Applications of Machine to Machine Communication in Remote Healthcare Systems

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DECLARATION

I certify that the work contained in this thesis, or any part of it, has not been accepted in substance for any previous degree awarded to me, and is not concurrently being submitted for any degree other than that of Doctor of Philosophy being studied at the University of Greenwich. I also declare that this work is the result of my own investigations, except where otherwise identified by references and that the contents are not the outcome of any form of research misconduct.

Signed:

Student ……………………………………

First Supervisor ……………………………

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ABSTRACT

Wireless Machine-To-Machine (M2M) communications in healthcare systems will play a large part in the medical sector in the near future, enabling a number of applications to speed up medical treatment, decreasing the cost, and increasing the flexibility and efficiency of the hospitals and medical bodies. The work undertaken in this thesis is to improve the spectrum and energy efficiency of M2M communications in the medical sector by exploiting Cognitive radio (CR) technology.

First, The thesis considered an efficient aggregation-based spectrum assignment algorithm for Cognitive Machine-To-Machine (CM2M) networks. The proposed algorithm takes practical thresholds including Co-Channel Interference (CCI) among CM2M devices, interference to the Primary Users (PUs), and Maximum Aggregation Span (MAS) into consideration. Simulation results clearly show that the developed algorithm outperforms State Of The Art (SOTA) algorithms in terms of network capacity and spectrum utilization. The developed algorithm can improve data rate of CM2M devices by at least 23% compared with the SOTA algorithms.

Furthermore, this thesis presents an optimal energy efficient spectrum management mechanism with multiple thresholds. The developed mechanism aims to reduce energy consumption in the system by optimizing spectrum sensing and channel switching, while at the same time decreasing the probability of collision and assuring the reliability thresholds, throughput, and delay. Subsequently, an Antenna Selection Sensing (ASS) scheme is used to improve sensing accuracy. The simulation results show that the energy efficiency of the CM2M gateways can be improved by at least 35%.

In addition, the thesis considered an Energy-Efficient Channel Selecting (EECS) algorithm for CM2M communications in the healthcare system. The proposed algorithm aims to select the best available channels to improve CM2M communication quality and reduce energy consumption in the system overall. Accordingly, the algorithm reduced the probability of CM2M gateways switching between available channels and improved the energy efficiency by at least 45%. The efficiency of the algorithm is discussed and demonstrated through simulations.

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ABBREVIATIONS

(3GPP)	3rd Generation Partnership Project
(AASAA)	Aggregation Aware Spectrum Assignment Algorithm
(ABI)	Allied Business Intelligence
(AI)	Artificial Intelligence
(ASS)	Antenna Selection Sensing
(CA)	Carrier Aggregation
(CCI)	Co-Channel Interference
(CM2M)	Cognitive Machine to Machine
(CR)	Cognitive Radio
(CRN)	Cognitive Radio Network
(CSCG)	Circularly Symmetric Complex Gaussian
(COPD)	Chronic Obstructive Pulmonary Disease
(CHF)	Congestive Heart Failure
(DOFDM)	Discontinuous Orthogonal Frequency Division Multiplexing
(DSA)	Dynamic Spectrum Access
(EWA)	Experience-Weighted Attraction
(EIU)	Economist Intelligence Unit
(ECG)	Electrocardiogram
(EE)	Energy Efficient
(EECS)	Energy Efficient Channel Selection
(EMI)	Electromagnetic Interferences
(ETSI)	European Telecommunications Standards Institute
(EWAH)	EWA Handoff (EWAH)
(FCC)	Federal Communications Commission
(FDA)	Food and Drug Administration
(FQL)	Fuzzy Q Learning
(GA)	Genetic Algorithm
(IBSG)	Internet Business Solutions
(IoT)	Internet of Things
(ISM)	Industrial, Scientific, And Medical
(LTE-A)	Long-Term Evolution Advance
(LUs)	Licensed Users
(M2M)	Machine to Machine
(MAS)	Maximum Aggregation Span

(MSA)	Maximum Aggregation Span
(MSR)	Maximising Sum of Reward
(MBAN)	Medical Body Area Network
(MSRA)	MSR Algorithm
(OFDM)	Orthogonal Frequency-Division Multiplexing
(OFDMA)	Orthogonal Frequency-Division Multiplexing Access
(PN)	Primary Network
(PUs)	Primary Users
(QoS)	Quality of Service
(QPSK)	Quadrature Phase Shift Keying
(RCAA)	Random Channel Assignment Algorithm
(SA)	Spectrum aggregation
(SAS)	Single Antenna Sensing
(SDR)	Software Defined Radio
(SNR)	Signal-To-Noise Ratio
(SOTA)	State-Of-The-Art
(SUs)	Secondary Users
(TBS)	Turn Based Strategy
(TVWS)	TV White Spaces
(UHF)	Ultra-High Frequency
(WMTS)	Wireless Medical Telemetry Service
(WRAN)	Wireless Regional Area Network
(WSN)	Wireless Sensor Networks

SYMBOLS

B	Reward vector
$\boldsymbol{LL}$	Channel availability matrix
ϕ_N	n^{th} CM2M devices number
y_M	m^{th} Channel number
N	CM2M devices
M	Non-Overlapping orthogonal channels
$\hat{\text{ɼ}}_n$	Available channels at ϕ_N location
$\boldsymbol{AA}$	The interference constraint matrix
R	Device requested bandwidth vector
r_n	Bandwidth demand of ϕ_N
Δf	Bandwidth of sub-channel
w_n	The number of requested sub-channels by ϕ_n
₦	The set of natural numbers
BW_m	The bandwidth of y_m
$\mathcal{F}_{i,m,}^{L}$	Lowest frequency of $\tilde{y}i,m$
$\mathcal{F}_{i,m,}^{H}$	Highest frequency of $\tilde{y}i,m$
a	Index of each sub-channel within the available spectrum
DD	The sub-channel assignment matrix
$\|.\|$	Cardinality of a set
U	Network utilisation function
k_m	Number of sub-channels in channel in y_m
BW	Channel bandwidth
$\tilde{y}i,m$	i^{th} Sub-Channel of y_m
Ł	Network load
PL	Path loss model
u	The ratio of the sum of rewarded bandwidth to the sum of all available bandwidth
T	Transmission slot duration
τ_s	Sensing slot duration
Pf	False alarm probability
Pd	Detection probability
fs	Sampling frequency
fc	Carrier frequency

$\bar{P}f$	Target false alarm probability
$\bar{P}d$	Target probability of detection
τ_s^{min}	Minimum sensing duration to achieve the reliability probabilities constraints
$(1 - L_s)$	The probability that CM2M gateways will switch to another free channel
L_s	The probability that CM2M gateways will wait and sleep in the current sensed channels
X	Overall energy cost needs to finish transmitting one packet of data
S	The time needs for the CM2M gateways to send a packet of data
$\mathcal{R}$	The average data rate or throughput
r	The minimum throughput that should be achieved in the system
P_3	The switching probability to another idle channel
P_1	The probability of a channel being idle
Pb	The probability of a channel being busy
pfc	Probability of collision between CM2M gateways
J_{sw}	The energy cost for single channel
E_t	Power cost per second due to sending data
E_s	Power cost per second due to sensing process
C_0	M2M gateways throughput
P_e	The probability of the CM2M gateways switching to a busy channel
B_t	The number of bits transmitted in one transmission slot
P_c	The probability of channels correctly sensed as busy
L_s^{opt}	Optimal sleep probability
R_0	The average throughput of CM2M gateways
Q	CM2M gateways number
μ	Throughput coefficient
ɱ	Random channels shared between secondary users and primary users
Ɲ	The number of frames
$\Delta\ (\tau_s)$	Feasibility region
J	Number of antenna
Z	RF chains
P_x	The probability that the CM2M gateways will choose to switch to an ideal channel when the current channel is occupied, and at least one of the other channels is free.

α_{K}	The idle probability of channel κ
β_{K}	The successful transmission probability of channel κ
y	The probability of selecting channel
γ	SNR regime
μ	Attenuation coefficients
σ	Attenuation coefficients of probability
Γ	The channel available probability vector
$I[\cdot]$	The indicator function

CHAPTER 1

INTRODUCTION

1.1 Background

Machine-to-machine communication can be defined as communication which can intelligently process and transfer data independently, without human intervention [1]. M2M communication enables the exchange of information between networked devices and business application servers and is considered an important part of the Internet of Things (IoT).

The number of machines connected to the internet has increased dramatically in recent years. In 2012 there were 8.7 billion machines/devices connected to the internet, and due in part to the growth of smart devices and tablet PCs, the number of devices reached 28.4 billion in 2017 [2]. Cisco Internet Business Solutions Group (IBSG) predicts M2M devices will increase massively in next few years, there will be 42.1 billion devices by 2019 and 50.1 billion by 2020, as shown in Figure 1.1 [2].

These devices are expected to be massively used in a number of applications, including agricultural and industrial automation, healthcare, automobiles, metering and control of electricity, gas, heat, and water, etc. [3].

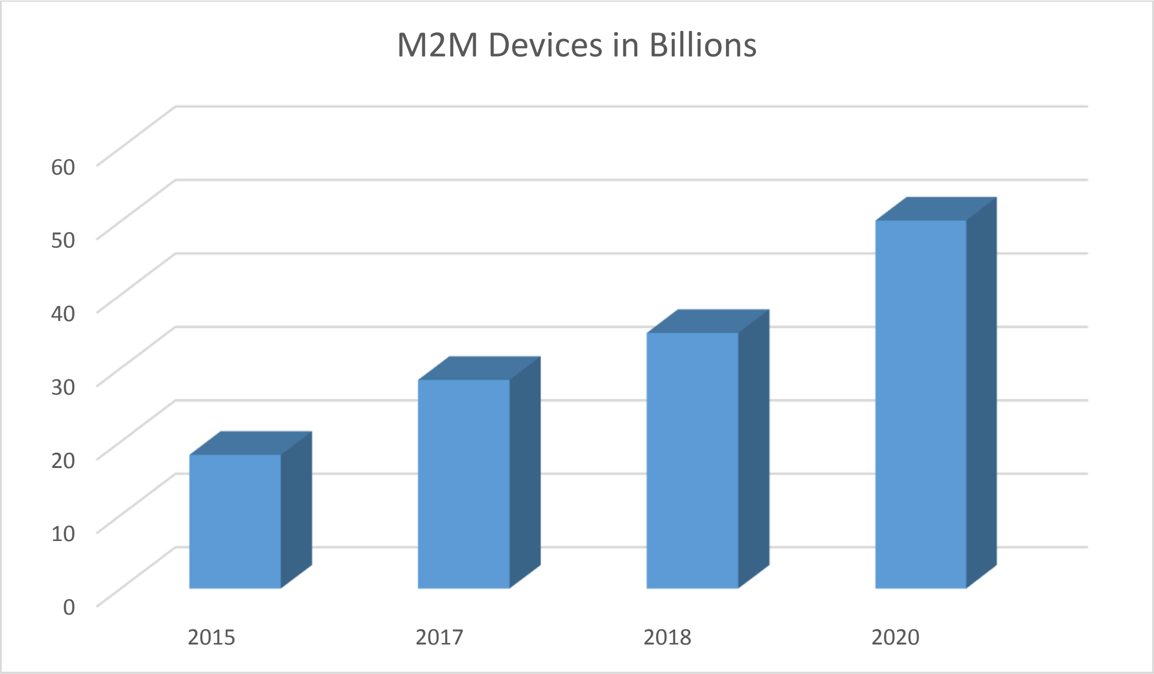

Figure 1.1: Machine-To-Machine (M2M) Devices Usage Expectations

M2M network architecture usually consists of a combination of wireless networks (Figure 1.2) that collaborate in collecting, processing and analyzing information [4]. The important parts of the M2M networks are illustrated as follows:

1. **M2M Device Domain**: installed at different places which send/receive data based on actions that occur due to changes in parameters of sensors connected to an M2M network.
2. **Network Domain**: represents different applications that receive, analyze, process and understand the data received from the sensors.
3. **Application Domain**: usually consists of IT applications, programs, and billing systems.

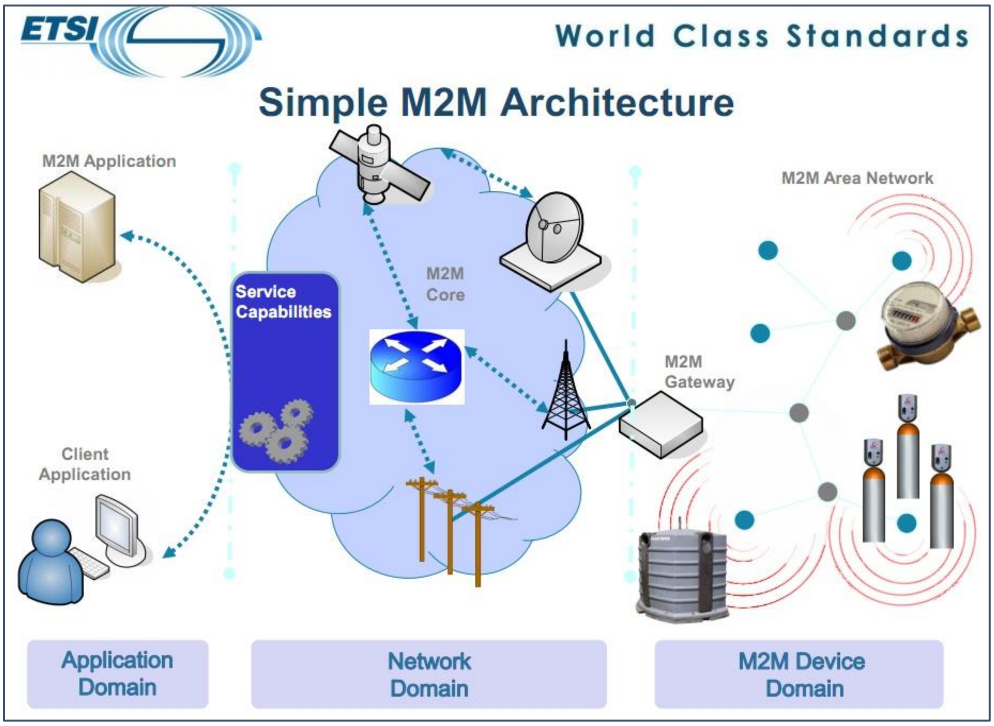

Figure 1.2: M2M Typical Network [6]

1.2 M2M Communications in Healthcare Applications

M2M in e-healthcare can help the current monitoring and healthcare services, particularly for children, the elderly, and the disabled people. A huge number of advantages can be achieved by using M2M communications in the healthcare system, for example, by improving the monitoring capability of hospitals and e-healthcare centers, and by, sending emergency information to the patient’s doctors or carers.

Healthcare applications in most cases can be defined as a soft real-time system, in which some latency is allowed [4, 5]. Coordination in emergency conditions, such as with sudden falls and heart attacks, is vital when it comes to saving lives. Therefore efficient and reliable communication between e-healthcare systems is required.

Recently, a huge amount of effort has been focused on wireless communication technologies for e-healthcare applications, such as electrocardiogram (ECG), blood pressure, oxygen, and temperature monitors. M2M wireless communication (Figure 1.2) is the foremost technology for enhancing service flexibility and mobility for different e-health applications [4], which leads to improved flexibility and efficiency in the e-healthcare systems, allowing patients an earlier discharge from hospitals and a faster return to their normal lives, while reducing the total cost for both the patient’s family and government spending [6].

This can be done by enabling hospital employees to remotely monitor and access patient data, increasing the accuracy of diagnoses by collecting data from different sources (e.g., therapeutic devices, images, and monitors) over time to build a clear and complete picture of the patient’s health status.

1.3 Cognitive Radio

Cognitive radio is a radio which is aware of its operational and geographical environment, established policies, and its internal state. It can dynamically and autonomously adapt its operational parameters and protocols and to learn from its previous experience [7].

Cognitive radio (CR) was developed to utilize the best available wireless channels in its vicinity, which is very important technology for the realization of M2M communication in future due to the limited availability of spectrum, especially with the explosion of the Internet of Things [8]. The idea of cognitive radio is to share the spectrum between licensed users, called primary users (PUs), and unlicensed users, called secondary users (SUs). CR is based on Dynamic Spectrum Access (DSA), a new spectrum sharing method that allows SUs to accessible spectrum portions within the licensed spectrum bands.

CR technology can solve spectrum limitation problems and can be utilized to increase energy efficiency in M2M networks and prolong the battery life of sensors. [7]. TV broadcast networks and cellular networks could be classified as PN, while CR networks can be classified as either infrastructure-less or infrastructure-based. The infrastructure-less cognitive radio CR Ad-Hoc networks can be used without infrastructure support (no central entity required), while the infrastructure-based networks have a master network entity, such as a base station or access point.

1.4 Cognitive Machine-to-Machine (CM2M)

Cognitive radio as a smart technology can address spectrum limitation and energy consumption problems in M2M networks. CR has recently become a zone of the most significant subjects in wireless communications [3].

A number of M2M applications can benefit from the new functionality and performance that can be achieved by the combination of cognitive radio and M2M communications, ranging from smart grid and healthcare to car parking [11]. CM2M networks can improve spectrum utilization and energy efficiency in M2M devices [12]. M2M devices in CM2M networks will act as SUs which can interact with the radio environment by performing spectrum sensing and accessing available channels. Normally M2M devices (e.g., Medical application sensors) will analyze the features of the free channels, following which spectrum assignment is made according to the needs of the M2M devices [13].

1.5 CR Motivations in M2M E-Healthcare Applications

1.5.1 Number of Healthcare M2M Devices

M2M communication will face challenges due to the vast number of M2M devices in the e-healthcare sector, such as wearable monitors and other medical sensors. The challenges relating to the number of connected devices need to be resolved using smart technologies. CR as smart technology can be programmed to deal with a huge number of devices and to manage the communications between the sensors domain and the applications domain [14, 15].

1.5.2 Battery Life and Green Technologies

Green means: less energy usage, and less CO2. Having a huge number of machines connected and interconnected wirelessly all the time is affecting the ecosystem. Hence, the standards bodies are facing problems on two fronts: electromagnetic pollution and excessive power consumption [16]. M2M devices (especially body sensors) need to be designed to run for a very long time without any battery replacement. Therefore, energy efficient schemes for those devices is necessary for the enhanced performance of the M2M communication systems [12][17]. CR radio proved to be energy efficient and able to decrease electromagnetic pollution and energy consumption in its network [17][18]. Such a technology can be utilized to tackle the energy problems in M2M communications.

1.5.3 Support Remote Area Devices

Cognitive M2M networks can exploit wireless technology to operate in remote areas and solve the problem of many companies that still grapple to gain a good service (e.g., with internet provision). CM2M networks as smart technology could access available channels and easily be configured. Therefore, CM2M could be used to reach remote areas as shown in figure 1.3 by exploiting lower frequencies (470-790 MHz) in the Ultra High Frequency (UHF) band, called TV White Spaces (TVWS) [19]. A number of M2M medical applications today could work in the TV white space spectrum using CR technology as TVWS can provide simple connectivity to remote areas with less expensive communications infrastructure [20, 21].

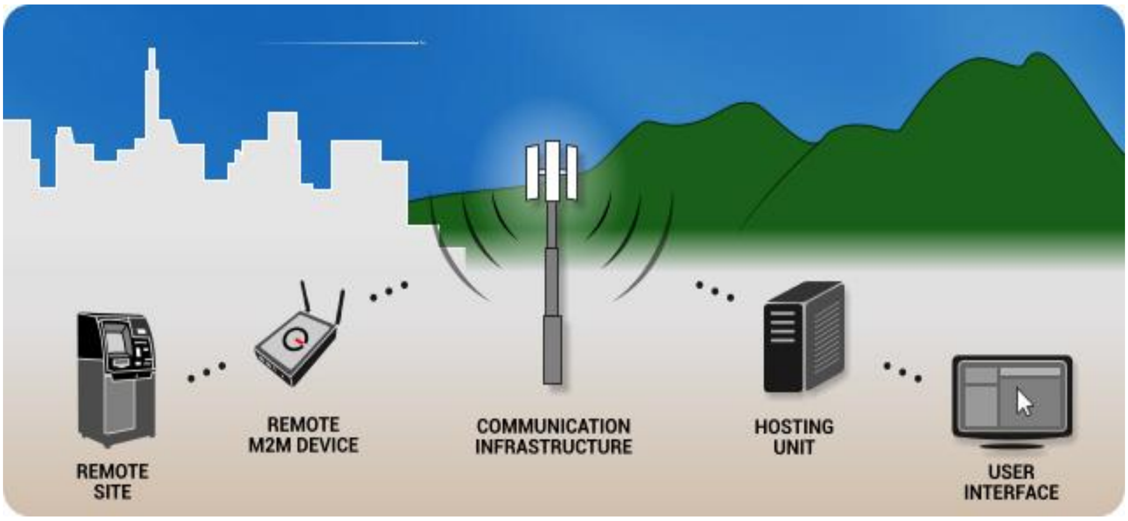

Figure 1.3 Remote Area Communications of Typical M2M Network [21]

1.5.4 Avoidance and Interference Reduction

Efficient techniques are needed to address the problem of interference as M2M devices are expected to number more than 50 billion by 2020, the majority of which will need to communicate wirelessly. Smart CR radio can be adjusted to cope with interference problems using spectrum broker technology, for example by avoiding interference with the primary users or with the other CM2M devices [22]. CM2M networks based on the IEEE 802.22 standard offer the chance to automatically find and utilize unused spectrum so CM2M users will be able to switch between various wireless channels.

1.5.5 Data Rate

Cognitive radio as smart technology can utilize idle spectrum to improve spectrum efficiency, which can significantly improve data rate and throughput [22][11]. CR self-configurations enable devices to learn from the past, for example, a cognitive radio can be adjusted to select the best quality of services available channels after testing the channels for a specific period, enabling M2M devices to send more data and achieve better throughput.

1.6 Aim and Objectives

This thesis aims to study M2M communications and to propose and develop efficient mechanisms to improve spectrum utilization and to reduce the energy consumption of M2M communications in e-healthcare applications. The main objectives of the thesis are listed below: -

1. **Spectrum efficiency:** Develop and design new algorithms to improve spectrum efficiency in e-healthcare M2M communications by exploiting CR technology. The developed algorithms will consider aggregation-based spectrum assignment algorithms for better spectrum efficiency and better channel utilization. Furthermore, genetic algorithms will take into consideration to maximize channels utilization.

2. **Energy efficiency:** Develop and design new schemes for better Energy Efficiency (EE) in e-healthcare M2M communications by considering CR spectrum accessing and sharing algorithms. The developed algorithm will consider sleep modes and switch modes schemes for better energy and spectrum efficiency. Furthermore, antenna selection algorithms and learning algorithms will be exploited to maximize the energy efficiency in e-healthcare M2M communications.

1.7 Thesis Contributions

The contributions of this thesis cover various aspects of M2M communications in healthcare systems. The key outcomes of this research in the form of novel solutions, algorithms, and mechanisms are summarised below.

1. An aggregation spectrum assignment for CM2M gateways is designed as a mixed integer optimization problem. The maximum aggregation span and the practical constraints of Co-Channel Interference in aggregation aware CM2M networks are taken into consideration.

2. A fast convergence, simple and robust algorithm, called a genetic algorithm (GA), is used to resolve the aggregation aware spectrum assignment and to produce better results. GA algorithm guarantees the results improve by at least 23 % compared with the current state of art algorithms.

3. An optimal energy efficient spectrum management mechanism formulates the number of constraints on the throughput, delay, and reliability of CM2M devices sensing. The proposed mechanism aims to decrease energy consumption in the system (by at least 35%) using efficient spectrum sensing and channel switching techniques, while reducing the probability of collision, with the guarantee of conforming to throughput, delay and reliability constraints. Subsequently, an antenna-selection sensing mechanism is used to improve sensing accuracy and reduce the probability of collision. The optimality of the used mechanisms is demonstrated through Matlab simulations.

4. An energy efficient channel selection algorithm has been formulated to work with CM2M communications in the e-healthcare system. The proposed algorithm aims to select the best available channels and reduce energy consumption in the system. Furthermore, the algorithm aims to reduce the probability of CM2M gateways switching the available channels. The efficiency of the used algorithm is shown through simulations.

1.8 List of Published Works

[1] **S. Alabadi**, Predrag Rapajic, and Kamran Arshad (2016) ‘’Energy-Efficient Cognitive M2M Communications’’, International Journal of Interdisciplinary Telecommunications and Networking, vol. 8, no. 3, pp. 1-9, 2016. **[Journal]**

[2] **S. Alabadi**, Predrag Rapajic, and Kamran Arshad (2016) “Efficient Cognitive M2M Communications”, Wireless Telecommunications Symposium, April 18-20, London, UK. **[Conference]**

[3] **S. Alabadi**, S. Rostami, Kamran Arshad and Predrag B. Rapajic (2016) Spectrum Assignment Algorithm for Cognitive Machine-to-Machine Networks, Hindawi Special Issue Smart Spectrum Technologies for Mobile Information Systems. **[Journal]**

[4] S. Rostami, **Sajad Alabadi**, Kamran Arshad, and Predrag Rapajic (2016) Efficient Sub-Carrier Allocation Algorithm for OFDM based Wireless Systems, 2016 Universal Technology Management Conference, Bemidji State University, Minnesota, USA, May 26-28- 2016. **[Conference]**

[5] **S. Alabadi**, Ruiheng Wu and Yehdego Habtay (2017) “Energy Efficient CM2M Communications in Healthcare Systems”, International Conference on Telecommunications and Signal Processing (TSP), IEEE, Spain. **[Conference]**

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1.9 Thesis Outline

The rest of the thesis is organized as follows: In Chapter 2 the literature review is presented and discussed; this chapter also presents related work on different aspects of Cognitive M2M communications in e-healthcare systems. The main contributions of the thesis, relating to three distinct areas, M2M gateways spectrum sensing, sharing, and accessing; spectrum aggregations; and selecting algorithms are discussed in Chapters 3, 4, 5 and six respectively. Each chapter addresses a unique research problem, as illustrated in Figure 1.4. Based on the overall picture of research conducted in the thesis, the future of M2M communications in the healthcare system and, the main conclusions together with some directions for future work are presented in Chapter 7 and 8.

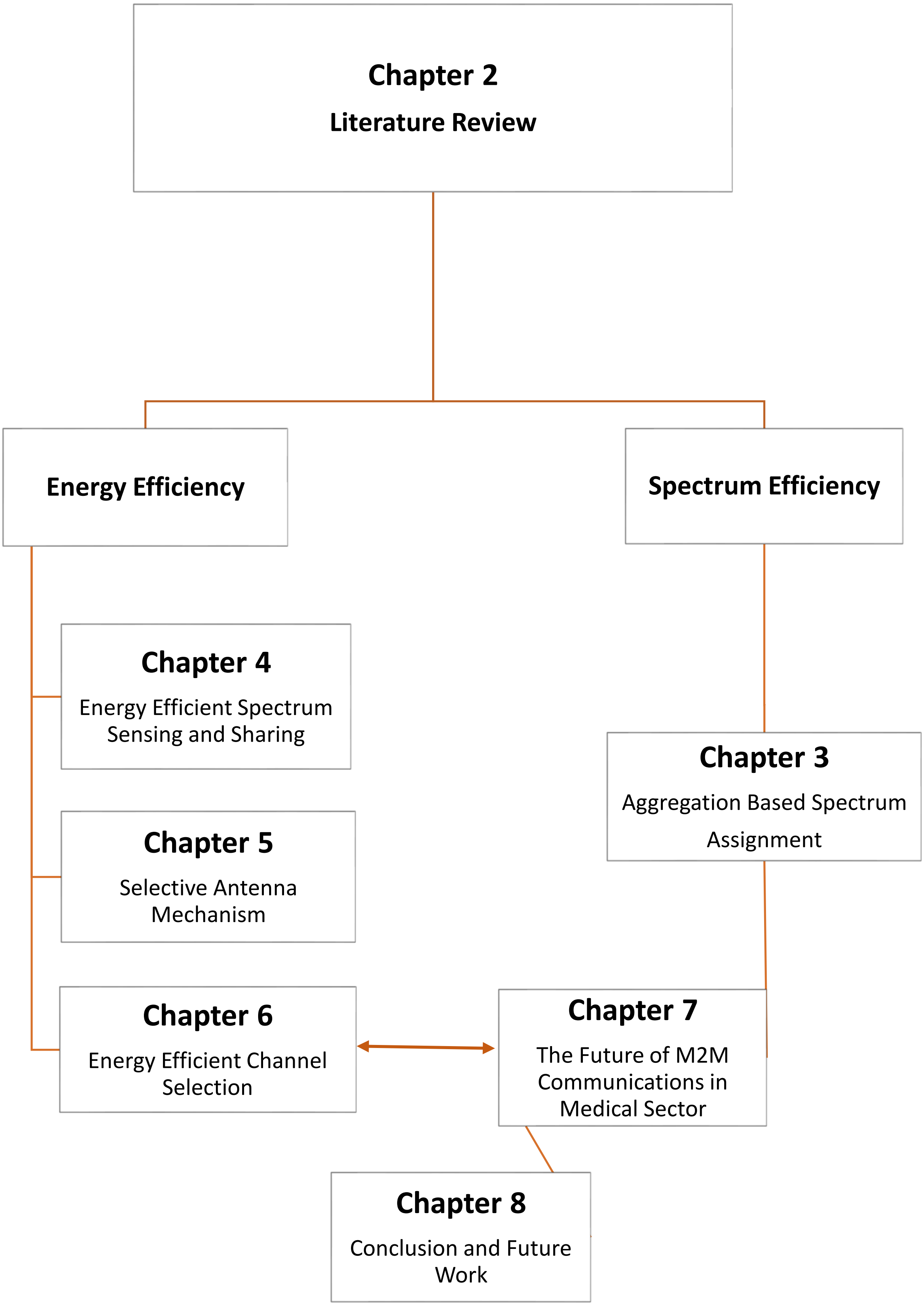

Figure 1.4: Flowchart of Thesis

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CHAPTER 2

COGNITIVE MACHINE TO MACHINE BACKGROUND

2.1 Introduction

The use of M2M communications in the healthcare system has gained large momentum in the past few years for some reasons, including distance monitoring of fitness information and patient health, triggering alarms when vital conditions are discovered, and requesting immediate treatment when needed. M2M sensors are usually deployed around the patient to monitor fitness and health indicators like body temperature, blood pressure, weight, heart rate, etc. These tracers typically follow certain protocols to communicate with each other and to forward the data to gateways. Furthermore, these tracers (sensors) have energy thresholds and are connected to the central monitoring system using a gateway or data aggregator by means of short-range devices, the majority of which operate wirelessly [1].

This Chapter investigate and discuss cognitive machine-to-machine (CM2M) in e-healthcare systems, the Chapter will explore a number of CR and M2M mechanisms, especially the ones related to spectrum and energy efficiency in healthcare applications.

2.2 Machine to Machine in Healthcare Applications

M2M communications can enable automation in healthcare applications; which is important in medical applications as it can improve the quality of healthcare by decreasing costs and enabling continuous monitoring [2]. M2M automation will reduce the need for the active involvement of medical personnel in gathering and analyzing patients' data, and dispensing prescriptions.

Various types of sensors could be employed to collect and transfer the data, leading to faster response time and preventing critical threats to a patient's life. In [3] the classifications for M2M in the healthcare sector has been proposed. A remote monitoring healthcare architecture is presented [4, 5], where the authors covered the following classifications:

- c-Health - classical health care.
- e-Health - electronic health care, a subset of c-health.
- m-Health - mobile healthcare - the use of mobile devices, a subset of e-health.
- s-Health - smart healthcare - the use of a set of measures to deliver data and enable the prevention of health hazards, e.g., informing on levels of pollution, pollen, and allergens.

The classification shows the needs for M2M communications in e-healthcare systems, however, the study didn't consider or address CR technology for better energy or spectrum efficiency in M2M healthcare systems. In [6] the European Telecommunications Standards Institute (ETSI) has marked a group of M2M healthcare applications such as aging independently, disease handling, health betterment, and body fitness.

These marked applications can benefit from remote monitoring for a variety of conditions such as cardiac arrhythmias and diabetes, which could support elderly people and make their lives better. Furthermore, the usage of M2M in fitness machines and health facilities is discussed, for example, the monitoring of breathing and heart rates, fat burning rate, and how much energy is spent in a specific session or exercise.

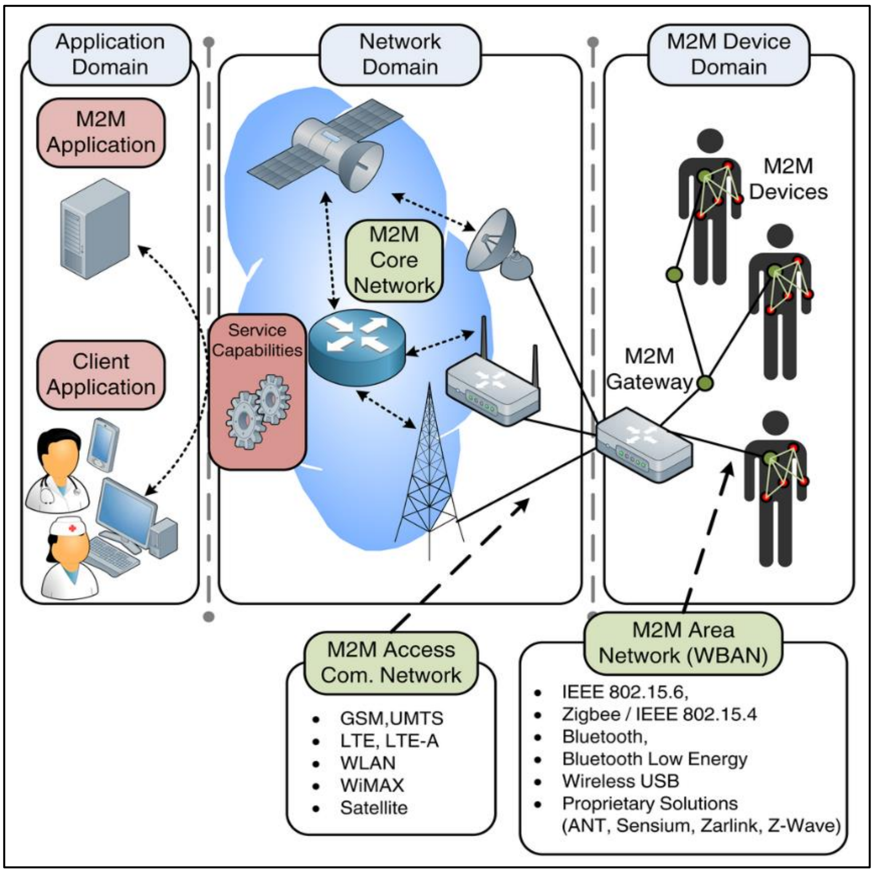

Figure 2.1: ETSI System Architecture for M2M Networks in Healthcare Systems [6]

All this data could be forwarded immediately, safely and securely, to the servers, causing less delay and faster communications between these machines and the end user. Remote healthcare monitoring has been used more intensively over the past few years, identifying low body signals via secure communications between the patients and carers. ETSI in [6] defined a high-level system architecture for M2M networks in healthcare systems. As shown in Figure 2.1, the frequent necessity for hospitals to monitor patients for important indicators like blood and oxygen pressure, electrocardiogram, and temperature has been discussed. Despite ETSI provided us with a good system architecture for M2M networks in healthcare systems, their architecture didn't consider CR as smart technology to enable M2M communications in a remote area with less spectrum and energy costs [7, 8].

Typically, M2M sensors connect with each other and with the gateways using wires but, due to limitations and cost problems many vendors have adopted wireless technology as a replacement for wire mediums in healthcare applications [9][10][11]. In [11], the use of wireless technology instead of wires is proposed and investigated, as wireless technology is promising to eliminate the use of wires. Enabling sensors to collect information from sensors and send it back securely to end users will help to increase the efficiency and flexibility of M2M medical applications.

Furthermore, using wireless communications can help with power efficiency and increase the battery life of sensors. [10]. Also, wireless communications can enable the use of remote monitoring services, reducing the cost of M2M sensors by using less expensive wireless sensors to communicate with each other and forward data to the gateways. Global monitoring can be extended to include a huge number of hospitals around the world by using such smart and intelligent systems. Moreover, any change in a patient's condition can be flagged up earlier, enabling hospitals and healthcare facilities to respond more quickly.

However, M2M healthcare applications will face challenges with regard to Electromagnetic Interferences (EMI) on the medical band, due to the massive number of devices. Also, mobile operators will become busier and more expensive and would almost certainly become unable to cope with the high volume of M2M traffic in the future [12]. To cope with these challenges cognitive radio as intelligent technology could be exploited in healthcare applications for better utilization of the medical band and an EMI-aware prioritized wireless access approach to avoid the malfunction of healthcare devices [12].

Spectrum and energy efficiency are two of the main targets of M2M communications standards [6]. Thus, it is very important to have a less crowded spectrum band and more energy efficient communications in M2M medical applications. At present, bands like MedRadio (402–

405 MHz) and Wireless Medical Telemetry Service (WMTS) are used in various types of healthcare applications, but these types of bands are very limited in terms of spectrum availability and have become very crowded recently [13].

Moreover, the Industrial, Scientific, and Medical (ISM) 2.4 GHz bands are not efficient for important and critical medical applications due to the congestion and interference problem caused by other IT wireless networks in hospitals and medical facilities such as normal Wi-fi networks. By having other types of spectrum resource (e.g., cognitive radio spectrum resource), the Quality of Service (QoS) for these important and critical applications can be improved [14]. In [14], the use of CR technology for sending medical and non-medical information to pharmacies and medication centers is proposed. This type of information can communicate wirelessly between the doctor and the nurse, and also offers video conferencing and surveillance.

In [15] an energy efficient cognitive radio algorithm is proposed; the proposed algorithm considers sending the information from the source (sensors) to the destination (servers) with maximum energy efficiency within the CR sensors healthcare networks. The proposed algorithm also considers the number of nodes and the distance between nodes. However, the algorithm considered only the energy efficiency while ignoring the spectrum efficiency and achieving user's high data rate requirements.

In [16] The use of M2M applications to reduce obesity in high percentage obesity countries is discussed. Mobile applications are used to recommend the types of food a person can have for a specific day, based on the data received by the monitoring sensors. The authors in [10] proposed M2M health monitoring and medication recommendation system for cardiovascular patients who receive their treatments at home.

Patients' critical signs (heart rhythm, blood pressure) will be supervised via M2M smart sensors, which will send notifications to the M2M main server. Next, the main server will assign medication recommendations automatically using techniques called artificial intelligence, based on information garnered from medical records (hospitals) and other healthcare facilities. Doctors will be involved in the process since the application deals with critical diseases which may threaten a patient's life. However, the system still complicated and required high latency communications.

In [5, 17] medical applications for M2M are studied and investigated. M2M will play a huge part in medical applications, enabling the use of information technology without the need for human control. But, generally, these applications need to be easy to install and cheap to buy and will need to work with a good spectrum and energy efficiency.

2.3 Cognitive Radio Spectrum Sensing and Sharing

2.3.1 Spectrum Sensing

A key feature of CM2M communications is the ability to choose the best available channels by exploiting cognitive ability and reconfigurability [18, 19]. As discussed at the beginning of this Chapter, there is a limitation in the available spectrum, and the most significant challenge is to share the primary user spectrum without affecting or interfering with the transmission of other primary users (PU) to achieve primary user protection. CM2M devices typically utilize temporarily unused spectrum, called white space or spectrum hole [19]. If this band is again needed by the primary user, CM2M devices should either switch to other free channels or stay in the current channel and stop transmission, changing its modulation scheme or transmission power level to avoid interference with the licensed user.

CM2M devices can interact in real time with the available channels to choose the best communication parameters and adapt to the dynamic radio environment. An illustration of the CM2M devices activities is shown in Figure 2.2 [20, 21]. As shown in Figure 2.2 CM2M devices using the free holes in the spectrum to make the transmission and improve the date of the secondary users.

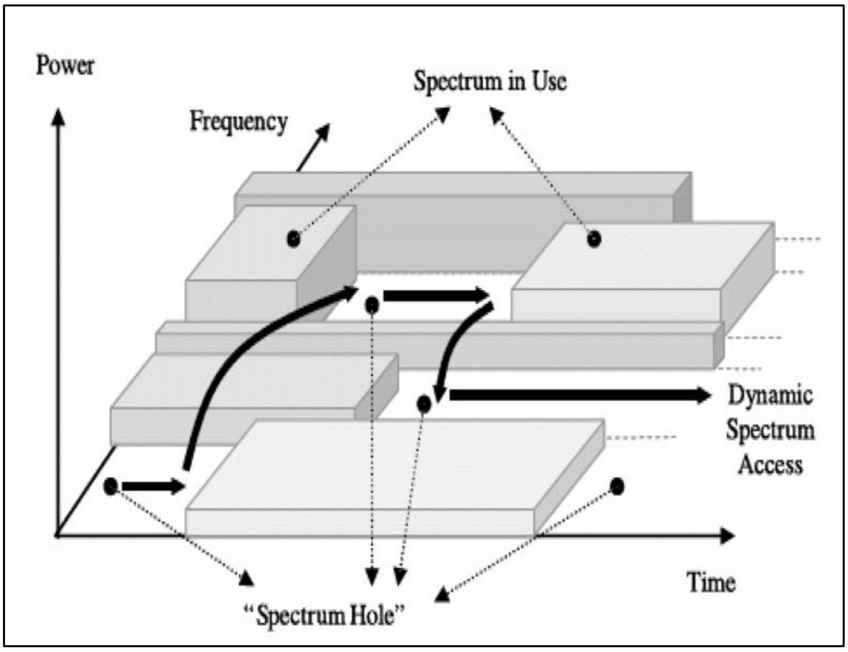

Figure 2.2: CM2M Activities with Channel Transmitting [20]

2.3.2 Transmission Detection

In the CM2M transmission detection scheme, CM2M devices detect the weak signals of licensed user transmissions through local observations [22, 23]. There are three approaches under this scheme, which rely on the detection of the energy of a signal: matched filter [24, 25], cyclostationary feature detection [26, 27], and energy detection [28]. The first two approaches are coherent detectors that achieve better detection probability but need information about the licensed signal, while the third one (energy detector) is a non-coherent detector that does not require knowledge about the licensed signal, and is cheaper and simpler to implement compared to the other approaches.

1. Matched Filter Detection

This approach requires the licensed user to send a pilot signal with the data. The pilot signal will be recognized by CM2M devices, enabling them to run timing and carrier synchronization to attain coherence [25]. CM2M devices must have complete knowledge of the licensed user's signaling conditions, for example, operating frequency, bandwidth, and modulation type [24, 29]. The core benefit of this approach is a reduction in the time needed to provide a huge processing gain, because of the coherent detector. Conversely, CM2M requires receivers for every type of primary system. Thus it increases the cost and the complexity and requires higher energy consumption to detect several primary signals.

2. Cyclostationary Feature Detection

This is a method of detecting licensed user transmissions by utilizing the cyclostationary characteristics of the received signals. The detection scheme can detect the random noise power and so tell the difference between noise and the licensed user's signals, thus achieving better detection efficiency than the energy detector in discriminating against noise. However, this approach is very expensive and complicated and needs a very long time for observation [30, 32].

3. Energy Detection

The energy detection approach is widely deployed for spectrum sensing due to its simplicity and low cost. This approach is typically used when the licensed user signal is unknown [33]. The signal is detected by matching the output of the energy detector with desired constraints which usually rely on the noise floor.

Typically, the effectiveness of the energy detection approach relies on the Signal-To-Noise Ratio (SNR) value of the sender signal. In actual applications, the output signal at each CM2M device may experience a problem from the hidden licensed user and suspicion due to shadowing and fading problems. Cooperative sensing techniques addressed and solved some of these issues [33, 34]. But, these techniques are based on the assumption that the noise power levels are clearly known.

In practice, noise power levels change with the location and time of the station. This is called noise uncertainty and cannot be predicted precisely. The effect of noise power levels uncertainty on energy signal detection has recently been studied in [34, 35]. In [34], the primary bounds of energy signal detection in the existence of noise uncertainty are investigated and addressed. The investigation demonstrates that there are several SNR constraints under noise uncertainty (e.g., 30 dB) that prevent satisfying, efficient detection. In [35], the authors suggest a novel approach that utilises dynamic constraints to cope with the noise power fluctuation issue, but as yet, the algorithm cannot ensure minimising spectrum sensing inaccuracy as more sensing schemes need to be utilised to increase the sensing accuracy such as increasing the number of antennas with the consideration of energy constraint.

In [36-38], an optimal constraint based on the energy detection approaches have been determined. The work also proves the efficiency, flexibility and the low cost that can be achieved by using the energy detection scheme. However, the work didn't consider the user reliability and primary user protection for example high probability of detection, a collision between the primary user and secondary user, and low probability of false alarm.

In conclusion, the behavior of energy detection depends on the accuracy of detection constraints and the SNR level of the output signal. From a CM2M perspective, the energy detection scheme is the best scheme that can be utilized to work with CM2M communications for its simplicity and low cost of the implementation. But yet more work needs to be developed to address the problems of user reliability and primary users protection.

2.3.3 Cooperative detection

The cooperative detection means, the cooperation among CM2M devices to reduce the uncertainty caused by the single user's detection. Using a number of sensing nodes, cooperative sensing can be utilized to mitigate multipath fading and spatial diversity, which are the key points that decrease the performance of single user's detection. Cooperative detection can achieve more precise performance [39].

However, it is more complicated and needs more overhead traffic and operations to cooperate with other CM2M devices. As a result, employing cooperative detection in CM2M networks will add more cost and complexity to its parameters, CM2M generally could utilize a cheaper and less complex detection such as energy detection to sense and find an available channel in the CM2M radio environment [35, 40].

2.3.4 Spectrum sharing

Based on the access schemes, spectrum sharing can be divided into [41]

1. **Overlay Spectrum Sharing:** In this kind of spectrum sharing scheme, CM2M users can access part of the spectrum that is not being used by the primary user. Consequently, there will be less interference between primary users and secondary users.
2. **Underlay Spectrum Sharing**: This kind of spectrum access scheme utilizes the spread spectrum mechanisms created for mobile operators. CM2M users start communication at the particular part of the spectrum assigned by a spectrum map with transmission

energy regarded as noise by the primary user. This kind of scheme can be used to maximize the bandwidth compared to the overlay scheme.

2.4 Spectrum Aggregation

The massive wireless volume generated by the modern era of machines (wearable sensors, smartphones, M2M devices, laptops..etc.) will soon become too large for the current networks to handle [42, 20]. The exploitation of extra spectrum resources with better throughput rate is one of the significant solutions for high demand and traffic explosion. Generally, because of the restricted spectrum allocation policy, wireless networks can only employ a continuous spectrum resource. Moreover, the wide continuous spectrum bands are difficult to utilize under the existing situation of spectrum resource. In the past few years, a huge amount of work both in industry and academia has encouraged the use of the flexible spectrum option to combat the so-called spectrum fragmentation problem.

To cope with such a problem, Spectrum Aggregation (SA) is proposed to boost system efficiency by adding extra bandwidth for mobile users. SA utilizes fragmented spectrum segments to expand bandwidth transmission. After CR finds white space bands sensed by its smart inspecting capabilities, the combination of diverse spectrum bands becomes optional by utilizing SA. A number of research centers, companies, and standard organizations began to address and study SA such is QinetiQ, which has developed a novel solution for SA to sustain broadband services [43]. CR is promising technology but comes with some challenges, one of which is the spectrum assignment problem [44, 45].

The spectrum assignment problem is extensively addressed and studied in typical wireless networks [35]. When considering spectrum assignation, the goal is to achieve the interference thresholds and increase the system data rate for the given spectrum. Moreover, CM2M devices could cause a number of challenges due to the discontinuous and fluctuating nature of the available spectrum, in addition to the various QoS needs of different applications. Despite the number of standardizations addressing SA in Long-Term Evolution-Advance (LTE-A) networks, little work has been done to utilize SA by exploiting CR technology. There is very limited literature considering spectrum assignment among users having SA capabilities.

In [46], proposed a prediction based spectrum aggregation scheme to increase capacity and decrease the re-allocation overhead. The proposed scheme is referred to as a Maximum Satisfaction Algorithm (MSA) for spectrum assignment. The main idea is to assign spectrum for the user with the largest bandwidth requirement first, leaving better spectrum bands for remaining users, while taking into consideration the different bandwidth requirements of users and channel state statistics.

Later, Fang in [47] introduced a genetic algorithm based spectrum assignment in CR networks. Authors in [48], suggest a utility-based SA algorithm to boost the performance of CM2M devices considering a number of objectives: 1) decrease the amount of channel switching. 2) increase the overall data rate. 3) decrease the number of sub-channels comprising the aggregate channel, aimed at opportunistic spectrum use by CM2M devices. The objectives work simultaneously with a weighted sum utility function. Furthermore, the suggested algorithm allows for the automated adaptable setting of objective-function weights depending on available channels.

In [49, 50], an Aggregation Aware Spectrum Assignment Algorithm (AASAA) is proposed to aggregate discrete spectrum fragments hugely. The algorithm in [50] utilizes the first available aggregation range from the low-frequency requirement. In [51], the authors analytically addressed the channel assignment optimization problem and the channel access problem as joint power control, with the goal of decreasing the required spectrum needs for specific CR parameters.

The optimization problem in [52] appeared to be a binary linear program, which is, usually a Non-deterministic Polynomial-time (NP)-hard problem. Thus, [53] suggest a near-optimal solution according to sequential fixing, where the binary variables are calculated iteratively by addressing a number of linear programs. For CM2M devices, the current SA and spectrum assignment solutions are not applicable directly as practical thresholds, such as MAS, must be taken into consideration. Furthermore, in an aggregation-based spectrum assignment, a significant challenge is to manage CCI among CM2M devices, again not taken into consideration in the current literature.

2.5 Spectrum Sensing and Sharing

A number of studies addressed and considered energy and spectrum efficiency sensing and sharing schemes for better communications in CM2M networks. In [9] energy efficient spectrum discovery design in the smart grid is considered. The design aims to improve the energy efficiency of the CM2M networks using machine coordination and assumes that machines cooperating with each other will decrease energy costs during the spectrum discovery phase. The results were promising, but the design has not considered the main requirements of CM2M networking relating to cost and complexity. The design considers cooperative sensing for improved sensing accuracy but has not taken into account the additional cost and complexity that cooperative sensing adds to the design.

In [45], CR in M2M communications has been addressed from a protocol stack perspective. However, the work needs more reliable and effective implementation of cognitive M2M networks. In [55], Weightless is proposed as an open standard for exchanging data between a base station and a huge number of devices around it. Weightless allows developers to build low energy wide area networks with a high throughput data rate by exploiting CR technology. Weightless aims and objectives are: to prolong battery life, reduce installation costs, allow wide outdoor and indoor coverage, and avoid interference caused by another unlicensed user. Weightless is still under review by 3GPP and other communications parties, achieving its targets will need more time and new schemes and algorithms especially, with the ones related to the energy efficiency and coverage.

The authors in [56] studied decreasing energy cost per bit for distributed cognitive radio devices in different types of network; the study assumed joint source and channel sensing for CR devices should be analyzed first, and then the optimal solution could be determined from fading channels. In [57] energy efficiency in CR wireless devices is addressed, the work of distributed sensing approach optimizes power efficiency with thresholds on the minimum desired detection probability, and the increase of the permissible probability of false alarms by selecting efficient sensing and sleeping design energy parameters proposed to improve energy efficiency. However, both studies didn’t consider spectrum sharing and sleep mode techniques that could be exploited to achieve more energy efficiency by switching the SUs to off mode when no data need to be transmitted.

In [58] the authors present two kinds of technique, real-time and non-real-time, which can split the SU into two priorities and develop a spectrum handoff scheme and a resource reservation mechanism to assure the QoS of SUs. In [59], a different type of opportunistic spectrum access approach is explored to provide the primary user and the secondary user with better QoS. Both users are analyzed by pre-emptive and non-pre-emptive priorities with the basic queueing system. In [60] the authors present a channel allocation system to enhance the QoS of the priority based secondary user with improved performance in terms of data rate, dropping probability, and blocking. Furthermore, the developed analytical Markov systems considerably enhance the multimedia QoS performance for the critical priority SUs.

However, the above studies neglected the energy efficiency of SU while the focus was only on the QoS for SUs, in e-healthcare CM2M applications it’s very important to have energy efficient communications to prolongs SU battery life and meet M2M expectations.

2.6 Learning and Channel Selecting

A huge amount of work has been done regarding learning algorithms for cognitive radio. Such as genetic systems, neural models, and the algorithms of Markova [60]. Galindo-Serrano, L. Giupponi, [61] suggest a frame composed of real-time decentralized Q-learning to control Wireless Regional Area Network (WRAN) systems and aggregated interference.

Katidiotis, [62] exploit neural models for learning to predict data bit rate for CR networks (e.g., CM2M gateways). Yang, M. F. and D. Grace [63] suggest intelligence based on reinforcement learning and transmitter energy system for better channel assignment in terrestrial multicast systems. Torkestani, [64] developed the learning based CR to solve the problem of the spectrum limitation in wireless ad hoc networks.

Panahi and Ohtsuki [65] present a Fuzzy Q Learning (FQL) based scheme for channel sensing in CR networks. Zhang in [66] presented a reinforcement learning-based double action algorithm intended to increase the efficiency of dynamic spectrum access in CR networks. A number of studies employ partially observable Markov decision processes [66,67] and reinforcement learning [65, 68]. The main disadvantage of these techniques is their dependence on highly accurate reward functions.

In [67] Meybodi and Torkestani suggest learning automation in CR to cope with the problems of spectrum limitations in wireless ad hoc networks. In [69] Zhu developed a reinforcement learning scheme to find an efficient protocol under undiscovered environment. The above proposals are comparatively useful when it comes to practical applications for huge wireless systems. But by taking into consideration, a new number of studies have concentrated on Experience Weighted Attraction (EWA) intelligent channel handoff approaches, due to stability and sensitivity advantages, conducted by comparing Q learning. A little effort has taken place with regard to designing and developing a learning engine for CR with (EWA) algorithms.

EWA algorithms [70, 71] give CR the ability to be aware of available channels characteristics online. By collecting the history of channel statuses, it can foresee, select, and amend the best available channel, dynamically test the quality of communication links, and eventually decrease system communication outage probability. The efficiency of this algorithm has been tested by the straightforward probability approach [72] and with the EWA Handoff (EWAH) algorithm [69] in our preliminary studies.

2.7 Summary

The present situation and the development of M2M and CR communications in healthcare applications are investigated and discussed in this Chapter. Furthermore, the viability of using cognitive radio as smart technology to achieve better energy and spectrum efficiency is explored. Current efforts utilize cognitive radio technology to prolong the battery life of sensors and improve sensing accuracy. In addition, the current efforts exploit CR radio for better spectrum utilization and throughput efficiency. However, for CM2M devices, the current SA and spectrum assignment solutions are not applicable directly as practical thresholds, such as MAS, must be taken into consideration.

Furthermore, in aggregation based spectrum assignment a significant challenge is to manage Co-Channel Interference (CCI) among CM2M devices, which is not taken into consideration in the current literature. On the other hand, no previous work has considered both spectrum handoffs and the wait/switch trade-off in a CM2M network with multiple CM2M devices (e.g., CM2M gateways) for more spectrum and energy efficient communications. Moreover, no previous work considers designing and developing a learning engine for CR with (EWA) algorithms for better spectrum and energy efficiency in CM2M communications. In the next Chapters, this thesis will consider the methods above/techniques as solutions to achieve better spectrum and energy efficiency in healthcare CM2M communications.

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CHAPTER 3

AGGREGATION BASED SPECTRUM ASSIGNMENT FOR COGNITIVE M2M NETWORK

3.1 Introduction

According to the Cisco company, a single M2M device currently produces as much traffic as three basic-feature phones while due to emerging applications and services of M2M networks the average traffic per device is forecasted to grow from 70 MB per month in 2014 to 366 MB per month in 2018 due to QoS requirements [1]. Because of the high growth rate of the number of devices and high demand for data traffic, the next generations of M2M networks will face a number of challenges, especially, with the spectrum limitations problem. Cognitive Radio (CR) comes as a promising technology to cope with the spectrum limitations problem in M2M networks.

CR has become one of the most intensively studied paradigms in wireless communications, allowing unlicensed users (e.g., CM2M devices or gateways) to opportunistically access licensed spectrum as long as interference to PUs is kept at an acceptable level [2]. A number of M2M applications (e.g., healthcare applications) can benefit from the combination of CR and M2M communications [3]. CM2M networks can increase spectrum utilization and energy efficiency in M2M networks [4].

The CM2M device can interact with available channels either by performing spectrum sensing and accessing spectrum databases to detect available channels [4]. After sensing, the CM2M device utilises the discovered unused spectrum according to the device needs, for example, TV bands which have significantly favourable propagation features are typically booked to broadcasters but after the recent transition from the analogue broadcast television system to the digital one, a massive number of TV channels (also known as TV White Spaces) were freed up and became unused.

In September 2010, the Federal Communications Commission (FCC) released an important ruling [5], enabling unlicensed broadband wireless devices to utilize TV White Space (TVWS). Unfortunately, due to spectrum fragmentation and as a result of an inefficient command and control spectrum management scheme, a continuous wide segment of TVWS is rare in many countries including the United Kingdom. As CM2M networks can sense and be aware of their radio environment, the aggregation of narrow spectrum opportunities becomes possible.

Spectrum aggregation provides wider bandwidth and higher throughput for the CM2M devices. CM2M devices can access discontinuous portions of the TVWS simultaneously using

Discontinuous Orthogonal Frequency Division Multiplexing (DOFDM) [6, 7]. DOFDM is a multi-carrier modulation technique and is a variant of OFDM used to aggregate discontinuous segments of spectrum. The main difference between OFDM and DOFDM is the ON/OFF subcarrier information block [8]. Multiple segments of the spectrum can be occupied by CM2M devices or PUs. As a result, these subcarriers are off-limits to CM2M devices [7]. Thus, to avoid interfering with other transmissions, the subcarriers within their vicinity are turned off and become unusable for CM2M devices, as shown in Figure 3.1.

Furthermore, active (usable) subcarriers are located in the unused segments of spectrum, which are calculated by spectrum aggregation to be one of the most important LTE Advanced technologies from the physical layer perspective and standardized in LTE Release 10 [9].

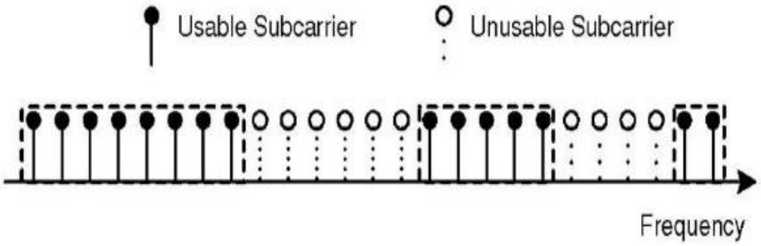

Figure 3.1: Subcarrier Distribution Over Spectrum [79]

However, despite the standardization of spectrum aggregation, little effort has been made to optimize spectrum aggregation by exploiting CR technology in M2M networks, as discussed in Chapter 2. There is limited literature available on spectrum assignment among CM2M devices having spectrum aggregation capabilities. In addition, for CM2M networks, existing spectrum assignment and aggregation solutions are not applicable directly to practical issues such as Maximum Aggregation Span (MAS) must be taken into account. In aggregation-based spectrum assignment, a major challenge is to manage Co-Channel Interference among CM2M devices which are not taken into account in the existing literature. The major contributions of this chapter are listed below:

1. To prevent multiple CM2M devices from colliding in the overlapping portions of the spectrum, a centralized approach is applied. Furthermore, an integer optimization

mechanism is formulated to maximize cell-throughput, considering CCI and MAS in an aggregation-aware CM2M network.

2. As the spectrum assignment problem is inherently seen as a Non-deterministic Polynomial (NP) - hard optimization problem, evolutionary approaches can be applied to solve this challenging problem. In this Chapter, GA is used to solve the aggregation aware spectrum assignment because of its simplicity, robustness and fast convergence of the algorithm [10].

The rest of this Chapter is organized as follows: In Section (3.2), the spectrum assignment and aggregation models are presented. The proposed algorithm is explained in Section (3.3). Simulation results are discussed in Section (3.4), followed by the conclusion in (3.5).

3.2 Spectrum efficiency (Systems Model)

3.2.1 Spectrum Assignment Model

A spectrum assignment model presumes to work with a CM2M network consisting of N CM2M devices ($\boldsymbol{\phi}$) defined as:

$$\boldsymbol{\phi} = \{\phi_1, \phi_2, \ldots\ldots \phi_N\}$$

competing for M non-overlapping orthogonal channels (Y) in uplink

$$Y = \{\, y_{1,}\, y_2 \;\ldots\ldots y_M \,\}$$

All spectrum assignment and access procedures are managed by a central entity called a spectrum broker. Furthermore, the model assumes a distributed sensing scheme and measurement conducted by each device is forwarded to the spectrum broker [11]. A spectrum occupancy map is constructed at the spectrum broker, and CCI among CM2M devices is calculated. In addition, the spectrum broker can lease single or multiple channels for $\phi_n \in \boldsymbol{\phi}$ in a fixed geographical region for a duration of time. Ultimately, a base station can transmit data to CM2M devices ϕ_n in the selected channels. Figure 3.2 depicts the system model used in this Chapter, as shown in the Figure the spectrum broker assign (Y) channels to the CM2M devices in order to make the transmission among the other remote CM2M devices using the available specrum in the radio environment.

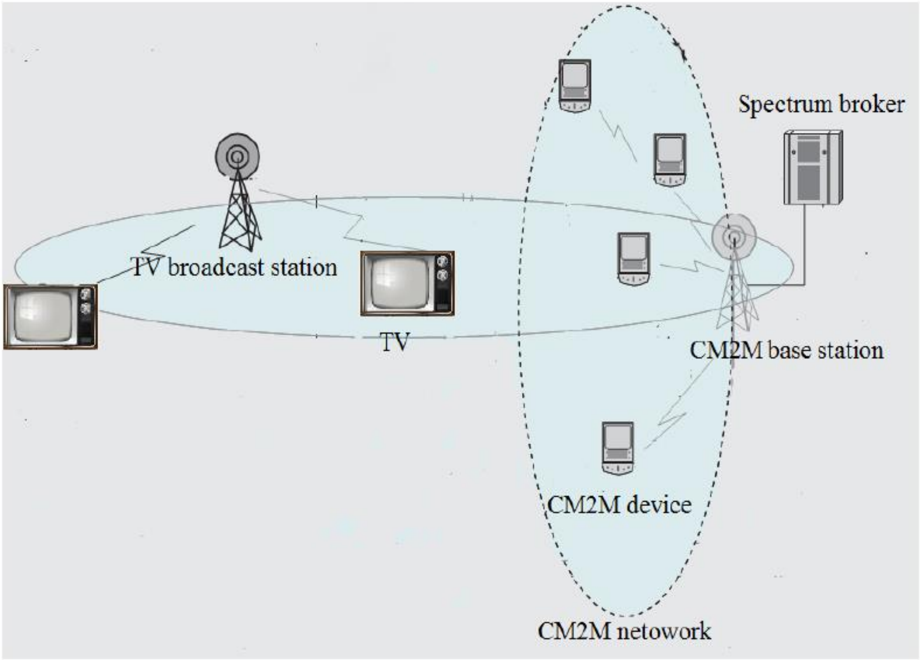

Figure 3.2: Architecture Diagram of CM2M network Operating in TVWS

The channel availability defined by matrix ($\boldsymbol{LL}$) anad as shown below

$$\boldsymbol{LL} = \left\{ L_{n,m,} | \, L_{n,m,} \in \{0,1\} \right\}_{NxM}$$

as a $N\ x\ M$ binary matrix representing channel availability where $L_{n,m} = 1$ if and only if channel y_m is available to CM2M ϕ_n and $L_{N,M,} = 0$ otherwise, each CM2M ϕ_n associated with a set of available channels at its location is defined as:

$$\hat{Y}_n \subset Y\,;\ \text{i.e}\ \hat{Y}_n = \{\,\mathrm{y}_m \mid L_{n,m} \neq 0\}$$

Due to the different interference range of each PU (which depends on the PU's transmission power and the physical distance) at the location of each CM2M device, $\hat{\mathrm{Y}}_n$ of different CM2M devices may be different [12, 13]. According to the sharing agreement, any $\mathrm{y}_m \in \mathrm{Y}$ can be reused by a group of CM2M devices in the vicinity defined by $\widehat{\boldsymbol{\phi}}_{\ \boldsymbol{m}}$ such $\widehat{\boldsymbol{\phi}}_{\ \boldsymbol{m}} \subset \boldsymbol{\phi}$ if CM2M devices are located outside the interference range of PUs; i.e. $\widehat{\boldsymbol{\phi}}_{\ \boldsymbol{m}} = \{\phi_\mathrm{n} | L_{n,m} \neq 0\}$.

The interference constraint matrix defined as ($\boldsymbol{AA}$) and as show below

$$\boldsymbol{AA} = \left\{ A_{n,k,m} \mid A_{n,k,m} \ \in \{0,1\} \right\}_{NxNxM}$$

N x N x M binary matrix representing the interference threshold among CM2M devices where $A_{n,k,m} = 1$ if CM2M ϕ_n and ϕ_k would interfere with each other on $\mathrm{y}_{m\,,}$ and $A_{n,k,m} = 0$ otherwise. It must be noted from $n = k$, $A_{n,k,m} = 1 - L_{n,m}$. The value of $A_{n,k,m} = 1$ depends on the distance between ϕ_n and ϕ_k.

Interference thresholds also depend on y_m as power and transmission rules change massively in various frequency bands. The bandwidth requirements of all CM2M devices are different because of the various quality of service requirements for each device. The model defines $R = \{r_n\}_{1xN}$ as device request bandwidth, where r_n represents a bandwidth demand of ϕ_n.

In a dynamic environment, the availability of channels and the interference threshold matrix both change continually; the spectrum availability is presumed to be static or varies slowly in each scheduling time slot (e.g., all matrices remain constant through the scheduling duration time). Furthermore, the model presumes a subset of CM2M devices is scheduled during each time slot, and the available spectrum is assigned among them without causing interference to PUs.

3.2.2 Spectrum Aggregation Model

In a typical case of spectrum assignment, each channel is formed from a continuous spectrum fragment; thus, it is not viable to use small spectrum fragments which are less than the user's bandwidth requirements. For example, consider a CM2M network where every machine needs 4 MHz channel bandwidth, and the available spectrum consists of two spectrum fragments of 4 MHz, and four spectrum fragments of 2 MHz (Fig. 3). For continuous spectrum allocation, the 2 MHz spectrum fragments cannot be used by any machine. Thus, a continuous spectrum assignment mode can only back two devices for communication (2 x 4 MHz). However, a spectrum aggregation-enabled device can exploit fragmented segments of the spectrum by utilizing specialized air interface techniques, such as DOFDM. In Figure 3.3, if a number of small spectrum fragments are aggregated into a wider channel, then 16 MHz of unused spectrum is available to support four CM2M devices (4 x 4 MHz).

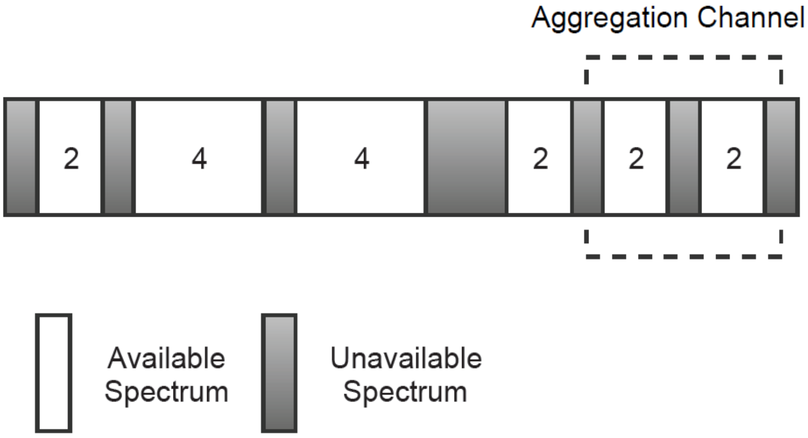

Figure 3.3: Aggregation of Disjointed Spectrum Fragments

Because of the limited aggregation ability of the RF frontend, only those channels can be aggregated that reside within a range of MAS. With this threshold, some spectrum fragments may not be aggregated because their span is larger than the MAS. The developed algorithm considers MAS, for the sake of simplicity, the following assumptions are taken into consideration:

1. All CM2M devices have the same aggregation capability (e.g., MAS for all devices is the same).
2. The guard band between adjacent channels is neglected.
3. The bandwidth requirement of each device and bandwidth of each channel are an integer multiple of sub-channel bandwidth Δf; which is the smallest unit of bandwidth (in fact, the smaller fragments would demand excessive filtering to limit adjacent channel interference), for example:

$$r_n = w_n \,.\, \Delta f,\ w_n\ \in \text{₦},\quad 1\ \leq n\ \leq N \tag{3.1}$$

$$BW_m = k_m \,.\, \Delta f,\ k_m\ \in \text{₦},\quad 1\ \leq m\ \leq M \tag{3.2}$$

where ₦ is the set of natural numbers, w_n is the number of requested sub-channels by CM2M ϕ_n, k_m is the number of sub-channels in y_m, and BW_m is the bandwidth of y_m.

The total available spectrum (e.g., M channels) is subdivided into multiple sub-channels. If the available spectrum band consists of A sub-channels, (e.g. total available bandwidth is $A.\Delta f$) then:

$$y_m = \bigcup_{i=1}^{k_m} \widetilde{yi}, m.\ \ k_m = \frac{BW_m}{\Delta f} \quad , \qquad \text{where}\ 1\ \leq m\ \leq M \tag{3.3}$$

$$\boldsymbol{AA} = \sum_{m=1}^{M} k_m \tag{3.4}$$

Where y_m and k_m sub-channels and $\tilde{y}i,m$ represent the i^{th} sub-channel of y_m. Each $\tilde{y}i,m$ can be represented in an interval defined as $[\mathcal{F}^L_{i,m},\ \mathcal{F}^H_{i,m}]$; where the $\mathcal{F}^L_{i,m,}$, and $\mathcal{F}^H_{i,m}$, are the lowest and highest frequency of $\tilde{y}i,m$.

$$\mathcal{F}^H_{i,m} - \mathcal{F}^L_{i,m,} = \Delta f,\ \text{For,}\quad 1 \le i \le k_m \text{ and } 1 \le m \le M \tag{3.5}$$

Based on this new sub-channel indexing, matrices **LL** and **AA** can be rewritten as:

$$\boldsymbol{LL}^{*} = \left\{ L^{*}_{n,a}, L^{*}_{n,a} = L_{n,m} \right\}_{Nx\,A} \tag{3.6}$$

$$\boldsymbol{AA}^{*} = \left\{ A^{*}_{n,k,a}, A^{*}_{n,k,a} = A_{n,k,.m} \right\}_{NxNxA} \tag{3.7}$$

If

$$1 \le a \le k_1 \quad for \quad m = 1$$

and

$$\sum_{j=1}^{m-1} k_j \ < \ a \ \le \ \sum_{j=1}^{m} k_j \ \ for\ 1 \le m \le M$$

where a represents the index of each sub-channel within the available spectrum. The sub-channel assignment matrix

$$\mathbf{DD} = \left\{ d_{n,c} \mid d_{n,c} \ \in \{0,1\} \right\}_{NxA}$$

is the $N\ x\ A$ binary matrix representing sub-channels allocated to CM2M devices for aggregation such that $d_{n,a=1}$, if and only if sub-channel a is available to ϕ_n and 0 otherwise.

$$\mathbf{B} = \left\{b_n = \Delta f . \textstyle\sum_{a=1}^{A} d_{n,a}\right\}_{Nx\ 1}$$

B defines as the reward vector represent the total bandwidth that is assigned to each CM2M device during scheduling time for a given sub-channel assignment.

3.3 Problem Formulation

3.3.1 Optimisation problem

One of the key objectives of the deployment of the CM2M network is to boost spectrum utilization. To accomplish/attain etc. this crucial goal, the model optimizes network utilization to maximize the total bandwidth that is assigned to CM2M devices and the technique/methodology/scheme, etc. is referred to as Maximising Sum of Reward (MSR):

$$\text{MSR} = \sum_{n=1}^{N} b_n \qquad (3.8)$$

To maximize MSR, the spectrum aggregation problem can be defined as a constrained optimization problem as shown in (3.9).

$$max_d = \sum_{n=1}^{N} b_n \qquad (3.9)$$

subject to,

$$b_n = \Delta f.\sum_{a=1}^{A} d_{n,c} = \begin{cases} 0 & if \;\; \phi_{\mathrm{n}} \;\; is\, rejected, \\ r_n & if \;\; \phi_{\mathrm{n}} \;\; is \;\; accepted, \end{cases} \; for\, 1 \le n \le N \qquad (3.10)$$

$$\mathcal{F}_{d,t}^{H} - \mathcal{F}_{e,f}^{L} \le MAS \qquad (3.11)$$

$$d_{n,a} = 0 \text{ if } L_{n,a}^{*} = 0 \;\; for \;\; 1 \le n \le N \;\; and \;\; 1 \le a \le A \qquad (3.12)$$

$$d_{n,a}.d_{k,a} = 0 \text{ if } A_{n,k,a}^{*} = 1 \text{ for } 1 \le n, \; k \le N\, and\, 1 \le a \le A \qquad (3.13)$$

Expression (3.10) assures that rewarded bandwidth b_n to each accepted ϕ_{n} must be equal to the ϕ_{n}'s bandwidth demand r_n; if the CM2M network cannot satisfy the ϕ_{n}'s bandwidth request, ϕ_{n} is rejected and $b_n = 0$.

If $\mathcal{F}_{e,f}^{L}$ $(1 \le e \le k_f$ and $1 \le f \le M)$ is the lowest frequency of an initial aggregated sub-channel and $\mathcal{F}_{d,t}^{H}$ $(1 \le d \le k_t$ and $1 \le t \le M)$ is the highest frequency of a terminative sub-channel, (3.11) guarantees that the range of allocated spectrum is equal to or less than MAS. The **DD** must satisfy the interference constraints (3.12) and (3.13); expression (3.12) and (3.13) guarantee that there is no harmful interference to PUs and other CM2M devices respectively.

3.3.2 Spectrum Aggregation Algorithm Based on Genetic Algorithm (GA)

Typically, the spectrum assignment problem has been classified as an NP-hard problem [10]. Herein, GA is employed to overcome the aggregation-based spectrum assignment problem to gain faster convergence. GA is a stochastic search method that mimics the process of natural evolution. In addition, it is easy to encode solutions for the spectrum assignment problem to chromosomes in GA and compare the fitness value of each solution. The specific operations of the proposed algorithm, referred to as MSR Algorithm (MSRA), can be described–in the following steps (Figure 3.4).

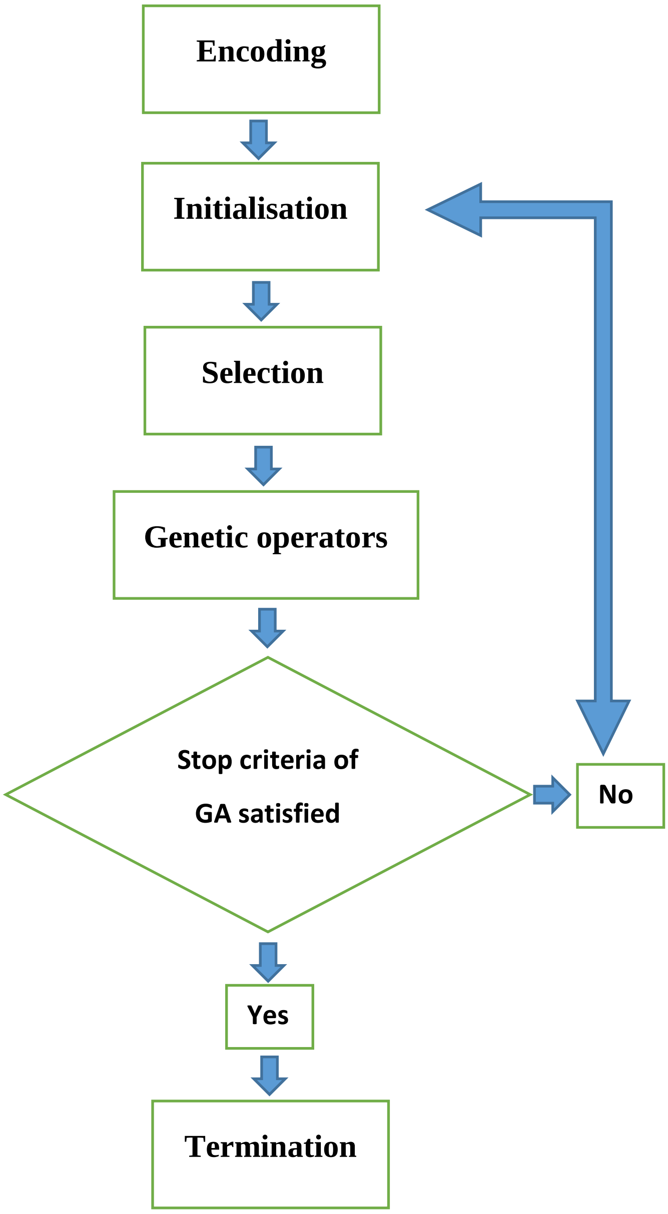

Figure 3.4: MSR Algorithm Flow Chart

1. **Encoding**: In MSRA, a chromosome represents a possible conflict-free sub-channel assignment. To decrease search space (by reducing redundancy in the data) and gain faster solutions, a comparable scheme as described in [10] is adopted in the model. The model also applies a mapping process between **DD** and the chromosomes based on the characteristics of $\boldsymbol{LL}^*$ and $\boldsymbol{AA}^*$.

   Only those elements of **DD** whose corresponding elements in $\boldsymbol{LL}^*$ take the value of 1 are encoded, for example $d_{n,a} = 0$, where (n, a) satisfies $L^*_{n,a} = 0$. As a result of this mapping, the chromosome length is equal to the number of non-zero elements of $\boldsymbol{LL}^*$ and the search space is greatly decreased. Based on a given $\boldsymbol{LL}^*$ length of the chromosome can be calculated as:

$$\sum_{i=1}^{N} \sum_{j=1}^{A} L^*_{i,j}$$

2. **Initialisation:** During the initialization process, the initial population is randomly generated based on a binary coding mechanism as applied in [81]. The size of the population depends on $|\boldsymbol{\phi}|$and |Y|; for larger $|\boldsymbol{\phi}|$and |Y| population size should be increased; where $|.|$ indicates cardinality of a set.
3. **Selection**: The fitness value of each individual of the current population according to the MSRA criteria defined in equations (3.8)-(3.10) is computed. According to the individual's fitness value, excellent individuals are selected and remain in the next generation. The chromosomes with the highest fitness values then replace the ones with the lowest fitness values via the selection process.
4. **Genetic operators**: To maintain the high fitness values of all chromosomes in a successive population, crossover and mutation operators are applied. Two randomly selected chromosomes are chosen in each iteration as the parents, and the crossover of the parent chromosomes is carried out at the probability of crossover rate. In addition to selection and crossover operations, a mutation at a certain mutation rate is performed to maintain genetic diversity.
5. **Termination:** The stop criteria of GA are checked in each iteration. If they cannot be satisfied, step three and four above are repeated. The number of maximum iteration and the

difference of fitness value are used as the criteria to determine the termination of GA. The population of chromosomes generated by initialization, selection, crossover, and mutation may not satisfy the given constraints defined in (3.10)-(3.13).

To find feasible chromosomes that achieve all thresholds, a threshold-free process is employed that has the following steps (in order):

1. Bandwidth requirements: The vector **B** as given in (3.3) is calculated. b_n should either equal r_n or zero, otherwise all genomes are related to ϕ_n changed to zero.
2. MAS: To satisfy the hardware limitations of the transceiver, expression (3.11) should be satisfied; otherwise all genomes related to ϕ_n are changed to zero.
3. No interference with PUs: expression (3.12) guarantees that CM2M transmissions do not interfere with LUs transmissions; ensuring that the CM2M network does not harm the PUs performance. If Expression (3.12) is not satisfied, all genomes related to ϕ_n are hanged to zero.
4. CCI: Expression (3.13) guarantees that there is no harmful interference to other CM2M devices. If expression (3.13) is not satisfied, one of two conflicted devices is chosen at random, and then all genomes of the selected device are changed to zero.

To obtain higher spectrum utilization and faster convergence, after each generation, MSRA assigns all unassigned spectrum to remaining CM2M devices randomly, whenever possible. At the same time, MSRA assures all the thresholds defined in (3.10)-(3.13) are satisfied at all times.

3.4 Simulation Results

In this section, a set of system-level performance results are presented to compare and show the efficiency of MSRA over MSA [14], AASAA [15] and Random Channel Assignment Algorithm (RCAA) [16]. The simulation results demonstrate the high potential of the proposed method in terms of spectrum utilization and system capacity. To assess the performance of the network, independent of each device’s traffic distribution model, a backlogged traffic model (known as a full-buffer model) is used where the packet queue length of every device is much longer than can be scheduled during each scheduling time slot.

Due to the random nature of the channel bandwidth and the devices bandwidth demand, Monte Carlo simulations are performed, and each simulation scenario is repeated 100,00 times. The default parameters used in the simulations are listed in Table 3.1, where $\mathrm{U}(1;\ 20)$ represents the discrete uniform random integer numbers between 1 and 20. Each of the channels is modeled as a flat Rayleigh channel with path loss model of $PL\ =\ 128{:}\,1\ +\ 37{:}\,6\ log10\ R$ (R is in km) and penetration loss of 20 dB. The mean and standard deviation of log-normal fading are zero and 8 dB respectively.

In the simulation model, the CM2M devices are located randomly without restrictions within a rectangular area of 2 $km\ X$ 1 km. All channels are randomly selected between 54 MHz and 806 MHz television frequencies (Channels 2-69), to investigate the simulation results effectively, the following terms are defined and used in the model analysis [14, 15]:

Table 3.1: Simulation parameters

Parameter	**Value**
Δf The Bandwidth of sub-channel	1 MHz
MAS	MAS 40 MHz
$\mathrm{BW_m}$ The bandwidth of y_m	Δ . U (1; 20)
$\mathrm{r_n}$ Bandwidth demand of ϕ_n	Δ . U(1; 20)
Total Transmit Power	26 dBm (400 mW)
Scheduling Time Slot	1 ms
Traffic Model Backlogged	Backlogged
Population Size	20
Number of Generations	10
Mutation Rate	0:01
Crossover Rate	0:8

1. **Spectrum Utilisation**: referred to as u which is defined as the ratio of the sum of rewarded bandwidth to the sum of all available bandwidth, e.g.

$$u = \frac{\sum_{N=1}^{n} b_n}{\sum_{m=1}^{M} BW_m} \tag{3.14}$$

2. **Network Load**: referred to as Ł which is defined as the ratio of the sum of all CM2M devices bandwidth requirements to the sum of all available bandwidth, e.g.

$$Ł = \frac{\sum_{N=1}^{n} r_n}{\sum_{m=1}^{M} BW_m} \tag{3.15}$$

3. **Number of Rejected Devices**: rejected devices are those machines that are not assigned any spectrum in a certain scheduling time slot.

3.4.1 Scenario-I: Without Co-Channel Interference

In this scenario, the performance of MSRA is compared with the SOTA algorithms including MSA [14], AASAA [15], and RCAA [16], when the CCI among CM2M devices is not considered. Therefore, the system model assumes that CM2M devices transmissions do not overlap with the transmission of other CM2M devices using the same channel. For M = 30, Ł increases by increasing the number of CM2M devices from 5 to 60. Figure 3.5 shows that when the number of CM2M devices increases, spectrum utilization also increases in all three methods, but MSRA utilizes all available whitespace in various network loading conditions more efficiently than MSA, AASAA, and RCAA.

This can be explained by the fact that in the case of higher Ł, the network can allocate better segments of the spectrum to users because of higher multi-user diversity. In addition, due to using a stochastic search method, MSRA achieves a near to optimum solution in comparison with other SOTA solutions which are based on approximate algorithms. For MSRA, when Ł is higher than three, the CM2M network becomes saturated due to the lack of available spectrum. However, for the remaining methods, there are still unassigned spectrum slices.

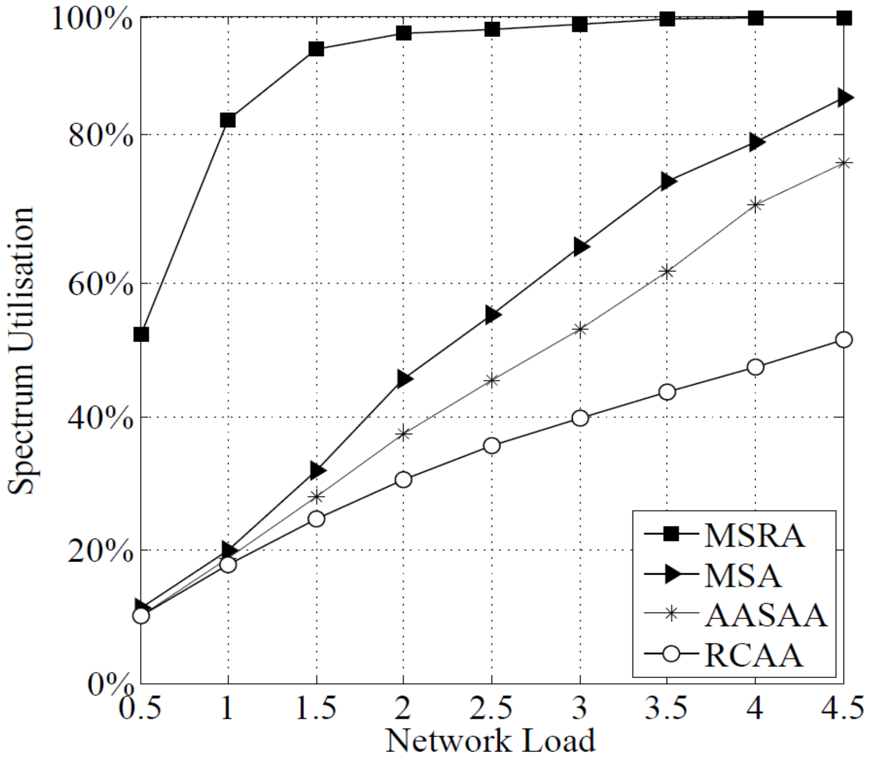

Figure 3.5: The Impact of Varying Network Load Conditions on Spectrum Utilisation (Scenario-I: Without CCI)

3.4.2 Scenario-II: With Co-Channel Interference

In this scenario, CCI exists among CM2M devices and MSRA compared with AASAA and RCAA. As MSA does not inherently consider CCI, the model here does not include MSA for comparison. Figure 3.6 shows spectrum utilization, according to different network loads by increasing the number of CM2M devices from 5 to 55 when there are only seven available channels (e.g., M = 7). As shown in Figure 3.6, MSRA outperforms AASAA and RCAA for different network loads. Similar to when compared to Scenario-I, MSRA utilizes TVWS even better, because some CM2M devices in the network may reuse spectrum previously used by other devices in the CM2M network.

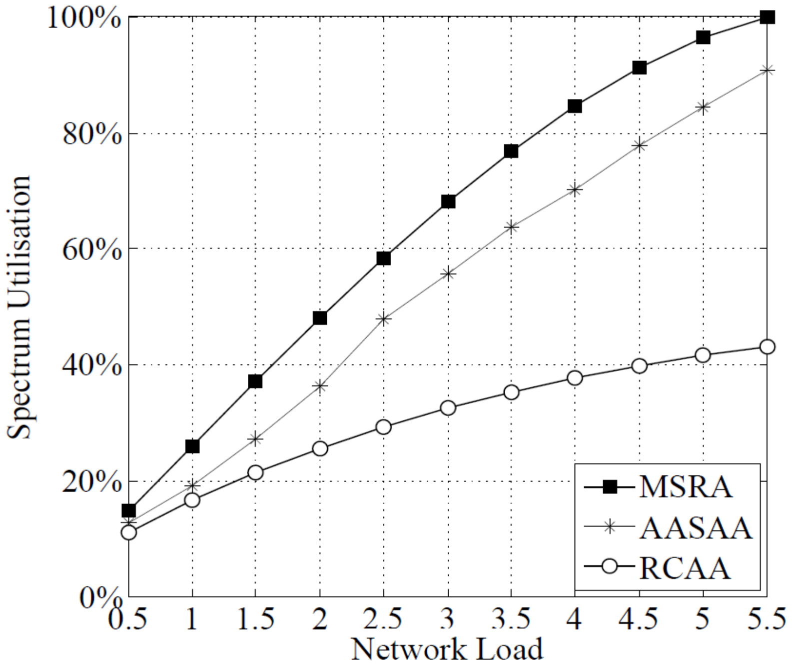

Figure 3.6: The Impact of Varying Network Load Conditions on Spectrum Utilisation (Scenario-II: With CCI)

Figure 3.7 represents the number of rejected CM2M devices when the network load increases. The number of rejected CM2M devices increases with the network load; MSRA has a lower number of rejected CM2M devices (or more satisfied devices) than AASAA and RCAA for different network loads. MSRA optimizes spectrum utilization by admitting devices with better channel quality to the network and allocates spectrum resources more effectively. Figure 3.7 implies that MSRA increases the capacity of the network, which is vital for M2M networks due to the huge number of devices.

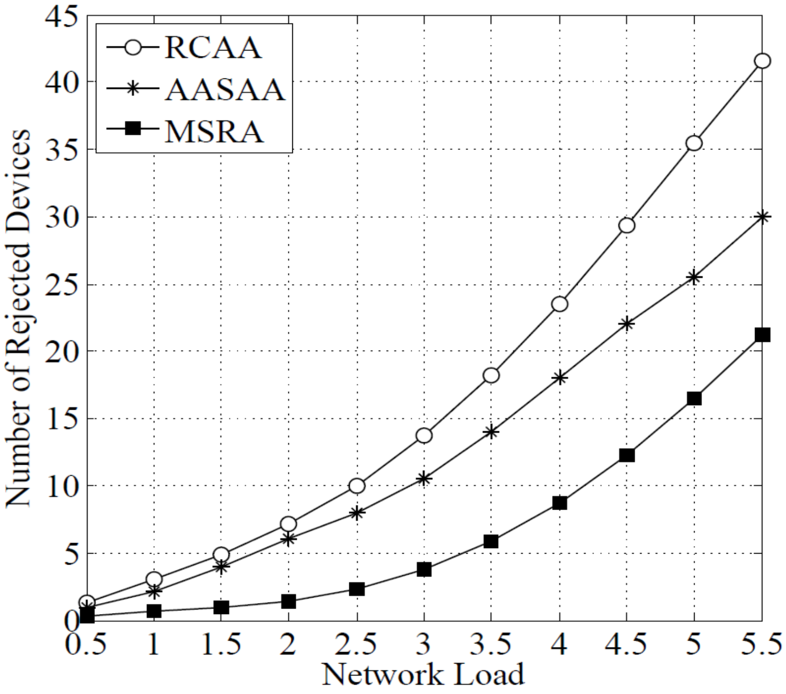

Figure 3.7: The Impact of Varying Network Load Conditions on the Number of Rejected CM2M Devices (Scenario-II: With CCI).

3.4.3 Convergence of MSRA

Because of the nature of genetic programming [17][12], it is arguably impossible to make formal guarantees about the number of fitness evaluations needed for an algorithm to find an optimal solution. However, herein, computer experiments are performed to show the impact of a number of generations on the performance of MSRA. The system parameters used in the section for simulation are listed in Table 3.2. For convergence studies, N is set/chosen, etc to be 200 and M = 10. Figure 3.8 shows the best fitness value (MSRA) for a population in a different number of generations. As shown in Figure 3.8, the performance of the algorithm is enhanced as the number of generations increases; after roughly 34 generations, the fitness value saturates at an optimal value which shows the effectiveness of using GA for spectrum assignment using spectrum aggregation.

Meanwhile, Figure 3.9 illustrates the distribution of processing time for MSRA to find an optimal solution. As shown in Figure 3.8, 85% of the time, MSRA finds an optimum solution in less than the scheduling time slot (1 ms) and 15 % of the time it takes more than the scheduling time slot which is a good rate comparing with the AASAA and RCAA which usually takes more than (3 ms) to find the optimal solution.

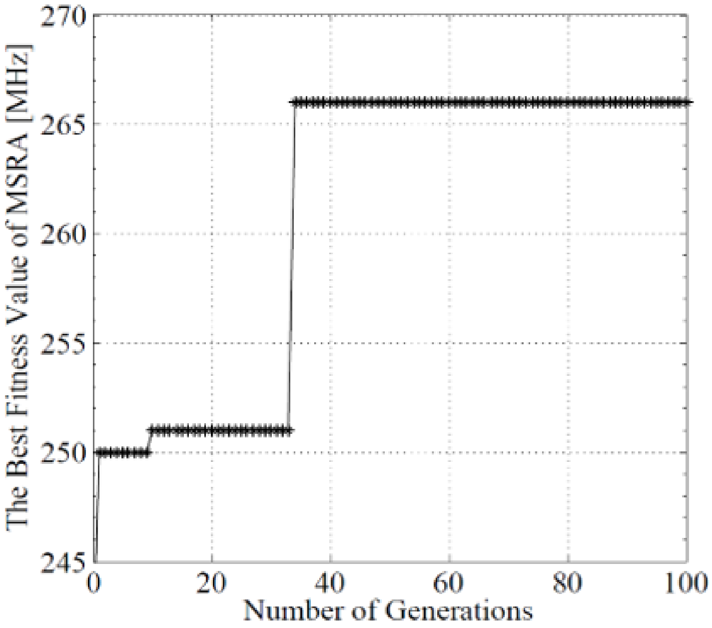

Figure 3.8: The Impact of Number of Generations on MSRA Results

Table 3.2: System Parameters

Parameter	Value
M	10
N	200
Processor	Intel Core i7-3667U 2.00 GHz
Memory (RAM)	4 GB
OS	Windows 7 (64-bit)

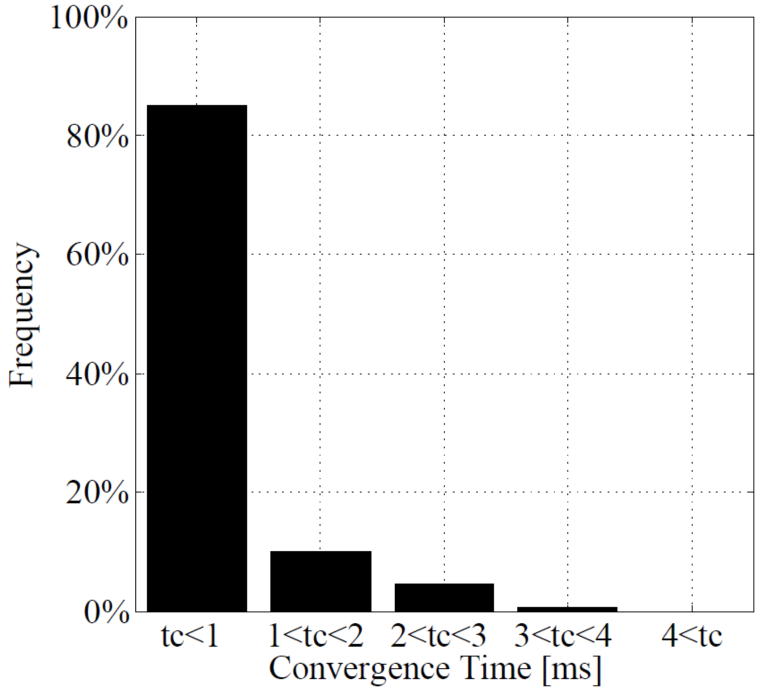

Figure 3.9: Distribution of Processing Time for MSRA to find an Optimal Solution

Furthermore, Lobo in [12] provided a theoretical and empirical analysis of the time complexity of traditional simple GAs. According to [12], GA has time complexities of

$$6\left(\sum_{i=1}^{N}\sum_{j=1}^{A} L_{i,j}^{*}\right)$$

which is dependent on the length of each chromosome. The linear time complexity for GA occurs because the population size grows with the square root of chromosome length. In this problem, the complexity depends on chromosome length which itself is dependent on a number of users and radio resources. The time complexity presented herein is for the worst-case scenario (6) when the population size is assumed fixed at the maximum number of generations.

3.5 Summary

This chapter introduces an aggregation-aware spectrum assignment algorithm using a genetic algorithm. The proposed algorithm maximizes spectrum utilization for CM2M devices as a criterion to realize spectrum assignment. Moreover, the introduced algorithm takes into account the realistic thresholds of co-channel interference and increase aggregation span. The performance of the proposed algorithm is validated by simulations, and the results are compared with algorithms available in the current literature (e,g, RCA, MSA, and MSRA). The proposed algorithm reduces the number of rejected devices and enhances spectrum utilization of the CM2M network. The algorithm increases the capacity of the network which is vital for M2M networks.

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CHAPTER 4

ENERGY EFFICIENT SPECTRUM SENSING AND SHARING

4.1 Introduction

M2M communication is the future of smart things; as discussed in the previous Chapters, hundreds of millions of devices will be connected in the near future for a number of different applications. M2M communication is very important due to its cost reduction, flexibility, time efficiency, and accuracy. M2M communications will face many challenges due to a high number of devices, cost, and the quality and reliability of the providing services [1, 2]. These challenges are mainly related to energy consumption, spectrum limitations, data rate, and security.

There are currently many attempts being made to address M2M communications challenges such as energy and spectrum efficiency. However, little consideration has been given to the idea of using cognitive radio as a solution. Cognitive radio is an intelligent technology which can be designed and configured to cope with the M2M communications problems.

As mentioned in Chapter 2 a number of studies have considered cognitive radio technology for better energy efficiency, one of these addressed spectrum discovery schemes such as the non-cooperative, cooperative and time-division energy efficient schemes [3] for improved energy efficiency in CM2M communications. The authors in [4] addressed optimal power allocation to improve quality of service and energy efficiency in a CM2M network. In [5] the energy efficiency in CR wireless devices is addressed. The distributed sensing approach optimizes power efficiency with thresholds on the minimum desired detection probability and the increase of the permissible probability of false alarms by selecting the sensing and sleeping design parameters.

Little efforts have considered spectrum handoffs and the wait/switch trade-off in a CM2M network with multiple CM2M devices (e.g., CM2M gateways). In addition, no previous work has considered the scenario of a number of CM2M gateways working together and addressed the collision probability among them.

This Chapter proposes an energy efficient mechanism for the CM2M network by optimizing the spectrum sensing and switching schemes. The proposed mechanism guarantees to sense reliability and users' throughput constraints simultaneously. To optimise the total energy cost, the mechanism ensures that spectrum handoff is not used excessively. Instead, CM2M gateways may occasionally decide to stop sending data and remain in a sleep state on their current channel for a specific duration of time.

The rest of this Chapter is organised as follows: section (4.2) presents the system model, section (4.3) addresses the problem and presents the solution, section (4.4) shows the optimality of our mechanism through simulation and discussion, and Section (4.5) concludes the chapter.

4.2 Spectrum Sensing and Sharing System Model

The system model considers working with Q number of secondary transmission CM2M gateways and primary transmission (Figure 4.1). As shown in Figure 4.1 CM2M gateways connected M2M device domain and network domain together and the the final signal can be send to the backend (application domain). Furthermore, the system considers the following assumptions:

1. ɱ random channels shared between secondary users and primary users, and Ɲ is the number of frames.
2. The secondary transmission (CM2M gateways) is slotted in via periodic sensing at specific periods.
3. Each frame builds a transmission slot of period T and from sensing slot of durations τ_s a transmission slot of period T, where only one of the ɱ channels is assigned to the CM2M gateways.
4. The CM2M gateways at the start of each transmission slot may prefer to send information/data on the sensed channel or select another available channel.
5. The PU transmission is presumed to be continuous and follow an off-on- traffic pattern for each channel [6].
6. The primary user transmission probability (ON/OFF) presumed to be the same for all the channels.
7. The average received SNR of the primary transmission signal for all channels is assumed to be the same through one packet of data transmission.

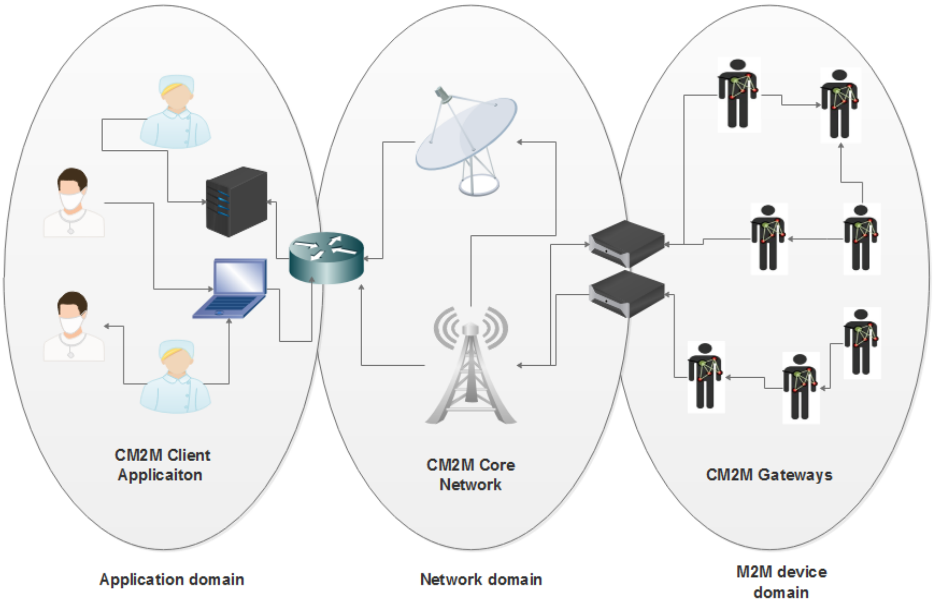

Figure 4.1: CM2M System with a Number of Secondary Transmission CM2M Gateways

Figure 4.2 shows the CM2M gateways performance when sending a packet of information/data assuming energy detection is applied to jointly sense the channels while the CM2M gateways apply wideband sensing to check the other free channels. Furthermore, Figure 4.2 shows how CM2M gateways sometimes choose to sleep (power off) when the current channels busy; and the collision between the CM2M gateways if they decided to jump at the same time into the same channel.

The false alarm probability and the detection probability, are defined as Pf and Pd. The received signal is sampled at sampling frequency fs, bandwidth BW and the frequency band with carrier frequency fc. The system model presumed when the primary transmission is active, the received signal at the CM2M gateways under assumption $S0$ and can be represented as :-

$$a(n) = s(n) + u(n)$$

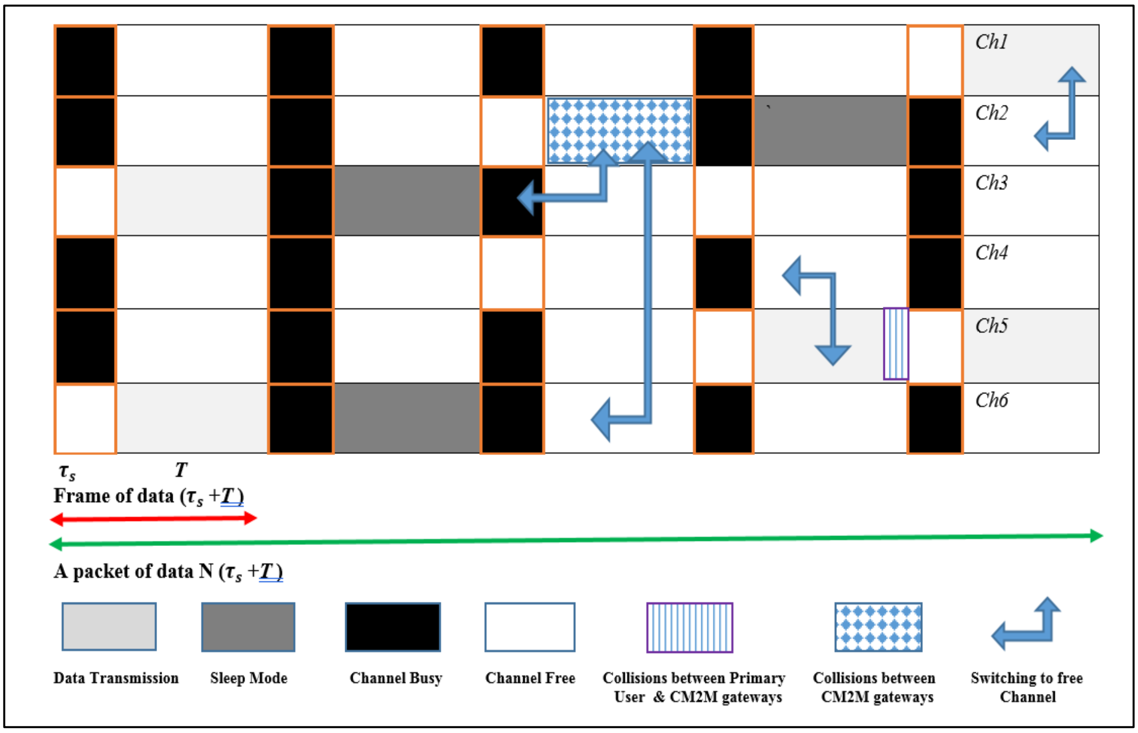

Figure 4.2: CM2M Gateways Performance in N Packet of Data

Where the system considers the following assumptions [7]:

- The first assumption is that the noise u(n) is Gaussian, identically and independently distributed in a random way with mean zero and; $\mathrm{E}|\mathrm{u(n)}|^2 = \sigma_\mathrm{u}^2$;
- The primary signal $s(n)$ is assumed to be a real-valued Gaussian signal [7].

When the primary user under idle state, the output under assumption $S1$. The received signal is given by

$$a(n) = u(n)$$

Two reliable probabilities are considered for spectrum sensing. The first is the probability of false alarm, which is determined under assumption stated in S0, is the probability where the algorithm falsely declares the existence of primary transmissions. The second is the probability of detection, which is determined under the assumption stated in $S1$, is the probability where the algorithm correctly detects the existence of primary transmissions [8].

For the primary user's transmission side to gain better protection, a higher probability of detection should be guaranteed. From the CM2M gateways transmission side, a lower probability of false alarm should be guaranteed for better CM2M gateways transmission (QoS). Therefore, for an efficient algorithm, the probability of false alarm should be the minimum possible, and the probability of detection should be the maximum possible. The probability of false alarm related to the target false alarm probability $\bar{P}f$ and the target probability of detection $\bar{P}d$ for similar system are given in [8] and as follows:

$$Pf = Q\left(\sqrt{2\gamma + 1}\, Q^{-1}\,(\bar{P}d) + \sqrt{\tau\, f_s \gamma}\right) \tag{4.1}$$

where γ is the SNR regime, f_s is the sampling frequency, τ is the CM2M sensing time. Similarly, the probability of detection related to the target false alarm probability $\bar{P}f$ and the target probability of detection $\bar{P}d$ for similar system are given in [8] and as follows

$$Pd = Q\left(\frac{1}{\sqrt{2\gamma+1}} Q^{-1}\,(\bar{P}f) + \sqrt{\tau\, f_s \gamma}\right) \tag{4.2}$$

Next, the system considers $\bar{P}d$ and $\bar{P}f$ are the same for all channels. From [88] it is known, for a stable sampling frequency f_s, there is a minimum sensing period such that the reliability constraints are achieved (false alarm and detection probabilities). The minimum required sensing time is defined by τ_s^{min} .

$$\tau_s^{min} = \frac{1}{\gamma f s}\,(Q^{-1}(\bar{P}f) - Q^{-1}(\bar{P}d)\sqrt{2\gamma + 1}\,)^2 \tag{4.3}$$

To decrease the energy consumption of the CM2M gateways due to spectrum sensing, τ_s^{min} sensing duration should be satisfied. The total energy consumption should be achieved with optimal τ_s to achieve higher energy efficiency in the model [6 , 9].

The CM2M gateways will choose before sending data whether to select another empty channel or remain on the current sensed channel after collecting credible knowledge of the availability of other surrounding channels. The system model assumed to deter CM2M gateways from switching and selecting another channel; they have to apply transmission for period T until the next sensing slot arrives (Figure 4.2.) If CM2M gateways remain on their current channels, CM2M gateways must decide whether to simply refrain from sending data until the next sensing slots become available, or to proceed with data transmission for a period of time T using other channels.

The delay due to spectrum handoff and the energy cost during the transmission slot is assumed to be negligible in the case where the CM2M gateways devices stay on the current channels with power off. However, the designed model switch/select-wait/sleep considers the trade-off between the activities of the CM2M gateways in cases of energy savings and throughput [10, 11]

For instance, one of the CM2M gateways may stay and sleep on the current channel and continue sending data when the current channel is sensed as free, and the other channels sensed as busy. Because neither energy savings nor throughput will improve if the CM2M gateways switch to another channel. Therefore, the CM2M gateways must remain on the current channel and sleep for a period of T seconds when all ɱ channels busy, as energy costs will increase when the CM2M gateways decide to switch and send data on the other channels without enhancing the data rate of the CM2M gateways [8, 6].

If the CM2M gateways sense the current channel is busy and one of ɱ channels is sensed as unoccupied by the primary user, they need to choose whether to spend energy to switch and select a free channel so that the CM2M gateways may be able to procced and make data transmission or to stay on the current channel and sleep to spare energy at the cost of reduced throughput [12]. In such a case, CM2M gateways are assumed to switch to another free channel with a probability of $(1-L_s)$ or stop transmission and wait on the current channels with a probability of L_s [13].

4.3 System Problem and Solution

4.3.1 Problem

The problem is formulated by jointly looking for both optimal values of (τ_s, and L_s). subsequently, the energy efficiency is maximized with the satisfied throughput. The optimization problem can be formulated as follows:

$$min_{\tau_s L_s} QX(\tau_s, L_s)$$

subject to

$$\begin{aligned} Pd(\tau_s) &\geq \bar{P}d \\ Pf\ (\tau_s) &\leq \bar{P}f \\ Q\mathcal{R}(\tau_s, L_s) &\geq r \end{aligned} \tag{4.4}$$

Where X is the overall average energy cost needed to finish sending a single packet of information/data, S is the time needed for the CM2M gateways to send a packet of data, $\mathcal{R}$ is the average data rate or throughput, and r is the minimum throughput that should be achieved in the system, respectively.

4.3.2 Problem Solution

The system model defines P_3 as the switching probability to another idle channel and apply transmission of T for a number of CM2M gateways and one primary user link as given as follows:

$$P_3(\tau_s, L_s) = (1 - P_1)(1 - P_b)(1 - L_s) \tag{4.5}$$

Where P_1 is the probability of a channel being free, and P_b is the probability of a channel being busy. The system model is assumed to work with a number of CM2M gateways thus, the probability of collision between CM2M devices need to be manged in case they decided to switch to the same idle channel at the same time. For this, the system model considered the transmissions of CM2M gateways for such a case equal to zero. At the same time, the system model assumed pfc as the probability of collision between CM2M gateways. Hence, the new probability of switching to another idle channel and performing transmission of T is given in equation (4.6):

$$P_3(\tau_s, Ls) = (1 - P_1)(1 - P_b)(1 - L_s)(1 - pfc) \tag{4.6}$$

Hence, the overall energy cost for such a system, including the energy cost due to spectrum handoff, spectrum sensing, and data transmission, can be calculated by the equation below: -

$$X(\tau_s, L_s) = SE_t + \text{Ɲ}\, \tau_s E_s + \text{Ɲ} P_3\, J_{sw} \tag{4.7}$$

where J_{sw} is defined as the energy cost for single channel switching, in the unit of joules, where E_t and E_s is defined as energy consumption per second due to sending data and sensing both in the unit of watts, presuming that E_t , E_s and J_{sw} are known as a given for CM2M gateways [8]. Similar power consumption is presumed when the CM2M gateways switch from one channel to another sensed as free. In such a situation, if there are free channels and the secondary user tries to switch one will be picked at random without compromising the overall average energy cost.

$C_0 = log\,(1 + SNR)$ bits/s/Hz is assumed to be the CM2M gateways throughput, the bits that are successfully sent in one transmission duration of T assumed to be C_0T.

There are two scenarios where the CM2M gateways choose to remain on the current sensed channel: when there is a minimum of one other free channel, but the CM2M gateways decide not to switch with a probability of L_s and when all M channels are sensed as occupied. The average data rate of the CM2M gateways is defined by

$$\mathcal{R}(\tau_{s,}L_s) = 1 - \frac{P_c \ + P_3\ (1 - P_e\ )B_t}{\tau_s + \mathrm{T}} \tag{4.8}$$

where B_t is number of bits sent in one transmission slot, P_c is the probability of channels truly sensed as busy, P_e those mistakenly sensed as busy [14], and r assumed to be small due to the CM2M system's small data rate requirements. It is observed from the equation given in (4.8) that, for a given τ_s, $\mathcal{R}$ is decreasing with L_s. This is true, because the longer the CM2M gateways remain on the current channel without sending any data (with a larger L_s), the less throughput can be achieved within a given T duration. In addition, it is known from (4.4) that the optimal L_s is measured by the last threshold (r), once it can achieve that threshold it can be absolutely fulfilled with the parameters given in the model. Accordingly, the optimal L_s is easily maximum the allowable of L_s that fulfilled the last threshold in (4.4). Which means the optimal L_s that solves (4.4) is given by

$$L_s^{opt}\ (\tau_s) = 1 - \frac{(\tau_s + T)r - Pc1\ Bt}{Bt(1 - P1)(1 - Pe)(1 - Pb)(1 - pfc)} \tag{4.9}$$

where L_s^{opt} is obtained by letting $\mathcal{R}(\tau_{s,}\ L_s) = r$, and from (4.6) and (4.8) it's possible to get the L_s^{opt}.

Furthermore, the first two thresholds $Pd(\tau_s) \geq \bar{P}d$ and $Pf\ (\tau_s) \leq \bar{P}f$ in (4.4) functionally designates that $\tau_s \geq {\tau_s}^{min}$, and from (4.3) its known that ${\tau_s}^{min}$ can satisfy the first two constraints. Furthermore, from (4.7) and (4.8) its known ${\tau_s}^{min}$ can achieve the minimum energy consumption in the system with guaranteed $\mathcal{R} > r$. This can be explained by the sensing duration of CM2M gateways: the less sensing time, the less energy required to sense the channels, which leads ultimately to decreased energy consumption in the system overall. Now, it's clear that ${\tau_s}^{min}$ can satisfy the three constraints given in (4.4) and at the same time achieve the minimum energy consumption in the system. Therefore, ${\tau_s}^{min}$ can be consider the

$\tau_s{}^{optimal}$ for the system that satisfies all constraints and reduces energy consumption in the system.

4.4 Simulation and Discussion

The efficiency of the designed spectrum sensing and accessing mechanism was demonstrated through Matlab simulations (Monte Carlo), and Table 4.1 shows the simulation setting. In simulations, the primary user is presumed to be a Quadrature Phase Shift Keying (QPSK) modulated signal with a bandwidth of 6MHz [8]. The sampling frequency is the same as the bandwidth of the primary user.

In the simulation, the following assumptions were made; m̧ is assumed to be 6 channels available for spectrum sharing between the CM2M gateways and the primary users, the period of each transmission slot is T = 0.8s, the period of a packet of information/data is S $=$ 8s, and the energy needed for spectrum sensing and sending data are E_t $=$ 69.5 mW and E_s $=$ 40 mW, respectively [15]. Furthermore, the received SNR of the primary user signal is assumed to be γ $=$ -10 dB, and the average throughput of CM2M gateways is defined as $R_0 = (1 - \rho)C_0$. The throughput constraint is defined as $r = \mu Q R_0$ where, the throughput coefficient $\mu \in [0, 0.6]$ and Q the CM2M gateways numbers.

Table 4.1: Value Setting of Simulations [8]

Parameter	Value	Description
m̧	6	Available channel number
S	8 s	Duration of one packet data
T	0.8s	Duration of each transmission
γ	-10dB	SNR
J_{sw}	40mJ	The energy consumption for single channel switching
$\boldsymbol{\rho}$	0.4	The probability of a channel being busy
$\bar{P}d$	0.9	The target probability of detection
$\bar{P}f$	0.1	The target probability of false alarm
Pfc	0.3	Collision probability of CM2M gateways
Q	2	CM2M gateways number

The energy consumption of the CM2M gateways in Table 4.2 is energy cost as a function of the throughput coefficient μ for $Jsw = 40\,mJ$. It is obvious that when the value of L_s increases, better energy efficiency is achieved, and the reason is that when L_s increases, fewer CM2M gateways will switch to a new channel and more CM2M gateways numbers will stay in the current channel and sleep for a period of time (T).

Accordingly, the optimal energy efficiency of X will be achieved when τ_s is equivalent to ${\tau_s}^{min}$ as explained in the aforementioned section. This is true because the lower the value of τ_s, the less energy will be spent in channel sensing, and the larger the T time duration transmission to send more data and increase the throughput. The numerical results in Table 4. 2 proved the analysis given in previous sections.

Table 4.2: Energy Consumption in CM2M Devices

Energy consumption (mW)	**Throughput coefficient**	$\boldsymbol{\tau_s}$ **Optimal**	$\boldsymbol{L_s}$
1235	[0,0.6]	32 ms	0
1125	[0,0.6]	32 ms	0.5
900	[0,0.6]	32 ms	L_s^{opt}

In Table 4.3, the developed mechanism results are compared with the ones reported in [8] which used only a sensing/throughput mechanism. By using simulations with the same value settings, it is shown that the developed mechanism (wait/switch trade-offs and sensing /throughput) is more energy efficient than the one given in [8].

${\tau_s}^{optimal}$ in [8] only optimises the sensing/ throughput trade-off and is not optimal in the case of reducing the overall energy cost, where it leads to more power cost compared with the state when ${\tau_s}^{optimal}$ of the developed mechanism is applied. Bear in mind that ${\tau_s}^{optimal}$ is created when both the wait/switch trade-offs and sensing/throughput are simultaneously considered.

Table 4.3: Energy cost when optimal L_s and τ_s are employed compared with the one in [8] which employed only τ_s

Energy consumption (mW)	**Throughput coefficient**	$\boldsymbol{\tau_s}$ **Optimal**	$\boldsymbol{L_s}$
1435	(0,0.6) [8]	41 ms	0
1350	(0,0.6) [8]	41 ms	0.5
1100	(0,0.6) [8]	41 ms	L_s^{opt}
1235	[0,0.6]	32 ms	0
1125	[0,0.6]	32 ms	0.5
900	[0,0.6]	32 ms	L_s^{opt}

4.5 Summary

In this Chapter, an energy efficient mechanism for CM2M communication has been proposed. The proposed mechanism simultaneously considers the wait/switch trade-off in terms of channel switching probability and the sensing /throughput trade-off in terms of the duration of sensing time. The proposed mechanism addresses the probability of collision between CM2M gateways by considering the transmission of devices to be zero when a collision occurs, and guarantees that the given constraints in terms of throughput and sensing reliability are always satisfied. Simulation results show the efficiency of performing spectrum handoff and the optimality of the mechanism that guarantees desirable throughput and reduced energy consumption in the system.

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CHAPTER 5

SELECTIVE ANTENNA SENSING

5.1 Introduction

M2M applications in the medical sector have become more significant for private and public entities, such as monitors for temperature, blood pressure and blood oxygen levels, and electrocardiograms [1]. This leads to improved efficiency in e-healthcare systems for instance by allowing early patient discharge from healthcare facilities and less time spent in recovery and reducing overall costs accrued by the patient’s family and allocated government spending [2, 3].

However, as mentioned in previous Chapters, the use of wireless M2M communications in e-healthcare systems creates new and complex interference scenarios. This intricacy is generated by medical devices which are normally sensitive to electromagnetic interference [4] caused by wireless antennas. The interference can cause many problems for the medical machines (e.g. waveform distortion, automatic shutdown, and automatic restart), which can be hazardous to patients. Furthermore, M2M applications in healthcare systems need to be energy efficient and able to work for a long period (e.g., 10 years) without battery replacement, while at the same time the quality of service should be sufficient to ensure the reliability thresholds required in e-healthcare applications. Cognitive radio can help with avoiding spectrum interference and improve spectrum and energy efficiency in the e-healthcare system [5, 6].

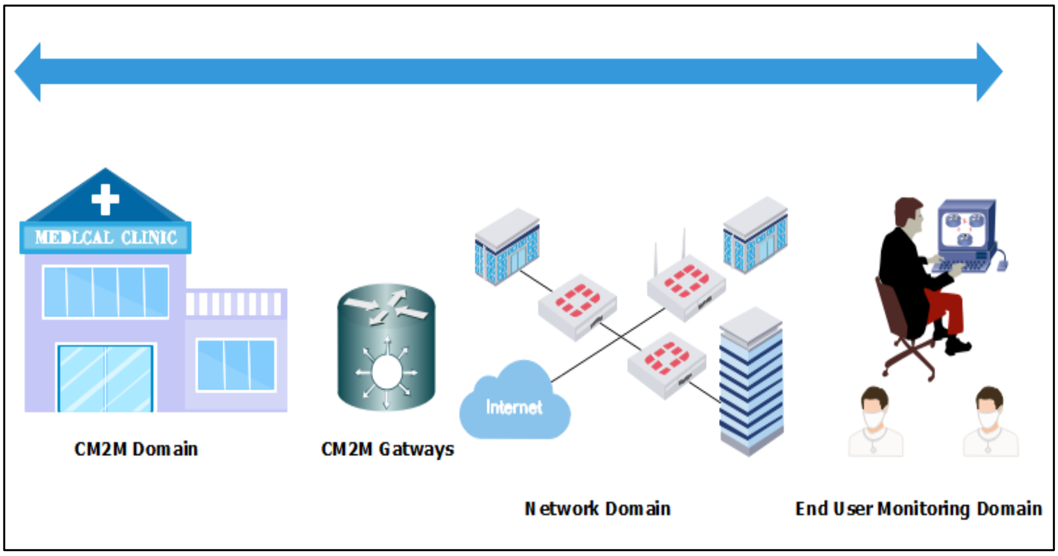

Figure 5.1: CM2M Network in Healthcare System

From the previous Chapters, its known a number of studies have proved that a "spectrum hands-off" operation can increase the data rate of the secondary users (e.g. CM2M gateways) when there is a variety of channels free for spectrum sharing [7], where the CM2M gateways can switch to another free channel and proceed with sending data when the current used channel is busy [8, 9].

This Chapter, propose an energy efficient spectrum management mechanism for the CM2M e-healthcare system as shown in Figure 5.1. The mechanism work illustrated in Figure 5.1 which connected the M2M devices with CM2M gateways to carry out the traffic to the backend through network domain which can be any networks (e.g., TVWS Bands). The proposed mechanism guarantees to sense reliability, throughput, delay and collision probability thresholds simultaneously. The rest of this Chapter is organised as follows: Section (5.2) defines the system model and explains spectrum sensing and access mechanisms. Section (5.3) formulates the optimization problem, while section (5.4) proposes a solution. Discussions and simulation results are illustrated in Section (5.5), and Section (5.6) summarises the Chapter.

5.2 Selective Antenna Sensing System Model

The system model supposes a CM2M network working in an e-healthcare environment with two CM2M gateways and a PU. Consider that there are ɱ channels shared between the CM2M gateways and a primary user. Energy detection is assumed to sense the channels, while the CM2M gateways apply wideband sensing to check the availability status of all channels. The additive noise is a zero-mean CSCG process. The system model considers a low SNR regime (γ), and we presume that the SU is slotted in via periodic sensing at a specific time, each frame consisting of a sensing slot of durations τ_s and a transmission slot of period T, where one of the ɱ channels is assigned to the CM2M gateways [10, 11].

The spectrum handoff delay assumed to be ksl is also added after the sensing slot in the CM2M gateways frames if the CM2M gateways decide to carry out channel switching after considering the sensing result and other thresholds.

Figure 5.2 shows CM2M gateways at the start of each transmission slot may decide to send information/data on the current channel, switch to another channel with a switch delay of $ksl,$ or remain on the current channel without sending any data. Moreover, the Figure shows the primary transmission activity which follows an off-on traffic pattern and is assumed to be continuous [12]. The average received signal-to-noise ratio (SNR) of the PU's signal for all channels assumed to be the same, also the false alarm probability Pf and the detection probability Pd assumed to be the same during one packet of data transmission [12]. The received signal is presumed to be sampled at sampling frequency fs, the frequency band with carrier frequency fc and bandwidth BW.

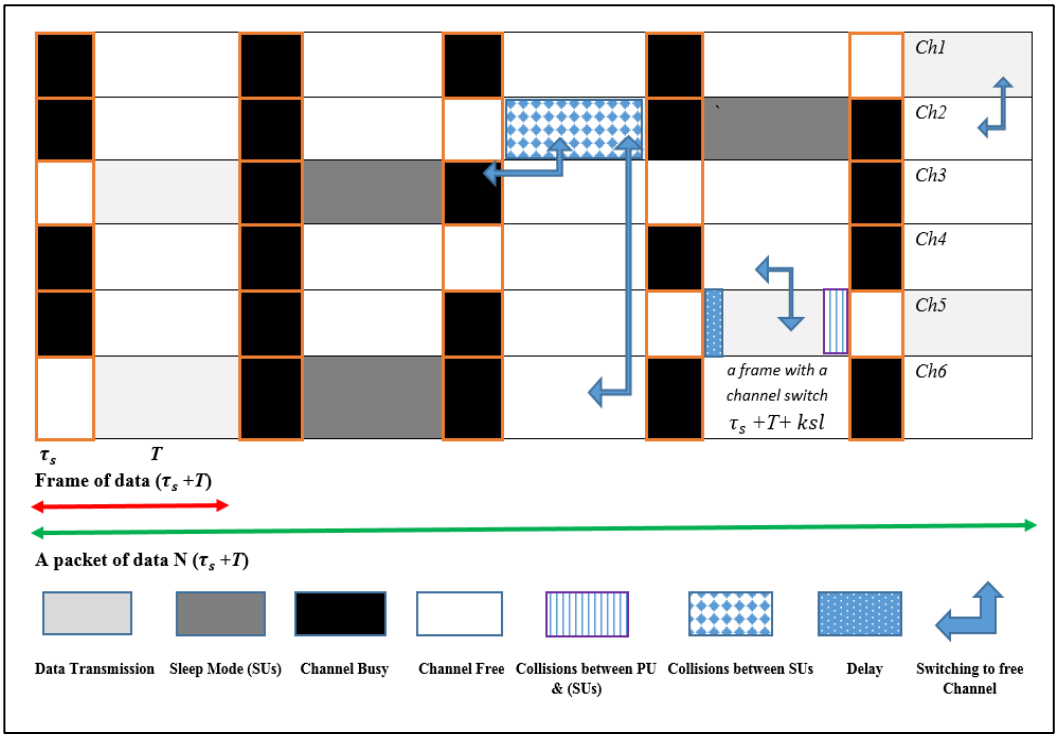

Figure 5.2: CM2M Gateways Performance in Transmitting N Packet of Data

The goal is to decrease energy costs for the CM2M gateways to send a packet of data under the probability of both false alarm and detection thresholds. As discussed in [12], we can jointly optimize the sensing slot length τ_s and the stay probability on the current channel L_s so that the energy consumption of one complete data packet transmission is reduced as follows:

$$({\tau_s}^{Optimal}, {L_s}^{Optimal}) = \min_{\tau_s, L_s} X(\tau_s, L_s) \qquad (5.1)$$

where ${L_s}^{Optimal}$ and ${\tau_s}^{Optimal}$ are the optimal stay probability and sensing slot length, respectively, while X is CM2M gateways total average energy cost for one data packet transmission, including spectrum handoff, spectrum sensing, and data transmission. It is worth noting that by applying energy detection, the energy consumption caused by the sensing process can be calculated by the length of the sensing slot. By assigning a target false alarm probability and a target detection probability ($\mathrm{e.g.}, \bar{P}f = 0.1\, and\, \bar{P}f = 0.9$) for each channel, we can consider the time required to satisfy the sensing accuracy requirements while, reducing this energy cost [13] as given below:

$$\tau_s^{\mu\iota\nu} = \frac{1}{yf_s}\,(Q^{-1}\left(\bar{P}_f\right) - Q^{-1}(\bar{P}_d)\sqrt{2\gamma + 1} \tag{5.2}$$

5.3 Selective Antenna Sensing System Problem

By taking into consideration the challenges and the design features in the sections above, it can be now present the proposed energy efficient mechanism to manage the available spectrum, given in (5.1), and as follows:

$$X(\tau_s, L_s) = SE_t + \mathrm{N}\,\tau_s E_s + NP_x\, J_{sw} \tag{5.3}$$

where E_t and E_s are the energy cost per second in Watts due to data transmission and sensing respectively, and J_{sw} is the energy cost for one channel switching, in joules [13, 12]. Presuming that E_t, E_s and J_{sw} are known for a given CM2M e-healthcare system, Ɲ is the number of frames and the number of transmission slots of duration T seconds required to complete one packet of transmission in the presence of a PU. S is the time duration (in the unit of seconds) of one data packet transmission without the PU's presence, and P_x is the probability that the CM2M gateways decide to switch to a sensed-as-idle channel when the current channel is sensed as busy and a minimum of, one of the other surrounding channels is sensed as free.

As shown in (5.1), the CM2M gateways minimum energy cost can be obtained by jointly optimizing τ_s and L_s under reliability thresholds. Despite this, it is not a convex optimisation problem under all thresholds, for a given τ_s, the lower energy consumption can always be found by employing the optimal L_s as ${L_s}^{Optimal} = {L_s}^{upper}$.

The reason is that function X becomes smaller as a function of L_s. Thus, the minimum value of X happens at the farthest possible value of L_s. Because ${L_s}^{Optimal} = {L_s}^{upper}$, this reveals that the probability of collision threshold is inactive in deriving ${L_s}^{upper}$ [14]. Furthermore, the probability of collision threshold is vital to get the shortest sensing slot, where L_s minimum (τ_s) is calculated from the probability of collision threshold. As a conclusion, the shortest τ_s required to meet all reliability thresholds is given by:

$$\tau_s^{\mu\iota\nu,2} = arg_{\tau_s} \min \left\{ {L_s}^{lower}(\tau_s) \le {L_s}^{upper}(\tau_s) \right\} \tag{5.4}$$

where L_s minimum (τ_s) is calculated by the collision threshold. Thus, the minimum τ_s needed to meet collision threshold, detection probability and false alarm probability is given by:

$$\tau_s^{\mu\iota\nu} = \max \left\{ \tau_s^{\mu\iota\nu,1}, \tau_s^{\mu\iota\nu,2} \right\} \tag{5.5}$$

Note that $\tau_s^{\mu\iota\nu,1}$, is calculated by the reliability thresholds: the probability of detection and the false alarm probability from (5.2), while $\tau_s^{\mu\iota\nu,2}$ from the other reliability thresholds defined as the target throughput, probability of collisions, and delay.

5.4 Problem Solution

Considering all the thresholds above, it will require longer τ_s, to satisfy the conditions of $({L_s}^{lower} \le {L_s}^{upper})$ ensuring a feasibility region of

$$L_s, \Delta\,(\tau_s) = ({L_s}^{upper}(\tau_s) \le {L_s}^{lower}(\tau_s) \ge 0)$$

and perhaps for practical values of τ_s no solution can optimise the existing problem. Furthermore, it is justified by the fact that, for a given sensing slot duration and false alarm probability, the probability of collision diminishes monotonically with any rise in the probability of detection value. Therefore, any increase in detection probability leads to a lower ${L_s}^{lower}$. Moreover, by enhancing the probability of detection, the feasibility region $\Delta\,(\tau_s)$ becomes obtainable with a shorter sensing slot time, which results in a decrease in energy consumption caused by the sensing process. There are many schemes to improve the probability of detection other than the typical Single Antenna Sensing (SAS), like multi-antenna parallel sensing and cooperative sensing, but as the system model work under CM2M concepts and goals it must avoid extra signalling to decrease cost and hardware complexity when running a number of RF chains.

An ideal possible solution here comes by applying an Antenna Selection Sensing (ASS) scheme to relieve the bounds of L_s. The ASS uses J antennas and Z RF chains (Z < J) for the sensing operation, where the CM2M gateways senses the channels for duration of time (τ_s). Furthermore, the sensing slot of τ_s period is divided into J/Z sub-slots of period τ_{as} (e.g., τ_s = J/Zτ_{as}).

Z antennas are used to proceed with spectrum sensing in each sub-slot at the same time. For instance, the system model can consider Z = 1 and J = 2. Compared to the multi-antenna (conventional) spectrum sensing (e.g., J antennas are employed for sensing at the same time as being employed for Z = K RF chains), the developed mechanism can decrease hardware complexity and cost, since only one or a subset of RF chains are employed with a huge number of antennas [14, 15].

5.5 System Simulation

The efficiency of the developed mechanism demonstrated using Matlab simulations. The simulation value setting is given in Table 5.1; the numerical results are given here to prove the analysis in the previous sections**.** The primary user is assumed to be a QPSK modulated signal with a bandwidth of 7MHz. The sampling frequency is the same as the bandwidth of the primary user. In the system model, the energy needed for spectrum sensing and sending data assumed to be $E_t = 65$ mW and $E_s =$ 45mW respectively.

Table 5.1: Value Setting of Simulations

Parameter	**Value**	**Description**
ɱ	6	Available channel number
S	6s	Duration of one packet of data
T	0.8s	Duration of each transmission
ρ	0.4	The probability of a channel being busy
$\bar{P}d$	0.9	The target probability of detection
$\bar{P}f$	0.1	The target probability of false alarm
γ	-10 dB	SNR
J_{sw}	40 (mJ)	The energy consumption for one channel switching

Figure 5.3 shows ASS (J = 2) can increase the detection probability which ultimately leads to a lower probability of collision than SAS (J = 1) with the same value of τ_s.

This can be explained by the relationship between the probability of collision, and the probability of detection as the probability of collision value decreases with any increase in the probability of detection and shows that ASS needs lower τ_s and energy consumption than the traditional antenna (SAS) sensing when achieving similar probability of collision thresholds.

Moreover, for a given L_s, the probability of collision also monotonically gets smaller with τ_s. Again, this can be explained because a higher value of τ_s leads to a higher probability of detection value and from the above we know, that will ultimately lead to decreasing the probability of collision. Bear in mind the probability of collision is mainly caused by CM2M gateways switching to channels with a primary user, due to failed detection.

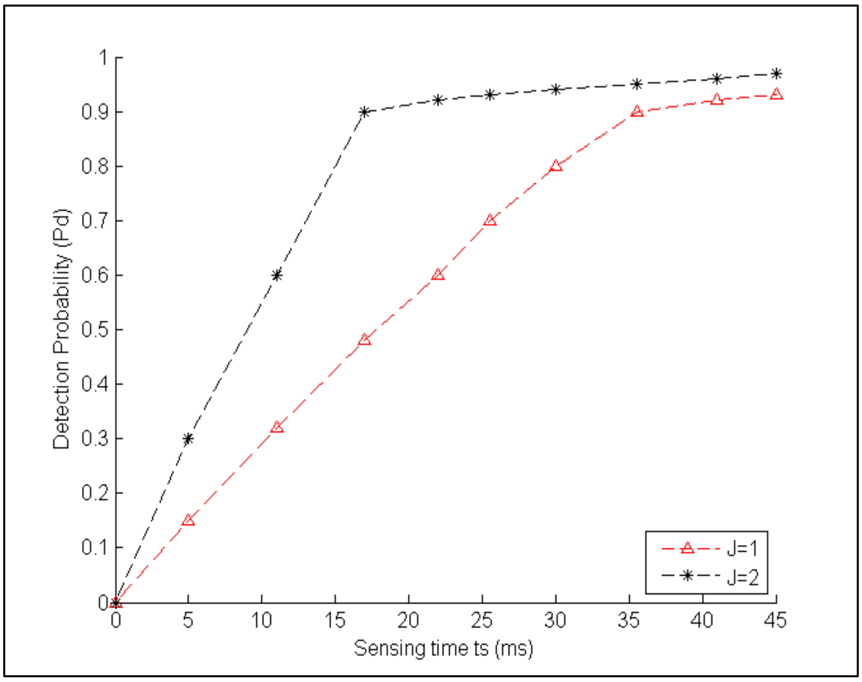

Figure 5.3: Using Antenna Selection Sensing (*J* = 2)

Figure 5.4 plots the L_s bounds of the CM2M gateways as a function of sensing time τ_s for SAS (*J* = 1), and ASS (*J* = 2). Using the same τ_s, ${L_s}^{lower}$ increased when an additional stringent probability of collision thresholds Q (e.g., from Qz = 0.4 to Qz = 0.3 under *J* = 2) was used as shown in Figure 5.4.

Such an increase in ${L_s}^{lower}$, because of the additional stringent Q, allows the CM2M gateways to remain on the current channel for a longer time to maintain the probability of collision thresholds. The upper bound ${L_s}^{upper}$ is decided by measuring which threshold (delay or throughput) is more significant at any given time. Figure 5.4 considers the throughput ($\tau_s, {L_s}^{upper}$) threshold. Bear in mind that any delay will yield a decrease in average throughput, and therefore the CM2M gateway will need to switch channels repeatedly to meet its required throughput thresholds The feasible region becomes available at τ_s = 16 (ms) if ASS (*J* = 2) is used. While using SAS (*J* = 1), the feasibility value can only achieve at τ_s = 41 (ms).

This confirms, as stated in the previous section, that by using the ASS, the bounds of L_s can be relieved. Similarly, the energy consumption in CM2M gateways due to sensing can be considerably reduced, as shown in Figure 5.5

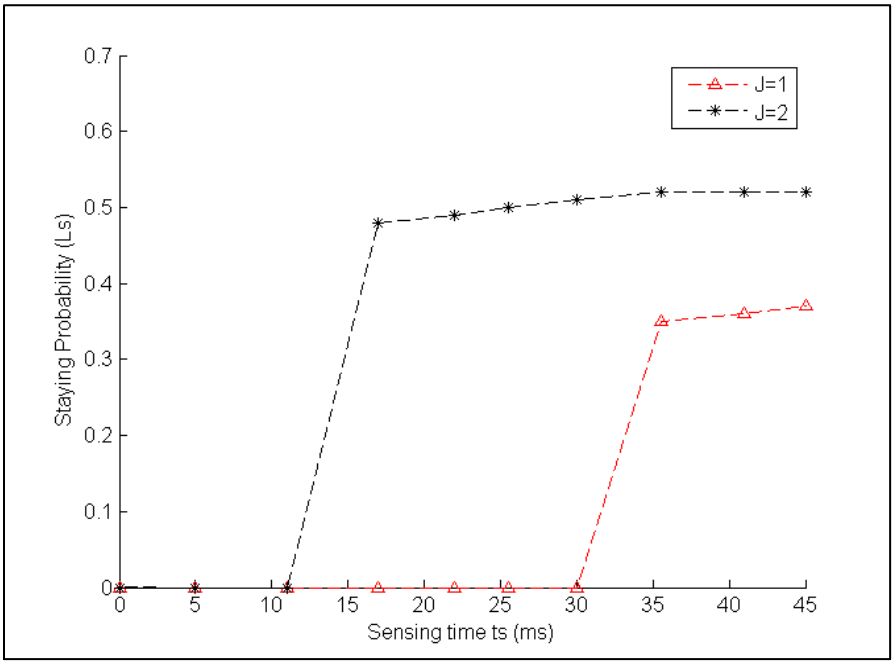

Figure 5. 4: L_s Bounds of CM2M Gateways as a Function of τ_s

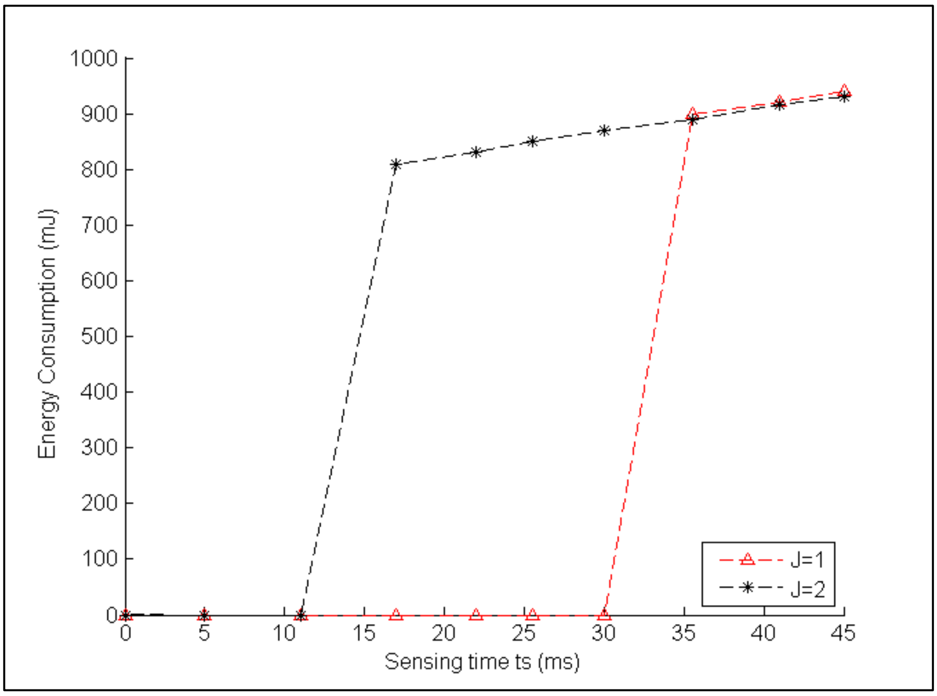

Figure 5.5: The Energy Consumption of The CM2M Gateways Under Various Sensing Mechanisms

Figure 5.5 shows the energy consumption of the CM2M gateways spectrum usage using ASS and SAS sensing mechanisms. It demonstrates that the best stay probability for τ_s can be found at ${L_s}^{upper}$. As explained before, the optimal sensing slot ${\tau_s}^{Optimal}$ is also calculated by the reliability thresholds. As seen in Figure 5.5 the ASS offers reduced sensing time (τ_s= 16 (ms)) to meet all the thresholds, compared to SAS (τ_s = 41 (ms)). Greater L_s = 0.48 can be satisfied while meeting all the thresholds with smaller τ_s by using ASS. As a total outcome, the energy efficiency of the CM2M gateways can be improved significantly by using ASS under the same thresholds.

5.6 Summary

In this Chapter, an energy efficient spectrum management mechanism for a CM2M e-healthcare system has been designed. The designed mechanism simultaneously considers the wait/switch trade-off in terms of channel switching probability, sensing /throughput trade-off in terms of the period of sensing time and collision probability. Furthermore, the proposed mechanism considers an ASS scheme for improved sensing accuracy and reduced energy consumption. Simulation results show the optimality and efficiency of the used mechanism with guarantees of the desired thresholds.

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CHAPTER 6

ENERGY EFFICIENT SCHEDULING ALGORITHM

6.1 Introduction

Learning and selecting algorithms had a huge impact on cognitive radio and machine to machine technologies. As mentioned in Chapter 2, a number of studies considered learning algorithms for different CR networks. Panahi and Ohtsuki [1] presented a Fuzzy Q Learning (FQL) based scheme for channel sensing in CR networks. Zhang et al. [2] presented a reinforcement learning-based double action algorithm intended to increase the efficiency of dynamic spectrum access in CR networks, in [3] channel allocation, Gallego et al. [4] presented a game theoretic optimal solution for joint channel allocation and energy control in CR. A number of studies employ partially observable Markov decision processes [5] and reinforcement learning [6].

The main disadvantage of these techniques is their dependence on highly accurate reward functions. Meanwhile, little effort has been made with regards to designing and developing a CR learning engine with Experience Weighted Attraction (EWA) algorithms. EWA algorithms [7, 8] give CR the ability to be aware of available channels characteristics online. By collecting the history of channel statuses, it can foresee, select, and amend the best available channel, dynamically test the quality of communication links, and eventually decrease system communication outage probability.

The efficiency of this algorithm has been tested by the straightforward probability approach [7] and with an EWA Handoff (EWAH) algorithm [105] in our preliminary studies. However, again not much work has been done using EWA algorithms for more energy efficiency in CM2M communications. This Chapter, utilise EWA algorithms to develop an EECS algorithm for more energy efficient communications in the M2M healthcare system.

The rest of this Chapter is structured as follows: Section (6.2) demonstrates the system model and explains our proposed algorithm. Simulation results and discussions are illustrated in section (6.3), and Section (6.4) summarises the Chapter.

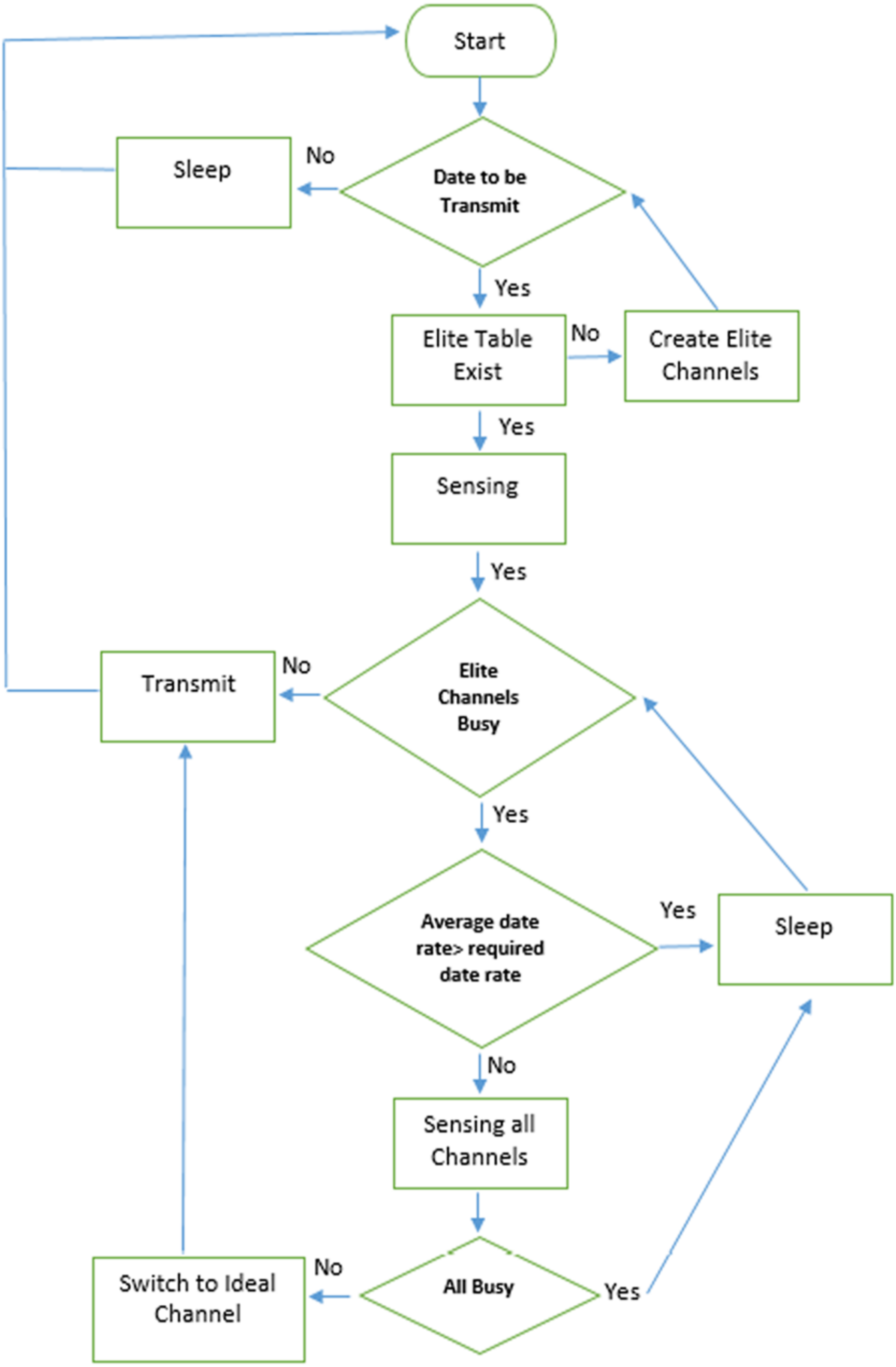

Figure 6.1: Energy Efficient Scheduling Algorithm Flowchart

6.2 Energy Efficient Scheduling Algorithm (System Model)

The system model considers a CM2M network is working with a number of CM2M gateways and the primary link (Figure 6.1). As shown in Figure 6.1 the CM2M devices at the beginning of transmission will choose to send data using elite channels, if the elite channels busy the CM2M will choose to sleep or send data through another ideal channel. The process depends on the throughput and delays thresholds if more data need to be transmitted CM2M devices will choose elite or ideal channel to transmit if not, CM2M devices will go to sleep mode case and save energy to prolong battery life.

The following assumptions considered up to the system requirements: the radio environment is divided into ɱ channels; detection is employed to sense the channels simultaneously, while the CM2M gateways apply wideband sensing to test the availability status of all channels. In the system, the secondary transmission assumed to be slotted in via periodic sensing at a specific time, each frame consisting of a sensing slot of duration τ_s and a transmission slot of duration T, where one of the ɱ channels is assigned to one CM2M gateway.

ksl is the spectrum handoff delay, which will be added to the sensing slot in the CM2M gateways frames, if the CM2M gateways decide to perform channel switching after addressing the sensing outcome and other thresholds. The CM2M gateways at the start of each transmission slot may then decide to send data on the current channel, switch to another free ideal channel with a switch delay of ksl, or remain on the current channel without sending any data; the primary user follows an on off traffic paradigm and is presumed to be continuous [9].

The average received SNR of the primary transition signal for all channels assumed to be the same, at the same time the false alarm probability Pf and the detection probability Pd assumed to be one for each packet of data transmission [10]. The systems model assumes that the received signal is sampled at sampling frequency fs, and the frequency band with carrier frequency fc.

The goal is to reduce the energy cost for the CM2M gateways to send a packet of data under both probabilities of false alarm and detection and constraints, as discussed in [11], proposing that it can simultaneously optimize the sensing slot length τ_s and the stay probability on the ideal current channel L_s so that the power cost of one complete data packet transmission is reduced as follows:

$$({\tau_s}^{Optimal}, {L_s}^{Optimal}) = \min_{\tau_s, L_s} X(\tau_s, L_s) \tag{6.1}$$

where ${L_s}^{Optimal}$ and ${\tau_s}^{Optimal}$ are the optimal stay probability and sensing slot length, respectively, while X is CM2M gateways overall average energy consumption for one data packet transmission, which includes spectrum sensing, spectrum handoff, and data transmission.

However, by employing staying probability, the energy cost due to sensing is calculated by the duration of the sensing slot. By allocating a target false alarm probability and a target detection probability $(e.g., \bar{P}d = 0.1\ and\ \bar{P}d = 0.9)$ for each channel, it can consider the duration required to satisfy the sensing threshold requirements while reducing the energy consumption [11] as given below:

$$\tau_s^{\min} = \frac{1}{yf_s} \left(Q^{-1}\left(\bar{P}_f\right) - Q^{-1}(\bar{P}_d)\sqrt{2\gamma + 1}\right. \tag{6.2}$$

By studying the design characteristics and challenges in the equations above, it can now develop an energy efficient mechanism (Figure 6.1) to select the best available channels, given in (1) and as follows:

$$X(\tau_s, L_s) = SE_t + \text{Ŋ}\, \tau_s E_s + \text{Ŋ} P_x\, J_{sw} \tag{6.3}$$

where E_t and E_s are energy consumption per second in Watts due to data transmission and sensing, and J_{sw} is the energy consumption for one channel switching, in joules [12].

Presuming, that E_t, E_s and J_{sw} are known for a given CM2M healthcare system, Ɲ is the number of frames and the number of transmission slots of time T seconds needed to finish one packet of transmission in the existence of primary transition, while S is the time duration (in the unit of seconds) of a single data packet of transmission without the primary transmissions existence, and P_x is the probability that the CM2M gateways will choose to switch to an ideal channel when the current channel is busy and at least one, of the other channels is free and its function of L_s and τ_s [13, 14].

As shown in (6.1), the CM2M gateways low energy consumption can be gained by simultaneously optimizing τ_s and L_s under reliability thresholds. Despite this it is not a convex optimisation problem under all constraints, for a given τ_s, the minimum energy cost can be found by utilising the optimal L_s as $L_s{}^{Optimal} = L_s{}^{upper}$.

On the other hand, in such a CM2M system the idle probability of channel К ($1 \leq$ К $\leq n$) can be expressed as α_k, or $AA = [\alpha_1, \alpha_2, \ldots, \alpha_{n-1}, \alpha_n]$ in vector form. Let $\beta_{\mathrm{К}}$ be the successful transmission probability of channel К ($1 \leq$ К $\leq n$); then $BB = \{\beta_1, \beta_2, \ldots, \beta_{n-1}, \beta_n\}$. Perhaps the radio channel features vary by time; the channel idle probability and effective transmission probability of channel К ($1 \leq$ К $\leq n$) should not be one at various time t; then the forms of probabilities after inserting time parameter t are

$$AA(t) = \{\alpha_1(t), \alpha_2(t), \ldots, \alpha_{n-1}(t), \alpha_n(t)\}$$

and

$$BB(t) = \{\, \beta_1(t), \beta_2(t), \ldots, \beta_{n-1}(t), \beta_n(t) \,\}$$

To decrease the level of complexity of the channel selecting strategy in the CM2M healthcare system, exponential functions should first be avoided. Next, the system model considers an algorithm which should facilitate the calculation procedure and optimize and update the objective operation to provide better energy efficiency and better throughput. Furthermore, the system model defines the probability of channel selecting y in the channel preferable selection policy $S_{\mathrm{К}}^{y}$ at time t as $P_{\mathrm{К}}^{y}(t)$ then the mathematical expression of $P_{\mathrm{К}}^{y}(t)$ is

$$P_{\text{К}}^{y}(t+1) = \frac{1\text{- σ}}{1\text{-σ}.\ \{1\text{-}\mathrm{I}[S_{\text{К}}^{y}, S_{\text{К}}(t)]\}} \tag{6.4}$$

Where

$$\mathrm{x}(\text{ К }) = \begin{cases} 1, & Tranmission\ failure\ on\ channel\ y, \\ 0, & Successful\ tranmision\ on\ \ channel\ y, \end{cases}$$

$$\pi_{\text{К}}\left[S_{\text{К}}^{y}, S_{-\text{К}}(t)\right] = \begin{cases} 0, & channel\ y\ is\ sensed\ busy \\ 1, & channel\ y\ is\ sensed\ Idle \end{cases} \tag{6.5}$$

and $I[\cdot]$ is the indicator function, which is defined as follows:

$$I(x,s) = \begin{cases} 1, & x = s, \\ 0, & x \neq s, \end{cases} \tag{6.6}$$

Parameters σ and µ are attenuation coefficients of probability and $\sigma < \mu \in (0,1)$. From the analysis of (6.4) it’s clear that in the CM2M environment sensing time, when knowing the current status of channel y as being occupied (primary user making transition), the status becomes 0 (unavailable), and the scheme of choosing channel y as a transmission channel will get no gain, or the award operation value of $\pi_{\text{К}}[S_{\text{К}}^{y}, S_{-\text{К}}(t)]$ is 0 and the channel selecting probability declines to $(1-\mu)\ P_{\text{К}}^{y}(t)$; while knowing the current status of channel y as being idle (no PU user transmission in the channel), the status changes to 1 (available), and the scheme of choosing channel y as a transmission channel will get the gain of $\pi_{\text{К}}\left[S_{\text{К}}^{y}, S_{-\text{К}}(t)\right]$

respectively. Furthermore, the value of $\pi_y\left[S_{\mathrm{K}}^{y}, S_{-\mathrm{K}}(t)\right]$ is presumed to equal 1 and the channel selection probability is updated to (1- μ). $P_{\mathrm{K}}^{y}(t) + \mu$.

The free available channels are elite channels for CM2M gateways transmission, and the elite channel with the biggest y probability of channel selecting will be chosen for sending data. If more than one channel reaches the biggest selection probability, then one of these channels will be selected at random after successful transmission, the channel selecting probability will go up to $(1 - \sigma)$.[$(1 - \mu). P_{\mathrm{K}}^{y}(t) + \mu$] $+ \sigma$. But, if the transmission fails, the channel selecting probability will update to $(1 - \sigma)$.[$(1 - \mu). P_{\mathrm{K}}^{y}(t) + \mu$].

6.3 Simulation and Results

This section demonstrates the efficiency of our algorithm EECS using Matlab simulation. The simulation value settings are listed in Table 6.1; the outcomes are given here to confirm the analysis in previous sections**.** The primary transmission is presumed to be a QPSK modulated signal with a bandwidth of 8MHz while the energy needs for spectrum sensing and transmission are $E_t = 69.5$ mW and $E_s = 40$mW respectively.

Since the value of σ should be lower than parameter μ, the coefficients μ assumed to be at initial value 0.1 due to comprehensive experience. While there must be a number of variations between each channel, the idle probabilities of such channels will not be one. To reflect the typical channels’ available probabilities, a symmetrical distribution vector in the range of 1 to 0 will be picked for the idle probability of each channel; that is, the first channel idle probability vector AA0 = {0.4, 0.9, 0.6, 0.5, 0.7}, while the first channel successful transmission probability vector BB0 = {3/4, 8/9, 5/6, 4/5, 6/7}.

Then the first channel available probability vector Γ0 = AA0 · BB0 = {0.3, 0.8, 0.5, 0.4, 0.6} In order to check that this smart algorithm is capable of deciding and guiding CM2M gateways real-time switch to the new transmission channel with the highest selecting probability online precisely, the channel idle probability vector will update to AA1 = {0.6, 0.4, 0.7, 0.9, 0.5} and the channel successful transmission probability vector will change to BB1 = {5/6, 3/4, 6/7, 8/9, 4/5} after 40 rounds through the simulation.

Thus, the channel available probability vector will be Γ1 = AA1 ·BB1 = {0.5, 0.3, 0.6, 0.8, 0.4} after the simulation circumstances change.

Table 6.1: Value Settings of Simulations

Parameter	Value	Description
ɱ	5	Available channel number
S	6s	Duration of one packet of data
T	0.8s	Duration of each transmission
γ	-10dB	SNR
J_{sw}	40mJ	The energy consumption for one channel switching
ρ	0.4	The probability of a channel being busy
$\bar{P}d$	0.9	The target probability of detection
$\bar{P}f$	0.1	The target probability of false alarm
CM2M	2	Cognitive Machine-to-Machine gateways

Taking randomness of the parameters above through a practical wireless network into account, the numbers formed in each simulation round meet exponential distribution of the corresponding parameter above accompanied by the general rule.

Next, the system model applies a simple repeated experimental method to check the effectiveness of the probability of our EECS algorithm. That is, Turn Based Strategy (TBS), a single uniformly distributed random number within the range (0, 1), is generated in each round. If this number is less than the channel available probability $\alpha_{\text{К}}$, channel К is judged as being in an idle available state; otherwise it is in a busy unavailable state.

The idle channel with the highest selection probability will be the preferred communication channel in the current round. If more than one channel reaches the highest probability of channel selecting, then one of these channels will be selected randomly. After the algorithm selects the preferred channel y, a single uniformly distributed random number within range (0, 1) is also generated. Communication channel transmission is successful if this number is less than the probability of successful data transfer completion β_y; otherwise it, fails.

After the parameters above are set, the outcomes of the channel selecting probability depending on the EECS algorithm are demonstrated in Figure 6.2. Using channel selecting probabilities, following a short establishing process, the EECS learning algorithm will typically choose and track channel 1 as the initial gateway channel, but its selection probability fluctuates slightly around 0.73.

Due to optimal channel availability, the probability changes after the 43rd round and the selection probability of channel 1 drops tremendously, while the selection probability of channel 2 grows, slowly but surely overtaking the selection probability of channel 1 after 48 rounds. Channel 2 finally takes over from channel 1 to become the optimal gateway channel under the new channel available probability status, and channel 1 will be the second in the list.

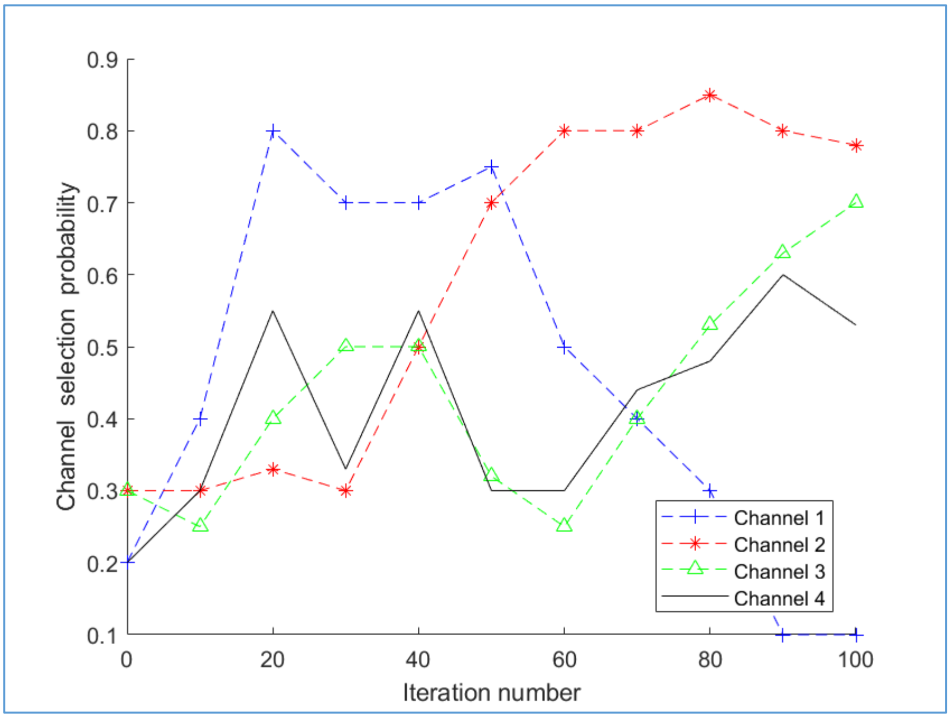

Figure 6.2: The Outcomes of Channel Selecting Probability Based on EECS Algorithm

Figure 6. 3 shows the staying probability increase (L_S) when EECS algorithm used, the reason being that the quality of the selected channels will be better which will lead to less switching of CM2M gateways in the available channels as only the preferred channels with fewer PU transmissions will be selected.

Figure 6.4, shows the energy cost of the CM2M gateways spectrum usage under the EECS algorithm. It proves that the optimal energy solution can always be found at the optimal maximum value of Ls. Because the higher probability of staying means less switching of CM2M gateways in the available channels. At the same time, better throughput could be achieved leading to less τ_s (less energy consumption through sensing process) and better energy efficiency in the system overall.

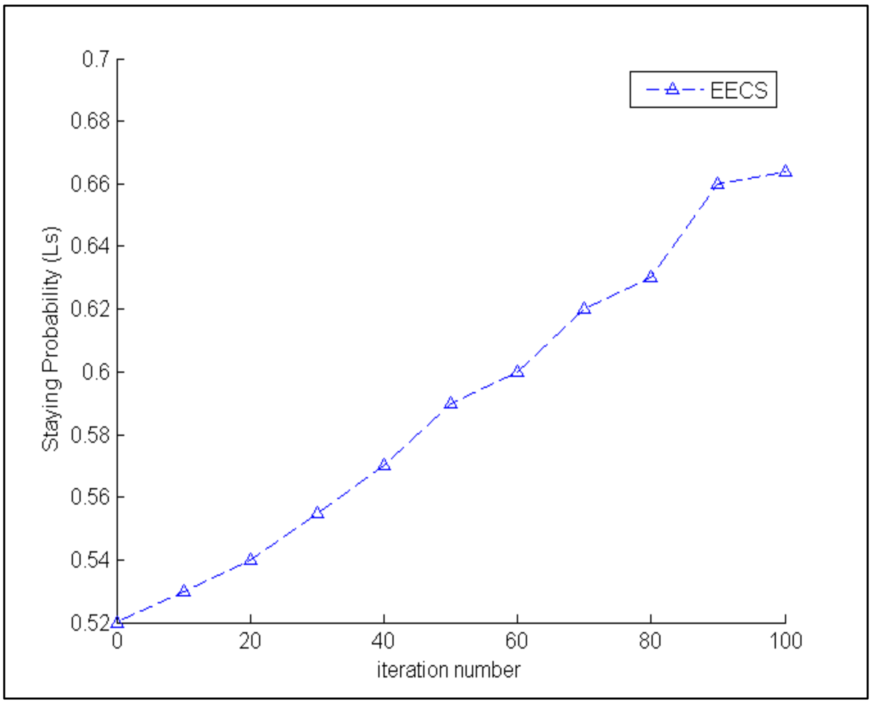

Figure 6.3: Staying probability at τ_s Optimal

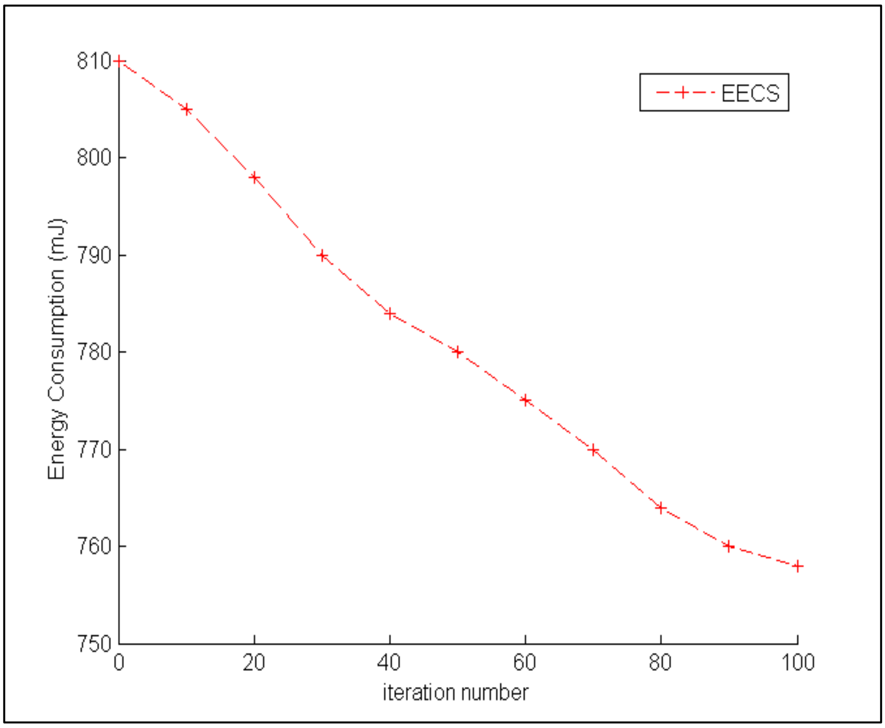

Fig 6.4: Energy Consumption at τ_s Optimal

6.4 Summary

This Chapter proposes an energy-efficient channel is selecting algorithm. The proposed algorithm improves CM2M gateways channel selection and the probability of staying by at least (12%) due to the increase in transmission channel quality which, leads to less switching of CM2M gateways between the available channels. Simulation results demonstrate the optimality and efficiency of the algorithm with the guarantees of the desired constraints.

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CHAPTER 7

THE FUTURE OF M2M IN THE HEALTHCARE SECTOR

7.1 Introduction

A dramatic shift in the business models of hospitals and healthcare systems is evident as we enter the 21st century, and at the heart of this shift is Machine-to-Machine technology [1]. This new technology marries the use of medical machines and wireless communication systems to offer new possibilities and application areas for the monitoring of both symptoms and diseases [1, 2]. The global telehealth market is soaring as the use of remote monitoring technology moves into the mainstream (Figure 7.1).

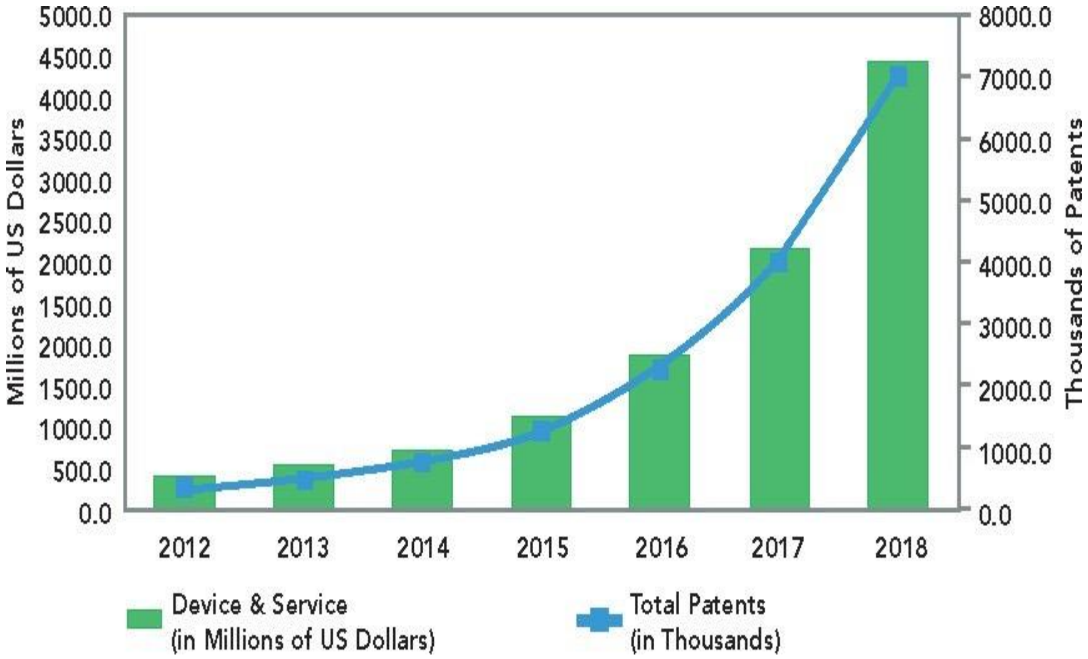

Figure 7.1: Telehealth Usage [2]

One of the primary objectives of the industry is to keep people from occupying hospital beds wherever possible, and occupancy rates are in fact slowly declining [3]. Inpatient hospital admissions dropped from an average of 123.2 per thousand people in 1991 to 111.8 per thousand in 2011, highlighting the switch from inpatient to outpatient care [4].

Medical bodies need to discharge patients as quickly as possible to maximize the number of beds available. Great care must be taken when selecting patients for release, as the Affordable Care Act stresses that medical bodies will be penalized if discharged patients are re-admitted within a specific timeframe. The best approach to minimize the chance of re-admission is through the implementation of M2M healthcare applications such as remote health monitoring [6] and smart sensors.

7.2 The Factors Driving M2M Adoption

The twin factors of an aging population (the post-war ‘Baby Boomers’) and an increase in chronic illnesses combine to put pressure on the health industry and its ability to monitor patients. The simple solution of remote monitoring for such patients will greatly assist in relieving this pressure. Fortunately, the appetite for wireless technology by the general public - and in particular the widespread dependence on mobile phones, and the use of these for purposes other than just communication has accelerated public acceptance of M2M healthcare applications. Among those surveyed by the Economist Intelligence Unit (EIU) in 2012, 48% of individuals stated that they believed mobile healthcare applications could increase the quality of services in the medical sector [6, 7, 8].

In addition, the economic benefits are considerable. In 2012, approximately 308,000 patients worldwide were remotely monitored for conditions such Chronic Obstructive Pulmonary Disease (COPD), Congestive Heart Failure (CHF), Hypertension, Diabetes, and mental health conditions, according to a report from InMedica [128]. This number is predicted to increase to 1.8 million patients in 2017 [9]. The growth in remote monitoring is predicted to save the medical sector worldwide up to $36 billion by 2018, according to a projection by Juniper Research [10]. The advantages are not just economical. Mareca Hatler, Director of Research at ON World, confirms the advancements of M2M healthcare applications ”In addition to reducing costs, cloud-connected wireless sensing solutions are improving the quality of healthcare services as well as supporting the latest innovations for aging in place, self-management of chronic conditions, and general wellness" [11].

7.3 M2M Opportunities in the Healthcare Sector

Currently, there are eight major healthcare application groups [7, 8, 9, 12]:

1. **Home monitoring**: Involves patients self-testing, which means home monitoring can become a treatment option. Data from the medical devices are then transmitted to healthcare providers for disease management. Some of the most common conditions being supervised

today are chronic diseases including cardiac arrhythmia, hypertension, ischemic diseases, sleep apnea, diabetes, hyperlipidemia, asthma, and COPD [12]. These conditions are costly to the healthcare service and reduce both life expectancy and quality of life. The use of information and communication technologies can lead to reduced costs and better medical delivery.

2. **Clinical monitoring:** Improves healthcare management by safely decreasing patients' hospital stays and visits. Patient sensors also assist doctors, helping them to spot early warnings of medical deterioration and enabling them to apply treatment earlier than physical diagnosis would allow. These solutions dramatically improve quality of life by helping patients regain their mobility and independence [13].
3. **Telemedicine:** Especially useful in rural areas, Telemedicine helps reduce the high costs of serious illnesses by allowing doctors to oversee the condition of several patient cases each day, eliminating the need for unnecessary visits. Portable, wearable, and even implantable sensors and tools may be used as tracking systems to determine a patient's location. Monitoring systems may be implemented to constantly scan vital signs and provide vital data to healthcare providers or, in case of an emergency, automatically send an alert to a doctor or healthcare facility. A real-time information system could mean the difference between life and death in case of heart failure, diabetic comas, and other serious illnesses [10].
4. **First responder connectivity**: In an emergency situation, every second counts and equipment have to be reliable, without exception. Unshakable reliability and innovation are required to deliver this service at its fullest potential [14].
5. **Connected medical environments**: The burgeoning fitness industry has led end-users to the point of making their own informed decisions on health and fitness programs. M2M solutions can not only be used to oversee vital signs during exercise by analyzing data obtained from connected heart-rate monitors and other devices but can also make real-time transmissions of the data. This enables users to keep track of their health and fitness progress and offers them the chance to share their workouts on social networks.
6. **Clinical remote monitoring**: Costly home visits to patients with chronic conditions may be reduced to a minimum by the use of clinical remote monitoring, whereby devices may be fitted to or used by the patient to enable continuous monitoring. For example, Silent

Observer, developed by Sukrut Systems, uses technology to police providers' activity on ultrasound machines. The data is collected, reported daily to local agencies, and cross-checked by those agencies to make sure the providers have filled out mandatory pregnancy reporting forms. The use of this intelligence may aid in decreasing the incidences of illegal female foeticide [16].

7. **Assisted living and clinical trials**: Patient tracking systems and monitoring devices may be used to ensure the health and safety of patients in the absence of caregivers. It also serves to assist the disabled and elderly with their daily tasks, helping them live independently in their own homes [17].
8. **Asset management:** This is used to track and show the availability of mobile healthcare equipment at any time, to schedule routine cleaning and maintenance tasks, and reduce costs with equipment safety monitoring and incident tracking [18].

7.4 Real World Examples

In the UK alone, nearly 1 million people have been diagnosed with heart failure, and this figure is growing by almost 60,000 new cases each year [4]. Continuous monitoring used to be unachievable, and health alerts (such as irregular heartbeats) were flagged up only after data from a body-worn external controller unit could be transmitted to clinicians via a local internet connection, causing delays and limiting patients' mobility [11, 12].

Figure 7.2: HeartAssist5, Numerex [19]

Among other businesses who are working to introduce improvements, a company called Numerex has developed “The Reliant Heart Assist Remote Monitoring System, HeartAssist5” (Figure 7.2), an M2M-enabled device which allows patients to monitor their heart health not only when at home, but also while traveling [19]. The system utilizes the secure, cloud-based, fully integrated fast platform. At the hub of the system is the HeartAssist5 Conquest Controller. At present, the device is being used by more than 110,000 patients, continuously receiving information from the monitoring system.

This information is then transmitted in packets to a controlled and safe data center monitored by trained supervisors in the same way as for domestic security systems. Physicians have remote access to this data whenever required, and in critical situations, the device sends an alert to the patient's caregivers, giving them the necessary information to arrange meetings with the patient’s physician or to make arrangements for hospital admission.

The HeartAssist5 is currently available in Europe, while in the US, it is undergoing evaluation by the Food and Drug Administration (FDA). Expected benefits, apart from patient reassurance, would be increased freedom and peace of mind for the caregiver, and better use of the healthcare system's resources.

Benefits are not restricted to patients alone; the stress of caring for a sick or elderly family member should not be under estimated and can seriously impact on the day-to-day life of caregivers. Many family members take time away from their jobs to care for sick relatives because they worry about what might happen when they are left at home by themselves. However, heart care home applications will monitor patients and send all the required information to the dedicated emergency services by exploiting wearable technology that tracks their condition.

These wearables range from pulse detectors and blood pressure monitors worn around the wrist to a personal emergency response framework worn as a necklace, to sleep apnea machines worn on the face. These devices report health information and statistics through mobile networks and other internet services to providers and health entities. This flow of information/data signals actual and possible healthcare emergencies, as well as detected abnormalities which should be dealt with immediately. The signals would travel via email or mobile alerts to doctors and family members/caregivers or summon an emergency medical technician, depending on the urgency of the situation [20].

Moreover, M2M healthcare home applications boost the level of self-sufficiency for the elderly and chronically ill by letting them proceed with their daily routines safe in the knowledge that they will be able to summon help in the case of an emergency [21, 22]. In forthcoming years, a significant number of patients' houses will have intelligent machine networks to remotely monitor their activities, allowing those living on their own to call for help when necessary.

Machines can be placed in cabinets, living rooms, and any other part of the home. Research carried out by Orange has proved that 73% of senior citizens in EU would feel safer with a 'tele-assistance' tool which could recognize problems and call for assistance in case of an emergency. M2M can be critical here, with devices like motion detectors in chairs and beds able to send off alerts after periods of non-movement – or in the event of unwanted movement already utilized in a number of markets nowadays [11].

Nowadays, the similar technology exists in the market thanks to innovators such as SimplyHome who are pioneering home M2M practices. The systems from SimplyHome monitor day-to-day activity and can alert caregivers or health professionals if no routine activity has taken place, or if something unusual has occurred in a patient's home [23].

GTX Corp, another innovator in remote patient monitoring machines, offers services to remotely supervise patients when they leave their homes. Their product, GPS SmartSole (Figure 7.3) is a GPS tracking shoe sole for those with Alzheimer's disease, dementia, and other mental issues. A carer or family member can create a geofence (e.g., designated boundaries placed around the patient's house or neighborhood) [24, 25].

Whenever SmartSole wearer crosses a geofence, family members and healthcare professionals will get an alert explaining the situation, which will help them take quick action to physically locate the patient, so the patient can either go back within the set geofence or return home or call for emergency services if need be.

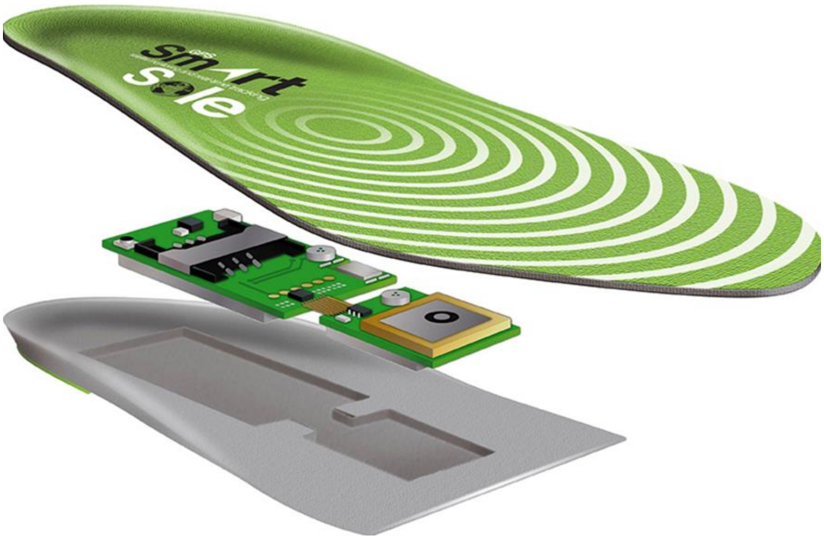

Figure 7.3: SmartSole, GTX Corp device [25]

Another challenge for patients, especially for those with dementia, Alzheimer's disease, or with a complex drug regime, is keeping track of their prescribed medicine routine. If a patient under or overdoses, it can lead to serious implications and possible health emergencies. M2M enabled “smart pill boxes,” and packaging makes it simple for health bodies and caregivers to keep track of a patient’s medicine intake and schedule [26]. Already in use today, pillboxes fitted with embedded sensors can tell if a pill has been removed from a bottle or packet and send a report to let the health care provider know whether the patient has been taking the correct dosage of their medication at the correct time [27].

This is instrumental in preventing accidental overdose. Furthermore, the pillboxes can be programmed to send an alert to family members and caregivers if the medicine has not been taken [28]. MedSignals’ have developed their M2M MedSignals Pill Case Device [29]. The Pill Case has 4 compartments, each capable of holding up to 70 small pills. The compartments remain closed until it is time for the patient to take the medication, at which point one of four corresponding buttons will light up, so patients know which compartment to open. MedSignals Pill Case also has voice devices (speakers) and a small monitor on board so that other directions can be played to clarify which pills to take along with the correct dosage required.

Other companies are taking a different approach to medicine accountability solutions by incorporating M2M technology directly into the medication’s original packaging. Mevia, for example, has developed smart packages that automatically send alerts whenever a pill is removed from a pack or bottle. Mevia’s packaging method spares the patient or carer the task of having to remember to remove pills from their original packaging and put them in a separate smart container - especially useful for patients with poor memory or confusion, and for caregivers with a busy schedule. In the next few years, pharmaceutical companies may start partnering with companies like Mevia to help patients remember to take their medication or notify caregivers to give medication and assure the right amount or dose is being taken every time.

The December 2013 mHealth Summit - the largest assembly of its kind concerned solely with the fusion of mobile and healthcare technologies saw the unveiling of several state-of-the-art devices currently in development. Some examples of future innovations include [10, 30]:

- A pendant with patented automatic fall detection algorithms which can send an alert in case of personal emergency;
- A bottle cap digitally enabled to allow for compliance monitoring and able to alert patients when medication is due, which may be fitted to standard prescription bottles;
- A service which will enable a mobile phone to automatically request a "house call" service, which brings medical assistance to the patient within two hours.

These are only a few examples. Other, further advanced, technologies are forecasted to be deployed within the next few years. A study released by the research company ON World estimates that 18.2 million health and wellness Wireless Sensor Networks (WSNs) are expected to be shipped globally in 2018, and this will generate around $16.3 billion in annual revenue. Another trend that is predicted to rise to prominence very quickly is the use of disposable body-worn wireless medical sensors.

7.5 M2M Applications: Future Challenges

The public has seen just the start of the M2M evolution in healthcare. Allied Business Intelligence (ABI) has predicted a huge development of more than 5 million disposable MBAN sensors being shipped by 2018, and even this is a tiny proportion of its potential [31]. Meanwhile, Machina Research has predicted a global installation of 847 million M2M connected health machines by 2023, totaling a price tag of $91 billion. North America will be the largest consumer of M2M technology during this time, with 386 million M2M machines by 2023. Similar numbers will follow in Asia and the EU. These projections cover the whole spectrum of remote health monitoring, connected medical environments, and improved assisted living aids.

Nonetheless, healthcare technology needs to be reliable, as malfunctions are not just frustrating but could be life-threatening. For M2M to succeed in healthcare applications, essential requirements must include the following: good quality and authentic communications in both very local wireless systems and national and international mobile networks; small, robust and user-proof hardware; good battery life without replacement; and secure and reliable communications.

Realistically, M2M in the healthcare sector could face extra challenges such as the following:

- Regulations that allow and promote development in sectors such as energy and automotive industries but are a hindrance to innovation in the healthcare sector. For instance, many healthcare practices are funded according to the number of patients they see, which doesn’t encourage them to prioritize the use of M2M applications that solve patient problems without the need for a hospital visit;
- Trying to identify business models that harmonize M2M technology with existing healthcare incentive schemes;
- Lengthy lead times required to win regulatory approval for new devices which will operate in a highly complex ecosystem, connecting doctors, hospitals, ambulances, and care homes; and
- Concerns regarding customer privacy and data security.

7.6 Security Risk and Vulnerabilities in Healthcare Sector

Cybersecurity is always of paramount importance. In 2017, the UK National Health Service was hit by a cyber-attack, causing major problems for a number of hospitals and affecting a large number of patients [32, 33]. This demonstrates how important it is to understand how security issues and vulnerabilities manifest themselves in M2M health devices. In this Chapter, a number of the security challenges are explored and presented as the following:

- **Products are rushed on to the market** – Security is usually the last concern of many manufactures due to a tight timescale. Devices are often released by the manufacturers having undergone little or no security assurance testing [28].
- **Small form factors and limited capability components** – Healthcare CM2M devices are generally made to be very small, with the unfortunate consequence of being restricted to using components with limited capability. For example, slots and memory have limits on the level of security or encryption that they can provide. These limits are usually not in line with current best practices and are exploitable through existing and known vulnerabilities.
- **Lack of, or vulnerable, secure update mechanism** – In the event of security vulnerabilities being detected in healthcare M2M devices, coping with the security risk and assuring successful updates to all compromised machines may not be a simple mission. It would not be feasible to entrust the end-user to periodically check for and install updates in, for instance, an implanted pacemaker or a connected insulin pump; and it is, in fact, questionable as to whose responsibility this actually would be - the vendor, the manufacturer, or the hospital/medical centre overseeing the patient's treatment?

However, new and efficient security schemes need to be deployed in the near future to achieve secure and reliable communications in M2M healthcare applications. A number of significant requirements needed to improve security in the M2M communication of healthcare applications are shown in table 7.1. Meeting these requirements will significantly boost security in healthcare systems and at the same time will encourage hospitals and other medical bodies to trust healthcare M2M applications and use them more widely [10, 18].

Table 7.1: CM2M Communications Security Requirements in Medical Applications Sector

Requirement name	**Requirement explanation**
Non-Repudiation	Non-repudiation implies that a node cannot deny sending a message or data sent earlier
Authorization & Authentication	Authorization & Authentication allows an M2M healthcare machine to assure the identity of the peer with which it is communicating
Data/Key Freshness	Because M2M healthcare networks provide some time-varying measurements, data or key freshness ensures that each data set is recent, and no adversary can replay old messages
Resiliency	If medical care machines are compromised, alternative security approaches should still protect the data from any hacking
Self-healing	If a healthcare machine in an M2M healthcare network fails or runs out of power, then collaborating machines should provide second-line security and maintain minimum security levels
Confidentiality	Confidentiality ensures that unauthorized users are denied accessibility to medical information, while confidential messages are protected from eavesdroppers

7.7 Summary

Healthcare mobile phone devices and applications will eventually become the standard for both caregiver and patient, while real-time technology (e.g., video) will become a significant part of most medical care management. The massive development of healthcare systems will face many challenges in terms of security, ~~s~~spectrum availability, and battery life limitations. Cognitive radio and smart technologies will solve some of these challenges, as explained in the previous chapters. However, new technologies and schemes need to be developed to cope with all M2M communications challenges and to enable efficient, reliable, and secure communications among all M2M applications in the medical sector.

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CHAPTER 8

CONCLUSION AND FUTURE WORK

8.1 Conclusion

M2M and IoT technologies will make up a large part of the future of medical treatment. Exploitation of the technology of implants and nano-network of sensors will enable remote healthcare treatments and improve medical services. Wireless technology can increase the flexibility of medical applications, besides enabling some applications such as remote monitoring. Meanwhile, wireless technology could face challenges in the medical sector, such as interference problems, battery consumption, and spectrum limitations. Cognitive radio as smart technology can help to address and solve these challenges.

To meet the requirements of spectrum needs in CM2M networks a novel aggregation-based spectrum assignment algorithm introduced. The algorithm maximizes spectrum utilization to CM2M devices as a criterion to realize spectrum assignment. Moreover, the introduced algorithm takes into account the realistic constraints of Co-Channel Interference and Maximum Aggregation Span. Simulations validate the performance of the proposed algorithm, and results are compared with algorithms available in the literature. The proposed algorithm decreases the number of rejected devices and improves spectrum utilization of the CM2M network. The developed algorithm increases the capacity of the network, which is vital for CM2M networks.

Moreover, the work in this thesis also considers the energy efficiency in CM2M networks, to prolong CM2M gateways battery life and increase the energy efficiency; Chapter 4 introduced an energy efficient mechanism boost the energy efficiency in CM2M e-healthcare system by 35%. The proposed mechanism simultaneously considers the wait/switch trade-off regarding channel switching probability and the sensing /throughput trade-off regarding the duration of sensing time. The proposed mechanism addresses the collision between CM2MDs by considering the transmission of devices to be zero when a collision occurs, and guarantees that the given constraints regarding throughput and sensing reliability are always satisfied. Furthermore, the algorithm considers when no channel available for transmission CM2M devices will sleep for a period of time-saving more energy and will go back to active/transmission mode when more data need to be transmitted.

Furthermore, the thesis in Chapter 5 and 6 considered antenna selection sensing scheme and learning algorithms for more sensing accuracy and better channel selection scheme for CM2M network environment. The developed scheme and algorithm improved the mechanism give in

Chapter 4 and increased the energy efficiency of CM2M network by 45%. Furthermore, the mechanism boosts the accuracy of CM2M devices, which leads to more probability of detection and less sensing time required from CM2M to sense the available channels. Chapter 7 explored the future of M2M technology in medical health, real-world examples given and explained. Besides, the Chapter explored the security aspects that could affect the service of M2M communication in medical health applications and finally recommendations given to cope with the security vulnerabilities.

8.2 Future work

1- For future work, from the CM2M spectrum efficiency perspective and based on the results of this thesis the impact of the various parameters could be explored by using a genetic algorithm to solve the introduced utilisation function; population size, crossover rate and mutation rate; in addition, future work could consider developing a genetic algorithm based method to assign spectrum to CM2M devices in an energy efficient manner [1].

2- For future work, from a CM2M energy efficiency perspective, different sensing and accessing techniques could be tested and designed to improve sensing accuracy and reduce interference problems. Match filter or Feature detections schemes can be used to ensure the low cost of the design due to M2M communications requirements of low cost and simplicity [2, 3]. Furthermore, additional monitoring techniques could be added to the current models such as Receiver Statistics and Energy Ratio to improve–channel observation and increase the sensing and accessing accuracy due to selecting better channels [4, 5].

3- Exploiting CM2M technology in wireless healthcare applications, as proved in this thesis, cognitive radio as smart technology can boost spectrum efficiency and decrease energy consumption. More studies on the use of cognitive radio in M2M healthcare applications could help to solve many problems of wireless M2M communications in healthcare systems.

4- Low latency is one of the important requirements of healthcare applications. For instance, in telesurgery services, latency in wireless communications has a significant effect on the operation and the process of robotic instruments. Low latency (less than 200 ms) is considered good and amenable for the next generation of telesurgery systems. Cognitive radio as smart technology can be designed to reduce the latency in operating systems (e.g., telesurgery systems) that will lead to unleashing further mobile applications working with a fixed latency rate [6]. Reducing latency using smart technologies such as cognitive radio will enable urgent and specialist operations to be carried out remotely by specialist surgeons anywhere in the world.

5- Due to the huge number of biomedical sensors with M2M capabilities, machine-generated data could soon exceed network capacity. Thus, efficient schemes and techniques should be developed to adapt to such challenges. Based on the literature review of this thesis, cognitive radio as intelligent technology can be adapted to work with a huge number of devices [7]. The SDR capability in CR enables it to manage a huge number of SUs with good communication quality and reliability. Weighted cooperative spectrum sensing schemes could be used to increase the optimality of secondary user (M2M devices) with a guarantee of good throughput and reliability constraints.

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APPENDIX A

MEDICAL TELEMETRY FREQUENCY BAND

Medical telemetry frequency Band	**Description**
Inductive coupling devices	<1MHz
Wireless Medical Telemetry System	608-614 MHz, 1395-1400 MHz, 1427-1429.5 MHz
Medical device radio communication service	401 to 406 MHz
802.11a WIFI	5 GHz
802.11b WIFI	2.4 GHz
802.11g WIFI	2.4 GHz
802.11n WIFI	2.4 / 5 GHz
802.15.1 Bluetooth Class-I	2.4 GHz
802.15.1 Bluetooth Class-II	2.4 GHz
802.15.4 (Zigbee)	868 MHz, 915 MHz, 2.4 GHz

APPENDIX B

MATLAB CODES FOR A NUMBER OF SIMULATIONS

```
%This is the main code of the Genetic Algorithm (GA) based in Spectrum
%aggregation (SA) configured for Maximum Satisfaction Algorithm and Random
%Channel Assignment Algorithm (RCA) (Chapter 3)

% A variable declared as global in multiple functions (and optionally the
base %workspace) share a single copy of that variable. Any assignment you
make to %that variable in one function is available to all functions that
declare it %global.

%INPUTS
% Define variables
% PU_Space = primary user space
& ra_cr = probability of Collison
% MAS = Maximum Aggregation Span
% Len_Chro = Length of the chromosome
% User_Req_Bw = User request bandwidth
% gen_num = generation number
% relative_white_space = relative white space to each channel
% C = matrix C


clear
clc


global ra_cr PU_space C white_space N M L MAS M_new N_Non_Inter M_Non_Inter
Len_Chro mutationRate size_pop Len_Chro L_new C_new User_Req_Bw
relative_white_space gen_num


%<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

iteration_num=20; % Iteration number

N=10;           %Number of CM2M device
M=30;           %Number of Overleaping channels
MAS=40;
size_pop=30;    % population size
gen_num=50;     % Number of Generation
mutationRate=.01;
% how_man=1;
% ra_cr=.6;
%>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
Max_User_Req=20;
Max_white_space=10;
Max_PU_space=20;

white_space=round((Max_white_space-1)*rand(1,M)+1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ashg=0;
for N=5:5:60
    ashg=ashg+1;
    Tx=0;
    Rx=0;
    Hx=0;
    Zx=0;
    n_LL=0;
    BBX=0;
    CCX=0;
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for kkee=1:iteration_num % loop for a number of iteration circle
        L=ones(N,M);
        C=zeros(N,N,M);
%         rng default
%         white_space=round((Max_white_space-1)*rand(1,M)+1);
        User_Req_Bw=round((Max_User_Req-1)*rand(1,N)+1);
        PU_space=round((Max_PU_space-1)*rand(1,M-1)+1);
        M_new=sum(white_space);
        L_new=[];
        C_new=[];

%..........................................................................
        for n1=1:N
            for n2=1:N
                for n3=1:M
                    if n1==n2
                        C(n1,n2,n3)=0;
                    else
                        C(n1,n2,n3)=1;
                    end
                end
            end
        end
        totall_bw_msa=0;
        num_of_rej_msa=0;
        [totall_bw_msa num_of_rej_msa]=MSA;
        BBX=BBX+totall_bw_msa;
        CCX=CCX+num_of_rej_msa;


TTotal_of_given_bw_random=0;TTotal_of_given_bw_aggreg=0;
NNumber_of_rejected_users_random=0;
NNumber_of_rejected_users_aggreg=0;

        %rng default
[TTotal_of_given_bw_random NNumber_of_rejected_users_random
assign_result_of_random] = Rand_chan_ass;
        %rng default
        [TTotal_of_given_bw_aggreg NNumber_of_rejected_users_aggreg
assign_result_of_aggreg  ] = aggre_aware;
  Tx=Tx+TTotal_of_given_bw_random;
  Rx=Rx+TTotal_of_given_bw_aggreg;

  Zx=Zx+NNumber_of_rejected_users_random;
  Hx=Hx+NNumber_of_rejected_users_aggreg;
  n_LL=sum(User_Req_Bw)/sum(white_space)+n_LL;

    end
       %-------------------------------------------------------------------
--

        Total_of_given_bw_random(ashg)=Tx/iteration_num;
        Total_of_given_bw_aggreg(ashg)=Rx/iteration_num;
        %------------------------------------------------------------------
---
        Number_of_rejected_users_random(ashg)=Zx/iteration_num;
        %
        Number_of_rejected_users_aggreg(ashg)=Hx/iteration_num;
```

```
    TTtotall_bw_msa(ashg)=BBX/iteration_num;
    NNnum_of_rej_msa(ashg)=CCX/iteration_num;



    n_L(ashg)=n_LL/iteration_num;

 end


%Plotting figures

 figure(1)
    hold on

          zzxx=sum(white_space)*ones(1,12)
       NNMM=[5:5:60];
       ccrrt=NNMM-Number_of_rejected_users_random;
   plot(n_L,zzxx,'-
rs','MarkerEdgeColor','yellow','MarkerFaceColor','r','MarkerSize',5)


    plot(n_L,Total_of_given_bw_aggreg,'-
rs','MarkerEdgeColor','r','MarkerFaceColor','r','MarkerSize',5)
    plot(n_L,TTtotall_bw_msa,'-
ks','MarkerEdgeColor','green','MarkerFaceColor','k','MarkerSize',5)


    plot(n_L,Total_of_given_bw_random,'-
ks','MarkerEdgeColor','k','MarkerFaceColor','k','MarkerSize',5)


    figure(2)
    hold on
    plot(n_L,(Number_of_rejected_users_random),'-
ks','MarkerEdgeColor','k','MarkerFaceColor','k','MarkerSize',5)
plot(n_L,NNnum_of_rej_msa,'-
ks','MarkerEdgeColor','green','MarkerFaceColor','k','MarkerSize',5)
    plot(n_L,Number_of_rejected_users_aggreg,'-
rs','MarkerEdgeColor','r','MarkerFaceColor','r','MarkerSize',5)
```

```
% This code for the main creation of different population size with Maximum
%Aggregation Span algorithm. During the initialization process, the initial
%population is randomly generated based on a binary coding mechanism.
%(Chapter 3)


% New functions may be added to MATLAB's vocabulary if they
%   are expressed in terms of other existing functions. The
%   commands and functions that comprise the new function must
%   be put in a file whose name defines the name of the new
%   function, with a filename extension of '.m'. At the top of
%   the file must be a line that contains the syntax definition
%   for the new function. For example, the existence of a file
%   on disk called stat.m with:
%
%           function [mean,stdev] = stat(x)
%           %STAT Interesting statistics.
%           n = length(x);
%           mean = sum(x) / n;
%           stdev = sqrt(sum((x - mean).^2)/n);

% Define variables
% PU_Space = primary user space
& ra_cr = probability of Collison
% MAS = Maximum Aggregation Span
% Len_Chro = Length of the chromosome
% User_Req_Bw = User request bandwidth
% gen_num = generation number
% relative_white_space = relative white space to each channel
% C_New = updated matrix C
% N= Number of CM2M devices
% M= Number of overlapping channels



function Population = main_creation( Len_Chro, MSR )
global N M_new M_Non_Inter size_pop N_Non_Inter User_Req_Bw L_new
relative_white_space MAS C_new white_space
Population=[];
%--------------------------------------------------------------------------


for n1=1:(size_pop)
    assignment_matrix=zeros(N,M_new);
    p=[];p=randperm(N);

%========================================================================
    for n9=1:N
        fff=zeros(1,M_new);
        ttt=zeros(1,M_new);
        rrr=zeros(1,M_new);
        yy=zeros(1,M_new);
        kk=User_Req_Bw(p(n9));
        xx=zeros(1,M_new);
        ll=[]; ll= find(L_new(p(n9),:));
        xx(1,ll)=1;
        hhhh=[];ttt=[];

======================================================================
        for n15=1:(n9-1)
            rrr(1,:)=C_new(p(n9),p(n15),:);
```

```
            yy=assignment_matrix(p(n15),:);
            fff=rrr.*xx.*yy;
            hhhh=xx-fff;
            xx=hhhh;
            ttt=find(hhhh);
            ll=[];
            ll=ttt;
        end

%========================================================================
        hh=size(ll);
        if hh(2)>=kk
            ppp=[];
            www=[];
            ppp=sort(ll);
            www=relative_white_space(ppp);
            var_temp3=0;
            iiii=[];

%========================================================================
            if kk~=1
                for n10=1:(hh(2)-1)
                    var_temp1=1;
                    for n11=(n10+1):hh(2)
                        if (www(n11)-www(n10))<=MAS
                            var_temp1=var_temp1+1;
                            if var_temp1==kk
                                var_temp3=var_temp3+1;

%in this if we can find without any aggregation
                                iiii(1,var_temp3)=ppp(n10);
iiii(2,var_temp3)=ppp(n11);
                                iiii(3,var_temp3)=n11-n10;
iiii(4,var_temp3)=n10;
                            end
                            if var_temp1>kk
                                iiii(1,var_temp3)=ppp(n10);
iiii(2,var_temp3)=ppp(n11);
                                iiii(3,var_temp3)=n11-
n10;iiii(4,var_temp3)=n10;
                            end
                        end
                    end
                end
            end

%========================================================================
            if kk==1
                for n10=1:hh(2)
                    var_temp3=var_temp3+1;
                    iiii(1,var_temp3)=ppp(n10);iiii(2,var_temp3)=ppp(n10);
                    iiii(3,var_temp3)=0;
                                iiii(4,var_temp3)=n10;
                end
            end

%========================================================================
            mm=size(iiii);
            if mm(2)~=0
                uuuu=[];
                hhhhh=[];
```

```
 %add one for number of space minus one for decreasing start point
                hhhhh=iiii(2,:)-iiii(1,:)+1-1;
                for n13=1:mm(2)
                    uuuu(n13)=nchoosek(hhhhh(n13),(kk-1));
                end
                uuuu2=sum(uuuu);
                uuuu3=uuuu/uuuu2;
                jjjjj=[];
                for n14=1:mm(2)
                    jjjjj(n14)=sum(uuuu3(1,1:n14));
                end
                rrrr=rand(1);
                jjjjj=[0,jjjjj];
                yyy=[];
                yyy=find(jjjjj>rrrr);
                cho_section=yyy(1)-1;
                pp=[];
                %pp=randperm(iiii(2,cho_section)-iiii(1,cho_section));
                pp=randperm(iiii(3,cho_section));
                ww=[];
                % ww=pp+iiii(1,cho_section);
                ww=pp+iiii(4,cho_section);
                rr=[];
                ee=[];
                %rr=ww(1:(kk-1));
                rr=ppp(ww(1:(kk-1)));
                rr=[iiii(1,cho_section),rr];
                ee=sort(rr);
                assignment_matrix(p(n9),ee)=1;
            end
        end
    end
    for n4=1:Len_Chro
        chro(n4)=assignment_matrix(N_Non_Inter(n4) ,M_Non_Inter(n4));
    end
    Population=[chro;Population];

end

 end
```

```
%This code to for Maximum Satisfaction Algorithm (MSA) to show the total
%bandwidth of MSA and the number of Rejected devices in MSA. The proposed
%algorithm takes into consideration interference to the PUs, CCI among SUs,
%and MAS to aggregate whitespaces (Chapter 3)



function  [totall_bw_msa num_of_rej_msa ] = MSA
global M MAS Max_white_space PU_space User_Req_Bw
global  PU_space white_space N M L MAS M_new N_Non_Inter M_Non_Inter Len_Chro
mutationRate size_pop Len_Chro L_new C_new User_Req_Bw relative_white_space
gen_num

%..........................................................................

%............................................................................

% Define variables

% totall_bw_msa = total bandwidth of MSA
% num_of_rej_msa = number of rejected devices
% PU_Space = primary user space
& ra_cr = probability of Collison
% MAS = Maximum Aggregation Span algorithm
% Len_Chro = Length of the chromosome
% User_Req_Bw = User request bandwidth
% gen_num = generation number
% relative_white_space = relative white space to each channel
% C_New = updated matrix CCI
% N= Number of CM2M devices
% M= Number of overlapping channels


accepted_users=zeros(4,N);
assignment_matrix=zeros(N,M);


accepted_users=zeros(4,N);
assignment_matrix=zeros(N,M);
V=0;modi_PU_space=[PU_space,2*MAS];
SC=[];
for n1=1:M
    if modi_PU_space(n1)>=MAS
        V=V+1;
%V is total number of CS(areas that separated because of PU space bigger
than mas)
        SC(V)=n1;

%each element the number of PU space that finish each CS
    end
end
[sa,so]=size(SC);

%............................................................................

CS=[];
for n1=2:so
    tem_r=0;
    xxx=SC(n1-1)+1;
%the number of first white space after previous pu space divider
```

```
    yur=1;
    for hhtt=(SC(n1-1)+1):SC(n1)
        bnrq(n1,yur)=xxx;

% rows show number of CS and coulmuns non zero are white space num in that
rwo
        tem_r=white_space(xxx)+tem_r;
        CS(n1)=tem_r;

% it is same size of sc but each column show how much white space is
available in that column number SC
        xxx=xxx+1;
        yur=yur+1;
    end
end
tem_r=0;
xxx=1;yur=1;
for hhtt=1:SC(1)
    bnrq(1,yur)=xxx;
    tem_r =white_space(xxx)+tem_r;
    CS(1)=tem_r;
    xxx=xxx+1;
    yur=yur+1;
end
%.......................................................................
R_CS=[];
R_CS=[CS;1:V];%make label for CS areas
R_User_Req_Bw=[];R_Des_User_Req_Bw=[];
R_User_Req_Bw=[User_Req_Bw;1:N];%make label for user req
d1=[];d2=[];
[d1,d2] = sort(R_User_Req_Bw(1,:),'descend');
R_Des_User_Req_Bw=R_User_Req_Bw(:,d2);
% Des_User_Req_Bw=sort(User_Req_Bw,'descend');
d1=[];d2=[];R_Asc_CS=[];
[d1,d2] = sort(R_CS(1,:));
R_Asc_CS=R_CS(:,d2);
% Asc_CS=sort(CS);
dytu=sort(white_space);
%.......................................................................
new_primary=PU_space;
new_white_space=[white_space;1:(M)];
M_nnn=M;
fla_empty_pu=0;
for jj=1:N
    M_nnn
    new_primary

    flag_assinged=0;
    for r=1:V
        if (flag_assinged~=1)&&(fla_empty_pu~=1)
            x_d=R_Asc_CS(2,r);
            tem_er=[];
            tem_ewer=[];
            tem198=[];
            tem_ewee33=[];
            tem012=[];
            t1=[];t2=[];PPP=[];
            %.............................................................
            tem_er=find(bnrq(x_d,:)>0);
            [sa3,so3]=size(tem_er);
            lljj=bnrq(x_d,tem_er);%so3 is always non zero
```

```
            zse=[];
            for ert=1:so3
                zse(ert)=find(new_white_space(2,:)==lljj(ert));

%because new white space changes to find out
            end
            t1=new_white_space(1,zse);
            t2=new_white_space(2,zse);%in fact t2 and zse are same
            %             t1=new_white_space(1,bnrq(x_d,tem_er));
            %             t2=new_white_space(2,bnrq(x_d,tem_er));
            tem012= t1-R_Des_User_Req_Bw(1,jj);
            tem_ewer= find(tem012==0);
            tem198=t2(1,tem_ewer);
            [sa,so]=size(tem198);
            %..............................................................
            if so~=0

assignment_matrix(R_Des_User_Req_Bw(2,jj),t2(tem_ewer(1)))=1;
                flag_assinged=1;
                %                 trei=new_white_space(1,tem_ewer(1));
                trei=R_Des_User_Req_Bw(1,jj);
                tnew_primary=[];
                tnew_primary=new_primary;
                new_primary=[];
                [sa2,so2]=size(tnew_primary);
                accepted_users(2,jj)=t2(tem_ewer(1)) ;
                accepted_users(3,jj)=t2(tem_ewer(1)) ;
                accepted_users(4,jj)=R_Des_User_Req_Bw(1,jj);

%__________________________________________________________________________
_
                if so2>=3
                    %                     if
(tem_ewer(1)>2)&&(tem_ewer(1)<so2+1-2)
                    if (zse(tem_ewer(1))>2)&&(zse(tem_ewer(1))<=so2+1-2)
                        new_primary=[tnew_primary(1:zse(tem_ewer(1))-
2),tnew_primary(1,zse(tem_ewer(1))-
1)+trei+tnew_primary(1,zse(tem_ewer(1))),tnew_primary((zse(tem_ewer(1))+1):
end)];
                        new_white_space(:,zse(tem_ewer(1)))=[];
                        %                         elseif
zse(tem_ewer(1))==3
                        %
                        %                          new_white_space(:,3)=[];
                        %
                    elseif zse(tem_ewer(1))==2

new_primary=[tnew_primary(1,1)+trei+tnew_primary(1,2),tnew_primary(3:end)];
                        new_white_space(:,2)=[];
                    elseif zse(tem_ewer(1))==1
                        tnew_primary(:,1)=[];new_primary=tnew_primary;
                        new_white_space(:,1)=[];
                    elseif zse(tem_ewer(1))==(so2+1)
                        tnew_primary(:,so2)=[];new_primary=tnew_primary;
                        new_white_space(:,so2+1)=[];
                    elseif zse(tem_ewer(1))==(so2)
                        new_primary=[tnew_primary(1,1:so2-
2),tnew_primary(1,so2-1)+trei+tnew_primary(1,so2)];
                        new_white_space(:,so2)=[];
                    elseif (so2==4)&&(zse(tem_ewer(1))==3)
                        new_white_space(:,3)=[];
```

```
new_primary=[tnew_primary(1,1),tnew_primary(1,2)+trei+tnew_primary(1,3),tne
w_primary(1,4)];
                    end
                end

%_________________________________________________________________________
                if so2==2
                    if zse(tem_ewer(1))==2

new_primary=[tnew_primary(1,1)+trei+tnew_primary(1,2)];
                        new_white_space(:,2)=[];
                    elseif zse(tem_ewer(1))==1
                        new_primary=[tnew_primary(1,2)];
                        new_white_space(:,1)=[];
                    elseif zse(tem_ewer(1))==3
                        new_primary=[tnew_primary(1,1)];
                        new_white_space(:,3)=[];
                    end
                end

%_________________________________________________________________________
                if so2==1
                    if zse(tem_ewer(1))==2
                        %
new_primary=[tnew_primary(1,2)];
                        new_primary=[];
                        new_white_space(:,2)=[];
                    elseif zse(tem_ewer(1))==1
                        %
new_primary=[tnew_primary(1,1)];
                        new_primary=[];
                        new_white_space(:,1)=[];
                    end
                    fla_empty_pu=1;
                end

%_________________________________________________________________________
                % v ro ham tagir kon
                %az loop for  kharaj sho
                M_nnn=M_nnn-1;
            else
                tem_ewee33=find(tem012<0);
                tem012(1,tem_ewee33)=789087;
                frty=min(tem012);
                if frty~=789087
                    PPP=find(tem012==frty);

assignment_matrix(R_Des_User_Req_Bw(2,jj),t2(PPP(1)))=1;
                    accepted_users(2,jj)=t2(PPP(1)) ;
                    accepted_users(3,jj)=0 ;
                    accepted_users(4,jj)=R_Des_User_Req_Bw(1,jj);
                    flag_assinged=1;
                    tnew_primary=[];
                    tnew_primary=new_primary;
                    new_primary=[];
                    [sa2,so2]=size(tnew_primary);

%__________________________________________________________________________
_
                    if zse(PPP(1))==1
```

```
                        new_primary=tnew_primary;
                        new_white_space(1,1)=new_white_space(1,1)-
R_Des_User_Req_Bw(1,jj);
                        %M_nnn=M_nnn-1;

                    elseif zse(PPP(1))==(so2+1)
                        new_primary=[tnew_primary(1:zse(PPP(1))-
2),tnew_primary(1,zse(PPP(1))-1)+R_Des_User_Req_Bw(jj)];

new_white_space(1,zse(PPP(1)))=new_white_space(1,zse(PPP(1)))-
R_Des_User_Req_Bw(1,jj);
                    else
                        new_primary=[tnew_primary(1:zse(PPP(1))-
2),tnew_primary(1,zse(PPP(1))-
1)+R_Des_User_Req_Bw(jj),tnew_primary(zse(PPP(1)):end)];
                        % v ro ham tagir kon

new_white_space(1,zse(PPP(1)))=new_white_space(1,zse(PPP(1)))-
R_Des_User_Req_Bw(1,jj);
                        %az loop for  kharaj sho
                        %                         M_nnn=M_nnn-1;
                    end
                end
            end
            if flag_assinged==1
                accepted_users(1,jj)=1 ;
            end
        end
    en

%.......................................................................
    if fla_empty_pu~=1
        %*****************
        modi_PU_space=[];
        modi_PU_space=[new_primary(1,:),2*MAS];

%.......................................................................
        V=0;
        SC=[];
        for n1=1:M_nnn
            if modi_PU_space(n1)>=MAS
                V=V+1;
                SC(V)=n1;
            end
        end
        [sa,so]=size(SC);

%.......................................................................
        CS=[];bnrq=[];
        for n1=2:so
            tem_r=0;
            xxx=SC(n1-1)+1;
            yur=1;
            for hhtt=(SC(n1-1)+1):SC(n1)
                %         bnrq(n1,yur)=xxx;
                bnrq(n1,yur)=new_white_space(2,xxx);
                tem_r=new_white_space(1,xxx)+tem_r;
                CS(n1)=tem_r;
                xxx=xxx+1;
                yur=yur+1;
            end
```

```
        end

%........................................................................
        tem_r=0;
        xxx=1;yur=1;
        for hhtt=1:SC(1)
            %     bnrq(1,yur)=xxx;
            bnrq(1,yur)=new_white_space(2,xxx);
            tem_r=new_white_space(1,xxx)+tem_r;
            CS(1)=tem_r;
            xxx=xxx+1;
            yur=yur+1;
        end

%........................................................................
        R_CS=[];
        R_CS=[CS;1:V]; d1=[];d2=[];
        [d1,d2] = sort(R_CS(1,:));
        R_Asc_CS=R_CS(:,d2);

        %*****************
    else
        tttttt=111111111111111111111

        for kkiioo=jj+1:N
            if R_Des_User_Req_Bw(1,kkiioo)<new_white_space(1,1)



assignment_matrix(R_Des_User_Req_Bw(2,kkiioo),new_white_space(2,1))=1;
                    accepted_users(1,kkiioo)=1 ;
                    accepted_users(2,kkiioo)=666 ;
                    accepted_users(3,kkiioo)=0;
                    accepted_users(4,kkiioo)=R_Des_User_Req_Bw(1,kkiioo);
                    flag_assinged=1;

                    new_white_space(1,1)=new_white_space(1,1)-
R_Des_User_Req_Bw(1,kkiioo);
            elseif R_Des_User_Req_Bw(1,kkiioo)==new_white_space(1,1)



assignment_matrix(R_Des_User_Req_Bw(2,kkiioo),new_white_space(2,1))=1;
                    accepted_users(1,kkiioo)=1 ;
                    accepted_users(2,kkiioo)=666 ;
                    accepted_users(3,kkiioo)=666;
                    accepted_users(4,kkiioo)=R_Des_User_Req_Bw(1,kkiioo);
                    flag_assinged=1; fla_empty_pu=1;
                    new_white_space(1,1)=new_white_space(1,1)-
R_Des_User_Req_Bw(1,kkiioo);
            end
        end


    end
end

%%%%%%TEST
for  uiyt=1:M
    tture1=[];
    tture1=find(accepted_users(2,:)==uiyt);
```

```
    [sa,so]=size(tture1);
    if so==0
       rqqp(1,uiyt)=99999;
    else
    iiop=sum(white_space(uiyt));
    zzqq=sum(R_Des_User_Req_Bw(1,tture1));
    rqqp(1,uiyt)=zzqq-iiop;
    end
end
totall_bw_msa=sum(R_Des_User_Req_Bw(1,find(accepted_users(1,:)==1)));
num_of_rej_msa=N-sum(accepted_users(1,:));
%NL(ilo)=sum(User_Req_Bw)/sum(white_space);
%%%%%%TEST



end
```

```
%This code for Maximizing Sum of Reward algorithm in cognitive radio systems
%( Chapter 3) To achieve higher spectrum efficiency and faster convergence,
%after each generation the MSRA whenever possible randomly assigns all
%unassigned spectrum to remaining SUs,

% Define variables
% Chro = Chromosome of GA
% totall_bw_msa = total bandwidth of MSA
% num_of_rej_msa = number of rejected devices
% PU_Space = primary user space
& ra_cr = probability of Collison
% MAS = Maximum Award summation algorithm
% Len_Chro = Length of the chromosome
% User_Req_Bw = User request bandwidth
% gen_num = generation number
% relative_white_space = relative white space to each channel
% C_New = updated matrix C
% N= Number of CM2M devices
% M= Number of overlapping channels



function MSR_OUT = MSR(Chro)
global  N M_new N_Non_Inter M_Non_Inter Len_Chro User_Req_Bw



A=zeros(N,M_new);
for n4=1:Len_Chro
    A(N_Non_Inter(n4),M_Non_Inter(n4))=Chro(n4);
end
tem_var1=0;
tem_var=0;
for n1=1:N
    tt=sum(A(n1,:));
    if tt==0
        tem_var=tem_var+1;
    else
        tem_var1=tem_var1+User_Req_Bw(n1);
    end
end
%max bw
MSR_OUT=-tem_var1;

%min rejection
%MSR_OUT=tem_var;
end
```

```
%This code for Monte Carlo simulation detection, when the primary signal is
%real Gaussian signal and noise is % additive white real Gaussian (Chapters
%4, 5, 6 )

clc
close all
clear all
L = 1000;
snr_dB = -10; % SNR in decibels
snr = 10.^(snr_dB./10); % Linear Value of SNR
Pf = 0.01:0.01:1; % Pf = False Alarm Probability
for m = 1:length(Pf)
 m
 i = 0;
for kk=1:10000 % Monte Carlo Simulations Numbers
n = randn(1,L); %AWGN noise with mean 0 and variance 1
s = sqrt(snr).*randn(1,L); % Real valued Gaussina Primary User Signal
y = s + n; % SU Received signal
energy = abs(y).^2; % Energy of received signal over N samples
energy_fin =(1/L).*sum(energy); % Test Statistic for the energy detection
thresh(m) = (qfuncinv(Pf(m))./sqrt(L))+ 1; if(energy_fin >= thresh(m))
% Check whether the received energy is greater than threshold, if so,
increment Pd
(Probability of detection)
counter by 1
i = i+1;
end
end
Pd(m) = i/kk;
end
plot(Pf, Pd)
hold on
```

```
%This Code for Spectrum Sensing for CM2M gateways to sense the available
%channels with the consideration to the primary users using QPSK Modulation
%and BPSK Modulation (Chapter 4, 5, ,6 ).

clear all;
%
% PARAMETERS
%
freq = 200; %operating frequency
Fs = 20*f; %sampling frequency
L=100; % Number of samples per symbol period
Ts = 1/Fs; % Sampling period
T = Ts:Ts:1/f;
alpha=0.5; % Roll-off factor for the (square-root) raised cosine filters
N=8*L; % N+1 is the length of the square-root raised-cosine filter.
sigma_v=0; % Standard deviation of channel noise
h=1; % Channel impulse response
%
%SOURCE: Take input data from user for transmission
%
pt_dt = input('Data you want to send:','s');
R = isempty(pt_dt);
if R == 1
pt_dt = 'Waleed Ejaz';
else
pt_dt = pt_dt;
end
display(pt_dt);
RR = double(pt_dt);
bb = 1;
Rp = dec2bin(RR,7);
[TA TC] = size(Rp);
for ll = 1:1:TA
for lg = 1:1:TC
msg(bb) = Rp(ll,lg);
bb = bb + 1;
end
end
rt = 1; ht = 1;
for ls = 1:1:TA
for ll = 1:2:(TC-1)
Inp_msg(rt,(ht:ht+1)) = Rp(ls,(ll:ll+1));
rt = rt + 1;
end
end
%
% Transmit Filter
%
pT=f_sr_cos_p(N,L,alpha); % Transmit filter:
xT=conv(f_expander(msg,L),pT); % Transmit signal
%
% Modulation
%
display('Select Type of Modulation');
display('1. BPSK');
display('2. QPSK');
Mod_Type = input('Plz Enter the Type of Modulation :','s');
Carrier = [];
%
% BPSK Modulation
%
```

```
if (Mod_Type=='1')
display('Binary PSK');
for ii = 1:1:length(T)
car1(ii) = sin((2*pi*freq*T(ii))); %CARRIER TO BE TRANSMITTED
end
for ii = 1:1:length(xT)
if xT(ii) == '0'
car = -1*car1;
else
car = 1*car1;
end
Carrier = [Carrier car];
end
%
% QPSK Modulation
%
else if(Mod_Type=='2')
for ii = 1:1:length(T)
car1(ii) = sin((2*pi*freq*T(ii))+360); %CARRIER TO BE TRANSMITTED
car2(ii) = sin((2*pi*freq*T(ii))+90); %CARRIER TO BE TRANSMITTED
car3(ii) = sin((2*pi*freq*T(ii))+180); %CARRIER TO BE TRANSMITTED
car4(ii) = sin((2*pi*freq*T(ii))+270); %CARRIER TO BE TRANSMITTED
end
for ii = 1:1:length(Inp_msg)
if Inp_msg(ii) == '00'
car = car1;
else if Inp_msg(ii) == '01'
car = car2;
else if Inp_msg(ii) == '10'
car = car3;
else if Inp_msg(ii) == '11'
car = car4;
end
end
end
end
Carrier = [Carrier car];
end
if true
% code
end end % end of if
end %end of else if
%
if true
% code
end
% CHANNEL
%
xR=conv(h,Carrier);
if true
% code
end
xR=xR+sigma_v*randn(size(xR)); % Received signal
```

```
%This code for Spectrum Sensing and sharing Algorithm. This algorithm to
%sense the available channels and switch/sleep off when the sensed channels
%busy (Chapters 5)..more details please read Chapter 5.

% System Parameters/Inputs.

fs=46000; %Sample frequency Hz
X=0.1;  %the probability  of false alarm
SNR=10;  %single to Nosie ratio
Bo=650;  %bandwidth
ps=1;   %probability  of channel been busy
M=6;    %number of available channels
S=8;    %time
T=0.8; %frame time
Es=0.04;  %Energy of Switching
Et=0.0695; %Energy of Transitions
y=10;  %SNR of Primary user
p=0.40;   %place holder
Pdt=0.9; %probability of detection
Pft=0.1; %Target probability of false alarm

% Sensing and Sharing Algorithm
Co=log2(1+SNR);
R0=(1-p)*Co;
R=U*R0*2
D=X*S;
Mue=D/D+S;
OOO=qfuncinv(Pft);
SSS=qfuncinv(Pdt);
pc1=(1-p)*(1-Pft);
pc2=p*(1-Pdt);
Pb=((Pdt*p+Pft*(1-p)))^(M-1);
P1=(1-p)*(1-0.1)+p*(1-0.9);
P3=(1-P1)*(1-Pb)*(1-ps)*(1-(0.5*(1-ps))); %Probability of Switching
PT=(P1+P3);
N=S/(PT*T);
t2=T-Bo*(1-exp(-(T/Bo)));
Bt=(1-(t2/T))*Co*T;
B1=pc1*Bt;
B2=P3*(1-Pe)*Bt;
tsoptr=(B1+B2-T*R)/R;
PWT=(1-P1)*Pb+(1-P1)*(1-Pb)*ps;
tsoptd=(D-N*T*PWT)/N;
Pt=P1+P3;
TS=S/Pt;
tsMIN=(1/fs*(y)^2)*(OOO-SSS*sqrt(2*y+1))^(2); % min sensing time
Power=(N*tsMIN*Es+N*P3*Jsw+S*Et)*2000; % Total power consumption
avgR=((B1+B2)/(tsMIN+T))*2;

% Ploting the results

psoptmal=1-(tsMIN+T)*R-pc1*Bt/Bt*(1-P1)*(1-Pe)*(1-Pb);
gg=(Mue*T-(1-Mue)*tsMIN)/(T*(1-P1)*(1-Pb))-(Pb/1-Pb);
avgD=N*tsMIN+N*T*PWT;
hold on
plot(U,Power,'--s')
```