in this section.

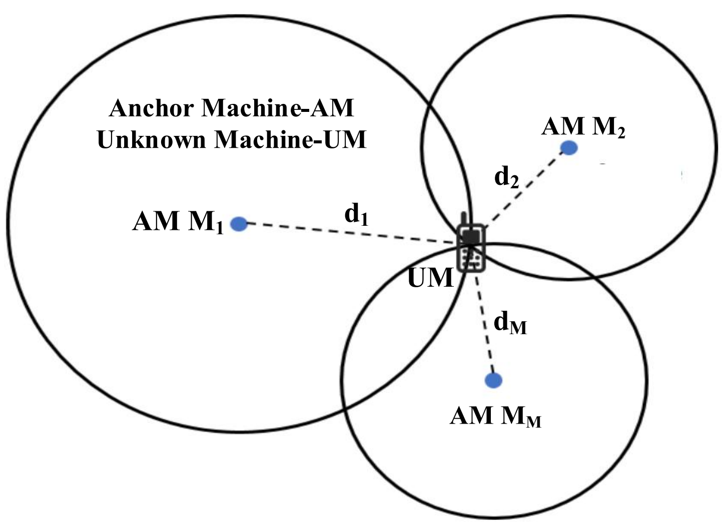


Fig. 3.1: TOA based UM location estimation scheme.

In the simplest conditions, in which the transmitter and the receiver share a common clock, TOA can be calculated by subtracting the sending time recorded by the transmitter from the receiving time recorded by the receiver. The distance in 2D between UM and m^{th} AM is represented by

$$d_m = \sqrt{(x_k - x_m)^2 + (y_k - y_m)^2}, \; m = 1,\; 2,\; ....,\; M \tag{3.1}$$

where (x_k, y_k) are the actual coordinates of the UM and (x_m, y_m) are the coordinates of the m^{th} AMs. Therefore, in the absence of noise and measurement errors as shown in Fig 3.1, the targets can be uniquely localized at the intersecting point of three circles. Similarly, in 3D, at least three AMs are required to determine a target's UM position. This method is also known as trilateration.

3.2.2 Time difference of arrival (TDOA) based localization approach

If there is no common clock between the AMs and target UMs, the TDOA approach can be applied as long as tight synchronization can be achieved among the AM and UM. [17]. As shown in Fig. 3.2, upon receiving a signal from a target UM, the TDOA of the signal from the UM to AM can be estimated. In absence of noise and measurement errors, the possible positions of target UM reside on a hyperbola specified by

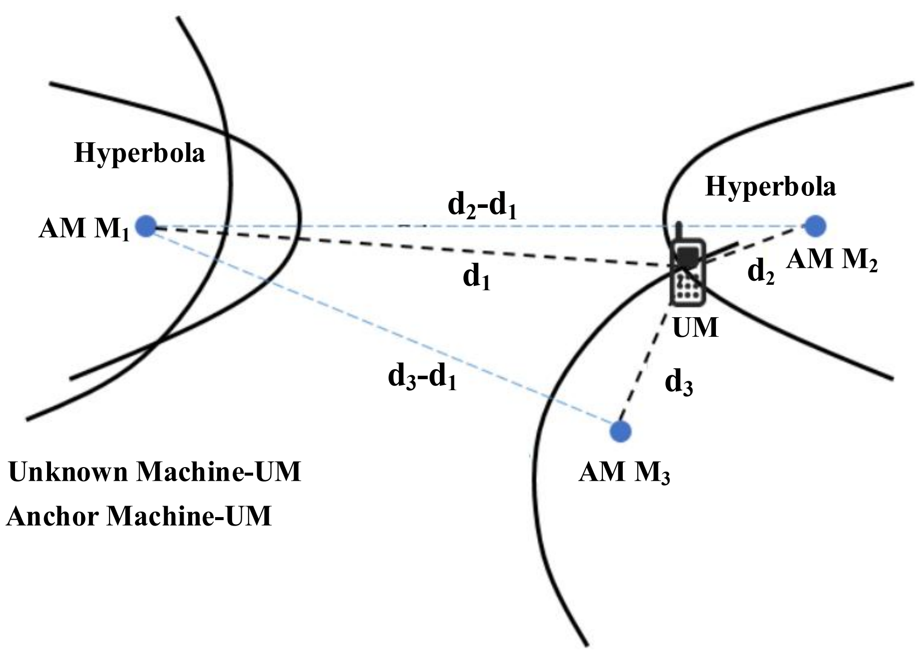


Fig. 3.2: TDOA based UM location estimation scheme.

$$t_{31}^{TDOA} \times c = d_3 - d_1$$

$$= \sqrt{(x_k - x_2)^2 + (y_k - y_2)^2} - \sqrt{(x_k - x_1)^2 + (y_k - y_1)^2} \qquad (3.2)$$

where, t_{21}^{TDOA} represents the TDOA between AM M_1 and M_2, c represents the speed of light, (x_k, y_k) are the coordinates of the UM, (x_1, y_1) and (x_2, y_2) are the coordinates of the AM M_1 and M_2, respectively. At least three AMs are needed to uniquely determine the UM location in M2M communications. The main challenge of TDOA-based localization approaches is the need for precise synchronization among AMs and UMs. However, TDOA-based localization approaches are advantageous where only one message transmission is needed from a UM resulting in high power efficiency. Moreover, with more AMs in the target's vicinity, location estimation accuracy can be improved. On the other hand, when the three or more AMs are used to estimate a UM location in two dimensions these is called multilateration. To improve the localization accuracy, TDOA localization approach can be used in M2M communications.

3.3 System Model

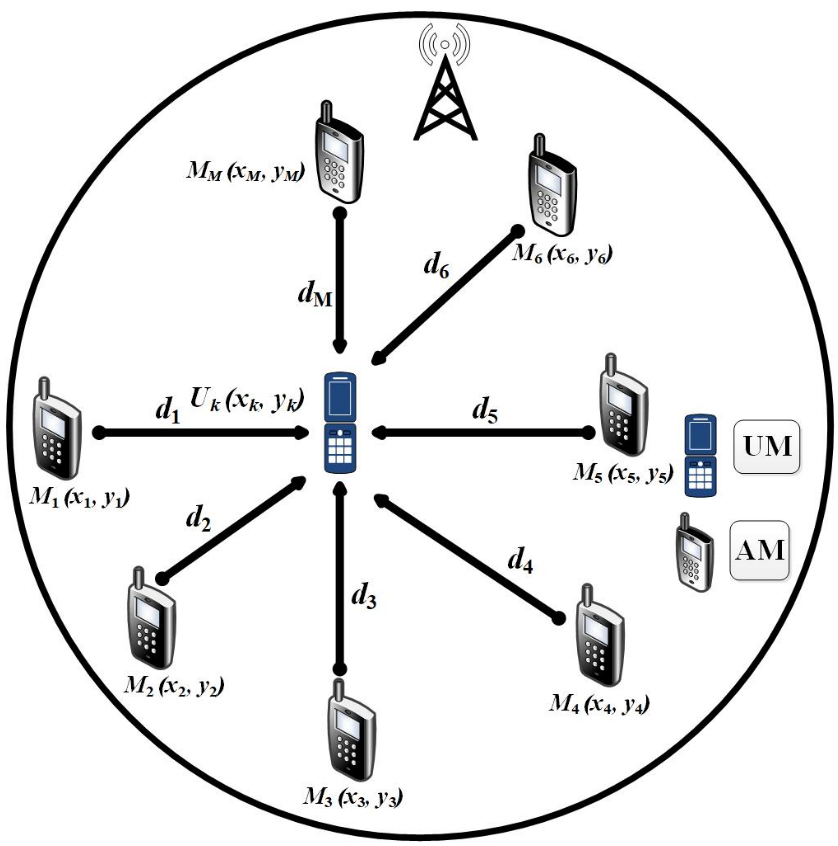


Fig. 3.3: TDOA based localization architecture.

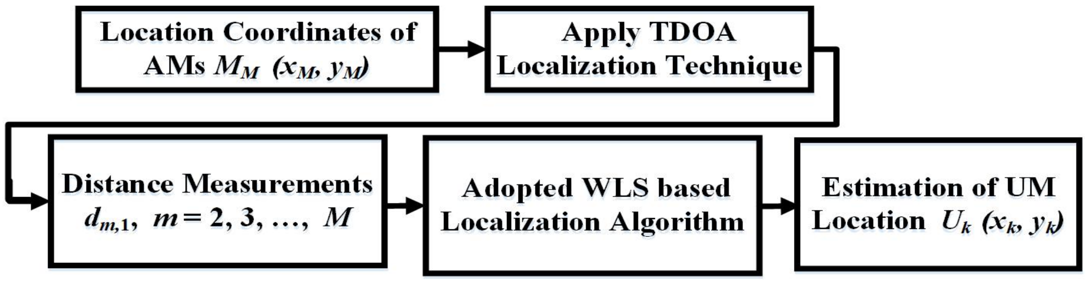


Fig. 3.4: UM localization process system.

3.3.1 Proposed localization architecture

We consider multiple AMs and one UM at the centre of the BS. Distances from these AMs to the UM are denoted by $d_1, d_2, \ldots, d_M$. Let the UM is located at the point $U_k \equiv [x_k, y_k]$. These AMs are either randomly distributed or placed in a fixed pattern in the proposed localization architecture. In this architecture, UM receives broadcast information which is send by multiple AMs as shown in Fig. 3.3. Likewise, (x_1, y_1), (x_2, y_2), …, (x_M, y_M) represents the coordinate vectors of the AMs M_1, M_2, …, M_{M} respectively. We assume that (x_k, y_k) be the coordinate vector of the UM which needs to be determined. TDOA localization technique is applied for estimating the UM location. This technique is the process for estimating the UM location from the location information of AMs. A WLS based algorithm is adopted in the proposed localization architecture. Furthermore, TDOA based UM localization process system is shown in following Fig. 3.4.

3.3.2 TDOA based localization algorithm

In this section, we first formulated the problem of UM localization using TDOA measurements and then a WLS localizing algorithm is proposed for estimation UM location in cellular networks. TOA estimates the time difference between UM and AMs as follows [18]

$$t_m = \frac{1}{c}\sqrt{\left(x_k - x_m\right)^2 + \left(y_k - y_m\right)^2} + t_k + n_{m,k}, \qquad m = 1, 2, \ldots, M$$

$$= \frac{d_m}{c} + t_k + n_{m,k} \tag{3.3}$$

where t_k is the instant at which AMs transmit signal, c is the speed of RF propagation and $n_{m,k}$ denotes the TOA measurement noise. For ease of presentation, TOA measurements are then converted to distance as follows

$$d_m = c(t_m - t_k) + w_{m,k} \tag{3.4}$$

where $w_{m,k} = cn_{m,k}$ is often assumed normally distributed with zero mean and variance of $\sigma^2_{m,k}$. Since t_k is unavailable, range-based methods such as TDOA localization method is more appropriate. Difference between the TOA of signals at the UM from the 1st and the m^{th} AMs then can be written as

$$(t_m - t_k) - (t_1 - t_k) + n_{m,k} - n_{1,k} \tag{3.5}$$

We can then transform (3.5) and write as below,

$$\begin{aligned} &= d_m - d_1 + w_{mk} - w_{m1} \\ &= \sqrt{(x_k - x_m)^2 + (y_k - y_m)^2} - \sqrt{(x_k - x_1)^2 + (y_k - y_1)^2} + w_{m,1} \end{aligned} \tag{3.6}$$

where m = 2, 3, …, M and $w_{m,1}$ is zero often assumed normally distributed with zero-mean and variance of $\sigma^2_{m,1}$.

The idea is the same as TOA, but the function is defined as [19]

$$\begin{aligned} f_m(x_k, y_k) &= \sqrt{(x_k - x_{m+1})^2 + (y_k - y_{m+1})^2} - \sqrt{(x_k - x_1)^2 + (y_k - y_1)^2} \\ &= \hat{d}_{m+1,1} + w_{m+1,1}, \quad m = 1, 2, \ldots, M\text{-}1 \end{aligned} \tag{3.7}$$

where $\hat{d}_{m+1,1}$ is the TDOA estimate of the $(m+1)^{th}$ AM with the first one and $w_{m+1,1}$ is the corresponding range difference estimation error and the elements of its are independent and zero-mean Gaussian random variable with covariance matrix

$$\mathbf{Q_{m,1}} = E\{\boldsymbol{w_{m,1}} \boldsymbol{w^T_{m,1}}\} = diag\left[\sigma^2_{2,1},\ \sigma^2_{3,1},\ \ldots,\ \sigma^2_{M,1}\right]$$

in which σ is the range difference estimation error.

If x_o and y_o are guesses of the initial UM location, then,

$$x_k = x_o + \delta_x, y_k = y_o + \delta_y,$$

where δ_x and δ_y are the location errors to be determined. Expanding (3.7) into Taylor series and retaining the first two terms produce

$$f_{mo} + a_{m,x}\delta_x + b_{m,y}\delta_y \approx \hat{d}_{m+1,1} + w_{m+1,1},\ m = 1, 2, \ldots, M\text{-}1 \tag{3.8}$$

where

$$f_{m,\mathrm{o}} = f_m(x_\mathrm{o}, y_\mathrm{o}),$$

$$\begin{aligned} a_{m,x} &= \frac{\partial f_m}{\partial x}\bigg|_{x_\mathrm{o}, y_\mathrm{o}} = \frac{x_1 - x_\mathrm{o}}{\hat{d}_1} - \frac{x_{m+1} - x_\mathrm{o}}{\hat{d}_{m+1}}, \\ b_{m,y} &= \frac{\partial f_m}{\partial y}\bigg|_{x_\mathrm{o}, y_\mathrm{o}} = \frac{y_1 - y_\mathrm{o}}{\hat{d}_1} - \frac{y_{m+1} - y_\mathrm{o}}{\hat{d}_{m+1}}, \end{aligned} \tag{3.9}$$

in which

$$\hat{d}_m = \sqrt{(x_m - x_\mathrm{o})^2 + (y_m - y_\mathrm{o})^2}. \tag{3.10}$$

Eq. (3.8) can be rewritten as

$$\mathbf{A\delta} = \mathbf{D} + \mathbf{w}, \tag{3.11}$$

where

$$\mathbf{A} = \begin{bmatrix} a_{1,x} & b_{1,y} \\ a_{2,x} & b_{2,y} \\ \vdots & \\ a_{M-1,x} & b_{M-1,y} \end{bmatrix}, \ \boldsymbol{\delta} = \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix},$$

$$\mathbf{D} = \begin{bmatrix} \hat{d}_{2,1} - f_{1,\mathrm{o}} \\ \hat{d}_{3,1} - f_{2,\mathrm{o}} \\ \vdots \\ \hat{d}_{\mathrm{M},1} - f_{M-1,\mathrm{o}} \end{bmatrix} \text{ and } \mathbf{w_{m,1}} = \begin{bmatrix} w_{2,1} \\ w_{3,1} \\ \vdots \\ w_{\mathrm{M},1} \end{bmatrix}. \tag{3.12}$$

The WLS based location estimation of UM can then be written as

$$\boldsymbol{\delta} = \left[\mathbf{A}^\mathbf{T}\mathbf{Q}_{\mathbf{m,1}}^{-1}\mathbf{A}\right]^{-1}\mathbf{A}^\mathbf{T}\mathbf{Q}_{\mathbf{m,1}}^{-1}\mathbf{D} \tag{3.13}$$

From the initial UM location guess $(x_\mathrm{o}, y_\mathrm{o})$ and δ computed from (3.13), estimation of the UM location can be updated according to $x_\mathrm{o} = x_\mathrm{o} + \delta_x, y_\mathrm{o} = y_\mathrm{o} + \delta_y$. The iterations end when δ_x and δ_y are small enough.

3.3.3 Performance metrics

Localization accuracy is considered to be the most important performance metric of a localization approach. For evaluating the performance of the proposed TDOA based localization architecture, RMSE is calculated in location estimation. RMSE can be expressed as [19-20]

$$RMSE=\sqrt{\sum_{k=1}^{N}\frac{\left(x_k-\hat{x}_k\right)^2+\left(y_k-\hat{y}_k\right)^2}{N}}, \tag{3.14}$$

where N, $\left(x_k, y_k\right)$ and $\left(\hat{x}_k, \hat{y}_k\right)$ are the number of UMs, the actual coordinate of the k^{th} UM and the estimated coordinate of the k^{th} UM respectively.

3.4 Simulation Results and Analysis

3.4.1 Simulation setup

Substantial MATLAB based simulations are carried out for evaluating the performance of the proposed TDOA based localization architecture. The results presented here are found by averaging the results for more than 1000 individual and independent locations of the target UM. We consider a $90\text{m}\times 90\text{m}$ network area. The location of UM is assumed random whereas AMs are either distributed randomly or placed in regularly spaced fixed pattern.

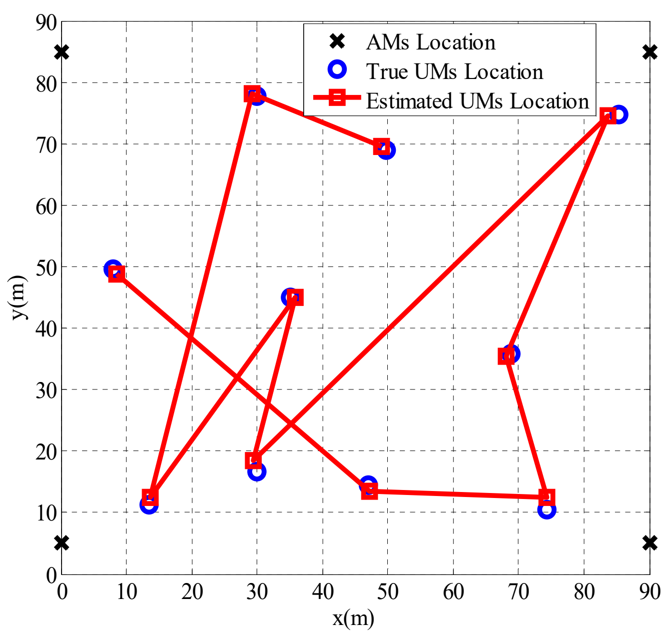


Fig. 3.5: Fixed pattern based AMs distribution.

3.4.2 Results and analysis

A view of the network with four AMs placed in fixed pattern is shown in Fig. 3.5. This figure also demonstrates that the true UMs location and the estimated UMs location. On the other hand, Fig. 3.6 shows a view of the network with 8 AMs distributed randomly. It is observed that for both the schemes, estimated UM locations are quite close to the true UM locations.

Fig. 3.7 provides the performance of the proposed localization architecture with the number of AMs. The transmission communication radius of any AM is assumed to 20m in the proposed network. The range difference estimation errors are Gaussian with zero mean and variance is -10 dB. As the number of AMs is increased, the RMSE of the UM location under this algorithm reduces sharply. In addition, it can be clearly identified that when the number of AM rises in the network from 4 to 24, the localization accuracy improves significantly. However, when the number of AM continues to increase, the effects on RMSE

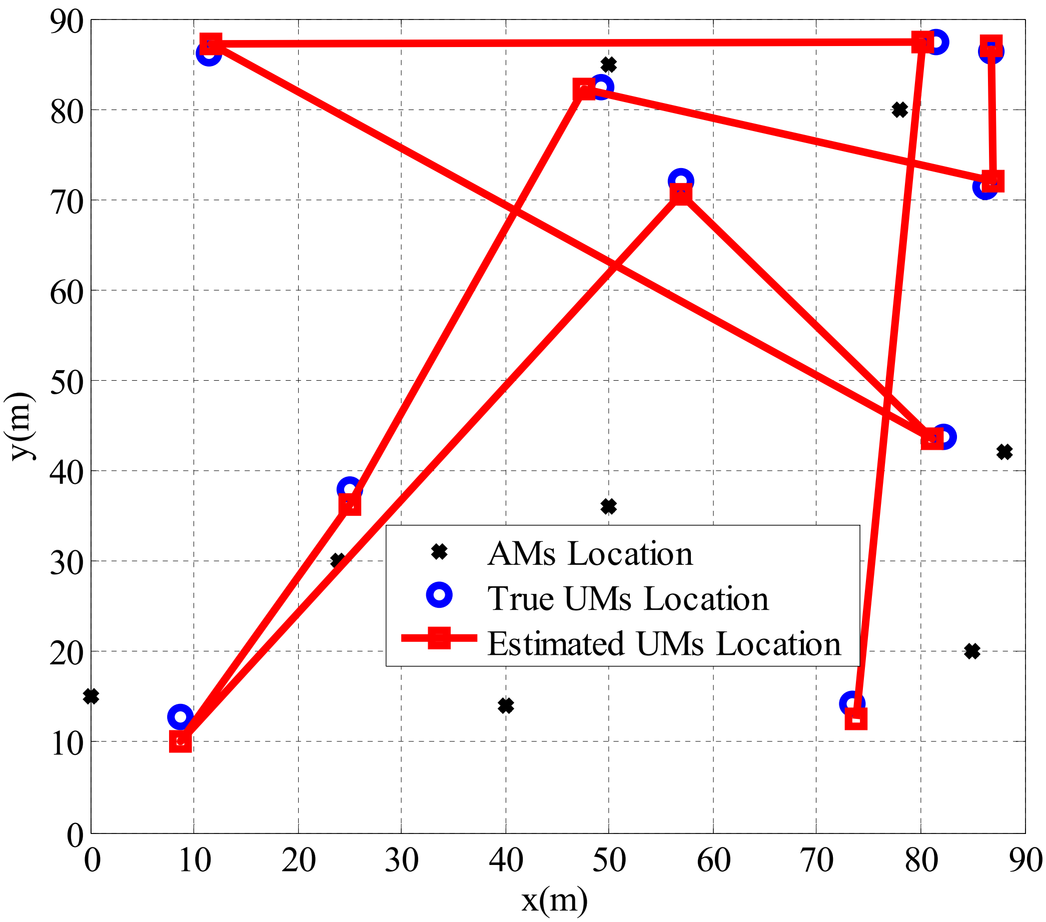


Fig. 3.6: Random pattern based AMs distribution.

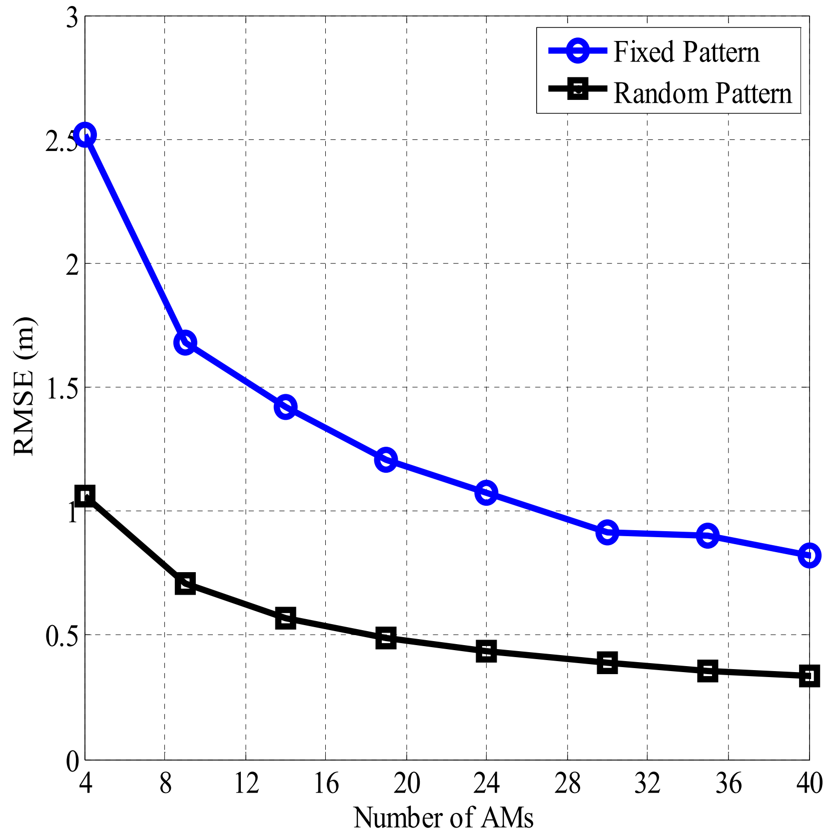


Fig. 3.7: RMSE variation with the number of AMs.

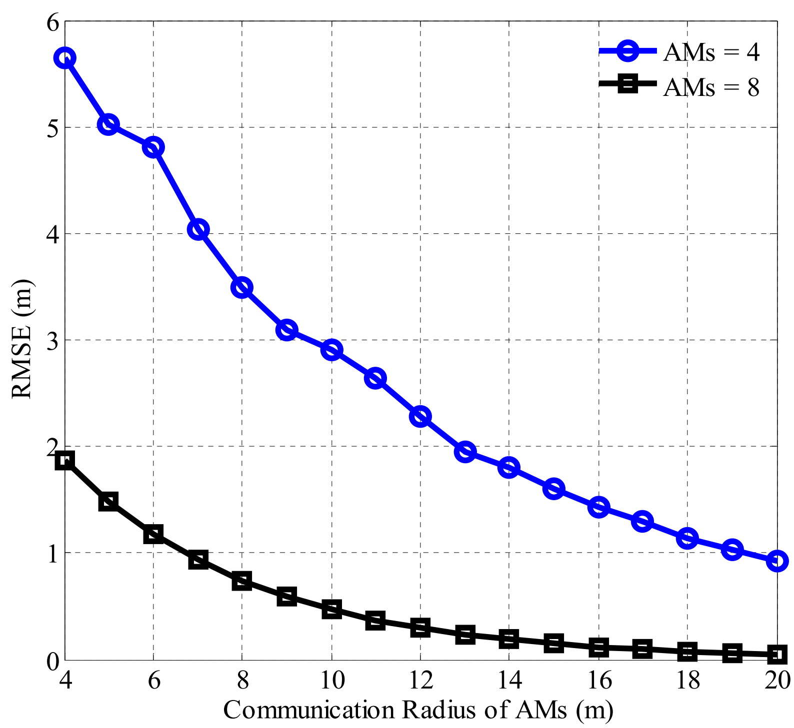


Fig. 3.8: Impact of the AMs communication radius on RMSE.

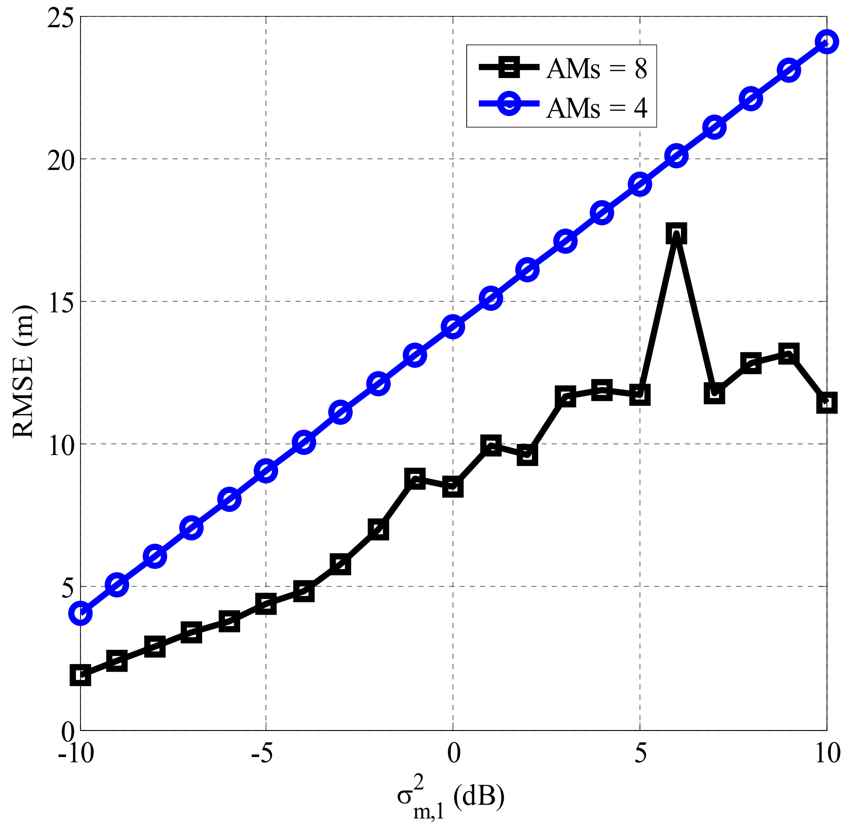


Fig. 3.9: Impact of TDOA measurement error variance on RMSE.

become insignificant. Obviously, the scheme with the randomly distributed AMs attains higher localization accuracy.

In Fig. 3.8, we plot the RMSE versus communication radius of AMs for different number of AMs. In this figure, AMs are randomly distributed in the network. It is observed that with the increase of the communication radius of AMs, RMSE gradually decreases. This is because, with the increase of communication radius of AMs, number of AMs from which the UM receives information increases resulting in reduced RMSE. Furthermore, when the communication radius of AMs changes from 4m to 8m, the RMSE decreases fast. Whereas the communication radius changes from 8m to 20m, the RMSE reduces slowly.

Fig. 3.9 illustrates the impact of TDOA measurement error variance on RMSE. In this figure, RMSE is plotted for two different number of AMs. It is observed that the RMSE increases with the increase of TDOA measurement error variance. Increase of error variance implies a less accuracy in TDOA measurement leading to higher RMSE.

3.5 Conclusion

In this chapter, a TDOA scheme using WLS algorithm based localization architecture has been proposed for M2M communications over cellular networks. The localization architecture has estimated the location of UM in the proposed network. The proposed localization architecture has been evaluated in terms of RMSE. The localization architecture have been impacted by several parameters, such as TDOA measurement error variance and communication radius. It has also been observed that the higher number of AM provided the higher localization accuracy. Besides, simulation results have shown that the scheme with randomly distributed AMs achieves substantial improvement in terms of localization accuracy.

CHAPTER 4

A LOCATION-AWARE COMMUNICATION MODE SELECTION MECHANISM

4.1 Introduction

This chapter proposes a location-aware RBs allocation strategy and communication mode selection mechanism for M2M communications over cellular networks. The mode selection mechanism depends on the threshold distance and threshold SINR which selects the appropriate communication mode. The proposed mechanism and RBs allocation policy are evaluated in terms of throughput and channel utilization, respectively.

The explosive enhancement of mobile users and their traffic requirements force researchers to seek new paradigms to revolutionize the traditional cellular networks. M2M communication recently has emerged as a promising concept for improving system performance. However, M2M communication imposes of a technical issues which include interference management in the network, RB allocation for M2M links, traditional cellular links and adaptive mode selection for the UE. By incorporating M2M communication into cellular networks, mobile UEs can be operated in three modes, such as direct, indirect mode and hybrid mode.

- **Direct mode:** Two MUEs communicate directly without using any cellular network infrastructure. MUEs in this mode consume less channel resource compared to those in the indirect mode and can improve the SE due to user proximity. Also if devices in direct communication mode are close to each other, transmission power levels could be lower than in indirect mode which can be turned into battery saving at the UEs and reduced interference levels in the system. Furthermore, reduced interference levels in the system lead to higher SE and EE. The architecture is shown in Fig. 4.1.

- **Indirect mode:** If two UEs choice the indirect mode, they referred to as the traditional cellular communication. It should be used only if the direct mode is not available in the proposed network. The indirect mode architecture is as shown in Fig. 4.2.

- **Hybrid Mode:** Hybrid mode means that UE automatically chooses the suitable communication mode based on the proposed mode selection condition. As depicted in Fig. 4.3 represents the hybrid mode.

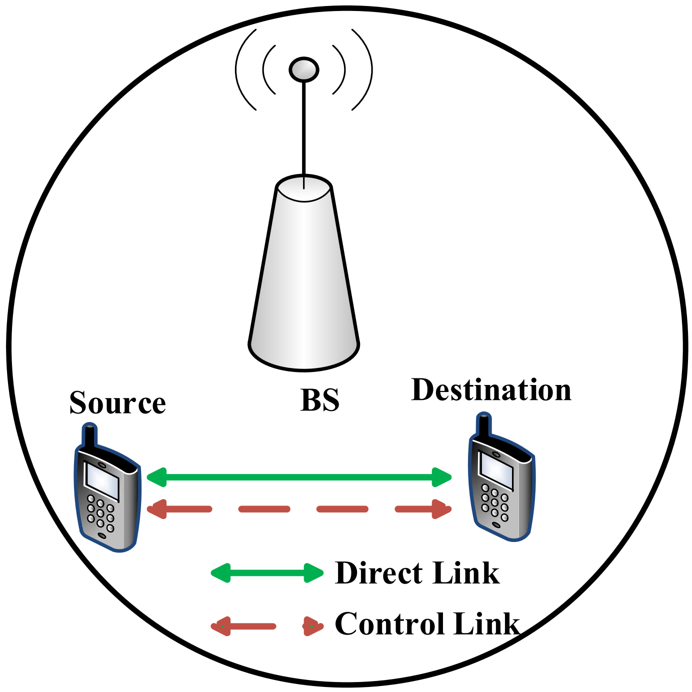


Fig. 4.1: Direct mode based M2M communication.

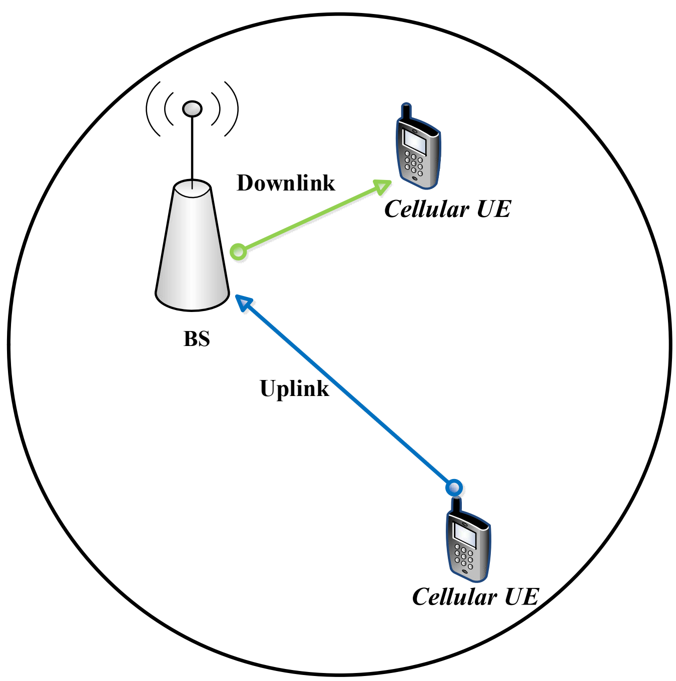


Fig. 4.2: Illustration of indirect mode.

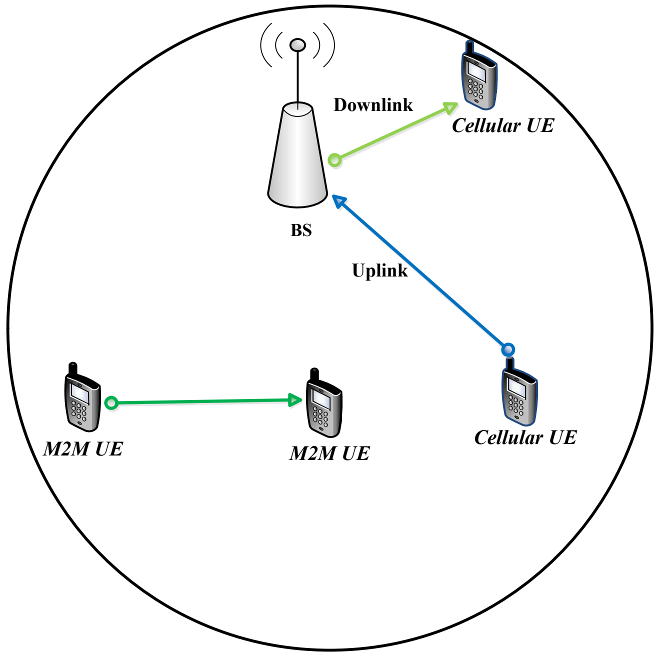


Fig. 4.3: Illustration of hybrid mode.

4.2 System Model

In this section, we first introduce the network model with the link model and the corresponding performance metric is derived for M2M communication systems.

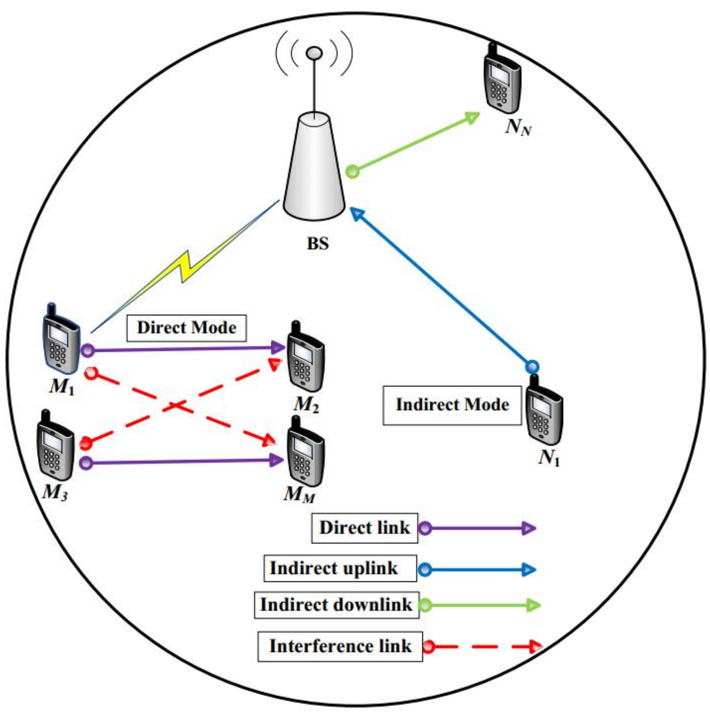


Fig. 4.4: Cellular network with M2M communications system.

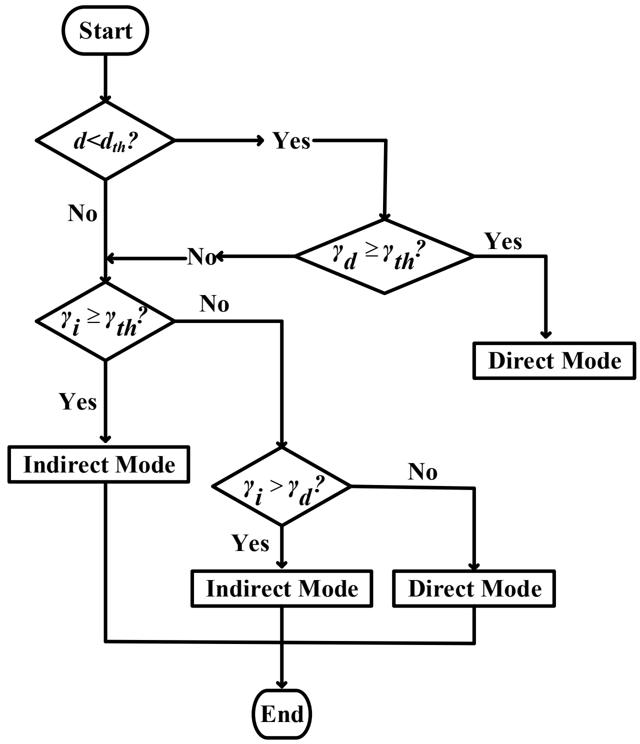


Fig. 4.5: Communication mode selection mechanism flow chart for M2M communications.

4.2.1 Network model

A M2M communication over cellular network system is depicted in Fig. 4.4. In a cell served by a BS, there are several UEs who need to communicate with each other for voice or data service. TDOA based localization architecture is applied in M2M communication. The proposed localization architecture estimates the location of the UM. We consider a location-aware communication mode selection scheme which depends on the threshold distance and threshold SINR. Furthermore, a location-aware communication mode selection mechanism flow chart is shown in Fig. 4.5. When the M2M pair distance (d) is smaller than the threshold distance (d_{th}) and direct mode SINR (γ_d) is greater than or equal to the threshold SINR (γ_{th}) it is indicated as the direct mode. Otherwise, when the d is greater than or equal to the d_{th} and indirect mode SINR (γ_i) is greater than the $\gamma_{d,}$ UE selects the indirect mode. Then, the communication mode selection mechanism makes a decision either the UE operates in direct mode or indirect mode. The mobile UEs which can communicate using the direct mode is denoted as the MUE. Otherwise, when the UEs communicate using the BS it is referred to as the CUE. This paper focuses on the M2M over cellular networks made up of two tiers, such as M2M and cellular tiers. The MUE uses the M2M tier. On the other hand, BS and it's associated CUE uses the cellular tier. There are M MUEs and N CUEs in the proposed network. M2M data transmission of indirect mode is made of uplink and downlink phase. In the uplink phase, N_1 initially transfers the M2M information to its associated cellular BS on the uplink frequency spectrum. Then, the cellular BS decodes the M2M information and sends it to N_N in the downlink phase. Considering the OFDMA scheme, the available frequency spectrum is separated into K orthogonal frequency sub-band. Each UE uses one of the orthogonal frequency sub-band. As a result, each UE is orthogonal to other UEs which avoid co-tier and cross-tier interference. However, a MUE can share the same frequency with other MUEs at the same time. When the number of UE increases in the proposed network, most of UEs are located within or near the mode selection threshold distance. If the number of RBs are not available in the proposed scheme, a MUE shares the same frequency with other MUEs. Then, the MUE receiver suffers the co-tier interference from other MUE transmitters.

4.2.2 Performance metrics

In this section, we derive the per-user throughput which is a performance metric for the assessment of the proposed mechanism. Each M2M link experiences a diverse SINR depending on the M2M pair distance and threshold distance. Then, we define the 3GPP communication channel model that determines the attainable data rate in each M2M communication mode. The received SINR at the m^{th} MUE can be written as

$$\gamma_{d,m} = \frac{P_m^d d_d^{-\alpha}}{I_m^d + N_0} \tag{4.1}$$

where

$$I_m^d = d_{tr}^{-\alpha} P_m^d$$

I_m^d is the interference from other M2M transmitters to M2M receiver and N_0 represents the power spectral density of the additive white Gaussian noise (AWGN). Whereas, P_m^d represents the transmit power of the m^{th} MUE. Moreover, α denotes the PL exponent and d_{tr} is the distance from other M2M transmitters to M2M receiver. The attainable data rate for m^{th} MUE can be obtained as

$$R_{d,m} = B\log_2(1+\gamma_{d,m}) \tag{4.2}$$

where B denotes the allocated bandwidth of the considerable RBs. The total data rate of direct mode is then given by

$$R_d^T = \sum_{m=1}^{\frac{M_d}{2}} R_{d,m} \tag{4.3}$$

where M_d denotes the number of direct mode users. In the downlink phase, the received SINR at the n^{th} CUE can be represented as

$$\gamma_{i,n} = \frac{P_n^i d_i^{-\alpha}}{N_o} \tag{4.4}$$

where P_n^i represents the transmit power of the n^{th} CUE. The attainable data rate of the n^{th} CUE is then given by

$$R_{i,n} = B\log_2(1+\gamma_{i,n}) \tag{4.5}$$

The total data rate of the indirect mode can be expressed as

$$R_i^T = \sum_{n=1}^{\frac{N_i}{2}} R_{i,n} \tag{4.6}$$

where N_i denotes the number of indirect mode users. The attainable total data transmission rate of the proposed mechanism can be written as

$$R_T = R_d^T + R_i^T \tag{4.7}$$

Finally, the per-user throughput of the proposed scheme is defined as

$$R_P = \frac{R_T}{M_T} \tag{4.8}$$

where R_P and M_T represents the per-user throughput and total number of UEs in the proposed network, respectively.

4.3 Resource Blocks (RBs) Allocation Strategy

The integration of M2M communications into the traditional cellular networks results in a two-tier network. Depending on how the spectrum is shared among MUEs and CUEs, there are direct and indirect mode. The proposed mechanism allocates the RB to M2M links that are far apart so as to reduce traffic delay and therefore improving the SE. Finally in the next section, the proposed location-aware mode selection scheme assisted RB allocation strategy is discussed.

4.3.1 A location-aware mode selection based RBs allocation strategy

The mode selection condition, such as threshold distance and threshold SINR are considered for the RB allocation process in the proposed network. Therefore, the proposed mechanism selects the appropriate mode and thus assigns the RB in the proposed scheme is shown in Fig. 4.6. When the d is less than d_{th} and γ_d is greater than or equal to the $\gamma_{th,}$ one RB is required for establishing a direct mode link in the proposed network. Otherwise, when the d is greater than or equal to the d_{th} and γ_i is greater than the $\gamma_{d,}$ an indirect mode link requires two RBs for uplink and downlink phase, respectively. The total number of required RBs in the proposed mechanism can be expressed as

$$RB_T = K_d + 2K_i \tag{4.9}$$

where K_d and K_i are the number of user pairs with direct and indirect modes, respectively. Therefore, RB_T can be rewritten as

$$RB_T = \frac{M_d}{2} + N_i \tag{4.10}$$

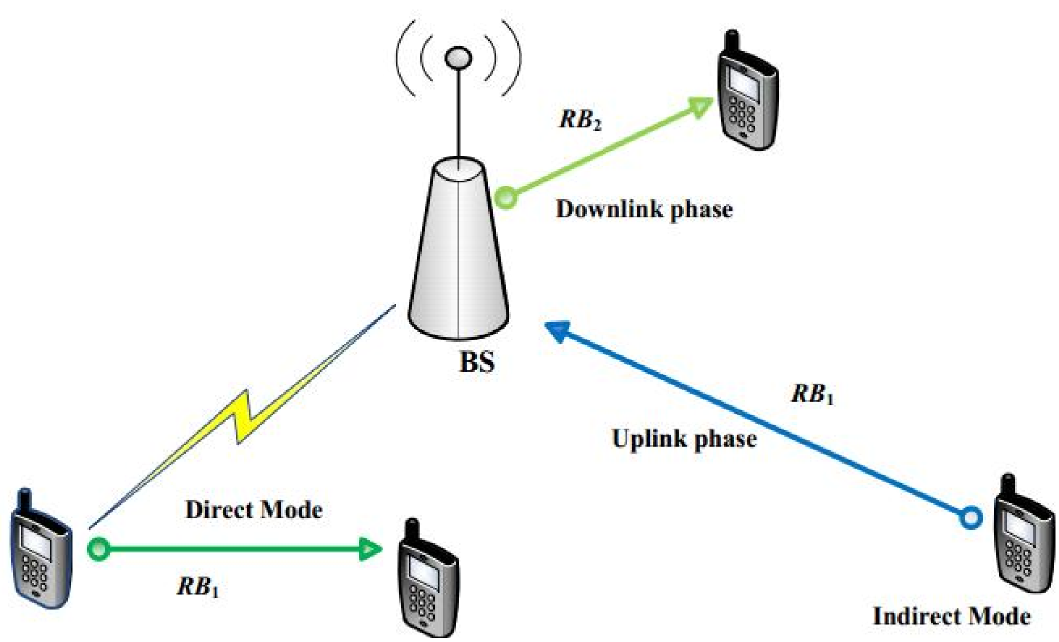


Fig. 4.6: Location-aware communication mode selection based RB allocation policy.

4.4 Simulation Results and Analysis

4.4.1 Simulation setup

Substantial MATLAB based simulation results are presented to evaluate the performance of the proposed mechanism and RBs allocation strategy. The location of UEs are randomly placed in the proposed network. Each figure is the result of the average of at least 10000 channel realizations. Moreover, the *d* is adopted to be available at the corresponding machines, which can inform the value of *d* periodically in the proposed scheme. On the other hand, hybrid mode means that UE automatically selects the suitable communication mode.

The total fifty number of RBs are considered in the proposed mechanism. All the simulation related parameters are listed in Table 4.1, whereas the settings in each figure take precedence.

4.4.2 Results and analysis

Fig. 4.7 demonstrates the impact of the number of UEs on the percentage of UEs connected in direct and indirect modes. From this figure, we can see that the percentage of direct mode

Table 4.1: Communication Mode Selection Mechanism Simulation Parameters

Parameters	**Settings**
Carrier frequency	2 GHz
Bandwidth per RB	180 KHz
Total channel bandwidth	9 MHz
Radius of cell	250m
Number of UEs	50
Mode selection threshold distance	50m-150m
Transmit power of MUE	20 dBm
Transmit power of CUE	23 dBm
SINR threshold	-10 dB
Number of simulations	10000
Noise spectral density	-174 dBm/Hz
Shadow fading standard deviation (BS-UE), σ	8 dB
Shadow fading standard deviation (UE-UE), σ	4 dB

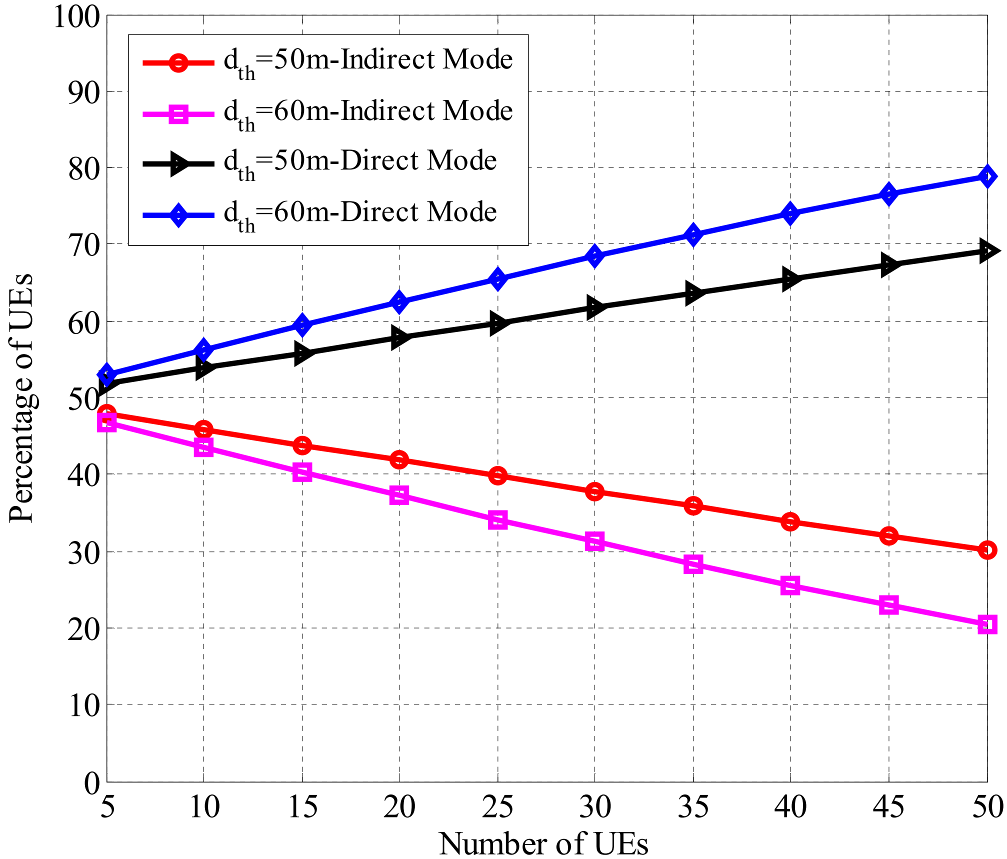


Fig. 4.7: Impact of the number of UEs on percentage of UEs connected in direct and indirect modes.

UEs is higher than the percentage of indirect mode UEs. This is due to the fact that for a large number of UEs, most of the UEs are situated within or near the mode selection threshold distance. We can see that if the threshold distance increases from 50m to 60m, it increases the percentage of direct mode UEs and decreases the percentage of indirect mode UEs.

Fig. 4.8 shows the impact of the threshold SINR on the percentage of throughput for different modes. This figure uses fifty number of UEs in the proposed network. When the threshold SINR rises in the proposed scheme, direct mode increases the percentage of throughput and indirect mode decreases the percentage of throughput. This is because for a large number of UEs, most of the UEs select the direct mode. It is observed that the threshold SINR is a significant factor among mode selection mechanisms. Based on these results, we can decide that the direct mode UE uses the lower transmission power which mitigates the co-tier interference. We can see that the data rate development mainly occurs with the change from indirect mode to direct mode. Finally, we can conclude that the direct mode achieves superior system performance in terms of the percentage of throughput.

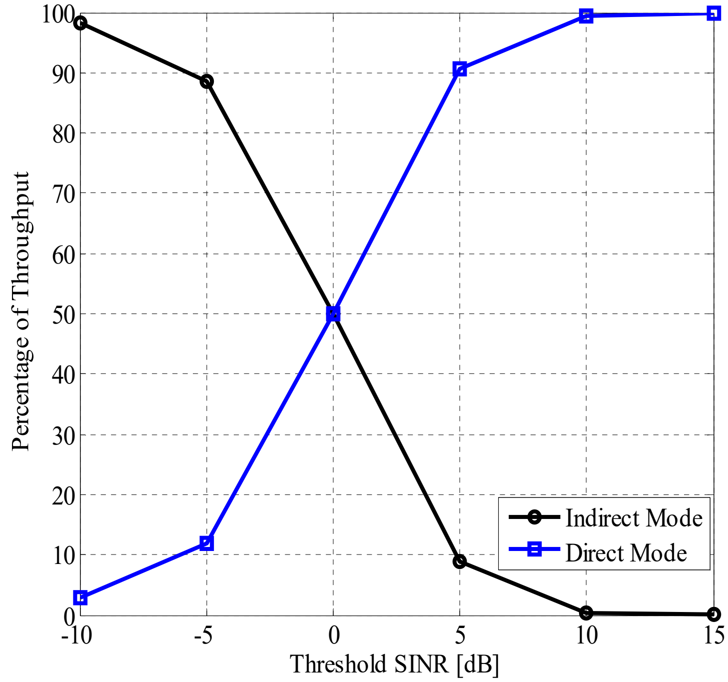


Fig. 4.8: Impact of threshold SINR on the percentage of throughput for different modes.

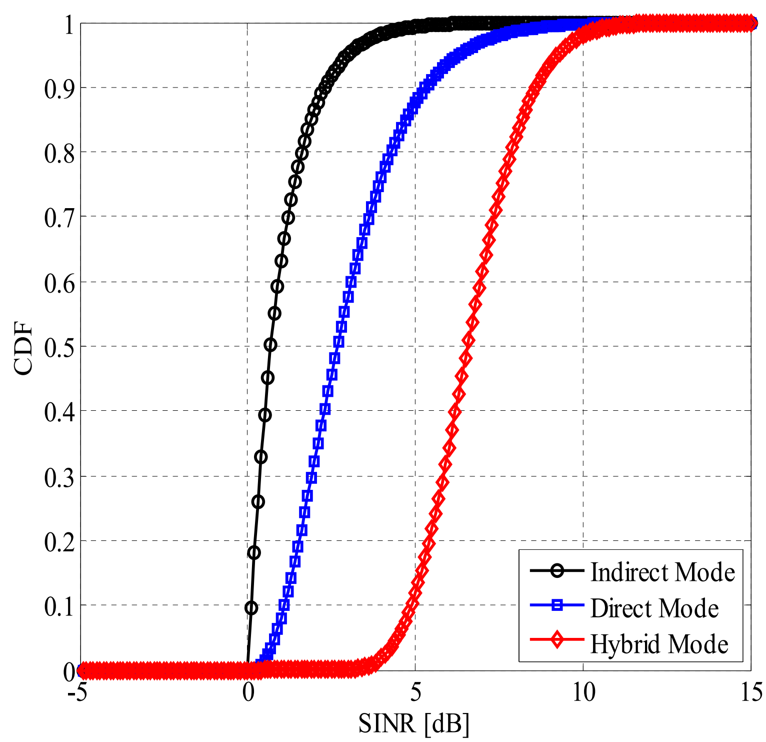


Fig. 4.9: CDF of SINR in the network for different modes.

Fig. 4.9 shows the CDF of the SINR for different modes. It is observed that the indirect mode provides the lowest SINR, whereas hybrid mode attains the highest SINR. From this

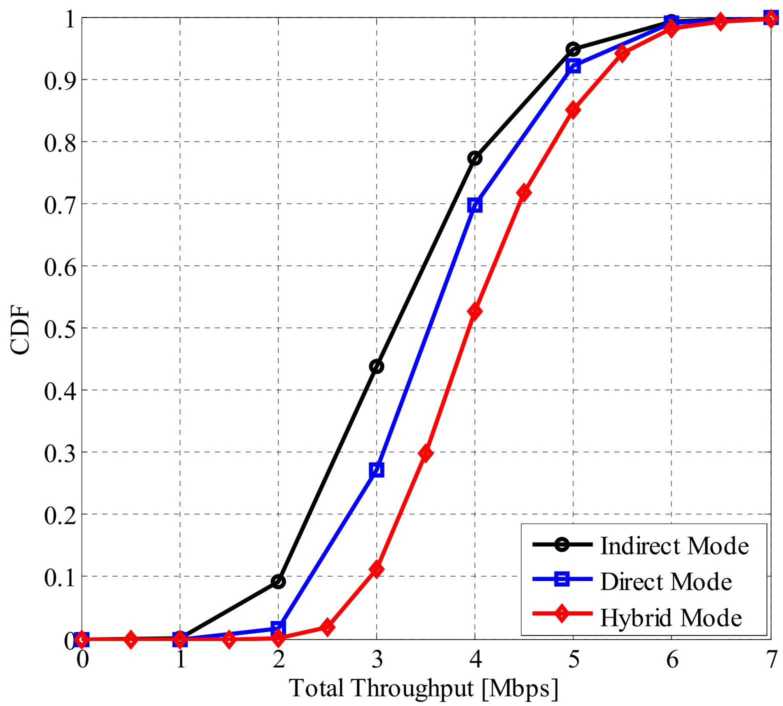


Fig. 4.10: CDF of total throughput in the network for different modes.

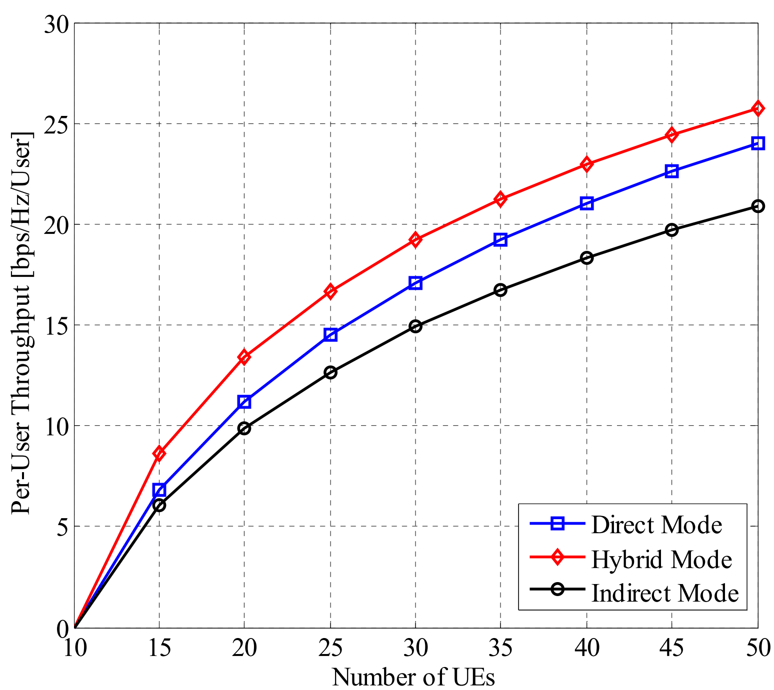


Fig. 4.11: Per-user throughput versus the number of UEs for different modes.

figure, we can see that the performance of the hybrid mode is much better than other modes. Therefore, a higher range of SINR is essential for significant improvement in throughput. We can conclude that selecting a proper mode can greatly improve system performance.

Fig. 4.10 represents the CDF curves of the total user throughput for the proposed mechanism. From this figure, we can see that the CDF under the proposed mechanism is shifted towards higher value. Based on these results, we can conclude that the proposed hybrid mode selection mechanism achieves higher throughput. This is due to the fact that for a large number of UE, most of the UE selects the suitable mode that provides better system performance in the proposed network.

Fig. 4.11 illustrates the impact of the number of UEs on per-user throughput for the proposed mechanism. It is observed that the per-user throughput increases with the increase of UEs. We can see that while using the smallest number of UE, per-user throughput improves rapidly. From Fig. 4.11, direct mode achieves more per-user data rate than indirect mode and less than that of hybrid mode. The system performance of the proposed network grows almost linearly with the rise of UEs, which indicates that the proposed scheme is extensively using different modes. This is due to the fact hat each UE chooses the appropriate mode

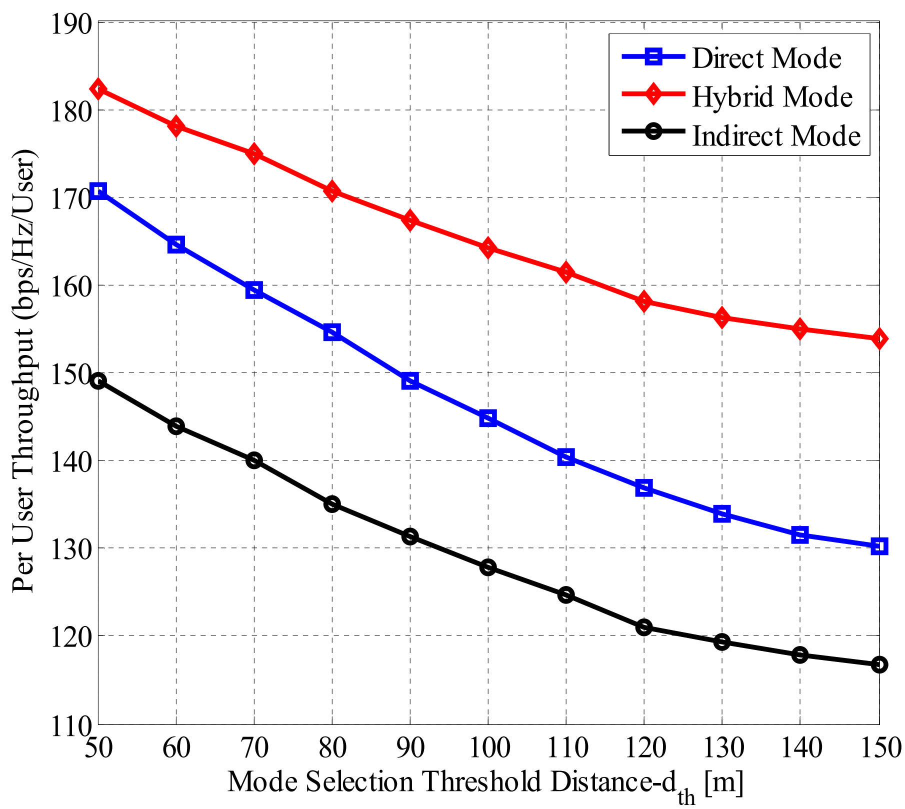


Fig. 4.12: Per-user throughput variation with the mode selection threshold distance for different modes.

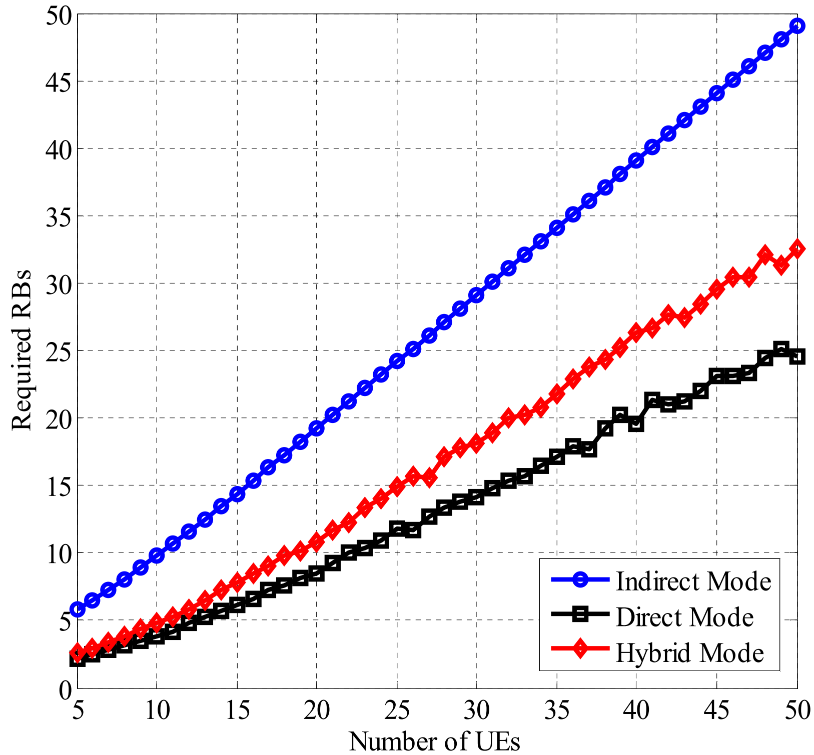


Fig. 4.13: Required RBs variation with the number of UEs for different modes.

which provides the greatest SINR and thus leads the per user throughput.

Fig. 4.12 represents per-user throughput variation with the mode selection threshold distance for different modes. When the threshold distance increases from 50m to 80m, per-user throughput reduces quickly. From this figure, we can observe that the per-user throughput reduces if the threshold distance increases for both modes. It is decided that the mode selection threshold distance has a great effect on the system performance. This figure illustrates that each UE automatically chooses the suitable communication mode and improves the system performance if the threshold distance increases. We can conclude that the hybrid mode achieves superior system performance in terms of the per-user throughput.

Fig. 4.13 provides the performance of required RBs variation with the number of UEs for different modes. We can see that the number of UE increases with the increase in the required RBs. From this figure, hybrid mode requires more RB than direct mode and less than that of indirect mode. If the RBs are not enough in the proposed network, the proposed mechanism selects the suitable mode. This is due to the fact that for a large number of UEs, the direct mode becomes available in the proposed scheme. However, the lower number of RB provides the lower traffic burden in the proposed mechanism. In Fig. 4.13, direct mode UE uses the lower number of RB compared to the indirect mode UE. Finally, we can conclude that the direct mode communication reduces traffic burden on the cellular BSs compared to other modes.

4.5 Conclusion

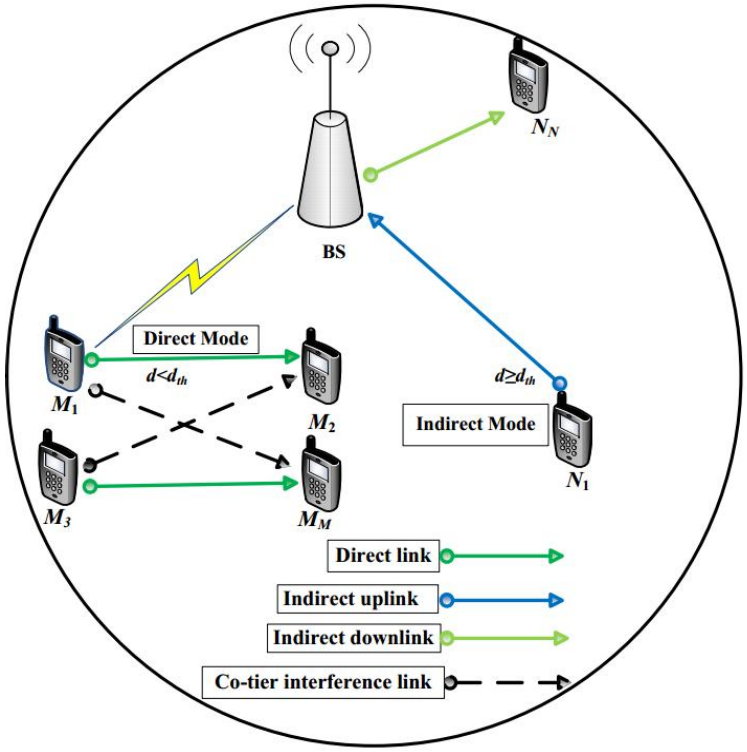
In this chapter, a novel location-aware RB allocation strategy and communication mode selection mechanism have been proposed for M2M communications over cellular networks. The M2M pairs have automatically selected the appropriate communication mode either direct mode or indirect mode according to the proposed mode selection scheme. Furthermore, the proposed mechanism has allocated RBs based on the selected mode. Performance of the proposed mechanism has been evaluated using extensive MATLAB simulations. It has been found that the number of UEs, mode selection threshold SINR and threshold distance have substantial impact on the system performance. Simulation results have shown that the selection of mode before data transfer can improve the network performance. Besides, it has been shown that direct mode communication reduces the traffic burden on cellular BSs compared to other modes.

CHAPTER 5
A LOCATION-AWARE POWER CONTROL MECHANISM FOR MITIGATING INTERFERENCE

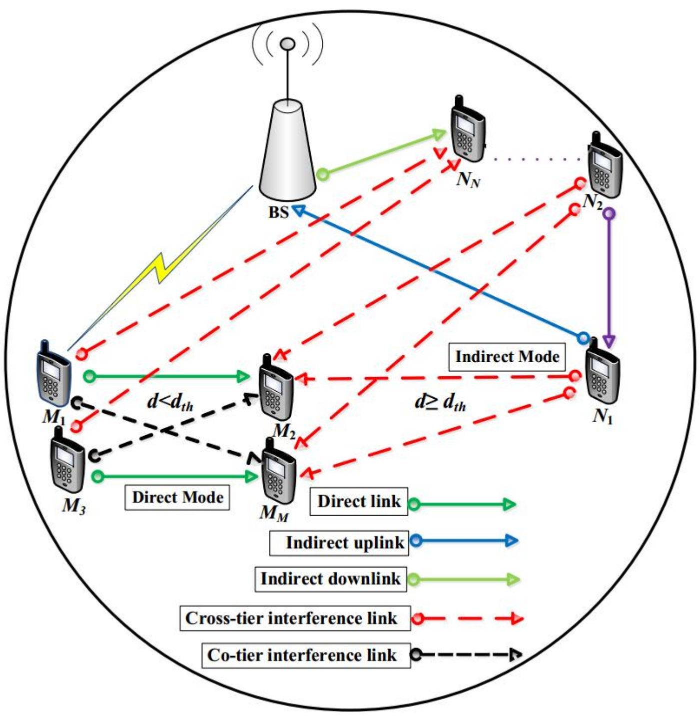
5.1 Introduction

This thesis proposes a novel location-aware communication mode selection based power control mechanism for M2M communications. Resource allocation between the MUEs and CUEs that share the resource in both orthogonal and non-orthogonal ways are analyzed for different modes. A water filling algorithm and Lagrange decomposition scheme based power optimization process is adopted in the proposed mechanism. The proposed algorithm allocates the proper optimal transmit power for each UE. As a result, the proposed mechanism can substantially mitigate the interference. We derive the per-user EE, which is a performance metric for the assessment of the proposed scheme. Performance of the proposed mechanism is evaluated using extensive MATLAB simulations. The proposed mechanism is evaluated under various changing parameters, such as the number of UEs, mode selection threshold distance and transmission power, etc. Simulation results show that the proposed mechanism assigns the proper optimal transmit power for each UE which substantially reduces the interference and thus improves user throughput. Besides, the orthogonal resource sharing scheme based proposed mechanism can significantly improve the system performance in terms of per-user EE compared to the non-orthogonal resource sharing based proposed mechanism.

Power control is an efficient method to mitigate interference in cellular networks. However, existing power control scheme cannot handle the interference perfectly and it needs a location-aware communication mode selection based power control mechanism for mitigating the interference. The transmit power of UE depends on the location-aware mode selection condition which protects wastage of transmission energy.



(a) Orthogonal resource sharing scheme.



(b) Non-orthogonal resource sharing scheme.

Fig. 5.1: Illustration of M2M communications over cellular network system.

5.2 System Model

5.2.1 Network model

A general scenario of M2M communication over cellular network system is shown in Fig. 5.1. There are several number of UEs and one cellular BS situated at the center of the cell. The number of UEs are randomly distributed in the proposed network. We consider a single cell environment where both the cellular BS and the users are equipped with a highly directional antenna. The TDOA based localization architecture is applied in M2M communication. The proposed localization architecture estimates the location of UMs. This thesis considers a location-aware communication mode selection scheme which depends on the mode selection threshold distance (d_{th}). Then, the communication mode selection mechanism makes a selection either the UE operates in the direct mode or indirect mode. When the M2M pair distance (d) is smaller than the d_{th} it is called as the direct mode. Otherwise, UE selects the indirect mode. The proposed network consists of two types of UEs, such as MUEs and CUEs. We focus on the M2M over cellular networks made up of two tiers, such as M2M and cellular tiers. The MUE uses the M2M tier. On the other hand, BS and its associated CUE uses the cellular tier. There are M MUEs and N CUEs in the proposed network. Data transmission in the indirect mode consists of an uplink and downlink phase. In the uplink phase, N_1 initially transfers the M2M information to its associated cellular BS on the uplink frequency spectrum. The cellular BS decodes the M2M information and sends it to N_N in the downlink phase. Considering the OFDMA scheme, the available frequency spectrum is separated into K orthogonal frequency sub-band. The UE can share the resource with the other UEs in orthogonal or orthogonal ways. With the non-orthogonal resource sharing scheme, the transmitter and the receiver of the cross-tier interference may be different while sharing the CUE uplink and downlink resources [62].

- **Orthogonal Resource Sharing (OS) Scheme:** A location-aware orthogonal resource sharing scheme for M2M communication over cellular network is shown in Fig. 5.1(a). Each UE uses one of the orthogonal frequency sub-band. As a result, each UE is orthogonal to other UEs which avoid co-tier and cross-tier interference. There is no interference between CUE and MUE. If the number of RBs are not available in the proposed mechanism, a MUE shares the same frequency with other MUEs. Therefore, the MUE receiver suffers the co-tier interference from other MUE transmitters.

- **Non-Orthogonal Resource Sharing (NOS) Scheme:** A location-aware non-orthogonal resource sharing scheme for M2M communication over cellular network is shown in Fig. 5.1(b). Both the MUE and CUE can share the same frequency in the proposed network, causing interference to each other. The MUE receiver suffers the co-tier interference from other MUE transmitters and cross-tier interference from the CUE. In the downlink phase, CUE is the victim receiver of cross-tier interference signals from the MUE in the proposed network. However, in the downlink phase of the proposed mechanism, there are sufficient number of RBs which help the CUE receiver to avoid the co-tier interference created from other CUE transmitters.

5.2.2 Performance metrics

In this section, we derive the per-user EE which is a performance metric for the assessment of the proposed mechanism. Each M2M link experiences a diverse SINR depending on the M2M pair distance and threshold distance. Then, we define the 3GPP communication channel model that determines the achievable data rate in each M2M communication mode. The orthogonal and non-orthogonal resource sharing scheme based received SINR at the m^{th} MUE, respectively can be written as

$$\gamma_{d,m}^{OS} = \frac{P_m^d d_d^{-\alpha}}{I_m^d + N_0} \tag{5.4}$$

$$\gamma_{d,m}^{NOS} = \frac{P_m^d d_d^{-\alpha}}{I_n^i + I_m^d + N_0} \tag{5.5}$$

where

$$I_n^i = d_{nr}^{-\alpha} P_n^i$$

$$I_m^d = d_{tr}^{-\alpha} P_{m'}^d$$

I_n^i and I_m^d denote the interference from the CUE to M2M receiver and from other M2M transmitters to M2M receiver, respectively and N_0 represents the power spectral density of the additive white Gaussian noise (AWGN). Whereas, P_m^d and P_n^i represent the transmit powers of the m^{th} MUE and the n^{th} CUE, respectively. Moreover, α and $P_{m'}^{d}$ denote the PL exponent and the transmission power of the co-tier interference link from the other MUE transmitter to the MUE receiver, respectively. In other words, d_{nr} and d_{tr} denote the distance from the CUE to M2M receiver and other M2M transmitters to M2M receiver, respectively. The orthogonal and non-orthogonal resource sharing ways based achievable data rate for m^{th} MUE, respectively then can be rewritten as

$$R_{d,m}^{OS} = B\log_2(1+\gamma_{d,m}^{OS}) \tag{5.6}$$

$$R_{d,m}^{NOS} = B\log_2(1+\gamma_{d,m}^{NOS}) \tag{5.7}$$

where B represents the allocated bandwidth of the considerable RBs. Each M2M pair consists of one transmitter and one receiver. The orthogonal and non-orthogonal resource sharing ways based total data rate of the direct mode are given by

$$R_d^T = \sum_{m=1}^{\frac{M_d}{2}} R_{d,m}^{OS} + \sum_{m=1}^{\frac{M_d}{2}} R_{d,m}^{NOS} \tag{5.8}$$

where M_d denotes the number of direct mode users. In the downlink phase, the orthogonal and non-orthogonal resource sharing methods based received SINR at the n^{th} CUE, respectively can be represented as follows

$$\gamma_{i,n}^{OS} = \frac{P_n^i d_i^{-\alpha}}{N_o} \tag{5.9}$$

$$\gamma_{i,n}^{NOS} = \frac{P_n^i d_i^{-\alpha}}{I_d^m + N_o} \tag{5.10}$$

where

$$I_d^m = d_{mr}^{-\alpha} P_m^d$$

I_d^m represents the interference from the MUE to the CUE receiver. Whereas, d_{mr} represents the distance from the MUE to the CUE receiver. The orthogonal and non-orthogonal resource sharing schemes based achievable data rate of the n^{th} CUE, respectively then can be rewritten as

$$R_{i,n}^{OS} = B\log_2(1+\gamma_{i,n}^{OS}) \tag{5.11}$$

$$R_{i,n}^{NOS} = B\log_2(1+\gamma_{i,n}^{NOS}) \tag{5.12}$$

The orthogonal and non-orthogonal resource sharing ways based total data rate of the indirect mode then can be expressed as follows

$$R_i^T = \sum_{n=1}^{\frac{N_i}{2}} R_{i,n}^{OS} + \sum_{n=1}^{\frac{N_i}{2}} R_{i,n}^{NOS} \tag{5.13}$$

where N_i denotes the number of indirect mode users. Hence, the total interference is originated in the proposed mechanism by CUE and MUE which are defined as

$$I_T = I_n^i + I_m^d + I_d^m \tag{5.14}$$

The achievable total data transmission rate of the proposed network then can be written as

$$R_T = R_d^T + R_i^T \tag{5.15}$$

The overall power consumption of the M2M link consists of two parts, such as power amplifier (PA) and circuit power [91-93]. The power consumed by m^{th} MUE and n^{th} CUE can be written as

$$P_t^d = \sum_{m=1}^{\frac{M_d}{2}} 2P_{c,m} + c_1 \sum_{m=1}^{\frac{M_d}{2}} P_m^d$$

$$P_t^d = \sum_{m=1}^{\frac{M_d}{2}} P_{c,m}^d + c_1 \sum_{m=1}^{\frac{M_d}{2}} P_m^d \tag{5.16}$$

$$P_t^i = \sum_{n=1}^{\frac{N_i}{2}} P_{c,n}^i + c_2 \sum_{n=1}^{\frac{N_i}{2}} P_n^i \tag{5.17}$$

where, P_t^d and P_t^i represent the total power consumption of the direct mode and indirect mode user, respectively. Moreover, $P_{c,m}^d$ and $P_{c,n}^i$ represent the total circuit power consumption of the m^{th} MUE and the n^{th} CUE, respectively. Whereas, c_1 and c_2 denote the reciprocal of drain efficiency for the PA of direct and indirect mode user, respectively. The total power consumption of the proposed mechanism can be written as follows

$$P_T = P_t^d + P_t^i \tag{5.18}$$

Then, the total EE of the proposed mechanism is given by

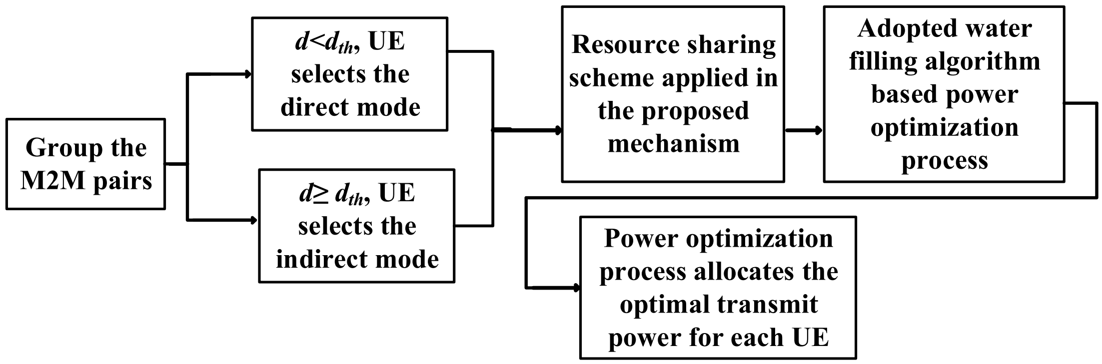


Fig. 5.2: The overall procedure of the location-aware power control mechanism.

$$\eta_{EE} = \frac{R_T}{P_T} \tag{5.19}$$

where η_{EE} represents the total EE. The per-user EE of the proposed mechanism is defined as

$$U_{EE} = \frac{\eta_{EE}}{M_T} \tag{5.20}$$

where U_{EE} and M_T represent the per-user EE and the total number of UEs, respectively in the proposed network.

5.3 Power Control Mechanism

To mitigate interference, the transmit power of UE needs to be controlled. At first, UE selects the suitable communication mode which depends on the mode selection threshold distance. Then, resource allocation between the MUEs and CUEs that share the resource in both orthogonal and non-orthogonal resource sharing ways are analyzed. A water filling algorithm and Lagrange decomposition scheme based power optimization process is adopted in the proposed mechanism. Then, the proposed algorithm allocates the proper optimal transmit power for each UE. The overall procedure of the location-aware power control mechanism for M2M communication is shown in Fig. 5.2.

5.3.1 Orthogonal resource sharing scheme based power optimization process using the water filling algorithm

Considering M2M communication over cellular networks, each UE has a minimum per-user data rate request, thus the transmit power of UE cannot provide insufficient or excess power. The orthogonal resource sharing scheme based proposed mechanism maximizes the per-user EE while considering the total data rate and the overall system power consumption. The orthogonal resource sharing scheme based energy-efficient power allocation for the direct and indirect UE can be converted into the following system optimization problem as

$$\max_{EE} \frac{\sum_{m=1}^{\frac{M_d}{2}} B\log_2(1+\gamma_{d,m}^{OS})}{\sum_{m=1}^{\frac{M_d}{2}} P_{c,m}^{d} + c_1 \sum_{m=1}^{\frac{M_d}{2}} P_m^d} \tag{5.21a}$$

$$\max_{EE} \frac{\sum_{n=1}^{\frac{N_i}{2}} B\log_2(1+\gamma_{i,n}^{OS})}{\sum_{n=1}^{\frac{N_i}{2}} P_{c,n}^{i} + c_2 \sum_{n=1}^{\frac{N_i}{2}} P_n^i} \tag{5.22a}$$

$$\text{s.t.} \quad P_{\max}^{OS,d} \geq P_m^d \geq 0 \tag{5.21b}$$

$$\sum_{m=1}^{\frac{M_d}{2}} B\log_2\left(1+\gamma_{d,m}^{OS}\right) \geq R_{d,m}^{OS,\min} \tag{5.21c}$$

$$P_{\max}^{OS,i} \geq P_n^i \geq 0 \tag{5.22b}$$

$$\sum_{n=1}^{\frac{N_i}{2}} B\log_2\left(1+\gamma_{i,n}^{OS}\right) \geq R_{i,n}^{OS,\min} \tag{5.22c}$$

where $R_{d,m}^{OS,\min}$ and $R_{i,n}^{OS,\min}$ denote the minimum required data rate of the orthogonal resource sharing scheme based direct mode and indirect mode user, respectively. Whereas, $P_{\max}^{OS,d}$ and $P_{\max}^{OS,i}$ represent the maximum transmission power of the orthogonal resource sharing scheme based direct mode and indirect mode UE, respectively. The problem (5.21b) and (5.22b) ensure that the transmit power is within the maximum power constraints of the m^{th} MUE and n^{th} CUE, respectively. On the other hand, equation (5.21c) and (5.22c) ensure the minimum user data rate for the orthogonal resource sharing scheme based proposed mechanism. The duality gap among problems (5.21) and (5.22) are zero [36], [94]. This means that the optimal solution of problem (5.21) and (5.22) can be achieved by applying the Lagrangian duality theory and decomposition method [36]. The orthogonal resource sharing scheme based Lagrangian dual function for the direct mode and indirect mode user of the problem (5.21) and (5.22), respectively can be obtained as

$$L_m^{OS,d}\left(P_m^d,\lambda_m^{OS,d},\mu_m^{OS,d}\right)=\sum_{m=1}^{\frac{M_d}{2}}(B\log_2(1+\gamma_{d,m}^{OS})-q_m^d(\sum_{m=1}^{\frac{M_d}{2}}P_{c,m}^d+c_1\sum_{m=1}^{\frac{M_d}{2}}P_m^d))$$

$$+\sum_{m=1}^{\frac{M_d}{2}}\lambda_m^{OS,d}(P_{\max}^{OS,d}-P_m^d)+\sum_{m=1}^{\frac{M_d}{2}}\mu_m^{OS,d}(\sum_{m=1}^{\frac{M_d}{2}}B\log_2(1++\gamma_{d,m}^{OS})-R_{d,m}^{OS,\min}) \quad (5.23)$$

$$L_n^{OS,i}\left(P_n^i,\lambda_n^{OS,i},\mu_n^{OS,i}\right)=\sum_{n=1}^{\frac{N_i}{2}}(B\log_2(1+\gamma_{i,n}^{OS})-q_n^i(\sum_{n=1}^{\frac{N_i}{2}}P_{c,n}^i+c_2\sum_{n=1}^{\frac{N_i}{2}}P_n^i))$$

$$+\sum_{n=1}^{\frac{N_i}{2}}\lambda_n^{OS,i}(P_{\max}^{OS,i}-P_n^i)+\sum_{n=1}^{\frac{N_i}{2}}\mu_n^{OS,i}(\sum_{n=1}^{\frac{N_i}{2}}B\log_2(1++\gamma_{i,n}^{OS})-R_{i,n}^{OS,\min}) \quad (5.24)$$

where q_m^d and q_n^i are the value of orthogonal resource sharing scheme based EE for the direct and indirect mode UE, respectively. In other words, $\lambda_m^{OS,d}$ and $\mu_m^{OS,d}$ are the orthogonal resource sharing scheme based Lagrange multipliers of the direct mode UE for transmission power and data rate constraints, respectively. Moreover, $\lambda_n^{OS,i}$ and $\mu_n^{OS,i}$ are the orthogonal resource sharing scheme based Lagrange multipliers of the indirect mode UE for transmission power and data rate constraints, respectively. Therefore, the dual problem is formulated as

$$\text{maximize } f\left(\lambda_m^{OS,d},\mu_m^{OS,d}\right)=\min L_m^{OS,d}\left(P_m^d,\lambda_m^{OS,d},\mu_m^{OS,d}\right) \quad (5.25a)$$

$$\text{s.t. } \lambda_m^{OS,d}\geq 0,\mu_m^{OS,d}\geq 0. \quad (5.25b)$$

$$\text{maximize } f\left(\lambda_n^{OS,i},\mu_n^{OS,i}\right)=\min L_n^{OS,i}\left(P_n^i,\lambda_n^{OS,i},\mu_n^{OS,i}\right) \quad (5.26a)$$

$$\text{s.t. } \lambda_n^{OS,i}\geq 0,\mu_n^{OS,i}\geq 0. \quad (5.26b)$$

We renumber $P_{m,d}^{OS^*}$ and $P_{n,i}^{OS^*}$ as the orthogonal resource sharing scheme based optimal power allocation to the m^{th} MUE and n^{th} CUE, respectively. Based on equation (5.21)-(5.26), the optimal power allocation of the m^{th} MUE and n^{th} CUE can be derived as the "water-filling" result [93]

$$P_{m,d}^{OS^*}=B\left[\frac{1+\mu_m^{OS,d}}{\left(q_m^d c_1+\lambda_m^{OS,d}\right)\ln 2}-\frac{d_{tr}^{-\alpha}P_{m'}^d+N_o}{d_d^{-\alpha}}\right]^+ \quad (5.27)$$

$$P_{n,i}^{OS^*}=B\left[\frac{1+\mu_n^{OS,i}}{\left(q_n^i c_2+\lambda_n^{OS,i}\right)\ln 2}-\frac{N_o}{d_i^{-\alpha}}\right]^+ \quad (5.28)$$

Table 5.1: Orthogonal resource sharing scheme based power optimization process using the water filling algorithm

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Initialization: $q(t)$, $\lambda(O)$ and $\mu(O)$ as zero vectors
Set $t = 0$
Repeat
  for $m = 1$to M **do**
    for $n = 1$ to N **do**
      if $d<d_{th}$
        Calculate $P_{m,d}^{OS*}$ according to (5.27)
        Update $\lambda_{m,t+1}^{OS,d}$ according to (5.29)
        Update $\mu_{m,t+1}^{OS,d}$ according to (5.31)
      end if
      if $d \geq d_{th}$
        Calculate $P_{n,i}^{OS*}$ according to (5.28)
        Update $\lambda_{n,t+1}^{OS,i,}$ according to (5.30)
        Update $\mu_{n,t+1}^{OS,i}$ according to (5.32)
      end if
        Update $q(t) = q(t+1)$
    end for
  end for
until Convergence

---

where $[.]^+$ represents the maximum of zero. We assume that t and v represent the update time and step size, respectively. By using the sub gradient method, then $\lambda_m^{OS,d}$ and $\lambda_n^{OS,i}$ can be updated as follows [36]

$$\lambda_{m,t+1}^{OS,d} = \left\{ \lambda_{m,t}^{OS,d} - v_m^{OS,d} \left[P_{\max}^{OS,d} - \sum_{m=1}^{\frac{M_d}{2}} P_m^d \right] \right\}^+ \tag{5.29}$$

$$\lambda_{n,t+1}^{OS,i} = \left\{ \lambda_{n,t}^{OS,i} - v_n^{OS,i} \left[P_{\max}^{OS,i} - \sum_{n=1}^{\frac{N_i}{2}} P_n^i \right] \right\}^+ \tag{5.30}$$

The orthogonal resource sharing scheme based data rate constraints of $\mu_m^{OS,d}$ and $\mu_n^{OS,i}$ can be performed with the subgradient method as follows [36]

$$\mu_{m,t+1}^{OS,d} = \left\{ \mu_{m,t}^{OS,d} + v_{OS,d}^m \left[R_{d,m}^{OS,\min} - \sum_{m=1}^{\frac{M_d}{2}} R_{d,m}^{OS} \right] \right\}^+ \tag{5.31}$$

$$\mu_{n,t+1}^{OS,i} = \left\{ \mu_{n,t}^{OS,i} + v_{OS,i}^n \left[R_{i,n}^{OS,\min} - \sum_{n=1}^{\frac{N_i}{2}} R_{i,n}^{OS} \right] \right\}^+ \tag{5.32}$$

where t is the iteration index, $v_m^{OS,d}$, $v_n^{OS,i}$, $v_{OS,d}^m$ and $v_{OS,i}^n$ are positive step sizes. The orthogonal resource sharing scheme based power optimization process using the water filling algorithm for problem (5.23) ad (5.24) are presented in Table 5.1.

5.3.2 Non-orthogonal resource sharing scheme based power optimization process using the water filling algorithm

Considering the M2M communication over cellular networks, the threshold interference (I_{th}) must be greater or equal to the power of receiving interference signals at the UE. The non-orthogonal resource sharing scheme based power allocation for the direct and indirect UE can be converted into the following system optimization problem as

$$\arg\min \sum_{m=1}^{\frac{M_d}{2}} \mathrm{P}_{\mathrm{m}}^{\mathrm{d}} \tag{5.33a}$$

$$\arg\min \sum_{n=1}^{\frac{N_i}{2}} P_n^i \tag{5.34a}$$

$$\text{s.t.} \quad \sum_{m=1}^{\frac{M_d}{2}} P_m^d d_{mr}^{-\alpha} \le I_{th} \tag{5.33b}$$

$$\sum_{m=1}^{\frac{M_d}{2}} R_{d,m}^{NOS} \ge R_{d,m}^{NOS,\min} \tag{5.33c}$$

$$\sum_{n=1}^{\frac{N_i}{2}} P_n^i d_{nr}^{-\alpha} \leq I_{th} \tag{5.34b}$$

$$\sum_{n=1}^{\frac{N_i}{2}} R_{i,n}^{NOS} \geq R_{i,n}^{NOS,\min} \tag{5.34c}$$

where $R_{d,m}^{NOS,\min}$ and $R_{i,n}^{NOS,\min}$ denote the minimum required data rate of the non-orthogonal resource sharing scheme based direct mode and indirect mode user, respectively. The problem (5.33a) and (5.34a) are to minimize the non-orthogonal resource sharing scheme based total power consumption of the m^{th} MUE and n^{th} CUE, respectively. In other words, equation (5.33b) and (5.34b) ensure that the receiving interference must be less than or equal to the threshold interference for non-orthogonal resource sharing scheme based proposed mechanism. Equation (5.33c) and (5.34c) ensure the minimum data rate for non-orthogonal resource sharing scheme based proposed mechanism of the m^{th} MUE and the n^{th} CUE, respectively. The non-orthogonal resource sharing scheme based Lagrangian dual function for the direct mode and indirect mode user of the problem (5.33) and (5.34) then can be written as

$$L_m^{NOS,d}\left(P_m^d, \lambda_m^{NOS,d}, \mu_m^{NOS,d}\right) = \sum_{m=1}^{\frac{M_d}{2}} P_m^d + \lambda_m^{NOS,d}\left(\sum_{m=1}^{\frac{M_d}{2}} P_m^d d_{mr}^{-\alpha} - I_{th}\right) + \mu_m^{NOS,d}\left(\sum_{m=1}^{\frac{M_d}{2}} R_{d,m}^{NOS} - R_{d,m}^{NOS,\min}\right) \tag{5.35}$$

$$L_n^{NOS,i}\left(P_n^i, \lambda_n^{NOS,i}, \mu_n^{NOS,i}\right) = \sum_{n=1}^{\frac{N_i}{2}} P_n^i + +\lambda_n^{NOS,i}\left(\sum_{n=1}^{\frac{N_i}{2}} P_n^i d_{nr}^{-\alpha} - I_{th}\right) + \mu_n^{NOS,i}\left(\sum_{n=1}^{\frac{N_i}{2}} R_{i,n}^{NOS} - R_{i,n}^{NOS,\min}\right) \tag{5.36}$$

where $\lambda_m^{NOS,d}$ and $\mu_m^{NOS,d}$ are the non-orthogonal resource sharing scheme based Lagrange multipliers of the direct mode UE for interference and data rate constraints, respectively. On the other hand, $\lambda_n^{NOS,i}$ and $\mu_n^{NOS,i}$ are the non-orthogonal resource sharing scheme based Lagrange multipliers of the indirect mode UE for interference and data rate constraints, respectively. The constraints of problem (5.35) and (5.36) are all affine and therefore, maintains the KKT condition [58]. We renumber $P_{m,d}^{NOS^*}$ and $P_{n,i}^{NOS^*}$ as the non-orthogonal resource sharing scheme based optimal power allocation to the m^{th} MUE and n^{th} CUE, respectively.

Therefore, the dual problem is formulated as

$$\text{maximize } f\left(\lambda_m^{NOS,d}, \mu_m^{NOS,d}\right) = \min \; L_m^{NOS,d}\left(P_m^d, \lambda_m^{NOS,d}, \mu_m^{NOS,d}\right) \tag{5.37a}$$

$$\text{s.t. } \lambda_m^{NOS,d} \geq 0, \mu_m^{NOS,d} \geq 0. \tag{5.37b}$$

$$\text{maximize } f\left(\lambda_n^{NOS,i}, \mu_n^{NOS,i}\right) = \min L_n^{NOS,i}\left(P_n^i, \lambda_n^{NOS,i}, \mu_n^{NOS,i}\right) \tag{5.38a}$$

$$\text{s.t. } \lambda_n^{NOS,i} \geq 0, \mu_n^{NOS,i} \geq 0. \tag{5.38b}$$

Based on equation (5.33)-(5.38), the non-orthogonal resource sharing scheme based optimal power allocation of the m^{th} MUE and n^{th} CUE can be derived as the "water-filling" result [93]

$$P_{m,d}^{NOS^*} = B\left[\frac{\mu_m^{NOS,d}}{\ln 2\ (\lambda_m^{NOS,d} d_{mr}^{-\alpha} + 1)} - \frac{d_{nr}^{-\alpha} P_n^i + d_{tr}^{-\alpha} P_{m'}^d + N_o}{d_d^{-\alpha}}\right]^+ \tag{5.39}$$

$$P_{n,i}^{NOS^*} = B\left[\frac{\mu_n^{NOS,i}}{\ln 2(\lambda_n^{NOS,i} d_{nr}^{-\alpha} + 1)} - \frac{d_{mr}^{-\alpha} P_m^d + N_o}{d_i^{-\alpha}}\right]^+ \tag{5.40}$$

By using the sub gradient method, then $\lambda_m^{NOS,d}$ and $\lambda_n^{NOS,i}$ can be updated as follows [93]

$$\lambda_{m,t+1}^{NOS,d} = \left\{\lambda_{m,t}^{NOS,d} - v_m^{NOS,d}\left[I_{th} - \sum_{m=1}^{\frac{M_d}{2}} P_m^d d_{mr}^{-\alpha}\right]\right\}^+ \tag{5.41}$$

$$\lambda_{n,t+1}^{NOS,i} = \left\{\lambda_{n,t}^{NOS,i} - v_n^{NOS,i}\left[I_{th} - \sum_{n=1}^{\frac{N_i}{2}} P_n^i d_{nr}^{-\alpha}\right]\right\}^+ \tag{5.42}$$

The data rate constraint of $\mu_m^{NOS,d}$ and $\mu_n^{NOS,i}$ can be performed with the subgradient method as follows [36]

$$\mu_{m,t+1}^{NOS,d} = \left\{\mu_{m,t}^{NOS,d} + v_{NOS,d}^m\left[R_{d,m}^{NOS,\min} - \sum_{m=1}^{\frac{M_d}{2}} R_{d,m}^{NOS}\right]\right\}^+ \tag{5.43}$$

$$\mu_{n,t+1}^{NOS,i} = \left\{\mu_{n,t}^{NOS,i} + v_{NOS,i}^n\left[R_{i,n}^{NOS,\min} - \sum_{n=1}^{\frac{N_i}{2}} R_{i,n}^{NOS}\right]\right\}^+ \tag{5.44}$$

The Lagrangian multiplier vector λ and μ can be initialized as zero vectors. Then, $v_m^{NOS,d}$, $v_n^{NOS,i}$, $v_{NOS,d}^m$ and $v_{NOS,i}^n$ the step size v is sufficiently small, which indicates that the convergence of the proposed water filling algorithm is guaranteed. Finally, the non-orthogonal resource sharing scheme based power optimization process using the water filling algorithm is presented in Table 5.2.

Table 5.2: Non-orthogonal resource sharing scheme based power optimization process using the water filling algorithm

Initialization: $\lambda(O)$ and $\mu(O)$ as zero vectors
Set $t = 0$
Repeat
  for m = 1 to M **do**
    for n = 1 to N **do**
      if $d<d_{th}$
        Calculate $P_{m,d}^{NOS*}$ according to (5.39)
        Update $\lambda_{m,t+1}^{NOS,d}$ according to (5.41)
        Update $\mu_{m,t+1}^{NOS,d}$ according to (5.43)
      end if
      if $d \geq d_{th}$
        Calculate $P_{n,i}^{NOS*}$ according to (5.40)
        Update $\lambda_{n,t+1}^{NOS,i,}$ according to (5.42)
        Update $\mu_{n,t+1}^{NOS,i}$ according to (5.44)
      end if
    end for
  end for
until Convergence

5.4 Simulation Results and Analysis

5.4.1 Simulation setup

Substantial MATLAB based simulation results are presented to evaluate the performance of the proposed mechanism. The BS is placed in the centre and fifty number of UEs are randomly situated in the proposed network. The d is adopted to be available at the corresponding machines, which can inform the value of d periodically in the simulation area. Each figure is the result of the average of at least 1000 channel realizations.

The total fifty number of RBs are considered in the proposed mechanism. The performance metric is evaluated under various changing parameters, such as the number of UEs, mode selection threshold distance, transmission power, various data rate requirement of each UE, circuit power of M2M transmitter and overall system interference, etc. Then, the overall system interference varies from -30 dBm to -10 dBm in the proposed network. All the

Table 5.3: Power Control Mechanism Simulation Parameters

Parameters	**Settings**
Carrier frequency	2 GHz
Bandwidth per RB	180 KHz
Total channel bandwidth	9 MHz
Radius of cell	250m
Mode selection threshold distance	50m-150m
Maximum transmit power of MUE	21 dBm
Circuit power consumption of UE	100 mW
Drain efficiency of power amplifier	0.38
Maximum transmit power of CUE	30 dBm
Various data rate requirement of each UE	2-20 bps/Hz/user
Number of simulations	1000
Noise spectral density	-174 dBm/Hz
PL exponent	4 dB
Shadow fading standard deviation (BS-UE), σ	8 dB
Shadow fading standard deviation (UE-UE), σ	4 dB

simulation related parameters are listed in Table 5.3, whereas the settings in each figure take precedence. The performance of the orthogonal and non-orthogonal resource sharing scheme based proposed mechanisms are compared with different modes, such as

OS based direct mode: The orthogonal resource sharing scheme based UE selects the direct mode without using the power control (PC) mechanism is called the OS based direct mode.

OS based indirect mode: The orthogonal resource sharing scheme based UE selects the indirect mode without using the PC mechanism is called the OS based indirect mode.

OS based hybrid mode (PC): The orthogonal resource sharing scheme based UE selects the appropriate communication mode, such as direct or indirect mode using the PC mechanism is called the OS based hybrid mode (PC).

NOS based direct mode: The non-orthogonal resource sharing scheme based UE selects the direct mode without using the PC mechanism is called the NOS based direct mode.

NOS based indirect mode: The non-orthogonal resource sharing scheme based UE selects the indirect mode without using the PC mechanism is called the NOS based indirect mode.

NOS based hybrid mode (PC): The non-orthogonal resource sharing scheme based UE selects the appropriate communication mode, such as direct or indirect mode using the PC mechanism is called the NOS based hybrid mode (PC).

5.4.2 Results and analysis

Fig. 5.3 represents the cumulative distribution function (CDF) curves of the overall system interference for the proposed mechanism. It can be seen from the figure that the CDF under the proposed mechanism is shifted towards higher value. It is observed that the hybrid mode suffers the lower interference than that the other modes and indirect mode suffers more interference in the proposed network. This is due to the fact that for a large number of UEs,

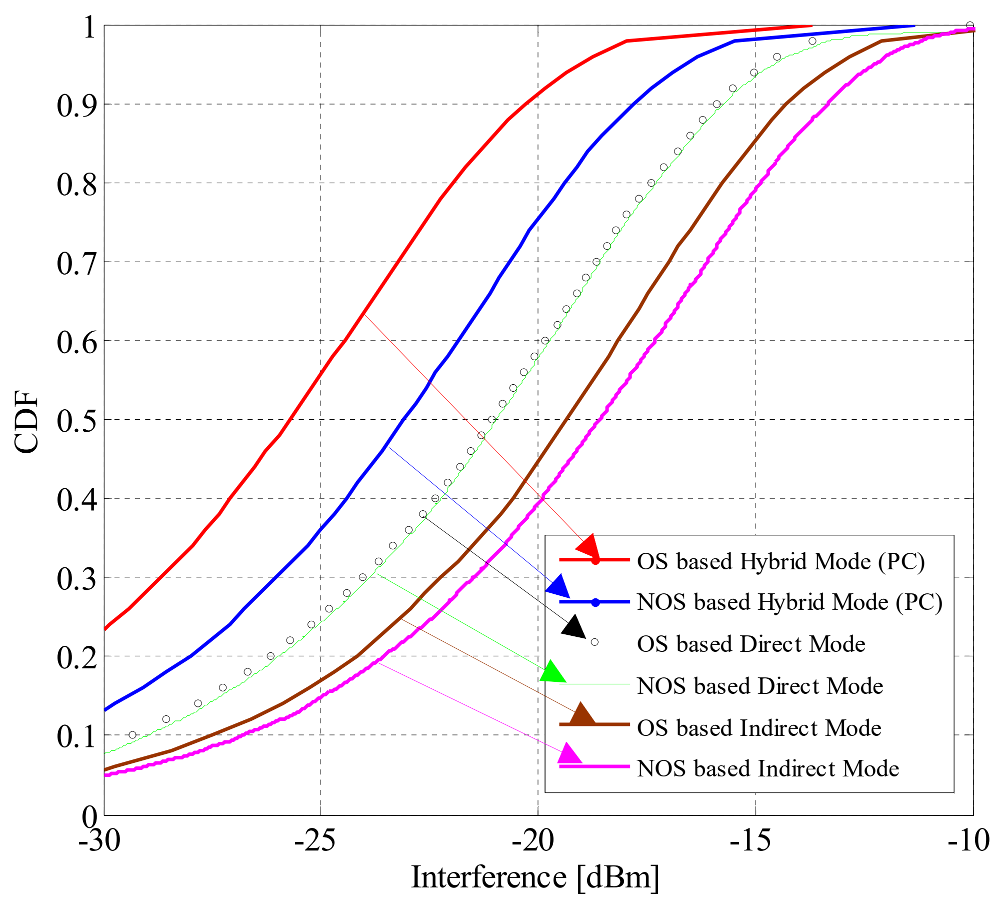

Fig. 5.3: CDF of the overall system interference for different modes.

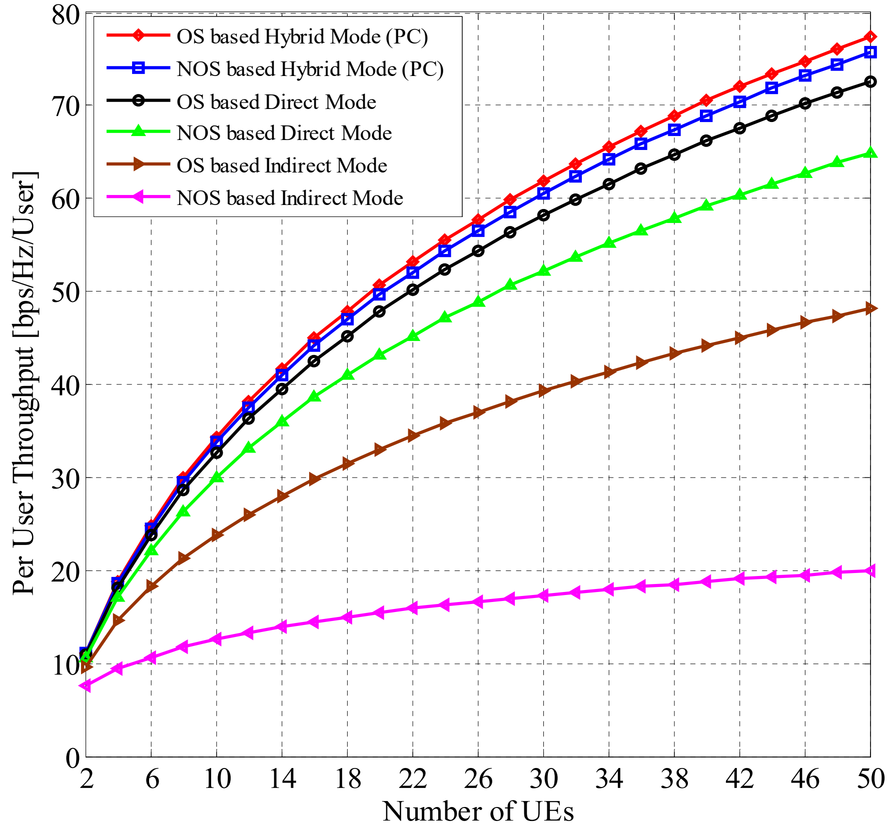

Fig. 5.4: Per-user throughput variation with respect to the number of UEs for different modes.

most of the UE chooses the suitable communication mode and then the proposed mechanism uses the proper optimal transmission power which mitigates the interference. Hence the proposed mechanism is crucial to the M2M system performance. As illustrated in Fig. 3, the non-orthogonal resource sharing based proposed mechanism suffers more interference compared to the orthogonal resource sharing scheme based proposed mechanism. This is because for a larger number of UEs, most of the UEs are sharing the same RBs in the proposed network. Besides, it is decided that the location-aware proposed mechanism can substantially mitigate the interference compared to the direct and indirect modes.

Fig. 5.4 depicts the per-user throughput versus the number of UEs with different modes. It can be observed that the per-user throughput increases with the number of UEs. We can see that the non-orthogonal resource sharing scheme based proposed mechanism achieves worse network performance compared to the orthogonal resource sharing scheme based proposed mechanism. This is due to the fact that for a large number of UEs, when the more UEs are sharing the same frequency which suffers more co-tier and cross-tier interference and thus degrades the per-user throughput. It can be decided that the proposed mechanism allows orthogonal resource sharing between MUE and CUE links to achieve the superior system performance in terms of per-user throughput. This is because for orthogonal resource sharing scheme based proposed mechanism can significantly mitigate the interference which improves the user throughput. Finally, we can conclude that the resource sharing scheme based proposed mechanism can improve the per-user throughput without deteriorating the QoS of the UEs.

Fig. 5.5 demonstrates the per-user transmit power variation with respect to the mode selection threshold distance for the proposed mechanism. This figure uses fifty number of UEs in the proposed network. We can observe that the mode selection threshold distance increases with the increase of the per–user transmit power. The proposed PC mechanism is consumed the lower power compared to the without PC mechanism. From this figure, the direct mode UE consumes more power than that the hybrid mode UE and less than that of

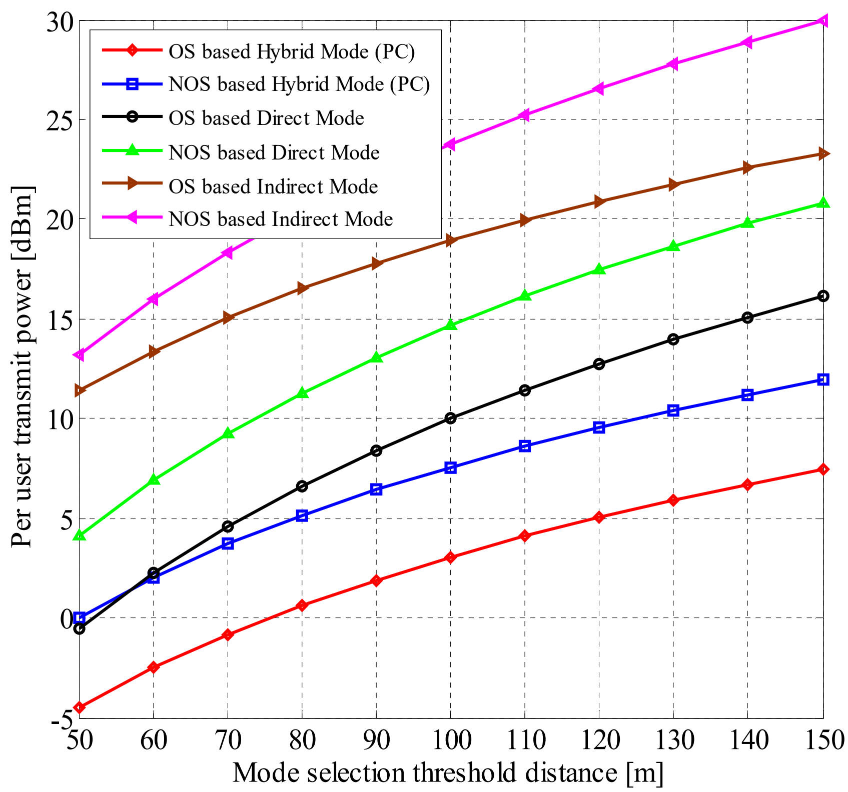

Fig. 5.5: Per-user transmit power variation with respect to the mode selection threshold distance for different modes.

the indirect mode UE. This is due to the fact that for a large number of UEs, water filling algorithm allocates the proper optimal transmit power for each UE. As a result, hybrid mode UE reduces the power consumption in the proposed network. We can decide that the hybrid mode outperforms than that the other modes. It can be seen that the transmission power of UEs operating the non-orthogonal resource sharing based proposed mechanism is always higher than that of the orthogonal resource sharing based proposed mechanism. This is because when the UE uses the non-orthogonal resource sharing scheme which suffers the more co-tier and cross-tier interference and thus degrades the system performance. Therefore, additional transmit power is required in non-orthogonal resource sharing scheme to fulfill the same QoS requirement with respect to the orthogonal resource sharing scheme.

Fig. 5.6 illustrates the impact of the overall system interference on the per-user EE for different modes. It is observed that the overall system interference increases with the decrease of the per-user EE, which is due to the increased interference power from MUEs to CUEs and vice versa. This is because larger interference results in worse system performance

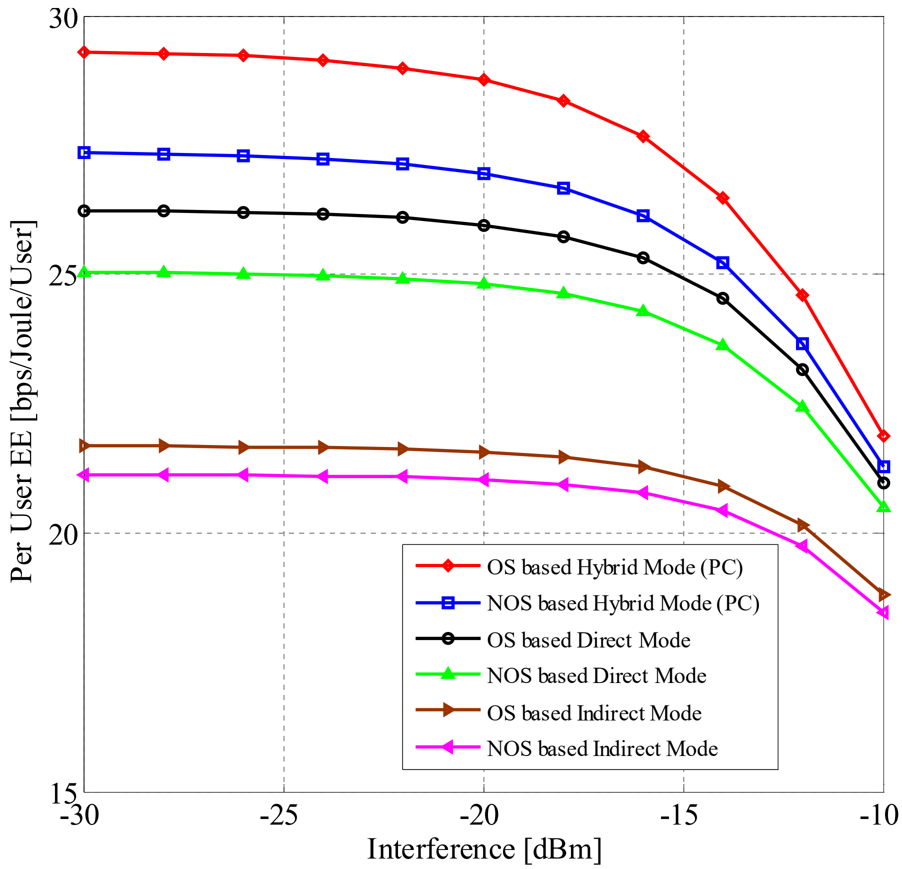

Fig. 5.6: Impact of the overall system interference on the per-user EE for different modes.

and thus provides the lower per-user EE. We can decide that the overall system interference between the M2M pairs have a large effect on network performance. From this figure, when total system interference increases from -30 dBm to -20 dBm, the per-user EE decreases slowly. It can be seen from the figure that the resource sharing scheme based proposed mechanism achieves superior system performance in the proposed network. This is due to the fact that the location-aware mode selection assisted water filling algorithm allocates the proper optimal transmit power for each UE which substantially reduces the power consumption. Therefore, we can conclude that the orthogonal resource sharing scheme based proposed mechanism substantially reduces the interference and thus improves the network performance compared to the direct and indirect modes.

Fig. 5.7 shows the per-user EE variation with respect to the number of UEs for the proposed mechanism. It is observed that the per-user EE enhances significantly with the increase of UEs. Moreover, we can see that while using the smallest number of UE,

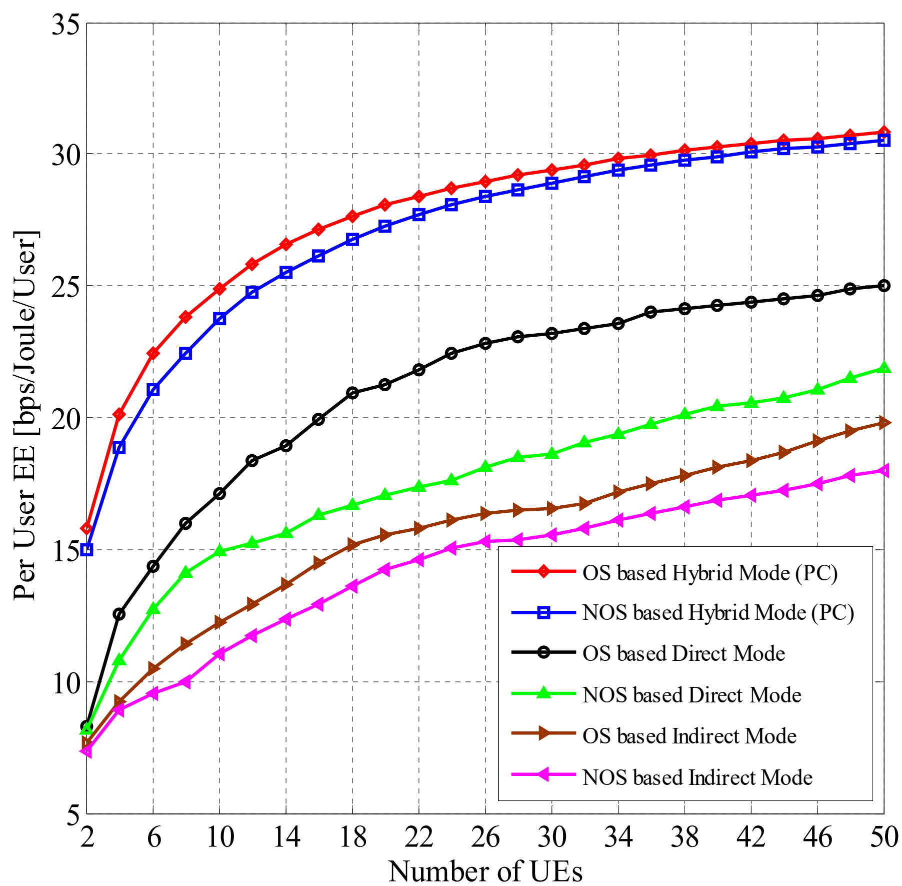

Fig. 5.7: Per-user EE variation with respect to the number of UEs for different modes.

per-user EE improves rapidly. From this figure, it can be seen that the direct mode achieves more per-user EE than the indirect mode and less than that of the hybrid mode. This is due to the fact that for a larger number of UEs, indirect mode UE suffers heavy interference which degrades the per-user EE. It is decided that the higher interference provides the lower per-user EE. Therefore, we can tell that the interference between M2M pairs have a large effect on system performance. The system performance of the proposed mechanism grows almost linearly with the rise of UEs, which indicates that the proposed mode selection mechanism can be widely used in different modes. The orthogonal resource sharing scheme based proposed mechanism outperforms compared to the non-orthogonal resource sharing scheme based proposed mechanism. Moreover, it is also shown that the orthogonal resource sharing scheme based proposed mechanism improves the system performance with the increase of the UEs due to select the suitable communication mode.

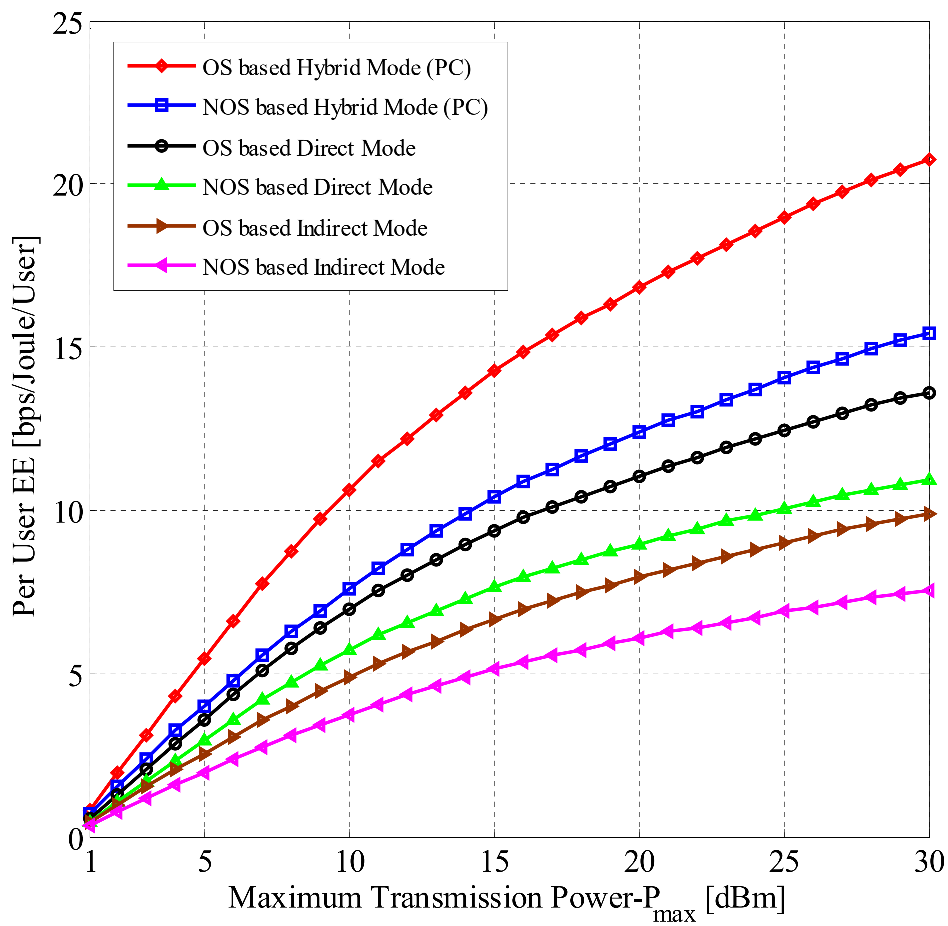

Fig. 5.8: Impact of varying the maximum transmission power of UE on the per-user EE for different modes.

Fig. 5.8 provides the per-user EE variation with respect to the maximum transmission power of UE for different modes. We can observe that the transmission power of UE increases with the increase of the per-user EE quickly. This is because that the M2M transmitter transmits higher transmission power which improves the data rate in order to fulfil the higher per-user EE. It can be seen from the figure 5.4 that the proposed PC mechanism consumes the lower power compared to the without PC mechanism. This is due to the fact that for a large number of UEs, water filling algorithm allocates the proper optimal transmit power for each UE which substantially reduces the power consumption of UE and also leads the per- user data rate, thus improves the per-user EE. This figure shows that the M2M communications using the orthogonal resource sharing scheme based proposed mechanism achieves higher EE without the need of additional transmission power. Furthermore, it is noticed that the proposed mechanism can substantially mitigate the co-tier and cross-tier interference which improve the system performance in terms of the per-user EE.

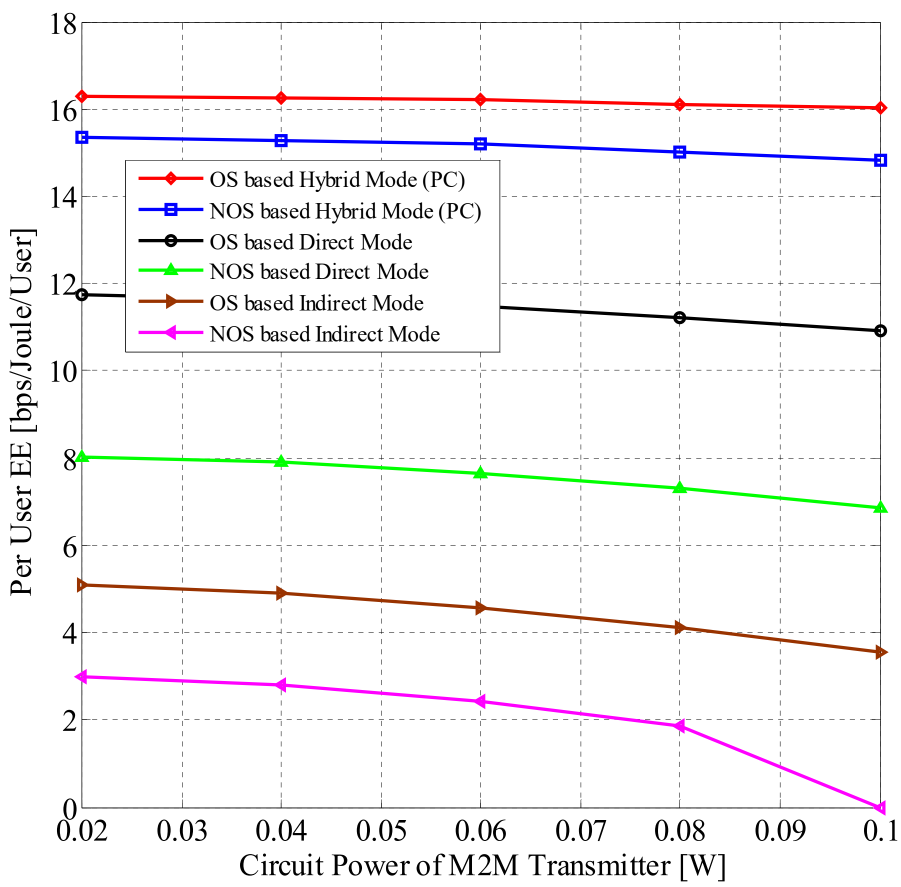

Fig. 5.9: Impact of the circuit power of M2M transmitter on the per-user EE for different modes.

Fig. 5.9 depicts the per-user EE versus the circuit power of the M2M transmitter. It can be seen that the per-user EE decreases with the increase of the circuit power of M2M transmitter. However, when the circuit power of M2M transmitter increases, the hybrid mode outperforms compared to the other modes. This is due to the fact that the orthogonal resource sharing scheme based hybrid mode UE substantially reduces the total power consumption by dominating the circuit power of M2M transmitter. It is decided that the proposed mechanism improves the system performance which is more crucial for limited capacity of battery.

Fig. 5.10 demonstrates the impact of varying the mode selection threshold distance on the per-user EE for different modes. We can observe that the per-user EE decreases with the increase of the mode selection threshold distance. This is because the UE suffers more interference which degrades the per-user EE. Moreover, it can be seen from the figure that

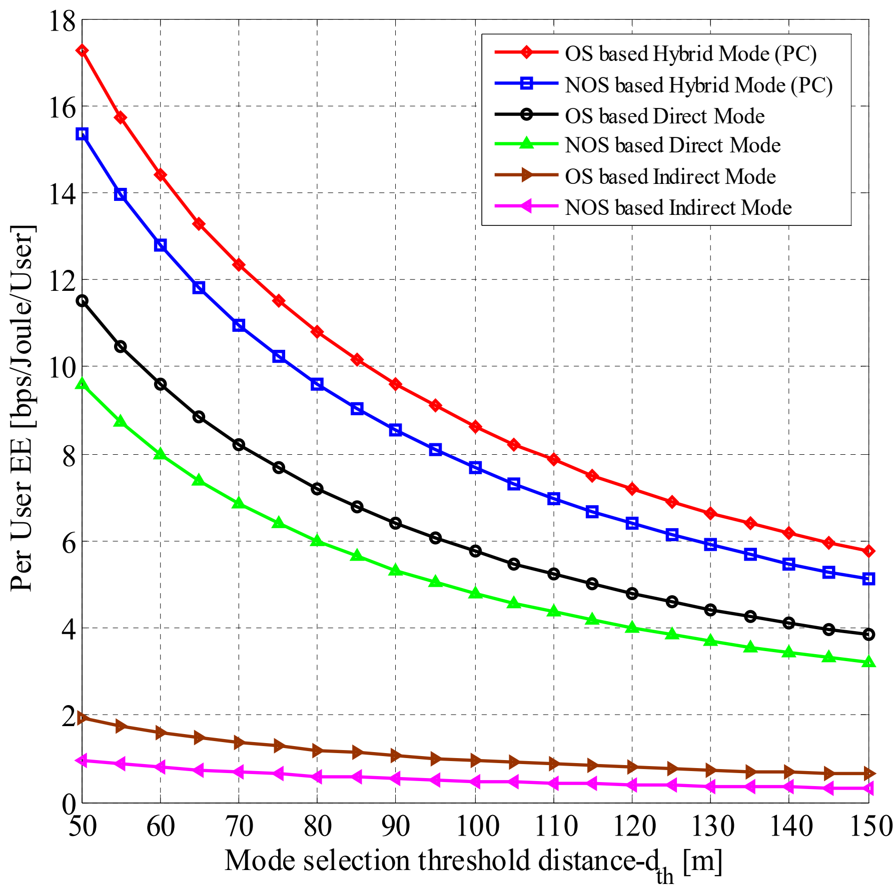

Fig. 5.10: Impact of varying the mode selection threshold distance on the per-user EE for different modes.

the mode selection threshold increases from 50m to 80m, thus the per-user EE reduces quickly. When the mode selection threshold distance is enhanced, the UE needs more transmit power. This is due to the fact that the higher transmission of UE is essential if the mode selection threshold distance enhances to overcome the deteriorating channel situation. Besides, we can decide that the mode selection threshold distance between the M2M pairs have a large effect on network performance. From this figure, it is observed that the orthogonal resource sharing scheme based proposed mechanism achieves superior system performance in the proposed network. This is because for a large number of UEs, when the more UEs are sharing the orthogonal frequency which substantially mitigates the interference and thus provides the higher per-user EE. Finally, we can conclude that the network performance substantially improves by using the proposed mechanism and consequently, the proposed mechanism mitigates the interference if the mode selection threshold distance increases.

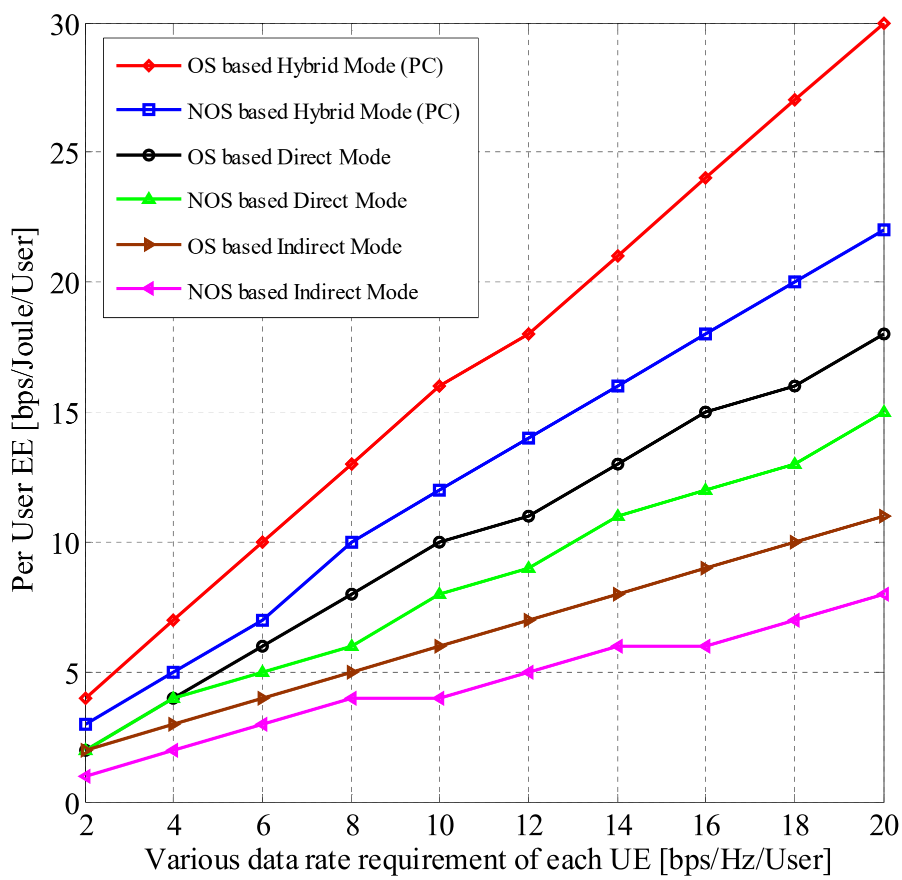

Fig. 5.11: Per-user EE performance comparisons under various data rate constraint for different modes.

Finally, Fig. 5.11 shows the per-user EE variation with various data rate requirement of each UE for different modes. It is observed that the per-user EE enhances with the increase of various data rate requirement of each UE approximately linearly. The proposed mechanism achieves superior system performance in the proposed network. This is due to the fact that each UE uses the proper optimal transmission power to satisfy the QoS constraints, which means that the location-aware information of M2M pair uses the water filling algorithm based power optimization process. In particular, the power optimization process adjusts the transmit power for each UE which generates low interference and thus improves the system performance. Based on these results, the orthogonal resource sharing scheme based hybrid mode selection mechanism achieves superior system performance compared to the other modes in terms of the per-user EE.

5.5 Conclusion

This paper has proposed a location-aware communication mode selection based power control mechanism for M2M communications over cellular networks. The M2M pairs have automatically selected the appropriate communication mode either direct mode or indirect mode according to the proposed mode selection scheme. RBs allocation between the MUEs and CUEs that share the resources in both orthogonal and non-orthogonal ways have analyzed for different modes. The power control mechanism has allocated the proper optimal transmit power for each UE using the water filling algorithm. Performance of the proposed mechanism has been evaluated using extensive MATLAB simulations. It has been found that the number of UEs, transmission power, communication mode selection threshold distance, circuit power of M2M transmitter, various data rate requirement of each UE and overall system interference have substantial impact on the system performance. Simulation results have shown that the proposed mechanism has mitigated the cross-tier and co-tier interference and thus has provided the higher throughput as well as higher EE in the proposed network. Besides, the orthogonal resource sharing scheme based proposed mechanism can significantly mitigate the interference that improved the system performance in terms of the per-user throughput and EE compared to the non-orthogonal resource sharing scheme based proposed mechanism

CHAPTER 6

CONCLUSIONS AND FUTURE WORKS

6.1 Conclusions

In order to make the implementation of M2M communications a reality, numerous technical issues needed more investigations. Integration of location information of UMs in designing power control and communication mode selection is the main contribution of the thesis. By permitting direct communication among the mobile UEs, which can communicate offload from cellular BSs and improve the system performance in terms of the per-user data rate and per-user EE. The key contributions can be outlined as follows

Chapter 3 presents the proposed localization architecture for M2M communications over cellular networks. Proposed localization architecture has used a TDOA based WLS algorithm. Then, the localization architecture has estimated the UM locations which improved the localization accuracy. For performance evaluation of the proposed architectures in terms of RMSE have been analyzed.

In Chapter 4, a location-aware RBs allocation policy and communication mode selection mechanism for M2M communications over cellular networks have been presented. The M2M pairs have automatically selected the appropriate communication mode either direct mode or indirect mode according to the proposed mode selection scheme. Furthermore, the proposed mechanism has allocated RBs based on the selected mode. The proposed mechanism has analyzed in terms of channel utilization and per-user throughput. The simulation results have shown that the proposed mode selection scheme before data transfer can improve network performance. In the proposed network, mode selection threshold distance has varied from 50m to 150m. When the threshold distance has increased from 50m to 60m, it has been increasing the percentage of direct mode UEs and decreased the percentage of indirect mode UEs. The simulation has been done for fifty number of UEs, after that the throughput has increased rapidly with the increment of UEs. Besides, hybrid mode selection mechanism has achieved superior system performance in terms of the per-user throughput.

In Chapter 5, a location-aware power control mechanism has been proposed. The integration of location information of UMs in designing power control mechanism improves the performance of 5G networks.

6.2 Major Contribution of this Research Works

This subsection summarizes the major contribution of this research. Some of the major contribution of this research are discussed below.

Resource allocation between the MUEs and CUEs that shared the resource in both orthogonal and non-orthogonal ways have analyzed for different modes. A water filling algorithm and Lagrange decomposition scheme based power optimization process has adopted in the proposed mechanism. The power control mechanism has allocated the proper optimal transmit power for each UE using the water filling algorithm. Therefore, the proposed mechanism has mitigated the cross-tier and co-tier interference and thus has provided the higher throughput as well as higher EE in the proposed network. Besides, the proposed mechanism has been evaluated under various network parameters, such as the density of machines, M2M transmission distance, circuit power of M2M transmitter and M2M transmit power etc.

The feasibility of the proposed mechanism has been investigated by comparing the hybrid mode with the other two modes. However, the lower number of RBs have provided the lower traffic burden in the proposed mechanism. In the proposed mechanism, direct mode UE has used the lower number of RBs compared to the indirect mode UE. When the number of UEs have increased, most of the UEs have selected the direct mode in the proposed network. Therefore, the direct mode of communication has reduced the traffic burden on cellular BSs in terms of channel utilization. It has been found that the proposed hybrid mode selection mechanism achieved superior system performance in terms of per-user throughput and per-user EE compared to different modes. Finally, a resource sharing scheme based proposed power control mechanism has been analyzed in terms of the per-user throughput and per-user EE. The orthogonal resource sharing scheme based proposed mechanism has substantially mitigated the interference which improves the system performance compared to the non-orthogonal resource sharing scheme based proposed mechanism.

6.3 Future Research Directions

From the current stage of the research work presented in this thesis, it can be extended in several directions. Some of the potential open issues are outlined below.

6.3.1 Interference mitigation for multi-cell system

In chapter 4, the proposed mode selection based RBs allocation policy is discussed. A crucial but challenging extension of this work is to consider direct based M2M communication where cellular resources are reused by M2M communications. Direct mode communication scenarios can improve the spectral efficiency in the proposed network. However, interference is produced between MUE and CUE which is a tough issue to mitigate. Furthermore, the proposed mode selection algorithm based RB optimization policy can be developed during this thesis. On the other hand, a future research direction is to include power control for M2M users and extend this analysis in a multi-cell environment, by considering intra-cell and inter-cell interference.

6.3.2 Millimeter wave (mmWave) M2M communication

Finally, investigate the interplay between M2M communications and massive MIMO in other higher frequency bands, such mmWave will be an interesting future direction. In mmWave systems, we need directivity gain to compensate for serve channel attenuation. This directionality, however, promises a significant gain in M2M communications due to a substantially lower amount of multiuser interference in mmWave networks.

6.3.3 M2M Communications with energy harvesting

Energy harvesting for M2M communications is worth to be investigated because UEs have limited battery capacity. Therefore, UEs can be equipped with the energy harvesting module and harvest energy from other sources and help in M2M communications.

6.3.4 M2M in heterogeneous and ultra-dense networks

Both small cell and M2M communications have the potential to offload traffic from the cellular network. Therefore, further work can be done to study the coexistence between M2M and small cell and their cooperation to improve the EE in the network. The performance of EE M2M communication underlays small cell network while taking into account the backhaul energy consumption can be investigated. Furthermore, ultra-dense networks are one of the emerging technologies for future wireless systems. In this type of network, CUEs and MUEs will be within the coverage of multiple small cells. Thus mitigating interference and improving the EE becomes complex and requires further investigation.

6.3.5 NOMA-M2M scenarios

The works that considered the existence of NOMA and M2M communications are still limited. M2M users can implement NOMA protocol where a MUE transmits to several MUEs in the group. To improve system performance, M2M users can communicate in underlay mode and share the resources of other NOMA users. However, the current works have not considered the capability of resource-constrained M2M users who have to perform power domain multiplexing at the MUE transmitter and SIC at the MUE receiver. Furthermore, cooperative NOMA-M2M scenario can be investigated.

List of Publications

The contributions of this thesis have been published international conferences as listed below.

International Conferences

[1] S. K. Das and M. F. Hossain, "A Location-Aware Communication Mode Selection Mechanism in M2M Communications over Cellular Networks", *Proceedings of the 2019 5th International Conference on Advances in Electrical Engineering (ICAEE)*, pp. 335-340, 26-28 September, Dhaka, Bangladesh.

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