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Adaptive and Efficient Radio Resource Sharing Schemes for Machine Type Communications underlying Cellular Networks

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To my beloved mother, Rafika Al Khémir ...

To my beloved father, Ali Hamdoun ...

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The light is in my heart and between my wings, so why shall I fear to walk in the darkness.
Aboul-Qacem Echebbi, a Tunisian poet, 1909-1934.

النور في قلبي و بين جوانحي   فعلام أخشى السير في الظلماء

List of Acronyms

- **Internet-of-Things:** IoT
- **Machine-to-Machine:** M2M
- **Machine-Type-Communication:** MTC
- **Human-to-Human:** H2H
- **Base Station:** BS
- **Machine-Type-Device:** MTD
- **Machine-Type-Head:** MTH
- **Device-to-Device:** D2D
- **Proportional Integral Derivative:** PID
- **Medium Access Control:** MAC
- **Long Term Evolution and its Advancement:** LTE-A
- **Machine-Type-Server:** MTS
- **Peer-to-Peer:** P2P
- **Third Generation Partnership Project:** 3GPP
- **Heterogeneous Network:** HetNet
- **Relay Node:** RN
- **Remote Radio Head:** RRH
- **Single-Carrier-Frequency-Division-Multiple-Access:** SC-FDMA
- **Orthogonal-Frequency-Division-Multiple-Access:** OFDMA

- **Peak-to-Average Power Ratio:** PAPR
- **Transmission-Time-Interval:** TTI
- **Resource Block:** RB
- **Evolved Universal Terrestrial Radio Access Network:** E-UTRAN
- **evolved Node B:** eNB
- **User Equipment:** UE
- **MTC Gateway:** MTG
- **Radio Access Network:** RAN
- **Time Division Multiple Access:** TDMA
- **Orthogonal Frequency-Division Multiplexing:** OFDM
- **Physical Random Access Control Channel:** PRACH
- **5th Generation:** 5G
- **Uplink Shared Channel:** UL-SCH
- **Downlink Shared Channel:** DL-SCH
- **Quality-of-Service:** QoS
- **Access Grant Time Interval:** AGTI
- **Long Term Evolution-Unlicensed:** LTE-U
- **Carrier Sense Multiple Access with Collision Avoidance:** CSMA/CA
- **Licensed-Assisted Access:** LAA
- **Listen Before Talk:** LBT
- **Path Loss:** PL
- **Signal-to-Interference-plus-Noise-Ratio:** SINR
- **Non-deterministic Polynomial Time Hard:** NP-hard
- **Bipartite Graph:** BG
- **Proportional Fairness:** PF
- **Round Robin:** RR

- **Maximum/Minimum Weighted Matching:** MWM
- **Kuhn Munkres:** KM
- **Channel State Information:** CSI
- **Physical Uplink Shared Channel:** PUSCH
- **Probability Density Function:** PDF
- **Discontinuous Reception:** DRX
- **Membership Function:** MBF
- **Mixed Nash Equilibrium:** MNE
- **Evolutionary Game Theory:** EGT

Abstract

The *Internet-of-Things* (IoT) refers to the ever-growing network of everyday objects that interconnect to each other or to other Internet-enabled systems via wireless sensors attached to them. IoT envisions a future where billions of smart devices will be connected and managed through a range of communication networks and cloud-based servers, enabling a variety of monitoring and control applications. *Machine-to-Machine* (M2M) communications supported by cellular networks, also known as *Machine-Type-Communications* (MTC) acts as a key technology for partially enabling IoT. M2M communications is a new technology paradigm that facilitates the ubiquitous connectivity between a myriad of devices without requiring human intervention. The surge in the demand for connectivity has further challenged network operators to design novel radio resource allocation algorithms at affordable costs to handle the massive scale of MTC.

Different from current radio access technologies tailored to traditional *Human-to-Human* (H2H) communications, the goal of this thesis is to provide novel efficient and adaptive radio resource sharing schemes for MTC under a H2H/M2M coexistence scenario. We first provide a suitable multiple access scheme to address the joint spectrum scarcity, scalability and *Base Station* (BS) overload issues. Toward this end, we design a group-based operation where MTC corresponds to local uplink communications between *Machine-Type-Devices* (MTDs), which represent a specific type of devices that do not rely on the presence of a human interface, and a *Machine-Type-Head* (MTH). This latter plays the role of a cluster head that relays the information to the BS. We thus address the need to aggregate M2M and *Device-to-Device* (D2D) technology, as one of the major components of the future evolving cellular networks. Having said that, we first propose in this thesis to model the radio resource sharing problem between MTDs and H2H users as a bipartite graph and develop a novel interference-aware graph-based radio resource sharing algorithm for MTC so as to mitigate the co-channel interference and thus enhance network efficiency. Moreover, low-complexity semi-distributed solution is investigated to alleviate the communication overhead of a centralized solution that we propose as well. Then, as a second contribution, we examine how M2M devices can share the available radio resources in cellular networks with no or limited impact on existing H2H services. Consequently, we propose a joint spectrally and power efficient radio resource sharing scheme. Convinced by the strength of the bipartite graph modeling for the resource sharing problem between H2H users and M2M devices, we empower the graph-based radio resource sharing algorithm with a novel adaptive power control feature using one of two following mechanisms: the *Proportional Integral Derivative* (PID) controller and the fuzzy logic. Finally, in our third contribution of this thesis, we develop a power efficient and fully-distributed radio resource sharing framework for MTC underlying cellular networks. We use game theory and model the resource sharing problem as an efficient hybrid-game where M2M devices compete for radio resources and switch opportunistically, as M2M devices are selfish in nature, between non-cooperative and cooperative games. The different derived solutions are extended to existing cellular networks, and extensive simulation studies in the context of LTE are conducted. The various simulation results show that the proposed solutions can significantly increase the efficiency of the spectrum usage, mitigate the negative effect on H2H services and save the battery life of M2M devices.

Keywords

Radio resource sharing, M2M communications, D2D technology, PID, Fuzzy logic, bipartite graph, game theory.

RÉSUMÉ

L'*Internet des objets* (IoT) fait référence à la croissance continue des réseaux d'objets du quotidien qui s'interconnectent entre eux ou avec d'autres systèmes Internet via les capteurs sans fil qui y sont attachés. L'IoT promet un futur où des milliards de terminaux intelligents seront connectés et gérés via une gamme de réseaux de communication et de serveurs basés dans le cloud, permettant ainsi l'apparition d'un large spectre d'applications de surveillance et de contrôle. Les communications *machine-à-machine* (M2M) représentent le pont de l'IoT prises en charge par les réseaux cellulaires. Elles sont également connues sous le nom de *"Machine-Type-Communication"* (MTC) et constituent une technologie clé permettant d'activer partiellement l'IoT. Les communications M2M sont un nouveau paradigme qui facilite la connectivité omniprésente entre une myriade de dispositifs sans ou avec intervention humaine limitée. La demande croissante de connectivité a mis au défi les opérateurs de réseau à concevoir de nouveaux algorithmes d'allocation de ressources radio pour gérer l'échelle massive des MTC à des coûts abordables.

Contrairement aux technologies d'accès radio traditionnelles, adaptées aux communications usuelles, dites de *humain-à-humain* (H2H), l'objectif de cette thèse est de développer de nouvelles techniques de partage de ressources radio efficaces et adaptatives pour les MTC dans un scénario de coexistence H2H/M2M. Dans le cadre de cette thèse, notre première contribution consiste en la proposition d'un système d'accès multiple adapté pour résoudre à la fois les problèmes liés à la rareté des ressources radio, à la scalabilité et à la surcharge de la *station de base* (BS). À cette fin, nous proposons de décomposer les opérations de communication en les groupant. Ainsi, les MTC correspondent à des communications locales en liaison montante entre des dispositifs connus sous le nom de *"Machine-Type-Device"* (MTD), et un cluster head appelé *"Machine-Type-Head"* (MTH). Les MTHs relayerons ensuite les informations vers le BS. Nous examinons ainsi la nécessité d'agréger la technologie M2M et le *"dispositif-à-dispositif"* (D2D), considéré comme composante majeure des réseaux cellulaires évolutifs du futur. Nous modélisons le problème de partage de ressources radio entre les MTDs et les utilisateurs H2H sous la forme d'un graphe biparti et développons un algorithme de partage de ressources radio pour MTC basé sur les graphes afin d'atténuer les interférences co-canal et donc améliorer l'efficacité du réseau. En outre, une solution semi-distribuée de faible complexité est développée pour atténuer la surcharge de communication d'une solution centralisée que nous proposons également. Ensuite, dans une deuxième contribution de cette thèse, nous nous intéressons à examiner comment les dispositifs M2M peuvent partager les ressources radio disponibles sans pour autant dégrader les performances des applications traditionnelles H2H. Par conséquent, nous proposons un système de partage de ressources efficace en terme de spectre et de puissance. Convaincu par la robustesse de la modélisation en graphe biparti, nous introduisons à l'algorithme de partage de ressources radio basé sur ces graphes une fonction adaptative de contrôle de puissance utilisant l'un des deux mécanismes suivants : un contrôleur *proportionnel intégral dérivé* (PID) et la logique floue. Enfin, comme troisième contribution de cette thèse, nous développons un système de partage de ressources radio efficace en terme de puissance et entièrement distribué pour les MTC. Nous utilisons la théorie des jeux et modélisons le problème de partage de ressources par un jeu hybride où les dispositifs M2M rivalisent pour les ressources radio et basculent de façon opportuniste, étant des dispositifs égoïstes de nature, entre un jeu non-coopératif et un jeu coopératif. Toutes les solutions dérivées dans cette thèse sont mises en place dans le cadre des réseaux cellulaires existants, et une évaluation des performances poussée par simulation dans le contexte des réseaux LTE est menée. Les résultats des simulations montrent que les solutions proposées ont un impact significatif sur la maximisation de l'efficacité de l'utilisation du spectre, l'atténuation de l'effet négatif sur les services H2H et la prolongation de la durée de vie des batteries des dispositifs M2M.

Mots-clefs

Partage de ressources radio, communications M2M, technologie D2D, PID, logique floue, graphe biparti, théorie des jeux.

CONTENTS

- Chapter 1 -

Thesis presentation

1.1 Introduction

With the burgeoning advance of intelligent devices and infrastructure, the *Internet-of-Things* (IoT) has emerged as a new paradigm that refers to the interconnection and interoperability of such smart devices. IoT will be widely used in an incredibly plethora of applications in almost every field from intelligent transportation systems to smart environment going through smart building, smart grids, smart healthcare and more. It has the aim of improving and considerably revolutionizing our everyday lives.

It is predicted that at least 50 billion devices will be deployed worldwide by 2020 [36, 35], and a major portion of them will be connected to cellular networks [85]. Thus, *Machine-to-Machine* (M2M) communications, also known as *Machine-Type-Communications* (MTC), supported by cellular networks will be one of the fundamental enablers of IoT. MTC aims to provide the communication infrastructure through facilitating the autonomous interconnection between billions of devices among each other or with the underlying data transport infrastructure, without human intervention.

A successful deployment of MTC requires a paradigm shift from the current radio access technologies tailored to traditional *Human-to-Human* (H2H) communications in order to handle the massive number of M2M devices. Furthermore, introducing M2M communications into cellular networks should not have a detrimental effect on the performance of existing H2H communications.

1.2 Research challenges and contributions

Taking advantage of the *Device-to-Device* (D2D) benefits, as one of the major components of the evolving 5G networks that refers to the direct communication between two users without traversing the infrastructure, it becomes an effective strategy to use D2D technology in cellular M2M networks. The present work is devoted to designing radio resource sharing schemes for MTC underlying cellular networks. In other words, the main goal of this dissertation is to develop novel radio resource allocation algorithms for MTC where the same spectrum is expected to be shared between H2H communications and M2M communications. In essence, the three high level key questions we should ask in order to achieve this are:

- Q1 How to provide a scalable *Medium Access Control* (MAC) protocol able to handle the massive number of M2M devices?
- Q2 How to have no or limited impact on existing H2H services with the introduction of M2M devices?
- Q3 Considering the selfish behavior of M2M devices, how to provide fully distributed and energy efficient concurrent access for MTC under cellular networks since M2M devices are battery driven and often deployed in remote areas which makes battery replacement hard?

Our first contribution then is to provide a suitable multiple access scheme to enable the large scale usage of M2M devices under a H2H/M2M coexistence scenario. More precisely, we advocate that M2M devices transmit traffic through D2D technology underlying cellular network. To cope with the huge complexity of the optimal radio resource sharing problem between H2H users and M2M devices in this case, we propose a two-stage radio resource allocation approach giving higher priority to H2H users. We consider a group-based operation where MTC corresponds to local uplink communications between *Machine-Type-Devices* (MTDs) and a *Machine-Type-Head* (MTH) with the aim of offloading the *Base Station* (BS). MTH plays the role of a cluster head that has higher capabilities in terms of memory and processing power. The MTH acts as the link between MTDs and the BS. The tasks of the CH includes that of aggregating the data from MTDs before sending it to the BS. This latter having "just" to establish communications with the MTHs in addition to handling H2H communications. Consequently, the scope of this contribution is suitable for the client-server model of M2M communications, where MTDs are connected to a *Machine-Type-Server* (MTS). Thus, we formulate the radio resource sharing problem as a bipartite graph and develop a novel interference-aware graph-based radio resource sharing algorithm for MTC so as to mitigate co-channel interference and consequently enhance network efficiency. Furthermore, we provide a semi-distributed instantiation to alleviate the communication overhead of the centralized instantiation. Simulation study is conducted under a static scenario to evaluate the impact of the proposed algorithm in conjunction with the centralized and semi-distributed instantiations on H2H services in terms of throughput. The proposed Fixed Centralized Radio Resource Sharing Algorithm (F-C-RRSA) achieves approximately a gain of 15% over the proposed Fixed semi-Distributed Radio Resource Sharing Algorithm (F-sD-RRSA) in terms of network sum-rate. However, the proposed F-sD-RRSA has lower communication overhead.

Our second contribution is devoted to examining how M2M devices can share the available radio resources in cellular networks with no or limited impact on existing H2H services. Therefore, we propose a joint spectrally and power efficient radio resource sharing scheme. Convinced by the strength of the bipartite graph modeling of the resource sharing problem between H2H users and M2M devices, we empower the graph-based radio resource sharing algorithm proposed in the first contribution with a novel power control feature. The latter uses two alternative mechanisms: the *Proportional Integral Derivative* (PID) controller and the fuzzy logic that aim to guarantee H2H services and maximize the spectrum usage of M2M communications. We consider a mobile scenario and conduct an extensive simulation study to evaluate the impact, in terms of throughput and fairness, of the different proposed graph-based radio resource sharing schemes on H2H communications. The fuzzy logic-based adaptive M2M radio resource sharing algorithm yields the best compromise between guaranteeing H2H performance and satisfying M2M services.

Our third contribution concerns designing power efficient and fully distributed radio resource allocation schemes for MTC. We consider a multiple radio resource sharing scheme where multiple M2M devices transmitting traffic through D2D technology can share the spectrum with a H2H user. We use game theory and model the resource allocation problem as an efficient hybrid-game where M2M devices which are selfish in nature compete for radio resources and switch efficiently and opportunistically between non-cooperative and cooperative games. In addition, our proposed scheme is fully distributed to cope with the heavy information exchange, between all M2M devices and the BS, heaviness that can result from a centralized approach. The proposed framework in contrast to the two previous contributions is convenient to the peer-to-peer model of the M2M communications- i.e., a situation when the devices (sensors, actuators or controllers) communicate directly between themselves. An extensive simulation study is conducted in order to assess the impact of the proposed hybrid-game-based transmission strategy selection algorithm on H2H services in terms of throughput and fairness and evaluate the gain in terms of power consumption. The battery life of MTDs is significantly extended with a gain of up to 40% compared to a pure non-cooperative game approach.

1.3 Thesis organization

The dissertation is structured as follows:

In chapter 2, we present an overview of M2M communications summarizing the literature. More precisely, we present M2M communications, introduce their characteristics and the different types of M2M applications. We discuss the architectural enhancements in the next generation wireless networks to enable cellular M2M communications with an emphasis on D2D technology. Then, we give a brief overview of D2D use cases. Particularly, we highlight the M2M communications as a use case of D2D technology. Finally, we conclude this chapter by focusing on the major challenges to be addressed for efficiently enabling MTC under a H2H/M2M coexistence scenario.

In chapter 3, we present our first contribution. It provides a novel spectrally efficient radio resource sharing scheme for MTC to address the scalability issue under a H2H/M2M coexistence scenario. We detail how we mitigate the co-channel interference due to the orthogonality loss through using a bipartite graph methodology and then present two alternatives of the proposed MTC radio resource sharing scheme: centralized and semi-distributed. Finally, we focus on evaluating the impact of both alternatives on H2H services.

In chapter 4, we present our second contribution, which further tackles the negative effect of introducing M2M communications on H2H services. We study and characterize our proposed power efficient radio resource sharing scheme using two mechanisms: PID controller and fuzzy logic. Then, we detail the performance evaluation of our proposal under a H2H/M2M coexistence scenario.

In chapter 5, we present our third contribution which addresses the case of multiple radio resource sharing between M2M and H2H communications. Hence, we detail and characterize our fully distributed and power efficient transmission strategy selection algorithm using game theory with the aim of saving the battery life of M2M devices characterized by a selfish behavior. The performance evaluation of our proposal is conducted and is also compared to existing approaches.

Finally, the conclusions of this thesis appear in chapter 6 which also describes some future research directions.

- Chapter 2 -

An overview of M2M communications

Contents

2.1 Foreword

Apart from the growing proliferation of smartphones and other human-oriented devices in conventional *Human-to-Human* (H2H) communications, the massive scale of *Machine-to-Machine* (M2M) communications or *Machine-Type-Communications* (MTC) introduced into cellular networks represents a detrimental factor. To design new radio resource allocation schemes to accommodate MTC underlying cellular networks, we need to investigate on MTC features, MTC applications and the existing cellular network standard.

In this chapter, we aim to give an overview of M2M communications to delimit the context of the thesis. We first define M2M communications, introduce the different types of M2M applications and M2M characteristics. We present in the next step the multiple access scheme used in *Long Term Evolution and* *its Advancement* (LTE-A) standard and discuss the architectural enhancement in the next generation wireless networks to enable cellular M2M communications. We also give an emphasis on *Device-to-Device* (D2D) communications as an emerging paradigm introduced in LTE-A networks along with M2M communications. Then, we give a brief overview of D2D use cases. Particularly, we highlight the M2M communications as a use case of D2D technology. Finally, we conclude this chapter with focusing on the major challenges to be addressed for efficiently enabling MTC under a H2H/M2M coexistence scenario.

2.2 M2M communications

Machine-to-Machine (M2M) communications is a new paradigm that refers to the ubiquitous connectivity between a myriad of machines without or with limited human intervention. The autonomous connection of devices facilitates the emergence of a wide range of intelligent M2M applications, enabling partially the *Internet-of-Things* (IoT) [23, 24]. The M2M applications can be envisioned in two major scenarios. The first scenario adopts the client/server model and considers the communication between M2M devices called *Machine-Type-Devices* (MTDs) and one or more *Machine-Type-Servers* (MTSs). This scenario is the most adopted by many M2M applications, such as health monitoring, water, gas, or power metering. The main concept consists of connecting seamlessly an autonomous and self-organizing network of MTDs to a remote client, through heterogeneous wired or wireless communication networks. At the remote client is deployed an intelligent software application that aims to process the collected data and provide the end user with a set of smart services through a user-friendly interface. The second scenario of M2M applications may require an alternative model of communication where MTDs are communicating directly through *Peer-to-Peer* (P2P) communications [87, 48]. This kind of inter-MTD communications can be either through the mobile network or in an ad hoc mode.

To enable M2M communications, different short range technologies can be proposed such as Bluetooth, Zigbee or Wi-Fi. Considering that the ultimate goal for M2M communications is to provide ubiquitous connectivity among all devices for serving human beings, scenarios for M2M communications supported by the *Third Generation Partnership Project* (3GPP) are considered the most promising solution. The 3GPP has standardized M2M as MTC in LTE-A. In addition, a specific network architecture known as *Heterogeneous Network* (HetNet) is provided by 3GPP LTE [29, 61, 22]. In addition to conventional macrocells, HetNet involves *Remote Radio Heads* (RRHs), femtocells, picocells as well as *relay nodes* (RNs) which are low-power overlaid *Base Stations* (BSs) underlying the macro-cellular layout. HetNets enhance the network performance (throughput) by reducing the distance between the transmitter and the receiver, improve the network coverage area and offload the macrocells. Besides, an ubiquitous connection among all MTC devices can be provided by attaching to these stations. The 3GPP infrastructure also offers a secure connection and is considered a good support for user or device mobility. Last but not least, an effort on enabling low cost MTDs is considered in 3GPP [90]. More precisely, release 12 of LTE has introduced low-cost MTDs also called Category 0 devices. The cost of Category 0 devices is about 50 % the cost of regular LTE Category 1 devices of release 8. The cost reduction is mainly achieved by reducing the number of radio transceivers and by limiting the maximum transport block sizes [9].

2.3 MTC applications

The autonomous connection of devices and the emergence of low-cost devices from sensors and actuators able to wirelessly communicate with each other facilitate the emergence of a large number of intelligent M2M applications. The latter have exhibited a strong potential to improve the quality of our lives in different aspects such as: at home, at work, when sick or when traveling, and so on and so forth. M2M applications can be classified into different domains as presented in [12, 39], for instance. We present a summary of different applications for each of these domains in Fig. 2.1. An overview of these domains and applications is given in the following.

2.3.1 Intelligent transportation systems

Intelligent transportation systems represent advanced applications that aim to provide innovative services related to different modes of transport and traffic management. On one hand, the increasingly wide range of advanced vehicles equipped with M2M sensors and actuators enables various users to be better informed and makes the use of transport networks smarter and safer. On the other hand, M2M sensors and tags used in roads and in transported goods provide relevant information to transportation control sites in order to better route the traffic, provide the traveller with appropriate transportation information and monitor the status of the transported goods. The major M2M applications in intelligent transportations systems are discussed below.

2.3.1.1 Logistics

M2M communications enhances the logistic services, as a major economic activity, that involve the process of planning, implementing and efficiently controlling the related information from point of origin to point of consumption. For instance, the surveillance of the status of goods, transportation, storage, sale and after sale services in real-time through M2M sensors can help in being conform to the customer requirements. Obtaining a current and accurate information about any product is possible so that customers become better informed about

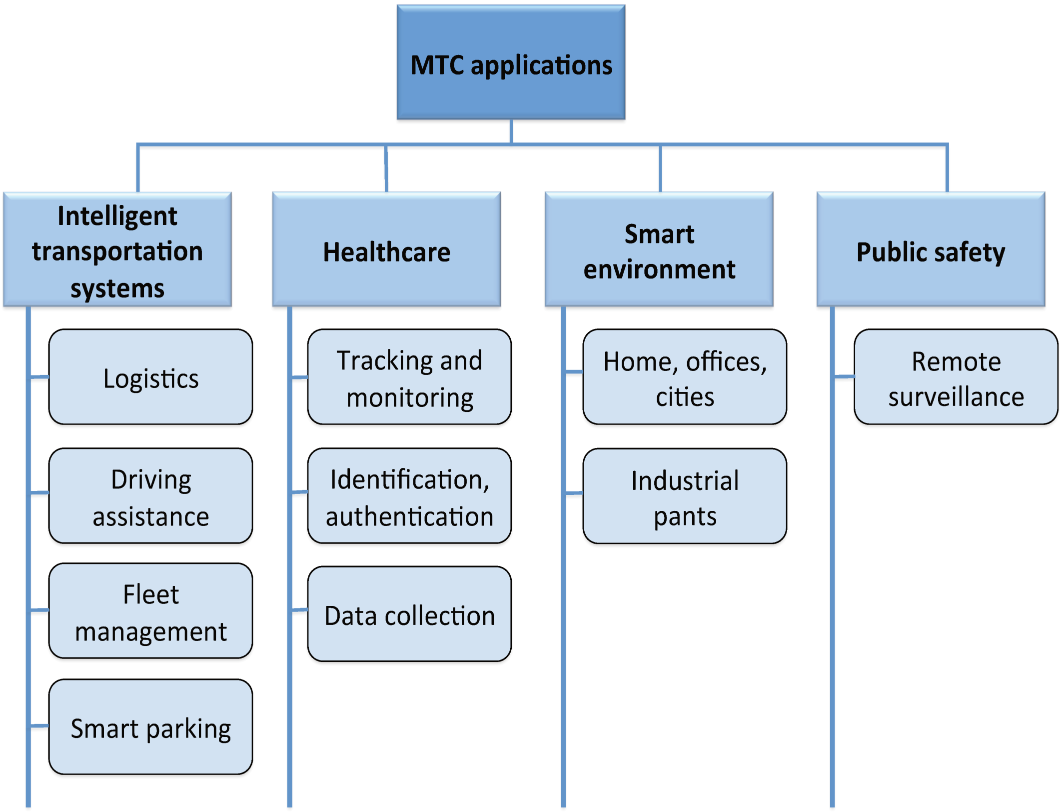


Figure 2.1 – MTC applications

the availability of products. In case any problem is detected, M2M devices can automatically send an alert to the M2M server [47].

2.3.1.2 Driving assistance

Transport vehicles along with roads and rails equipped with M2M sensors provide the driver and passengers of a vehicle with relevant information with the goal to enhance navigation and safety. M2M communication systems can for example alert drivers of incidents and assist them to avoid collisions and jams or also alert people when hazardous materials on vehicles are detected.

2.3.1.3 Fleet management

M2M communications provides solutions to enable efficient fleet management systems that aim to reduce risks, optimize costs and improve the operational efficiency of a fleet. Furthermore, fleet management has a significant role in reducing carbon emissions and negative environmental impact. For instance, It was reported in [18] that approximately 27% of the total carbon dioxide emissions are the result of the combustion of fuels from vehicles.

2.3.1.4 Smart parking

M2M applications in smart parking help drivers to identify if the parking space is occupied or not and let them know where unoccupied car parking spaces are. Parkings are equipped with M2M sensors. Each of these M2M sensors is able to detect that a car has parked over it and then sends the information to a gateway. The latter relays the information to the core network. Finally, the information is sent to a M2M database server to inform users in real-time about the occupancy of parkings.

2.3.2 Healthcare

M2M communications will play a major role in healthcare domain including: the tracking of objects and people (staff and patients), the identification and authentication of people and the automatic medical data collection [84].

2.3.2.1 Tracking and monitoring

Tracking is the operation of identifying an object (organ) or a person in motion. M2M communications helps in preventing left-ins during a surgery through real-time stock tracking, for instance. In addition, M2M communications enables remote monitoring of a patient, triggers alarms or enables remote treatment and crisis interventions in case of emergencies.

2.3.2.2 Identification and authentication

Identification and authentication in healthcare play a major role in securing and protecting patients. On one hand, it reduces the risk of incidents (such as wrong drug, time, or operation). On the other, it is used to grant access and security for both employees and patients.

2.3.2.3 Data collection

Automatic data collection in healthcare involves administrative enrollment, billing records, and medical records. It helps with optimizing the processing time as well as enhancing medical care services and medical inventory management.

2.3.3 Smart environment

The ubiquitous communication among devices deployed at homes, in offices, in cities or industrial plants helps in building a smart environment.

2.3.3.1 Smart homes, offices and cities

M2M sensors and actuators deployed in houses and offices play a prominent role in easing and making comfortable our lives. For instance, sensors installed in various electronic appliances such as air conditioners, heaters, cookers provide a controllable and more efficient utilization of energy. Another example is adapting the lighting in offices to the time of a day and to the number of occupants inside the offices. Besides, a smart city framework provides authorities and citizens with real-time information and assistance in the decision-making to obtain a cost-efficient management of resources, and thus the life quality of citizens is promoted.

2.3.3.2 Industrial plants

By collecting and exchanging information among sensors, M2M communications can improve the degree of automation in industrial plants. For instance, M2M devices can transmit an event-related information in real-time to the M2M server in case an emergency event is triggered.

2.3.4 Public safety

M2M communications enhances the security level through making the process of security including remote surveillance reliable, simple and cost-efficient. Public safety networks provide communications for services like police, fire and ambulance. Security-relevant events such as fire are detected by deployed sensors and relayed in real-time and automatically via M2M communications to a control center allowing triggering a timely response.

2.4 Characteristics of MTC

H2H communications has always been the center of attention of many researchers. Consequently, current mobile networks such as LTE-A networks have been mainly designed to support human-oriented services such as voice calls or data applications [6]. Unlike traditional H2H applications, M2M services are characterized by a massive number of deployed devices with specific features such as: short payload size, extra low power consumption and centralized data collection. Many new potential MTC use cases are more limited by power consumption than the offered data rate or latency [66]. Indeed, M2M devices in most M2M applications are battery driven and it is often very difficult to replace devices' batteries once deployed. Thus, low power consumption is essential for battery operated terminals to prolong time between battery charges. Different from H2H communications that are downlink-oriented, M2M communications are mainly uplink-centric. Thus, H2H devices along with M2M devices bring new requirements and challenges to LTE-A cellular networks originally optimized to carry high data rates for broadband applications. From a MAC layer perspective, the coexistence between H2H users and M2M devices raises the problem of radio resource competition among each other in the same network due to the limited licensed spectrum.

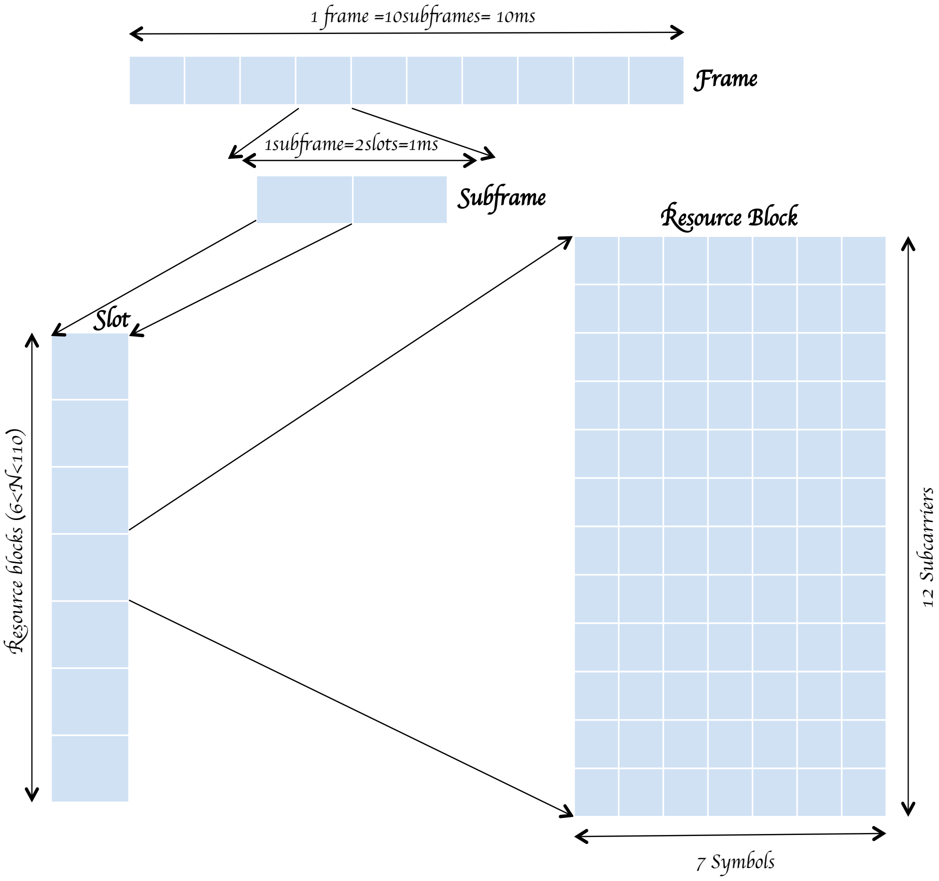


Figure 2.2 – Resource block structure in LTE networks

2.5 SC-FDMA in LTE networks

Since most M2M applications are uplink-centric, we give a brief overview of *Single-Carrier-Frequency-Division-Multiple-Access* (SC-FDMA) as the multiple access scheme used in the uplink transmission of the 3GPP LTE standard [49]. Different from *Orthogonal-Frequency-Division-Multiple-Access* (OFDMA), SC-FDMA is a modified version that offers increased uplink coverage due to its low *Peak-to-Average Power Ratio* (PAPR). Radio resources are distributed in the time-frequency domain. More specifically, radio resources are distributed every *Transmission-Time-Interval* (TTI) in LTE networks which consists of one subframe and has a duration of one ms. Each TTI consists of two slots, thus, 20 slots equivalent to 10 TTI constitute one LTE frame. In the frequency domain, the available bandwidth is divided into a number of sub-channels each including 12 subcarriers with a spacing of 15 Khz. Each sub-channel has a bandwidth of 180 Khz and along with 7 symbols in the time domain constitutes a *Resource Block* (RB) as illustrated in Fig. 2.2. This latter is the minimum unit of the resource allocation process. Depending on the available bandwidth, the number of RBs can vary from 6 to 110. The use of SC-FDMA in the uplink implies certain restrictions on power and RB allocation [68, 40]. Because of the adjacency restriction, multiple RBs allocated to a user must be adjacent. Besides, the transmit power on all RBs allocated to a user should be equal for retaining the low PAPR benefits [8]. Consequently, the constraints associated with SC-FDMA in LTE uplink networks in terms of RB adjacency and transmit power restriction must be respected in case multiple RBs are assigned to a MTD.

2.6 Architectural enhancement to enable MTC

The access network of LTE and its advancements, known as *Evolved Universal Terrestrial Radio Access Network* (E-UTRAN) consists of *evolved Node Bs* (eNBs) which provide user plane and control plane protocol terminations toward the *User Equipment* (UE). The E-UTRAN architecture is flat since there is no centralized controller in radio access network. The eNBs may be interconnected with each other by means of the X2 interface and to the core network by means of the S1 interface as illustrated in Fig. 2.3. The current LTE cellular network is designed to support only H2H services for UEs. With the introduction of M2M communications into LTE-A cellular networks, architectural enhancement needs to be addressed to accommodate future M2M services without degrading the performance of existing traditional H2H services. Fig. 2.3 illustrates three different methods which are feasible to enable M2M communications: direct access, multi-hop access and peer-to-peer access.

2.6.1 Direct access

A MTD can directly access an eNB without any intermediate device as illustrated in Fig. 2.4. This type of direct link is similar to the one established by a regular UE. Even though the direct link access is the simplest access method, it may cause a network congestion when a huge number of devices send communication requests to the eNB simultaneously.

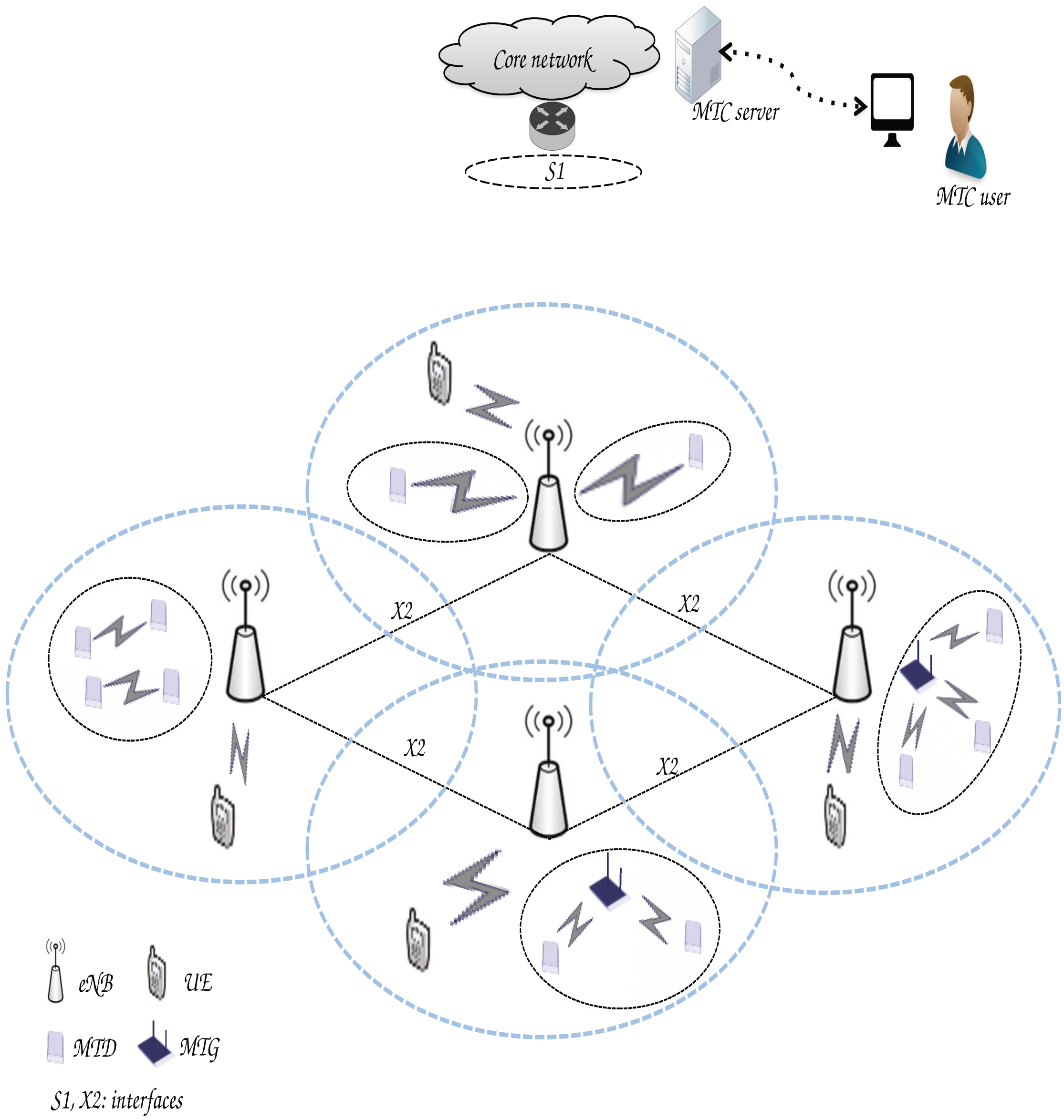


Figure 2.3 – Machine-Type-Communications in LTE-A networks

2.6.2 Multi-hop access

A MTC Gateway (MTG) can be deployed to counter the negative effect of a direct access link. In this case, MTDs are indirectly connected to the eNB through the MTG as illustrated in Fig. 2.5. A MTG relays data between the group of MTDs and the eNB. In other cases, a two or multi-hop communication can be provided through MTDs. Some MTDs can play the role of cluster heads or coordinators, where adjacent MTDs can be grouped and assigned to them. Then, each coordinator transmits the data from all MTDs of its group and communi-

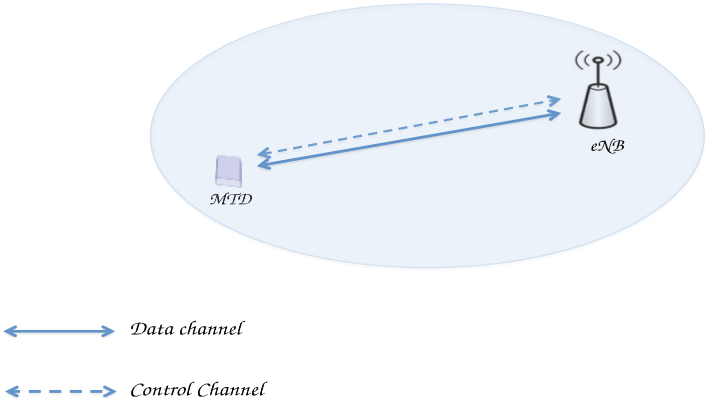


Figure 2.4 – Direct access

cates to the eNB. Even though, a group-based operation through the deployment of MTGs may offload the eNB, the introduction of the MTG makes the network topology more complex.

2.6.3 Peer-to-peer access

Peer-to-Peer (P2P) communications enables M2M devices to communicate directly with each other when they are in close proximity as illustrated in Fig. 2.6. Short range wireless technologies such as IEEE 802.15.4 are designed to support peer-to-peer links. An alternative model of enabling P2P communications is LTE *Device-to-Device* (D2D) communications that we introduce in the next Section. P2P communications can be considered a promising local connectivity solution when local services are available between nearby MTDs.

2.7 D2D communications

Along with MTC new paradigm, 3GPP has introduced a new technology called *Device-to-Device* (D2D) communications for LTE-A in release 12. D2D is defined as the direct communication between two users without traversing the *Base Station* (BS) and appears to be a promising technology in 5G networks [10].

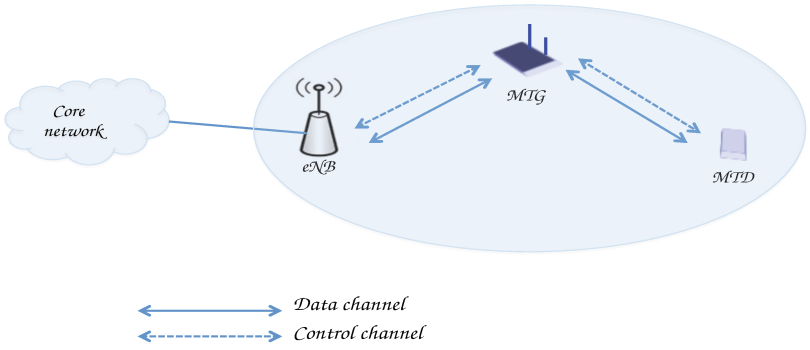


Figure 2.5 – Multi-hop access

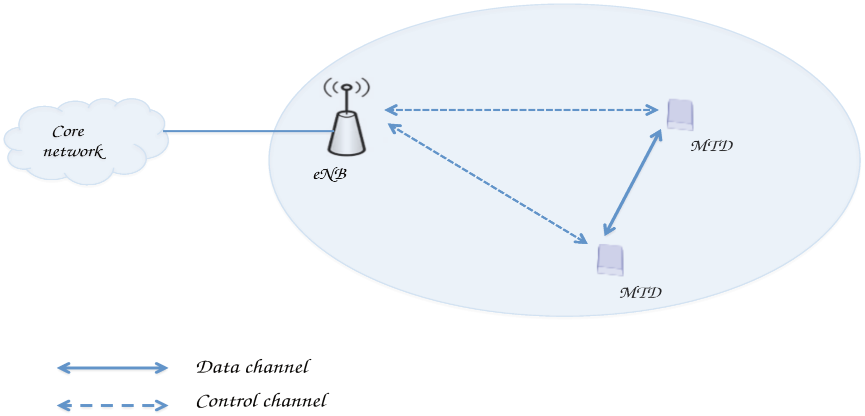


Figure 2.6 – P2P access

2.7.1 D2D categories

D2D communications in the cellular spectrum or inband D2D can be divided into two categories: underlay D2D and overlay D2D as illustrated in Fig. 2.7. In

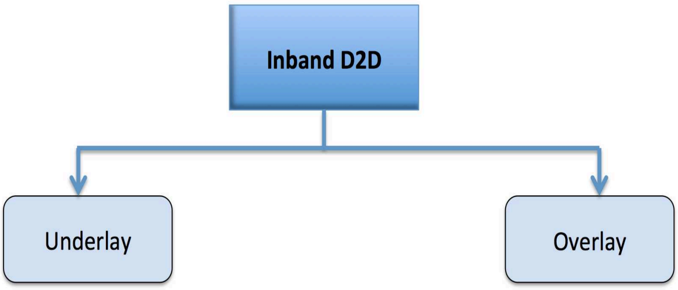


Figure 2.7 – D2D communications in cellular spectrum

contrast to underlay D2D communications where D2D and cellular links share the same spectrum, D2D links in overlay D2D are assigned dedicated resources. Fig. 2.8 shows the interference scenario for D2D communications underlying cellular networks when considering an uplink transmission. A mutual interference can be created between D2D and cellular links. Particularly, the BS may be interfered by the signal transmitted from the D2D transmitter and the D2D receiver may be interfered by the signal transmitted from the cellular user. While the spectrum efficiency is the major advantage of underlay D2D communications compared to overlay D2D, the co-channel interference remains the prominent issue to solve. Consequently new radio resource allocation algorithms should be designed to mitigate such co-channel interference.

2.7.2 D2D use cases

Different use cases for D2D communications have been addressed in literature as follows:

- **P2P communications**: In this case, D2D devices represent the source and destination of the exchanged data [55]. The major applications of P2P communications are:
    - Local voice service: when two geographically proximate users want to talk, D2D communications can be used to offload local voice traffic.
    - Local data service: when two geographically proximate users want to exchange data, D2D communications can be used to provide local data service for enabling content sharing or context aware applications.
- **Video dissemination**: authors in [32, 42] have proved that D2D communications can be a key enabler for video content delivery. Indeed, D2D

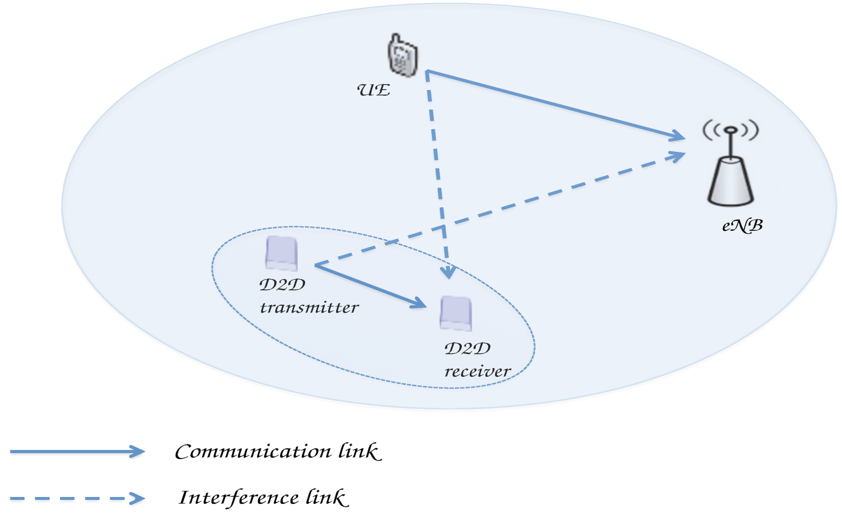


Figure 2.8 – Interference scenario in uplink D2D communications underlying cellular networks

communications has the capability of increasing the throughput of wireless video networks.

- **Cellular offloading**: for example, authors in [16] have explored the case where a user reaching areas characterized by a dense cluster of mobile devices can connect locally with other users having similar interests.

- **Multicasting**: combining multicast with D2D communications becomes an efficient way to improve the network throughput. For example, authors in [33, 77] have shown that aggregating multicast with D2D communications over an orthogonal channel improves the efficiency of the dissemination process while saving resources at the BS.

- **M2M communications**: M2M communication is an other architecture that may benefit from D2D technology. We discuss in the next Section some scenarios and motivations behind aggregating M2M communication and D2D technology.

2.7.3 D2D and M2M aggregation

In a similar way to D2D communications, MTC focuses on exchanges between M2M devices or between M2M devices and the infrastructure. Nevertheless, M2M communications is technology-independent and application-oriented since there is no requirements in terms of distances for example between devices as in D2D communications. On the other hand, D2D communications aims to establish proximity connectivity services which is technology-dependent [10].

Many researchers in the literature have focused separately on the two emerging paradigms in the next generation cellular technologies, M2M and D2D communications. However, only few have addressed the combination of M2M and D2D communications. Indeed, M2M communication is usually handled by a random medium access technique. However, random access can potentially lead to increased collisions for a dense system such as massive MTC. Therefore, network-assisted D2D communication can be considered a prominent technology to accommodate M2M communications. Although few authors have exploited the benefits of D2D to accommodate M2M communications in cellular networks, the motivation between M2M and D2D aggregation has been different. For instance, motivated by the reduced power consumption and the hop gain enabled through D2D communications, authors in [78] have considered a multi-hop D2D communication for end-to-end M2M connectivity, where cellular and D2D links have been assigned orthogonal radio resources to avoid the co-channel interference. In [75], authors have developed a relay-based technique in a M2M use case and have proved that relay-aided D2D communications could be an elegant solution to provide reliable transmission as well as improve the overall network throughput.

Group-based operation of MTDs is considered a promising solution to offload the eNB. The ultimate goal behind grouping MTC devices remains mainly in reducing the number of communications through the BS. The advantages of transmitting MTC traffic using D2D links are twofold: (i) MTC in a group can communicate to the group head called *Machine-Type-Head* (MTH) without traversing the BS, thus the number of connections between devices and the BS is reduced and the *Radio Access Network* (RAN) overhead is prevented. (ii) the energy consumption at the uplink side (M2M applications are uplink-centric) is reduced since traversing the BS is not always the optimal way particularly when the transmitter is nearby the receiver. For instance, authors in [79] have proposed a protocol access scheme with the aim to mitigate the access overload due to the massive number of deployed MTDs. Specifically, authors exploited D2D communications in a *Time Division Multiple Access* (TDMA) scheme to aggregate M2M traffic and forward data generated by low-power MTDs through nearby cellular users. However, the design of the system model for group based M2M communications is still considered to be subject to further study [22].

2.8 Major challenges in enabling MTC

Different from H2H communications, M2M communications has different requirements due to their specific features. Designing efficient radio resource allocation schemes convenient to the two major scenarios of M2M communications, namely the peer-to-peer model and the client-server model, is still an open problem. Recent research works are addressing the key question of: “how existing cellular networks should be improved to enable the massive scale of MTC?”. However, only few have considered the H2H/M2M coexistence scenario. In essence, at least the following major issues have to be addressed to provide efficient radio resource allocation algorithms under a H2H/M2M coexistence scenario.

The first issue to tackle is the *scalability* due to the limited licensed spectrum. Current cellular networks have been optimally designed to support human-oriented services and consider only a small number of H2H users. Due to the high penetration of M2M devices in order of the billions, the competition on the limited radio resources will significantly increase. Hence, our first contribution in chapter 3 is devoted to design a spectrally efficient radio resource sharing scheme under a H2H/M2M coexistence scenario.

The second issue that must be addressed is the *guarantee of the desired Quality of Service (QoS) of H2H links while maximizing the efficiency of the shared spectrum usage*. Indeed, the massive scale of M2M communications introduced in cellular networks can play a detrimental role in degrading the performance of existing H2H services. Hence, our proposed radio resource sharing algorithm in the second contribution in chapter 4 is not only spectrally efficient but also power efficient with the aim to reduce the negative impact on H2H services and maximize the M2M spectrum usage which is crucially important.

The two first contributions in chapters 3 and 4 are convenient to the client-server model of M2M communications, where MTDs are connected to a MTS. Throughout these two chapters, on can say that we design an efficient M2M group-based operation to *alleviate the air interface overload* due to the huge number of deployed MTDs while considering a client-server communication model for MTC.

The third issue concerns designing *distributed and power efficient* radio resource sharing schemes. Indeed, a centralized radio resource sharing scheme can be prohibitive since it requires a huge computational complexity due to heavy information exchange between all MTDs and the eNB. We propose in the third contribution, described in chapter 5, a fully distributed and power efficient transmission strategy selection algorithm. The proposed framework is convenient to the second scenario of M2M communications, which is the peer-to-peer model.

2.9 Conclusions

MTC is a new paradigm that refers to the autonomous communication between devices without or with limited human intervention. MTC has exhibited a strong potential for enhancing human life through different intelligent M2M applications ranging from e-health, smart grids, intelligent transportation systems and much more. Existing cellular networks are not tailored to the scale of M2M communications, which makes conventional resource allocation algorithms for H2H communications prohibitive to cater to MTC requirements. Orthogonal resource allocation is a simple solution adopted by many researchers. However, sharing the same spectrum between H2H and M2M communications represents a promising solution but results in a co-channel interference. The scope of this thesis is hence to design novel radio resource sharing schemes for MTC underlying cellular networks that tackles jointly the scalability and energy efficiency at a low computational cost and thus enabling the massive scale of M2M without degrading the perceived quality of service of existing H2H services.

- CHAPTER 3 -

GRAPH-BASED RADIO RESOURCE SHARING SCHEME FOR M2M COMMUNICATIONS

Contents

3.1 Foreword

Considering the high proliferation of *Machine-to-Machine* (M2M) devices which is in the order of billions along with smartphones in *Human-to-Human* (H2H) communications, significant challenges are posed to the wireless cellular networks. In this chapter, we address the coexistence issues between H2H and M2M communications, by proposing a novel radio resource sharing scheme for *Machine-Type-Communications* (MTC).

We first highlight the coexistence problem between H2H and M2M communications. Then, we formulate the radio resource sharing problem throughout M2M devices and H2H users such as both are allowed to access the same radio resources, as a sum-rate optimization problem. In order to reduce the high computational complexity of the optimal solution, we model the radio resource sharing problem in a H2H/M2M coexistence scenario as a bipartite graph and consider a two-stage radio resource allocation approach, giving higher priority to H2H communications. Then, we develop a novel interference-aware graph-based resource sharing algorithm aiming to efficiently re-assign *Machine-Type-Devices* (MTDs) one of the available radio resources already assigned to H2H users. In addition, we propose a centralized and a semi-distributed instantiations of the proposed interference-aware graph-based radio resource sharing algorithm.

To that end, we introduce the context of this work in Section 3.2, followed by a brief overview of the related works in Section 3.3. The scenario under study is described and the resource assignment optimization problem is formulated in Section 3.4. In Section 3.5, the interference-aware graph-based radio resource sharing algorithm is proposed. The performance evaluation of our proposal is drawn is Section 3.6, followed by the conclusion in Section 3.7.

3.2 Context and motivation

The need of the various public and private organizations to automate their real-time monitoring and control processes, as well as the growing reputation of smart applications aiming to enhance the human well-being demonstrate the explosive growth predicted for M2M applications. The most prominent fields of potential M2M applications include environmental monitoring, smart grids, healthcare, intelligent transportation systems and surveillance. It is expected that over 25 billion devices will be connected to the cellular network in 2020 which far exceeds the existing number of devices in current wireless networks [85].

From a *Medium Access Control* (MAC) layer perspective, an increased competition on radio resources will be generated due to the massive scale. Unlike traditional H2H applications, M2M systems are characterized by a massive number of deployed devices with specific features such as: small data transmission, extra low power consumption and centralized data collection. Hence, designing novel radio resource allocation algorithms is of paramount importance to be able to cater to specific M2M requirements, ensure network efficiency and deal with the massive scale of *Internet-of-Things* (IoT). In addition, low-computational complexity as well as distributed algorithms are required to tackle the exponential computational complexity of an optimal resource allocation scheme and the huge signaling overhead of a centralized approach, respectively.

To address the scalability issue and motivated by the low M2M transmit power constraint, we propose to exploit *Device-to-Device* (D2D) communications underlying cellular networks for M2M traffic, as a convenient way to scale the network capacity and handle millions of devices. As a consequence, new radio resource allocation methods should be developed to mitigate the co-channel interference due to the orthogonality loss. Within this aim, we propose a two-stage radio resource allocation approach in order to reduce the high computational complexity of the optimal solution. Then, we develop a novel interference-aware graph-based resource sharing algorithm to minimize the interference and thus improve the network performance. Finally, we propose a centralized and a semi-distributed instantiations of the proposed algorithm. Simulation study is conducted to evaluate the impact of the proposed algorithm along with the centralized and semi-distributed instantiations on H2H services in terms of throughput.

3.3 Related works

Literature addressing the radio resource allocation schemes for M2M communications has gained much momentum. However, jointly handling the scalability issue associated with the emergence of the high number of MTDs while designing M2M radio resource allocation algorithms is of a paramount importance. Therefore, the multiple access channel is considered as a convenient way to avoid the spectrum scarcity and thus support M2M communications. We present here some existing solutions of M2M radio resource allocation schemes in a H2H/M2M coexistence scenario along with their limitations and classify them into three main categories based on the used access channel method.

3.3.1 Random access procedure

The random access procedure has been considered a promising solution to enable the massive scale of M2M communications since it allows a multiple M2M access. There are two types of random access procedure in *Long Term Evolution* (LTE): contention-based and contention-free. In a contention-based approach, a device (either a MTD or a H2H device) normally initiates random access by randomly choosing a preamble. A preamble is an *Orthogonal Frequency-Division Multiplexing* (OFDM)-based signal. In each LTE cell, there are 64 preambles. Some preambles are reserved for contention-free (or coordinated) random access, while the remaining ones are used for contention-based (or uncoordinated) random access. In a contention-based manner, more than one device can possibly choose the same preamble, which necessitates further contention resolution processes. In a contention-free random access, an *evolved NodeB* (eNB) has complete control over devices to initiate random access by using dedicated preambles. Hence, it guarantees a faster access than the contention-based approach which explains its use in handover purposes where the delay requirement is strict. Fig. 3.1(a) illustrates the contention-based random access procedure, which involves the following four steps [28]:

1. The first step consists of the transmission of a random access preamble. Specifically, the device (either a MTD or a H2H device) selects one of the eNBs' preambles and transmits over the *Physical Random Access Control Channel* (PRACH), allowing the eNB to estimate the transmission timing

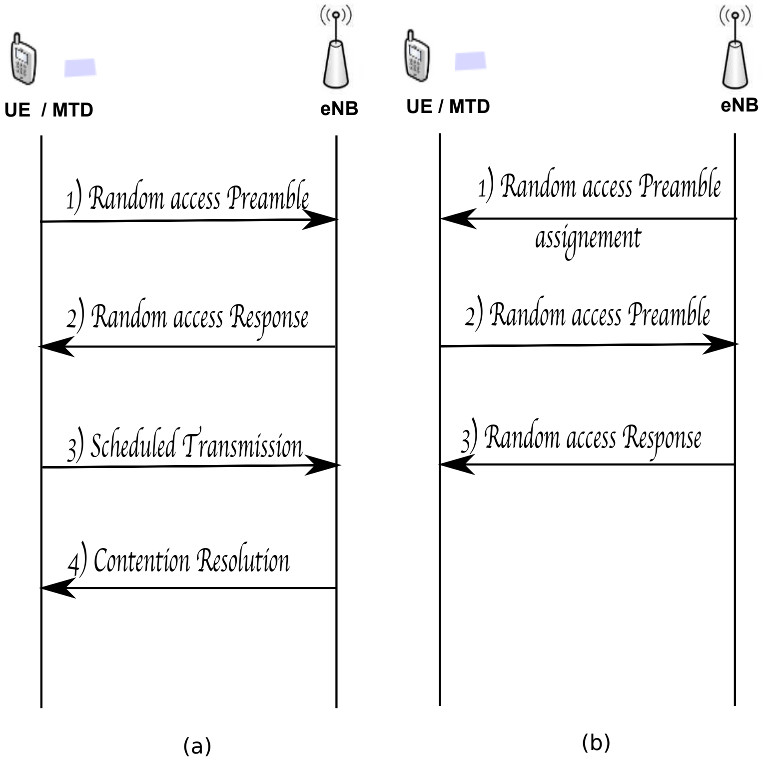


Figure 3.1 – Overview of the random access procedure: (a) contention-based random access procedure; (b) contention-free random access procedure

of the device. Uplink synchronization is necessary in order to allow the device to transmit uplink data to the eNB, otherwise the device cannot transmit any uplink data.

2. The second step consists of the network transmitting a timing advance command to adjust the device transmit timing, based on the timing measurement in the first step. In addition to establishing uplink synchronization, the second step also assigns uplink resources to the device to be used in the third step in the random access procedure.

3. The third step consists of the transmission of the mobile-device identity to the network using the *Uplink Shared Channel* (UL-SCH) similar to normal scheduled data. The exact content of this signaling depends on the state of the device, in particular whether it is previously known to the network or not.

4. The fourth and final step consists of the transmission of a contention-resolution message from the network to the device on *Downlink Shared Channel* (DL-SCH). This step also resolves any contention due to multiple devices trying to access the system using the same random access resource.

A contention-free random access procedure is illustrated in 3.1(b). This latter consists of the following three steps [44]:

1. The procedure starts with the random access preamble assignment by the eNB. This step consists of allocating dedicated preamble signatures to a *User Equipment* (UE).

2. The transmission of an assigned random access preamble by the UE.

3. The eNB responds with the random access response. This is the last step of the contention-free random access since there is no need to resolve further collision.

Authors in [44] have discussed the random access procedure in LTE-A networks as a convenient way to provide the multiple access channel for MTDs. However, significant congestions may occur in a scenario with a massive number of MTDs such as in IoT. A *Quality of Service* (QoS) guaranteed M2M massive access management scheme has been proposed in [57, 58]. In this scheme, MTDs sharing the same QoS requirements, i.e. the jitter, have been grouped logically into clusters. Then, fixed *Access Grant Time Interval* (AGTI) has been allocated to each cluster. The major limitation is that contrarily to the randomness of the real M2M traffic, only constant-rate traffic patterns have been considered. Furthermore, the impact of this mechanism on traditional H2H users has not been discussed.

3.3.2 Multi-radio access technologies in LTE-U

The use of the unlicensed spectrum by the LTE technology is seen as a convenient way to offload the existing traffic from the licensed spectrum. In this context, *LTE-Unlicensed* (LTE-U) technology is initiated as part of LTE release 13 [3], and is considered as a groundbreaking innovation to ensure a seamless and a high quality user experience through extending LTE to the readily available unlicensed spectrum. However, the coexistence between LTE-U systems and the incumbent unlicensed systems such as WiFi systems remains a prominent challenge. Indeed, LTE and WiFi have distinct features. While LTE has been designated to use the licensed spectrum exclusively in a centralized manner endowing its devices with a continuous transmission, WiFi uses *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) which is a distributed media access control protocol that allows transmissions only when the channel is idle. In case the LTE protocol is not properly designed to coexist with the unlicensed spectrum, the WiFi devices suffer from the LTE interference [20, 69, 96]. To enable a friendly and a fair coexistence with the incumbent unlicensed systems, a modification to the LTE protocol is required. For instance, authors in [46, 67] have opted to use the *Licensed-Assisted Access* (LAA) in 3GPP [1, 17] known also as the *Listen Before Talk* (LBT) feature. This latter requires to detect the channel status (occupied or free) at a millisecond scale before a potential transmission of LTE-U devices, meaning that a device is allowed to transmit only if the channel is detected free for a specified period [4, 2]. However, the main drawback of this approach is the starvation problem for LTE-U devices in case of a high WiFi traffic. Several solutions tried to overcome this with more or less efficiency. For instance, authors in [56] have empowered the LTE protocol with a discontinuous duty-cycle transmission pattern. Specifically, LTE-U devices access the unlicensed spectrum for a fraction η of time ($0 \leq \eta \leq 1$), and are muted for the complementary $1 - \eta$ fraction of time, enabling the WiFi devices to transmit. In [25], a hybrid method to perform both traffic offloading and resource sharing in an LTE-U scenario using a coexistence mechanism based on optimizing the duty cycle of the system has been proposed. In [34], authors have investigated the joint radio resource management on licensed and unlicensed bands and have shown its capability to further improve the cellular system performance. In [43], authors have considered the joint channel selection and fractional spectrum access problem through a cognitive coexistence scheme to enable spectrum sharing between LTE-U and WiFi networks. On the other hand, authors in [73] have investigated the coexistence of LTE and ZigBee networks at the unlicensed frequency band of 2.4 GHz in order to offload the existing traffic from the licensed spectrum in a smart meter communication scenario. In this regard, in an IoT scenario, devices with relaxed QoS constraints can be served by the WiFi network while devices with strict QoS constraints can be served by the LTE-U network. However, in most of these solutions, LTE-U requires MTDs to be equipped with dual radio interfaces.

3.3.3 OFDM-LTE systems

A handful of works [59, 100] have recently investigated the radio resource allocation issue in a H2H/M2M coexistence scenario for LTE. For instance, authors in [59] have proposed two fully dynamic (per transmission time interval) M2M scheduling algorithms for the LTE uplink based on a delay tolerance objective and channel conditions. Higher priority has been given to UEs, then the remaining resources have been assigned to MTDs. In the first scheduling algorithm, radio resources have been ranked based on the channel quality. The resource with the highest rank has been assigned to a MTD only if its maximum delay tolerance is smaller than the mean delay tolerance of all remaining MTDs. Meanwhile, in the second algorithm, MTDs have been ranked first based on their delay tolerance, then the best resources in terms of channel quality have been assigned to the least delay tolerant machine. In [100], a mixed scheduling algorithm for H2H and M2M communications has been introduced. Here, authors have classified devices into two queues: the high-priority queue that includes all classical H2H users and some delay-sensitive M2M service users, while remaining MTDs have been grouped in the low-priority queue. Then, the authors have applied different scheduling algorithms for each queue by implementing a compound two-phase procedure. In the first phase, resources in the LTE uplink channel have been allocated to the devices in the high-priority queue while the residual resources have been assigned to the MTDs in the low-priority queue. However, the starvation problem for M2M devices is the major drawback of these algorithms in case of a heavy H2H traffic scenario. Besides, the quite good performance achieved comes at the expense of a huge signaling load due to the centralized feature of the proposed scheme consisting of sending reports and receiving allocation decisions from the eNB individually per MTD. On the other hand, authors in [79] have opted for the aggregation of M2M traffic exploiting D2D links in a classical *Time-Division Multiple Access* (TDMA) scheme to cope with the massive number of machines and to reduce the number of connections between MTDs and the base station. In a TDMA scheme, the time is divided into slots and each device is allocated a time slot. Even though the TDMA scheme as well as the orthogonal D2D resource allocation through overlay D2D communications limit the interference of D2D transmissions, it leads to inefficient utilization of resources.

In this chapter and differently from the cited works, we propose to investigate a new multiple access scheme for MTD in a H2H/M2M coexistence scenario using underlay D2D communications. Indeed, MTDs here can reuse the cellular spectrum, and communicate directly while remaining controlled by the eNB. Therefore, new radio resource allocation methods for D2D communications should be developed to mitigate the co-channel interference due to the orthogonality loss. This is the objective of our first contribution.

3.4 System model and H2H/M2M coexistence problem formulation

3.4.1 System description

We focus on the 3GPP LTE uplink cellular system in which we consider a single cell and a H2H/M2M coexistence scenario. Fig. 3.2 illustrates the proposed system model where the eNB is located at the center of the cell. As illustrated, we also consider the *Peer-to-Peer* (P2P) communications known also as D2D communications. The latter has its unique control and signaling requirements rendering the resource allocation problem for D2D a separate field of investigation. *Machine-Type-Devices* (MTDs) here communicate through D2D communications to overcome the spectrum scarcity, making MTC as an underlay to H2H communications. For simplicity, we assume that D2D corresponds to local uplink communications between MTDs and a *Machine-Type-Head* (MTH). A MTH plays the role of a cluster head.

In order to overcome the challenge of the spectrum scarcity, we consider a simultaneous access to radio resources between H2H users and MTDs transmit-

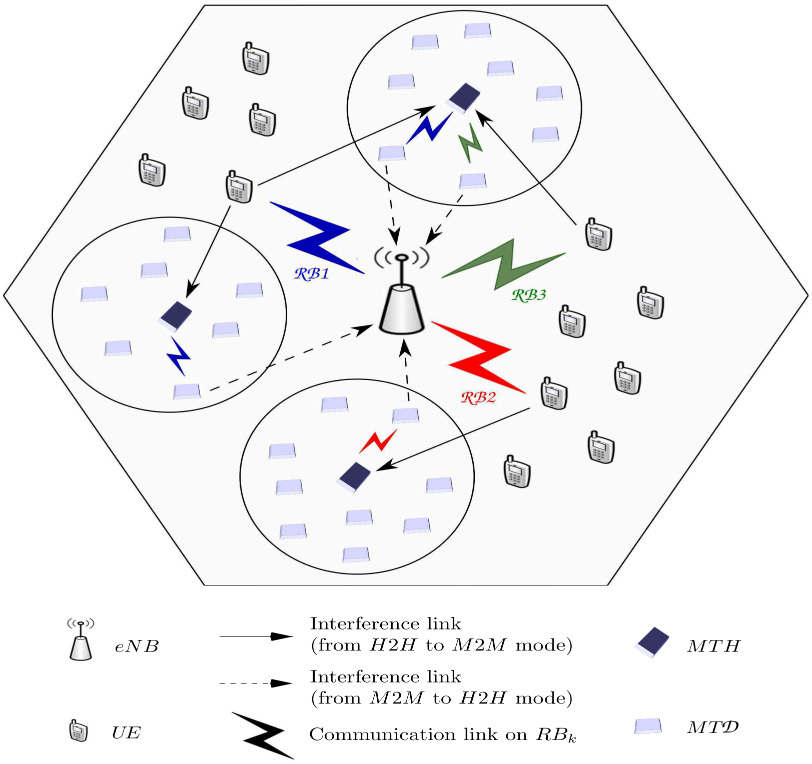


Figure 3.2 – System model under study: inter-MTD within D2D underlying cellular network

ting data through D2D communications. For the ease of notation, H2H users would be referred to as UEs. Specifically, we assume that *Resource Blocks* (RBs) between UEs cannot be shared due to the UE's relatively high transmit power. Thus, there is no interference between UEs. Moreover, we suppose that MTDs are allocated at most one RB due to their small data transmission. No MTDs belonging to the same cluster share the same RB. However, resource sharing among UEs and MTDs as well as among MTDs of different clusters is allowed owing to the MTD's low transmit power. Our focus is on the intra-cell interference, particularly the interference from UEs to MTHs (*interference from H2H mode to M2M mode*) and from MTDs to the eNB (*interference from M2M mode to H2H mode*). We assume that the inter-cluster or inter-D2D interference is negligible due to the relatively low transmit power of MTDs.

The channel gains of the different communication and interference links, determined from the *Path Loss* (PL) and the small scale fading (h), are listed in Table 3.2. The notations used are defined in table 3.1. We assume a frequency flat fading in each RB where the small scale fading for a certain communication link is independent, but remains the same on each RB.

We evaluate the instantaneous *Signal-to-Interference-plus-Noise-Ratio* (SINR) at the UE U_n, $n \in \mathcal{N}$ when the resource block, RB_k, is assigned to it as:

Table 3.1 – Notations

Notation	**Description**
$\mathcal{K} = \{1, 2, \cdots, K\}$	Set of sub-channels
$\mathcal{M} = \{1, 2, \cdots, M\}$	Set of MTDs
$\mathcal{N} = \{1, 2, \cdots, N\}$	Set of UEs
$\mathcal{L} = \{1, 2, \cdots, L\}$	Set of clusters
W	Bandwidth
P_n	UE transmit power
P_m	MTD transmit power
U_n	Traditional UE
C_l	Cluster l
$D^l_{m,t}$	MTD transmitter m that belongs to C_l
$D^l_{m,r}$	MTH or MTD receiver of C_l
$D^l_{m,t\to r}$	M2M pair : MTD transmitter to MTD receiver of C_l

Table 3.2 – Channel gains

Channel gain on RB_k	**from ⇒ to**
$g^k_{U_n} = PL_{U_n} h^k_{U_n}$	UE ⇒ eNB
$g^k_{D^l_{m,t},D^l_{m,r}} = PL_{D^l_{m,t},D^l_{m,r}} h^k_{D^l_{m,t},D^l_{m,r}}$	MTD ⇒ MTH
$g^k_{D^l_{m,t},eNB} = PL_{D^l_{m,t},eNB} h^k_{D^l_{m,t},eNB}$	MTD ⇒ eNB
$g^k_{U_n,D^l_{m,r}} = PL_{U_n,D^l_{m,r}} h^k_{U_n,D^l_{m,r}}$	UE ⇒ MTH

$$SINR^k_{U_n} = \frac{P_n g^k_{U_n}}{\sum\limits_{l\in L} \sum\limits_{m\in M} I^k_{(D^l_{m,t},eNB)} + \sigma^2} \tag{3.1}$$

where the first term in the denominator, $I^k_{(D^l_{m,t},eNB)}$, represents the interference from the MTDs of different clusters, sharing the RB_k with the UE, to the eNB and the second term represents the variance of the thermal noise, denoted by σ^2 and modeled as an independent Gaussian distribution with zero mean.

We evaluate the instantaneous SINR of M2M pair $D^l_{m,t\to r}$, with $l \in \mathcal{L}$ and $m \in \mathcal{M}$ when RB_k is assigned to it as:

$$SINR^k_{D^l_{m,t\to r}} = \frac{P^k_m g^k_{D^l_{m,t},D^l_{m,r}}}{\sum\limits_{n\in N,U_n} I^k_{(U_n,D^l_{m,r})} + \sum\limits_{l'\in L,l\neq l'} \sum\limits_{m\in M} I^k_{(D^{l'}_{m,t},D^l_{m,r})} + \sigma^2}) \tag{3.2}$$

where the first term in the denominator, $I^k_{(U_n,D^l_{m,r})}$, represents the interference from UEs to the MTH ($D^l_{m,r} \in C_l$, $l \in \mathcal{L}$), while the second term, $I^k_{(D^{l'}_{m,t}, D^l_{m,r})}$, represents the inter-cluster interference that consists of the interference on RB_k caused by MTDs of different clusters ($D^{l'}_{m,t} \in C_{l'}$, $l \neq l'$) to the MTH ($D^l_{m,r} \in C_l$). We assume that the inter-cluster or inter-D2D interference is negligible due to the relatively low transmit power of MTDs.

3.4.2 Resource sharing optimization problem

After defining our system model, let us now investigate the resource allocation problem in the uplink transmission case for group-based MTDs within D2D underlying cellular network. The goal is to maximize the sum of the Shannon capacity within the network involving both H2H and MTC communication links. Let $S_{(N+M\times L)\times K} = \begin{pmatrix} X_{N\times K} \\ L \times Y_{M\times K} \end{pmatrix}$ be a RB assignment solution with $m \in \mathcal{M}$, $n \in \mathcal{N}$, $k \in \mathcal{K}$, $l \in \mathcal{L}$ and where $X_{N\times K} = [\alpha_{N,K}]$ and $Y_{M\times K} = [\beta_{m,k}]$ are the RB assignment matrices for UEs and in-range MTDs, respectively as:

$$\alpha_{n,k} = \begin{cases} 1, & \text{if } RB_k \text{ is allocated to } U_n \\ 0, & \text{otherwise.} \end{cases}$$

and

$$\beta^l_{m,k} = \begin{cases} 1, & \text{if } RB_k \text{ is allocated to } D^l_{m,t} \\ 0, & \text{otherwise.} \end{cases}$$

Hence, we can obtain the optimal RB assignment solution denoted by S_{opt}, through solving the optimization problem defined as follows:

$$\begin{aligned} S_{opt} = arg \max_{S_{(N+L\times M)\times K}} \sum_{k=1}^{K} \frac{W}{K} \Bigg[& \sum_{n=1}^{N} log_2 \left(1 + SINR^k_{U_n}\right) \alpha_{n\times k} \\ & + \sum_{l=1}^{L} \sum_{m=1}^{M} \log_2 \left(1 + SINR^k_{D^l_{m,t\to r}}\right) \beta^l_{m\times k} \Bigg] \end{aligned} \tag{3.3}$$

subject to

$$\begin{cases} \sum_{n=1}^{N} \alpha_{n,k} \leq 1, \\ \sum_{m=1}^{M} \beta^l_{m,k} \leq 1, \\ \sum_{k=1}^{K} \beta^l_{m,k} \leq 1, \end{cases} \tag{3.4}$$

where W is the channel bandwidth and $SINR^k_{U_n}$ and $SINR^k_{D^l_{m,t\to r}}$ are given respectively by Eq. 3.1 and Eq. 3.2. Note that the first constraint in Eq. 3.4

guarantees the exclusivity of occupying the same RB by traditional UEs. The second constraint in Eq. 3.4 guarantees that two MTDs belonging to a same cluster are not allowed to re-use the same RB. The third constraint in Eq. 3.4 ensures that at most one RB is assigned to a MTC communication link.

3.4.3 Complexity analysis

The optimal RB assignment S_{opt} solution in Eq. 3.3 can be obtained through an exhaustive search for all $\alpha_{n\times k}$ and $\beta^{l}_{m\times k}$ in each cluster subject to the constraints in Eq. 3.4. The computational complexity to allocate a set of RBs to N H2H users (UEs) considering all the possible choices while taking into account the first constraint in Eq. 3.4 is $\mathcal{O}\left(\frac{N!}{(N-K)!K!}\right)$. Meanwhile the computational complexity when considering all of the possible choices of RB assignment to MTDs in each cluster subject to the second and third constraint in Eq. 3.4 can be computed in $\mathcal{O}\left(M^{LK}\right)$. Thus, the total computational complexity of the optimal RB assignment solution is given by:

$$\mathcal{C}_{S_{opt}} = \mathcal{O}\left(\sum_{k=0}^{K} \frac{N!}{(N-k)!k!} \cdot M^{Lk}\right) \tag{3.5}$$

Hence, the computational complexity obtained in Eq. 3.5 is exponential. From [98, 74], the optimization problem of Eq. 3.3 is a *Non-deterministic Polynomial time Hard* (NP-hard) combinatorial optimization problem with non linear constraints.

3.4.4 Interference-aware bipartite graph modeling

In view of the inherent high complexity of solving the optimization problem of Eq. 3.3, we propose a *Bipartite Graph* (BG) based scheduling approach to provide a suboptimal solution for the radio resource allocation problem in a H2H/M2M coexistence case. The fundamental paradigm shift from a single user to a multiuser communication system with the introduction of *Orthogonal Frequency-Division-Multiple-Access* (OFDMA) in *Fourth Generation* (4G) LTE networks, motivates us to model the resource sharing problem as a bipartite graph. Indeed, in contrast to the traditional physical layer transmission with a single user communication such as *Orthogonal Frequency-Division Multiplexing* (OFDM) where only a single user can transmit on all of the subcarriers at any given time, OFDMA and *Single Carrier-Frequency-Division-Multiple-Access* (SC-FDMA) allow multiple users to transmit simultaneously on the different subcarriers per OFDM symbol. Thus, the bipartite graph is a powerful tool to model the channel assignment between M2M devices and H2H users. Indeed, each MTD can be assigned to one of the available radio resources which is a bipartite graph matching problem. In our proposed D2D communications underlying cellular network, traditional cellular communications (H2H communications) have higher priority than M2M communication links. Therefore, we propose a two-stage resource allocation approach to minimize the interference and thus improve the network performance. We consider that radio resources, RBs, are assigned to traditional H2H users. At the same time, MTDs seek to re-use the RBs occupied by UEs to transmit their data. Specifically, *in the first stage*, H2H radio resource allocation is performed exclusively using conventional scheduling algorithms *(Proportional Fairness (PF), Round Robin (RR))* [65] whose are optimally designed for H2H users. Note that there is no MTC sharing any of the RBs in this phase. *In the second stage*, we model the H2H/M2M resource sharing problem as a weighted BG. While doing so, we propose different instantiations of the proposed graph-based radio resource sharing algorithm for MTC.

Let us represent the MTD resource sharing assignment problem as a BG. The goal is to re-assign to MTC links the RBs already allocated to UEs in a way to minimize the total interference. A weighted BG $G = (U, E)$ is constructed, where the vertices are divided into two disjoint subsets, $U_{n,k}$ and U_m with $n \in \mathcal{N}$, $k \in \mathcal{K}$ and $m \in \mathcal{M}$. While $U_{n,k}$ is the pair (UE, RB) given by the sub-channel allocation solution $\bar{\alpha}$ obtained when applying a traditional H2H resource allocation algorithm, U_m^l represents the set of MTDs- i.e. $U_m^l = \bigcup_{m=1}^{S_l} D_{m,t}^l$ with S_l is the size of a cluster l. Each vertex in $U_{n,k}$ is neighbor to all vertices in U_m. According to the proposed system model in Fig. 3.2, nodes in the subset U_m are divided into L clusters, $U_m = \bigcup\limits_{l=1}^{L} U_m^l$. We define that $U = U_m \cup U_{n,k}$ and $U_m \cap U_{n,k} = \emptyset$. Each edge, denoted by $e_{i,j}^l$ with one endpoint in $U_{n,k}$ and the other one in U_m^l represents the RB assigned to UEs and re-used by MTC links with $i = 1, 2, ..., N$ and $j = 1, 2, ..., M$. The set of edges of G are denoted by:

$$E = \bigcup_{l=1}^{L} E^l = \bigcup_{l=1}^{L} e_{i,j}^l \mid u_i \in U_{n,k}, u_j \in U_m^l \tag{3.6}$$

We express the weight assigned to edges by the sum of the mutual interference between H2H and M2M communications. In Fig. 3.3 (a), an example of G in a network with $U_{n,k} = 4, U_m = 5$ and $L = 2$ is illustrated. Dashed lines in Fig. 3.3 are used only to highlight the different clusters.

3.5 Fixed Radio Resource Sharing Algorithm

Having modeled the radio resource sharing problem in a H2H/M2M coexistence scenario as a bipartite graph, we propose a Fixed Radio Resource Sharing Algorithm (F-RRSA) along with two instantiations, namely, the Fixed Centralized Radio Resource Sharing Approach (F-C-RRSA) and the the Fixed semi-Distributed Radio Resource Sharing Approach (F-sD-RRSA). These algorithms are denoted as fixed since the M2M transmit power is set to a fixed value.

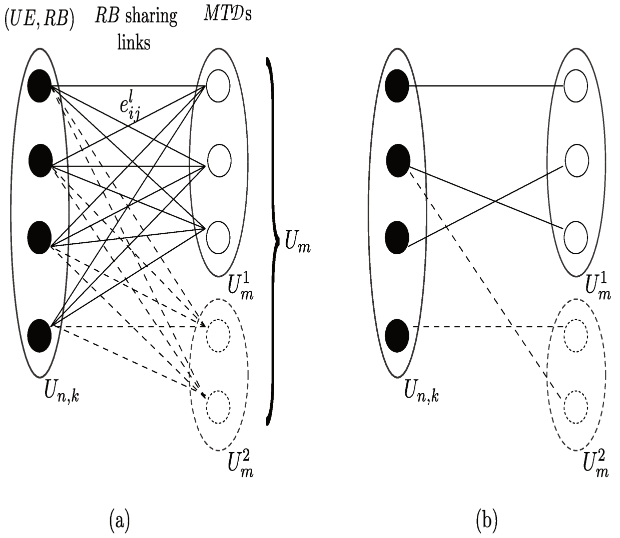


Figure 3.3 – Exemple of a bipartite graph and its matching $U_m = 5$, $U_{n,k} = 4$

3.5.1 Fixed Centralized Radio Resource Sharing Algorithm

The Fixed Centralized Radio Resource Sharing Algorithm (F-C-RRSA) is composed of two steps. In a first step, we establish a proper edge weight assignment scheme, then we obtain the minimum of the sum-interference through solving the *Maximum/Minimum Weighted Matching* (MWM) problem in the BG. These two steps are described in the following.

3.5.1.1 Edge weight assignment

Based on the knowledge of the path loss and fading for each interference link on each RB_k, the eNB calculates the accurate interference power that will be associated to the weight of each edge. We define the weight of each edge, $w(e^l_{i,j})$, by the sum of the mutual interference power between two vertices expressed in (i) and (ii) as:

(i) *Interference caused by H2H mode on M2M mode:*

Considering the M2M mode as the primary mode; it represents the interference, $I_{(U_n,D^l_{m,r})}$, caused by U_n to $D^l_{m,r}$ on RB_k.

$$I^k_{(U_n,D^l_{m,r})} = P_n g^k_{U_n,D^l_{m,r}} \tag{3.7}$$

(ii) *Interference caused by M2M mode on H2H mode:*

Considering the H2H mode as the primary mode; it represents the interference, $I^k_{(D^l_{m,t},eNB)}$, caused by $D^l_{m,t}$ to eNB on RB_k.

$$I^k_{(D^l_{m,t},eNB)} = P^k_m g^k_{D^l_{m,t},eNB} \tag{3.8}$$

3.5.1.2 MWM Solving

A match of G is denoted by M^l for each cluster and is defined as follows:

- $M^l \subseteq E^l$
- If $e^l_{i,j} \in M^l \mid e^l_{i,y\neq j} \notin M^l \wedge e^l_{x\neq i,j} \notin M^l$

  For each MTH ($D^l_{m,r}$), we obtain a matching M^l (see Fig. 3.3 (b)). M^l consists of the subset of the edges in G where each pair of edges in U^l_m has no common ends.

  Given the following optimization function:

$$W^l = \sum_{e^l_{i,j} \in M^l} w_{e^l_{i,j}} \tag{3.9}$$

  the minimum weighted matching satisfies that:

$$W^l_{opt} = min \sum_{e^l_{i,j} \in M^l} w_{e^l_{i,j}}, l \in \mathcal{L} \tag{3.10}$$

$$W^l_{opt} = arg \min_{M^l} W^l \tag{3.11}$$

where $w(e^l_{i,j})$ is defined as $w(e^l_{i,j}) = Eq.3.7 + Eq.3.8$ in algorithm 1 which describes the MTC resource allocation process. We then use the *Kuhn Munkres* (KM) algorithm that has been proved to achieve MWM for BGs [52]. Here, the eNB acts as a scheduling operator and no MTD within its communication coverage is allowed to transmit before receiving its permission. MTDs periodically feedback current status report to the eNB via *Physical Uplink Shared Channel* (PUSCH). Such report information includes *Channel State Information* (CSI), *Signal-to-interference-plus-Noise-Ratio* (SINR) and so on. Having the total control of all D2D link activities, the eNB will send the information to the MTH via a common control channel (see algorithm 1).

3.5.2 Fixed semi-Distributed Radio Resource Sharing Algorithm

In contrast to the centralized radio resource sharing algorithm that requires to gather in a single point, the eNB, all the accurate channel information of the communication and interference links leading to a significant communication overhead, only the positions of MTDs belonging to its cluster are needed for each MTH (cluster head) in the Fixed semi-Distributed Radio Resource Sharing Algorithm (F-sD-RRSA) that are not greedy in terms of resources. The interference calculation is the key parameter to determine the scheduling operator, the eNB for the centralized MTC radio resource sharing approach and MTHs for the the semi-distributed radio resource sharing approach.

3.5.2.1 Edge weight assignment

A path loss model is used to compute the interference power without the need of the accurate channel information.

The interference is calculated as the sum of the following interferences defined in (i) and (ii) as:

(i) *Interference caused by H2H mode on M2M mode:*

Considering the M2M mode as the primary mode; it represents the interference caused by the U_n to the $D^l_{m,r}$.

$$I_{(U_n, D^l_{m,r})} = c(d_{U_n, D^l_{m,r}})^{-\alpha} P_n \tag{3.12}$$

(ii) *Interference caused by M2M mode on H2H mode:*

Considering the H2H mode as the primary mode; it represents the interference caused by $D^l_{m,t}$ to the eNB.

$$I_{(D^l_{m,t}, eNB)} = c(d_{D^l_{m,t}, eNB})^{-\alpha} P^k_m \tag{3.13}$$

Where $I_{(x,y)}$ means the interference power from x to y, $d_{x,y}$ denotes the distance between x and y nodes, c and α are a path loss constant and a path-loss exponent, respectively.

3.5.2.2 MWM Solving

Here, each MTH acts as a scheduling operator that collects the communication requests from MTDs of the same cluster, then announces the RB allocations to MTDs of the corresponding cluster by solving the MWM problem using the same

Algorithm 1: MTC resource allocation algorithm

```
Construct $G(U, E)$ according to $\mathcal{K}$, $\mathcal{M}$, $\mathcal{N}$, $\mathcal{L}$ and $\bar{\alpha}$
while $l \leq \mathcal{L}$ do
  for each vertex in $U_m^l$ connected to all vertices in $U_{n,k}$ do
    if Centralized MTC resource allocation approach then
      According to CSI of different links and $\bar{\alpha}$, the eNB computes the weight to be assigned to each edge as
      $w(e_{i,j}^l)$ = Eq. 3.7+ Eq. 3.8
    else if semi-Distributed MTC resource allocation approach then
      According to MTDs locations, UEs locations and $\bar{\alpha}$, MTH computes the weight to be assigned to each edge as
      $w(e_{i,j}^l)$ = Eq. 3.12 +Eq. 3.13
    end if
  end for
  Find the best matching using Kuhn Munkres algorithm to solve the MWM in Eq. 3.10
end while
```

method as in the centralized case as explained in Section 3.5.1.2 (see algorithm 1). In this case, $w(e_{i,j}^l)$ is defined as $w(e_{i,j}^l) = Eq.3.12 + Eq.3.13$.

3.5.3 Complexity analysis

The computational complexity of the proposed two-stage resource allocation approach is the sum of the complexity of both algorithms performed in each stage. In the first phase, the complexity of the H2H resource allocation depends on the algorithm used. On one hand, the PF algorithm assigns each RB after performing a linear search on the users in order to maximize a given utility function. Hence, the total complexity of the PF algorithm is approximated to $\mathcal{O}(N^2K)$. On the other hand, the RR algorithm assigns randomly a RB to a UE. Thus, the computational complexity of the RR algorithm is $\mathcal{O}(1)$. In the second stage, the computational complexity of the *Kuhn Munkres* algorithm applied for each MTH to solve the resource sharing problem is $\mathcal{O}(LN^3)$ which is polynomial [53]. Thus, the total computational complexity of the two-stage resource allocation is $(O(N^2K) + O(LN^3))$ and $(O(1) + O(LN^3))$ when the PF and RR algorithm are used in the first stage, respectively. Consequently, the total computational complexity of the two-stage resource allocation approach is of polynomial complexity, achieving a lower computational cost compared to the optimal method formulated in Section 3.4.2.

3.6 Performance evaluation

In order to evaluate the performance of the proposed radio resource sharing algorithm along with both instantiations, we consider an isolated cell, where H2H communications and MTC within D2D communications coexist and share the

RBs for their data transmission. The UEs are distributed randomly within the network. MTDs are grouped into clusters, where there is one MTH per cluster. For demonstration purpose, the total number of MTDs per group is assumed to be the same. The detailed simulation parameters are given in table 3.3. We consider the LTE-A bandwidth set to 20 MHz. Thus, there is a total of 100 RBs to be shared between MTC and H2H communication links in each TTI. The network performance in terms of sum-rate is evaluated in a scheduling period of 10 TTI. The simulation results are obtained through averaging over 100 different realizations using MATLAB as the simulation platform. For simplicity, we suppose that the proposed Fixed Radio Resource Sharing Algorithm (F-RRSA) along with both instantiations: centralized (F-C-RRSA) and semi-distributed (F-sD-RRSA) are executed under the same conditions. Thus, the *Round Robin* (*RR*) resource allocation algorithm is used to assign radio resources for UEs in the first phase, where we suppose that all UEs are served during a scheduling period.

Table 3.3 – Simulation parameters

Parameter	**Value**
Cellular layout	Isolated cell
Cell radius	250 m
Mobility	Static scenario
Cluster radius	50 m
UEs per cell	N = 100
MTDs per cluster	M =70
Path loss model	UMi in [80]
UE transmit power P_n	24 dBm
MTD transmit power P_m	15 dBm
Noise power spectrum density	-174 dBm/Hz
Carrier frequency	2.5 GHz
Small scale fading	Rayleigh fading coefficient with zero mean and unit variance
Channel bandwidth	W= 20 MHz

3.6.1 Average network sum-rate

Fig 3.4 shows the average network sum-rate versus the total number of users when using only one cluster of MTDs. We compare the two proposed instantiations of the fixed radio resource sharing algorithm for MTC, centralized (F-C-RRSA) and semi-distributed (F-sD-RRSA). These algorithms are also compared to the case where a random M2M radio resource sharing algorithm is used, as a baseline algorithm. In a random M2M radio resource sharing approach, MTDs are

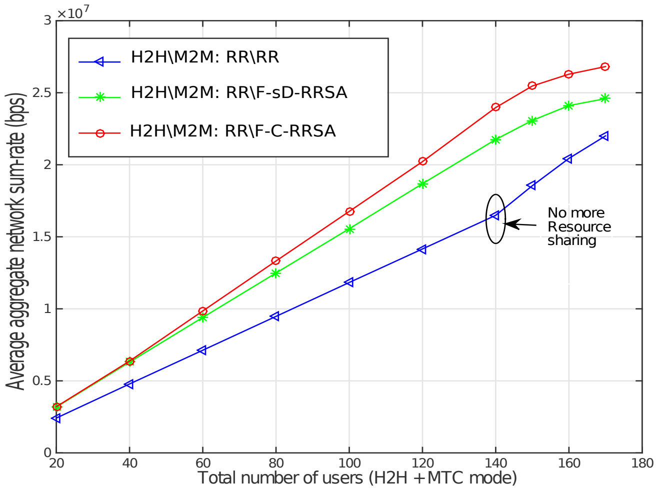


Figure 3.4 – Average network sum-rate (MTC + H2H mode)

scheduled according to a fixed pattern by assigning MTDs radio resources one after another without taking into account the channel quality information. We see that the worst average network sum-rate is obtained for the random M2M radio resource sharing algorithm. Indeed, RBs are allocated uniformly without considering any interference management mechanism. We also notice that the slope of the average network sum-rate for the random M2M radio resource sharing algorithm slightly increases above 140 users since there is no more resource sharing (M MTDs have been served). We observe that the F-C-RRSA instantiation achieves approximately a gain of 15% over the F-sD-RRSA instantiation. However, the proposed F-sD-RRSA has lower communication overhead.

3.6.2 Average H2H sum-rate

Fig 3.5 illustrates the average H2H sum-rate versus the number of H2H users (UEs) when introducing one cluster of MTDs. We aim to focus on the impact of introducing MTC on H2H performance when sharing the spectrum. The best performance is obtained when the RBs are not shared with MTDs. Indeed, there is no interference in an exclusive H2H case since radio resources are not shared. As expected, we see that the worst performance is obtained when using the random M2M radio resource sharing algorithm. For instance, below 70 users (M = 70), the H2H sum-rate dramatically decreases. We observe that F-sD-RRSA and the random M2M radio resource sharing algorithms achieve similar performance when all the RBs are used. Indeed, both methods do not rely on the condition of the links, even though the F-sD-RRSA has shown better performance. In addition, we clearly see that the F-C-RRSA achieves better performance than the F-sD-RRSA since the F-C-RRSA considers the accurate interference information

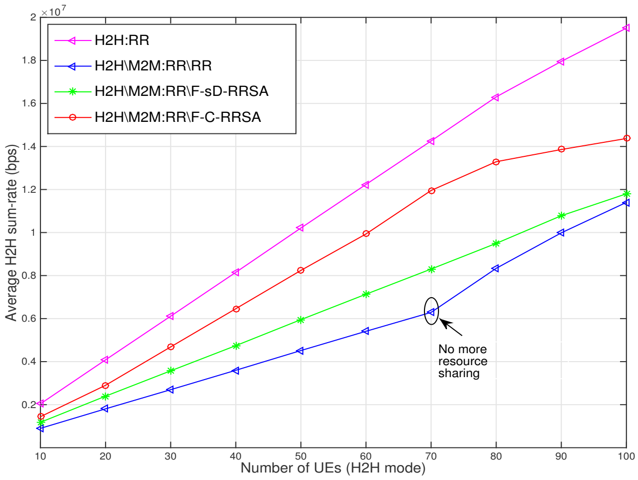


Figure 3.5 – Impact of MTC on average H2H sum-rate (H2H mode)

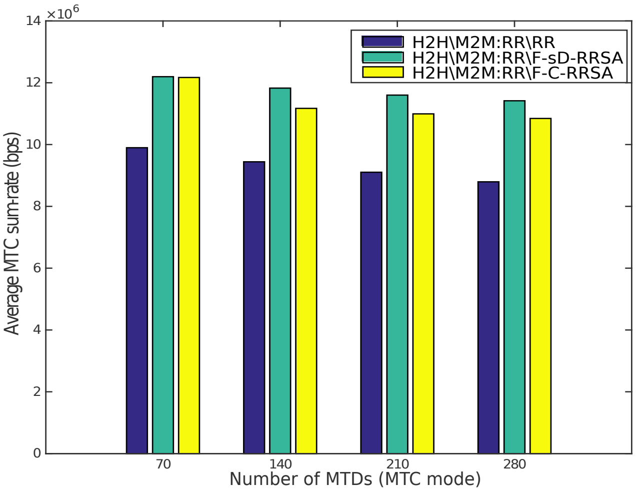


Figure 3.6 – Average MTD sum-rate of one cluster when varying the number of introduced clusters (MTC mode)

on each RB_k. However, the F-C-RRSA has higher communication overhead than the F-sD-RRSA algorithm.

3.6.3 Impact of the inter-cluster interference

In order to justify why the inter-cluster interference has not been considered in the weight allocation process, we plot in Fig. 3.6 the average MTC sum-rate for a number of MTDs ($M = 70$) when only one cluster is used and the impact of introducing different clusters on the obtained average MTC sum-rate of the reference cluster. The positions of different clusters are generated randomly and the results are obtained through averaging over 100 realizations. Compared to the M2M random resource sharing algorithm, both F-C-RRSA and F-sD-RRSA instantiations achieve better performance in terms of average MTC sum-rate. The worst case is obtained when using the random M2M radio resource sharing algorithm since RBs are assigned randomly to MTDs. As we expected, the higher is the number of clusters introduced, the lower is the average MTC sum-rate of the reference cluster. This result is quite reasonable since more MTDs are sharing the same spectrum. Moreover, this result shows that the inter-cluster interference is negligible. For instance, for a number of 70 $MTDs$, the sum-rate difference is about 1 mbps between the case where only one cluster is used ($M = 70$) and the case where 3 clusters ($L \cdot M = 3 \cdot 70 + 70 = 280$ $MTDs$) are emerged. On the other hand, we notice that contrarily to the average network sum-rate and the average H2H sum-rate where the F-C-RRSA has been proved to achieve better performance compared to the F-sD-RRSA, this latter reaches slightly better performance in terms of MTC sum-rate compared to the F-C-RRSA which is quite surprising. However, by analyzing in detail what happens, this can be explained by the resource allocation process based on the mutual interference (interference from H2H to M2M and the interference from M2M to H2H). Indeed, the interference introduced by H2H communications is higher due to its high transmit power.

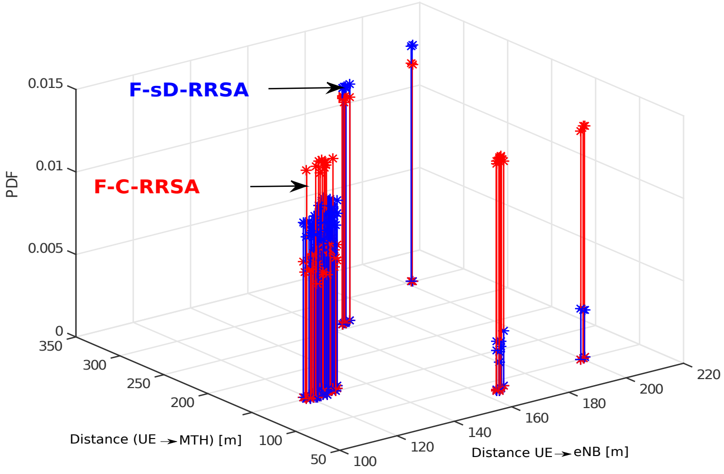


Figure 3.7 – Probability density function (PDF) of the distance of selected UEs respectively to their eNB and MTH

3.6.4 Potential H2H users selected for resource sharing

Fig. 3.7 represents the *Probability Density Function* (PDF) of the distance of selected UEs sharing the spectrum respectively to eNB and MTH. For the proposed F-sD-RRSA, we observe that the density of UEs sharing the spectrum increases the farther they are from the eNB and MTH. This result can be explained by the mutual interference weight allocation process that has been computed based on distances. However, we can notice that the density of UEs sharing the spectrum in the proposed F-C-RRSA is fairly distributed. Indeed, the resource allocation process in the F-C-RRSA is based on the accurate channel quality of the links and not on distances.

3.7 Conclusions

In this chapter, we have addressed the coexistence issue between M2M communications, as an emerging revolution that can change radically human lives, and incumbent H2H communications. Different from traditional H2H applications, M2M services have their own specific features such as small data transmission, extra low power consumption and centralized data collection. Another distinguishing characteristic remains the high penetration of MTDs. Consequently, new challenges are posed to the cellular network. Indeed, both the network efficiency as well as the scalability can be severely affected.

To face these challenges, we have first designed a spectrally efficient M2M system architecture. We have considered group-based MTC using underlay D2D. Indeed, group-based communications is a promising solution to alleviate the air interface overload and using particularly underlay D2D is a convenient way to increase the spectrum efficiency. In a second step, we have formulated the radio resource sharing problem, where both H2H and M2M communications coexist and are allowed to access the same radio resources, as a sum-rate optimization problem. However, the computational complexity to solve the underlying optimal resource sharing problem is NP-hard. Convinced by the strength of the graph theory and in order to reduce the high computational complexity of the optimal solution, we have modeled the radio resource sharing problem in a H2H/M2M coexistence scenario as a bipartite graph and considered a two-stage radio resource allocation approach giving higher priority to H2H communications. Then, we have developed an interference-aware graph-based resource sharing algorithm aiming to re-assign MTDs one of the available radio resources already assigned to H2H users assuming a fixed M2M transmit power. In addition, we have proposed a centralized and a semi-distributed instantiations of this algorithm. The latter instantiation aims at reducing the high communication overhead of the proposed centralized M2M radio resource sharing instantiation.

Our evaluation study has shown that the proposed Fixed semi-Distributed Radio Resource Sharing Algorithm (F-sD-RRSA) achieves a good trade-off between the network performance and the network overhead compared to the Fixed Centralized Radio Resource Sharing Algorithm (F-C-RRSA), and also achieves significantly better performance compared to the random M2M radio resource sharing approach. In addition, we have evaluated the inter-cluster interference and have shown that this one remains marginal.

This work has been carried out in order to jointly consider the scalability issue and the design of a low-computational complexity radio resource sharing scheme in a H2H/M2M coexistence scenario. Nevertheless, the proposed M2M system architecture should not only be spectrally efficient but also power efficient. Thus, we aim to empower the proposed algorithm with power control mechanisms for a successful proliferation of M2M applications again without sacrificing existing H2H applications. In addition, we have considered a static scenario (i.e. no mobility) and have used only one example of a radio resource allocation algorithm for H2H communications, namely Round Robin (RR). Evaluating the impact of introducing M2M communications on the performance of H2H services when using only one H2H scheduling algorithm is not sufficient and a static scenario as well is not considered to be real. All these issues are addressed in the next chapter.

- Chapter 4 -

Adaptive Graph-Based radio resource sharing scheme for M2M communications

Contents

4.1 Foreword

With the massive emergence of M2M communications into cellular networks, the performance of H2H communications will be affected severely. In the previous chapter, we have proposed an interference-aware graph-based radio resource sharing scheme in a H2H/M2M coexistence scenario with a low-computational complexity. However, our main concern has been to minimize the mutual interference between M2M devices and H2H users when sharing the spectrum without considering any QoS guarantees. Indeed, the M2M transmit has been set to a fixed value. In addition, the M2M impact on H2H services has been evaluated in terms of throughput when only one radio resource allocation algorithm for H2H links, in particular Round Robin (RR), was used and when considering a static scenario.

To further counteract the degradation of H2H services due to the M2M spectrum sharing, we aim to introduce in this chapter a novel adaptive power control feature into the interference-aware graph-based resource sharing algorithm. This feature uses one of two alternative mechanisms, namely, the *Proportional Integral Derivative* (PID) controller and the fuzzy logic controller.

To that end, we introduce the context of this work in Section 4.2, followed by the related works in Section 4.3. An overview of the two major controllers in the control field: PID and fuzzy logic controllers is presented in Section 4.4 . The scenario under study is described in Section 4.5. In Section 4.6, the fixed radio resource sharing is presented. The adaptive radio resource sharing scheme using PID is proposed in Section 4.7 while the adaptive radio resource sharing scheme using fuzzy logic is developed in Section 4.8. The performance evaluation of our proposal is drawn in Section 4.9, followed by the conclusion in Section 4.10.

4.2 Context and motivation

To efficiently support massive M2M services over LTE-Advanced cellular networks, novel radio resource allocation schemes that tackle both spectrum scarcity and energy efficiency are required. Underlay D2D has been considered as a promising paradigm that allows to increase the spectrum efficiency, since the same spectrum can be shared between H2H and M2M communications. Furthermore, adopting a group-based M2M operation through D2D technology offloads significantly the BS. Meanwhile, the interference between H2H and M2M links under such a coexistence scenario becomes a critical issue. Emerging M2M services must have little or no impact on existing H2H services.

Convinced by the strength of the bipartite graph tool to model the resource sharing problem, we aim to empower the proposed graph-based radio resource sharing algorithm in the previous chapter with a novel power control feature. Our goal is to guarantee the desired QoS of H2H links as well as to maximize the efficiency of the shared spectrum usage though efficiently adjusting the M2M transmit power. Consequently, we introduce and express the service requirements in terms of achievable throughput which is a more accurate approach to the calculation of the channel capacity compared to the Shannon capacity. The achievable throughput is based on channel properties as well as the symbol constellations. The power control feature uses one of two alternative mechanisms: the PID controller as the controller used in most automatic process control applications in industry and the fuzzy logic as a versatile tool that proposes a simpler language using linguistic information.

We consider a mobile scenario and conduct an extensive simulation study to evaluate the impact, in terms of throughput and fairness, of the different proposed graph-based radio resource sharing schemes (fixed and adaptive) on H2H services for UEs when these latter have been assigned radio resources using two well known traditional scheduling algorithms for H2H communications, Round Robin (RR) and Proportional Fairness (PF).

4.3 Related works

M2M devices have stringent battery power constraints. Therefore, optimizing the power saving mechanisms is among the primary requirements. Considerable work in the last decade has been conducted in order to save the energy of MTDs and IoT devices, and thus extend their battery life. With this aim, different methods have been proposed, which we can divide into three major classes, namely: *Discontinuous Reception*, energy-efficient MTC scheduling and group-based MTC.

4.3.1 Discontinuous reception

In LTE standards, *Discontinuous Reception* (DRX) has been specified as an energy saving method that enables an equipment (a UE or a MTD) to turn off its wireless receiver and enter a low power state [37]. Several values defining the length of a DRX cycle have been proposed in the LTE standard where the maximum has been fixed to 2560 ms. However, to achieve an efficient power saving for MTC, there is a need to improve the operation of DRX. Indeed, few technical reports have investigated the possibility of extending the DRX cycle length in order to accommodate the specific requirements of MTC [30, 86, 31]. The extended DRX (eDRX) can be up to 43.69 minutes. Authors in [89] have addressed possible energy consumption gains for M2M devices when using long DRX cycles. They have shown that longer DRX cycles would significantly reduce the power consumption of M2M devices. The configuration of a DRX cycle is a tradeoff between latency and power consumption. On one hand, a long DRX period enables extended device battery life. On the other hand, a short DRX enables a faster response. Thus, authors in [21] have investigated the optimal length of an eDRX cycle for M2M communications to mitigate the signaling cost for the networks under the latency constraint.

4.3.2 Energy-efficient resource allocation for MTC

Studies that focus on energy-efficient resource allocation schemes for MTC when considering a H2H/M2M coexistence scenario have gained much momentum. For example, authors in [7] have considered a SC-FDMA uplink system in a

H2H/M2M coexistence scenario as M2M devices generate principally uplink traffic. A radio resource allocation algorithm has been proposed with the objective to minimize the total transmit power while satisfying the service requirements of all users. Two heuristic algorithms have been proposed. The power minimization in the first algorithm has been conducted for both UEs and MTDs. However, in the second algorithm, the power minimization has been conducted for UEs only. In [15], the uplink scheduling and power control have been investigated to maximize the lifetime of cellular-based M2M networks. However, the formulated optimal solutions involve significant computational complexity. In addition, traditional H2H users have higher priority which motivate us to consider that MTDs should be those that need to adapt their transmit power to ensure H2H services.

4.3.3 Group-based MTC

Considering a direct communication between MTDs and the BS, a network congestion cannot be avoided specifically in case of a large number of deployed MTDs sending requests simultaneously to the BS. Consequently, a group-based M2M communications has been considered as a promising solution to offload the eNB. In addition to the eNB offloading, authors in [14, 13] have shown that adopting a group-based operation can significantly extend the lifetime of the M2M network. We can envision two major scenarios for group-based MTC: group-based MTC through gateways and group-based MTC using D2D technology. Group-based MTC can be achieved through gateway deployment. In such case, a MTC Gateway (MTG) is required. This latter is an equipment that ensures the interconnection of MTDs to the network. Considering an uplink scenario, the role of a MTG is to gather requests, uplink data packets and status information from MTDs in its group, and then forward such traffic to the eNB [22]. Consequently, MTDs are directly connected to the MTG and thus indirectly connected to the eNB. The end-to-end communication between a MTD and an eNB is a multi-hop communication between **(i)** MTDs and MTG and **(ii)** MTG and the eNB. On one hand, the local connectivity between a MTD and the MTG can be assured through either 3G LTE specifications or through capillary network such as short-range radio access technologies. On the other hand, the MTG to eNB wireless link is based mainly on 3G LTE specifications [99]. Several works have focused on the deployment scenarios for gateways. For instance, authors in [60] have shown that the optimal number of gateways in a smart grid M2M network can be achieved by maximizing the ratio of network lifetime to cost, i.e. the tradeoff between the network lifetime and the deployment cost. A group-based MTC can also be achieved using D2D technology, where a direct communication between MTDs and a *Machine-Type-Head* (MTH) can occur using underlay D2D, as explained in the previous chapter. Therefore, new radio resource allocation methods for D2D communications should be developed to mitigate the co-channel interference due to the orthogonality loss. This can be achieved through adequate power control. For instance, authors in [64] have proposed an interference limited area to prevent cellular user equipments located in a calculated area from re-using radio resources assigned to D2D users. In [93], authors have empowered the BS the ability to control the maximum D2D transmit power in order to manage the D2D interference. The transmitter of the cellular flow, within a D2D flow transmits concurrently, must increase its transmit power to compensate for the interference created by the D2D flow. However, in a H2H/M2M coexistence scenario, traditional H2H users have higher priority which explains our motivation to make MTDs using D2D links being those that need to adapt their transmit power in order to ensure H2H services.

In this chapter and differently from the cited works, we consider a group-based M2M operation using D2D links and propose a novel adaptive power control feature that we integrate into our proposed interference-aware graph-based resource sharing algorithm. We aim to efficiently adjust the M2M transmit power and the reason is twofold: **(i)** further guarantee H2H services and **(ii)** maximize the efficiency of the spectrum usage.

4.4 Overview of PID and Fuzzy logic controllers

Both controllers, *Proportional Integral Derivative* (PID) and fuzzy logic, are widely used in the control field to solve many problems in different application areas varying from leveling the security services in wireless sensor networks, controlling the flow in packet networks, controlling the congestion problem or managing the radio resources [76, 51, 50, 26]. PID controllers are the most commonly used controllers in automatic process control applications to regulate flow, temperature, pressure, and many other industrial process variables for over 50 years and require a rigorous mathematical knowledge of the system. Different from the PID controllers, fuzzy logic is a versatile tool that proposes a simpler language using linguistic information and thus is easier and cheaper to implement. Fuzzy logic has prominent applications in almost every field where mathematical tools are not the best conceptual system for dealing with the imprecision of the real world. We are motivated here to use one among the two controllers to efficiently adjust the M2M transmit power in order to avoid the interference situations in a H2H/M2M coexistence scenario.

4.4.1 PID controller

The PID controller is a well-known feedback controller that stands for proportional integral derivative. The basic concept of a feedback controller is to keep a measured process variable close to a desired value despite of the variation of process dynamics. Fig. 4.1 illustrates the PID feedback control system. The error signal $e(k)$ is the input of the PID controller that represents the difference between the measured process variable Q_k and a reference value Q_{ref}. The PID controller in turns gives as output the control variable u_k. A PID controller has three types of control actions:

- **Proportional to the error (*P* part)**: The P part is proportional to the current error. Thus, it reacts immediately to the sensed error. The proportional controller works on the information of present time.
- **Proportional to the integral of the error (*I* part)**: The integral controller integrates the history of the error. The I controller is thus made much slower than the P controller.
- **Proportional to the derivative of the error (*D* part)**: The derivative controller tries to predict the immediate future and then makes corrections based on the estimated error. It is faster than the P or I controller.

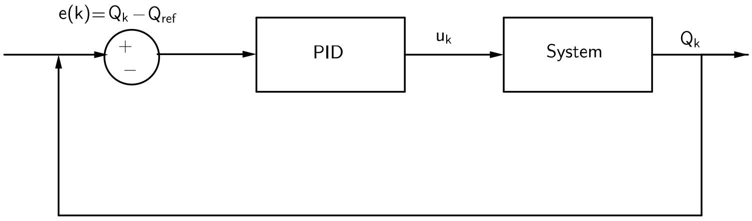


Figure 4.1 – The PID-controller based system

These three parameters can be used separately or in a combination [62].

4.4.2 Fuzzy Logic

Fuzzy logic is another mathematical tool in the control field. This one exploits a linguistic model of the process to be controlled [27]. Unlike conventional methods (PID controller, for instance) that rely on a quantitative and precise data value and then apply a mathematical tool to generate a specific output, fuzzy theory deals with imprecision and is easier to prototype and implement. Thus, fuzzy logic is more appropriate when a mathematical model of the process cannot be defined or it is too complex to be evaluated in real time. The fuzzy logic decision making process is composed of three consecutive steps as illustrated in Fig. 4.2:

- **Fuzzification:** The input variables are fuzzified using predefined *Membership Functions* (MBFs). MBFs are a set of fuzzy regions that define the control variables in the fuzzy model. More precisely, an MBF represents a function that specifies the degree to which a given input belongs to a set. Unique names known as labels are given to these regions, within the domain of the variable. The above MBF: $X \rightarrow \{0,1\}$ assigns every control variable, x ∈ X numbers from 0 and 1 unlike in the binary logic where only a value from two-element set $\{0, 1\}$ is assigned. That is why it is called fuzzification.

- **Fuzzy inference system** (based on a set of fuzzy control rules): Fuzzy numbers or input variables are fed into a predefined fuzzy control rules which tie input values to output model properties and are written with an IF-THEN clauses syntax. These rules represent the core of the inference system.
- **Defuzzification:** The output of the fuzzy set is converted into a crisp value. The defuzzification can be performed in several ways. The most popular method is the centroid, where the center of area of the fuzzy set is determined and the value at which this occurs is used as the defuzzified output.

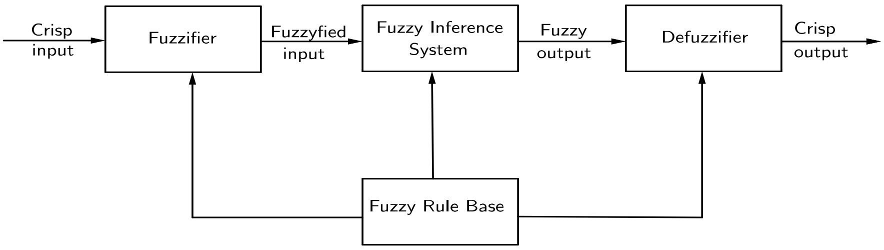


Figure 4.2 – A fuzzy system

While the PID controller is applied when there is a mathematical knowledge of the system to be controlled, the fuzzy logic is more oriented to human understanding based knowledge converted into computer based decision making. The computational simplicity of the fuzzy logic is seen as a strength in embedded systems. We are motivated in this chapter to use and thus compare both tools, PID and fuzzy logic controllers, for designing an efficient power control strategy with the aim to protect H2H services and maximize the M2M efficiency in spectrum usage.

4.5 System description

We focus on the uplink scenario of a single cellular network where both H2H and M2M communication links coexist, as illustrated in Fig. 3.2. In the previous chapter, we have proposed a two-stage resource allocation approach, where radio resources, RBs, have been assigned to traditional H2H users in a first step using conventional scheduling algorithms, then a fixed interference-aware graph-based resource sharing algorithm for MTC in conjunction with two instantiations, centralized and semi-distributed, have been developed in the next step. Convinced by the strength of the bipartite graph modeling (see Fig. 3.3), our objective here is to integrate a novel power control feature into our proposed fixed interference-aware graph-based radio resource sharing scheme for MTC in a H2H/M2M coexistence scenario. This feature uses one among two alternative mechanisms presented in Section 4.4. Thus, the first mechanism uses the PID controller while the second one uses the fuzzy logic controller. Specifically, we focus on adjusting the M2M transmit power while (i) guaranteeing the H2H service requirements and (ii) maximizing the efficiency of the M2M spectrum usage. Within this aim, we express the service requirements in terms of throughput. Thus, we introduce two constraints in Eq. 4.1 and Eq. 4.2 to represent the minimum required throughput of a UE, $n \in \mathcal{N}$, and a M2M device, $m \in \mathcal{M}$, respectively as follows:

$$R_{U_n}^{k} \geq R_{U_n}^{min} \tag{4.1}$$

$$R_{D_{m,t \to r}^{l}}^{k} \geq R_{D_{m,t \to r}^{l}}^{min} \tag{4.2}$$

Shannon evaluates the capacity of a Gaussian propagation channel as a function of the *Signal-to-Interference-plus-Noise Ratio* (SINR) and its bandwidth [81]. The Shannon capacity is defined by the maximum rate at which the information can be transmitted over a communication channel while ensuring error-free transmission.

The Shannon capacity (in bits per second) for the UE, $R_{U_n}^{k}$, on resource block RB_k with $n \in \mathcal{N}$ and $k \in \mathcal{K}$ is given by:

$$R_{U_n}^{k} = W.log_2(1 + \frac{P_n g_{U_n}^{k}}{\sum\limits_{l \in L} \sum\limits_{m \in M} I_{(D_{m,t}^{l}, eNB)}^{k} + \sigma^2}) \tag{4.3}$$

where the first term in the denominator represents the interference from MTDs of different clusters to the eNB, while the second term represents the variance of thermal noise, denoted by σ^2 and modeled as an independent Gaussian distribution with zero mean. W is the channel bandwidth and P_n is the transmit power of a UE n that is fixed.

We evaluate the Shannon capacity of M2M pair $D_{m,t \to r}^{l}$, with $m \in \mathcal{M}$ and $k \in \mathcal{K}$ as:

$$R_{D_{m,t \to r}^{l}}^{k} = W.log_2(1 + \frac{P_m^k g_{D_{m,t}^{l}, D_{m,r}^{l}}^{k}}{\sum\limits_{n \in N} I_{(U_n, D_{m,r}^{l})}^{k} + \sum\limits_{l' \in L, l \neq l'} \sum\limits_{m \in M} I_{(D_{m,t}^{l'}, D_{m,r}^{l})}^{k} + \sigma^2}) \tag{4.4}$$

where the first term in the denominator represents the interference from UEs to the MTH ($D_{m,r}^{l} \in C_l$, $l \in \mathcal{L}$), while the second term represents the inter-cluster interference. This latter represents the interference generated from MTDs of different clusters to the MTH when sharing the radio resource, RB_k. P_m^k is the transmit power of a MTD m that is adaptive. Throughout this chapter, we assume that the inter-cluster or inter-D2D interference is negligible due to the relatively low transmit power of MTDs.

Shannon capacity of a communication channel is the theoretical maximum information transfer rate of the channel. Thus, we consider in the simulation the useful throughput. This throughput is always less than the maximum capacity of the channel since it is theoretically impossible to ensure an error-free communication. An evaluation of the channel capacity based on channel properties as well as the symbol constellations is a much more accurate approach to the calculation of the channel capacity. In case of a linear modulation with a constellation of M complex symbols (a_0, a_1, ..., a_{M-1}) emitted in an equiprobable manner, the formula of the achievable throughput becomes [45]:

$$R^k = \eta(M^k).W \tag{4.5}$$

$$\eta(M^k) = \mathbb{E}_{\mathbb{H}}\left(\log_2(M) - \frac{1}{M}\sum_{i=0}^{M-1}\mathbb{E}_{\mathbb{N}}\left(\log_2\sum_{j=0}^{M-1}\exp\left(-\frac{\mid P^k.h^k.a_i - P^k.h^k.a_j + n^k \mid^2 - \mid n^k \mid^2}{\sigma^2 + I^k_{(x,y)}}\right)\right)\right) \tag{4.6}$$

where η is the spectral efficiency and n denotes an additive Gaussian noise that varies according to a zero mean complex Gaussian distribution with a variance $(\sigma^2 + I^k_{(x,y)})$. h is the coefficient of a Rayleigh fading channel and the symbol $\mathbb{E}$ designates the mathematical expectation. The interference power on RB_k, $I^k_{(x,y)}$, is replaced with $I^k_{(D^l_{m,t},eNB)}$ and $I^k_{(U_n,D^l_{m,r})}$ if we are interested to calculate the evaluated throughput $R^k_{U_n}$ and $R^k_{D^l_{m,t\to r}}$, respectively. P^k is the transmit power on RB_k and is replaced with P_n and P^k_m if we are interested to calculate the evaluated throughput $R^k_{U_n}$ and $R^k_{D^l_{m,t\to r}}$, respectively.

4.6 Fixed Radio Resource Sharing Algorithm

For a comparison purpose with the adaptive radio resource sharing algorithm that we introduce in the next Section, we describe here the Fixed Radio Resource Sharing Algorithm (F-RRSA). Indeed, the MTD transmit power is set to a fixed value in F-RRSA contrarily to the adaptive radio resource sharing algorithm. F-RRSA, similarly to the previous chapter, is composed of two steps. In a first step, we establish a proper edge weight assignment scheme, then we obtain the maximum sum-throughput through solving the *Maximum/Minimum Weighted Matching* (MWM) problem in BG. These two steps are described in the following. In contrast to the previous chapter where the edge weight assignment process in the first stage of F-RRSA is calculated based on interference, we consider here the achievable throughput in the edge weight assignment process. Consequently, the maximum weighted matching is performed here in the second stage rather than the minimum weighted matching used in the previous chapter. We consider two instantiations for the proposed F-RRSA: centralized (F-C-RRSA) and semi-Distributed (F-sD-RRSA). The difference between the centralized and the semi-distributed instantiations remains in the interference calculation as explained in the previous chapter.

4.6.1 Edge weight assignment

Similarly to the previous chapter, we assume in a centralized approach that the path loss and fading for potential interference links on each RB_k are well known. In this case, the eNB calculates the sum-throughput that will be associated to the weight of each edge. Consequently, the interference power caused by M2M mode on H2H mode $I^k_{(D^l_{m,t},eNB)}$ in Eq. 4.3 is replaced by Eq. 3.8. In addition, the interference power caused by H2H mode on M2M mode, $I^k_{(U_n,D^l_{m,r})}$, in Eq. 4.4 is replaced by Eq. 3.7.

If we consider a semi-distributed approach, a path loss model is used to compute the interference power without the need of accurate interference channel informations. In this case, each MTH calculates the sum-throughput that will be associated to the weight of each edge. The value of this latter is the sum of the throughput of both H2H and M2M links expressed respectively in Eq. 4.3 and Eq. 4.4. The interference identified in Eq. 4.3, $I^k_{(D^l_{m,t},eNB)}$, is replaced by Eq. 3.13 while the interference $I^k_{(U_n,D^l_{m,r})}$ identified in Eq. 4.4 is replaced by Eq. 3.12 (see algorithm 2).

4.6.2 MWM Solving

A match of G is denoted by M^l for each cluster and is defined as follows:

- $M^l \subseteq E^l$
- If $e^l_{i,j} \in M^l \mid e^l_{i,y\neq j} \notin M^l \wedge e^l_{x\neq i,j} \notin M^l$

  For each MTH ($D^l_{m,r}$), we obtain a matching M^l. M^l consists of the subset of the edges in G where each pair of edges in U^l_m has no common ends.

  Given the following optimization function:

$$W^l = \sum_{e^l_{i,j} \in M^l} w_{e^l_{i,j}} \tag{4.7}$$

  the maximum weighted matching satisfies that:

$$W^l_{opt} = max \sum_{e^l_{i,j} \in M^l} w_{e^l_{i,j}}, l \in \mathcal{L} \tag{4.8}$$

Algorithm 2: MTC resource allocation algorithm

```
Construct $G(U,E)$ according to $\mathcal{K}$, $\mathcal{M}$, $\mathcal{N}$, $\mathcal{L}$ and $\bar{\alpha}$
while $l \leq \mathcal{L}$ do
  for each vertex in $U_m^l$ connected to all vertices in $U_{n,k}$ do
    if Centralized MTC resource allocation approach then
      According to CSI of different links and $\bar{\alpha}$, the eNB computes the weight to be
      assigned to each edge as
      $w(e_{i,j}^l)$ = Eq. 4.3 + Eq. 4.4
      with $I^k_{(D^l_{m,t},eNB)}$ in Eq. 4.3 and $I^k_{(U_n,D^l_{m,r})}$ in Eq. 4.4 are replaced by Eq. 3.8 and
      Eq. 3.7, respectively
    else if semi-Distributed MTC resource allocation approach then
      According to MTDs locations, and $\bar{\alpha}$, MTH computes the weight to be assigned
      to each edge as
      $w(e_{i,j}^l)$ = Eq. 4.3 + Eq. 4.4
      with $I^k_{(D^l_{m,t},eNB)}$ in Eq. 4.3 and $I^k_{(U_n,D^l_{m,r})}$ in Eq. 4.4 are replaced by Eq. 3.13 and
      Eq. 3.12, respectively
    end if
  end for
  Find the best matching using Kuhn Munkres (KM) algorithm to solve the MWM in
  Eq. 4.8
end while
```

where $w(e_{i,j}^l)$ is defined as $w(e_{i,j}^l) = Eq.4.3 + Eq.4.4$ as explained in algorithm 2 that describes the MTC resource allocation process.

$$W^l_{opt} = arg \max_{M^l} W^l \tag{4.9}$$

We then use the *Kuhn Munkres* (KM) algorithm that has been proved to achieve MWM for BGs [52].

4.7 Adaptive Radio Resource Sharing Algorithm using PID controller

In this Section, we propose to integrate into the fixed radio resource sharing algorithm a novel power control mechanism that uses the PID controller. The basic idea behind this integration is to efficiently adjust the M2M transmit power in order to protect the QoS of H2H users. Thus, the MTD transmit power in the Adaptive Radio Resource Sharing Algorithm using PID controller (A-RRSA-PID) is adaptive contrarily to the F-RRSA where the MTD transmit power is fixed. More precisely, we prioritize H2H users by driving MTDs to adjust their transmit power in order to protect H2H services. The primary goal is to drive the actual UE throughput, $R^k_{U_n}$, obtained in a H2H/M2M case to converge to its corresponding required QoS in terms of throughput, $R_{U_n}^{min}$. By properly adjusting the MTD transmit power, the QoS of H2H users is assured and the efficiency of the M2M spectrum usage is maximized. The PID controller takes as input the error signal *e(k)* that should be related to the MTD transmit power $P_m^k(k)$. Particularly, *e(k)* represents the gap between the current MTD transmit power and the maximum MTD transmit power. This latter is determined given the UE's interference threshold that assure the desired QoS of the UE, $R_{U_n}^{min}$. The PID controller gives as output the power control ratio, *u(k)*, determined by a weighted sum as follows:

$$\begin{aligned} u(k) = u(k-1) + k_p\Big(1 + \frac{T}{T_i} + k_p\frac{T_d}{T}\Big)e(k) \\ -k_p\Big(1 + 2\frac{T_d}{T}\Big)e(k-1) + k_p\frac{T_d}{T}e(k-2) \end{aligned} \tag{4.10}$$

where T and e(k) denote the sampling period and the error signal at the k^{th} sampling period, respectively. The parameters T_i and T_d depend on the proportional gain k_p, the integral gain k_i, and the derivative gain k_d. There are equal to (kp/ki) and (kd/kp), respectively.

In each scheduling period (TTI), the new MTD transmit power is determined by multiplying the actual MTD transmit power and the power control ratio R_{pc} derived from the output of the PID system. The transmit power control ratio of the MTD with $m \in \mathcal{M}$, is defined as:

$$R_{pc}^k = \frac{(P_m^k)^{new}}{(P_m^k)^{actual}} \tag{4.11}$$

where $(P_m^k)^{new}$ is the new transmit power and $(P_m^k)^{actual}$ is the actual transmit power of MTD on RB_k. R_{pc}^k is expressed as follows in dB domain:

$$R_{pc}^k(dB) = 10.log10\frac{(P_m^k)^{new}}{(P_m^k)^{actual}} = (P_m^k)^{new}(dBm) - (P_m^k)^{actual}(dBm) \tag{4.12}$$

Therefore, by applying the PID controller, the transmit power is limited to assure the desired QoS of H2H users and also to maximize the efficiency of MTC spectrum usage. Having properly adjusted the transmit power using the PID controller, we implement the result of the power control process in the edge weight assignment phase and solve the MWM problem. The flowchart of the adaptive radio resource sharing algorithm is illustrated in Fig. 4.3. Having the current MTD transmit power and the maximum allowed MTD transmit power, the PID controller gives as output the power control ratio. Thus, the new MTD transmit power is determined from the power control ratio and used in the edge weight assignment process in algorithm 2 rather than using a fixed MTD transmit power as in F-RRSA. Finally the best matching is achieved through solving the MWM of the BG.

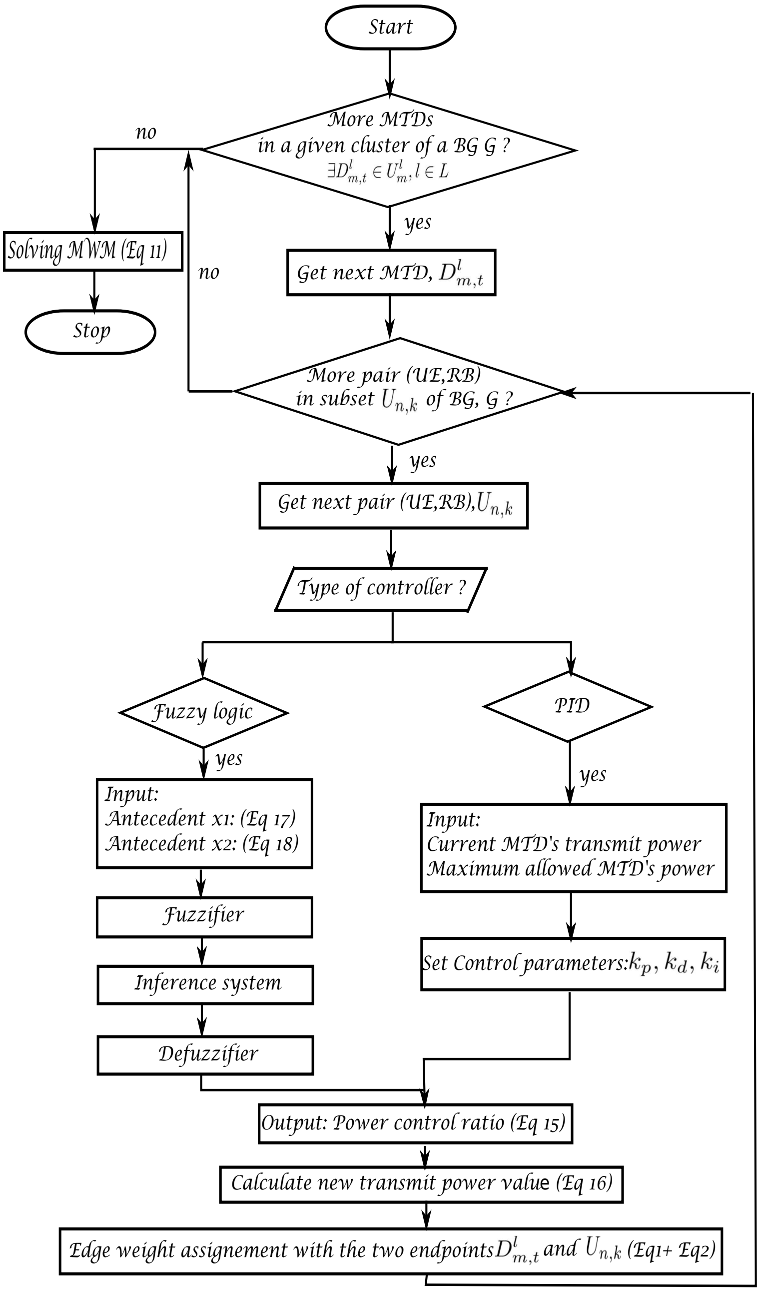


Figure 4.3 – Flowchart of adaptive power control-based radio resource sharing algorithm

4.8 Adaptive Radio Resource Sharing Algorithm using Fuzzy Logic

Contrarily to the proposed MTD transmit power control process using a PID controller where a specific and a precise output is produced by applying a mathematical model, fuzzy controllers approximate the mathematical solution and thus require less computational complexity and are easier to implement and prototype. Besides, another advantage of the fuzzy logic is the capability to benefit from the human knowledge and convert it into a machine-based decision process. We only develop here the novel power control scheme using fuzzy logic named Adaptive Radio Resource Sharing Algorithm using Fuzzy Logic (A-RRSA-Fuzzy) along with their two instantiations centralized and semi-distributed. Please refer to the previous subsection 4.6.1 for the details of the interference calculation in the centralized and semi-distributed approaches, respectively.

Particularly in this Section, we design a fuzzy power controller to dynamically adjust the transmit power of the specific MTD in order to assure the QoS of H2H users as well as to maximize the efficiency of MTD spectrum usage. The desired UE throughput given by Eq. 4.3 should be greater than a predetermined threshold given in Eq. 4.1. From Eq. 4.3, we notice that the MTD transmit power is influenced by the following two parameters called antecedents in the fuzzy logic.

Antecedent $\boldsymbol{x}1$: The UE's throughput level in a H2H scenario. Indeed, the UE's throughput given by Eq. 4.3 with $I^k_{(D^l_{m,t},eNB)} = 0$ obtained in the first stage in an exclusive H2H mode is a predominant parameter of the MTD transmit power:

- If the throughput of the H2H user is well below the threshold in an exclusive H2H scenario, then the MTD can transmit with its maximum power since the QoS of the H2H user is already unsatisfied.

- If the throughput of the H2H user is well above the threshold, the MTD can transmit with its maximum power since the H2H communication is robust to interference.

- If the throughput of the H2H user is below but close to the threshold in an exclusive H2H scenario, then the UE is sensitive to interference. Therefore, the MTD needs to adjust its transmit power.

- If the throughput of the H2H user is above but close to the threshold, then the UE is sensitive to interference. Therefore, the MTD needs to adjust its transmit power.

Consequently, the antecedent ($x1$) is the ratio of the throughput of a UE in an exclusive H2H scenario to the corresponding QoS. It is given by:

$$x1 = \frac{R^{k}_{U_n}}{R^{min}_{U_n}} \tag{4.13}$$

The linguistic variable x1 characterizes the transmission state of the H2H link with the term set: *robust*, *weak* and *moderate*.

Antecedent $x2$: The channel information level of the interference link, caused by a MTD to the reclaiming UE. The channel information of the interference link is also predominant to determine the MTD transmit power:

- If the interference level caused by the MTD to the reclaiming UE is high, MTD have to adjust its transmit power (decrease).
- If the interference level caused by the MTD to the reclaiming UE is low, MTD have to adjust its transmit power (increase).

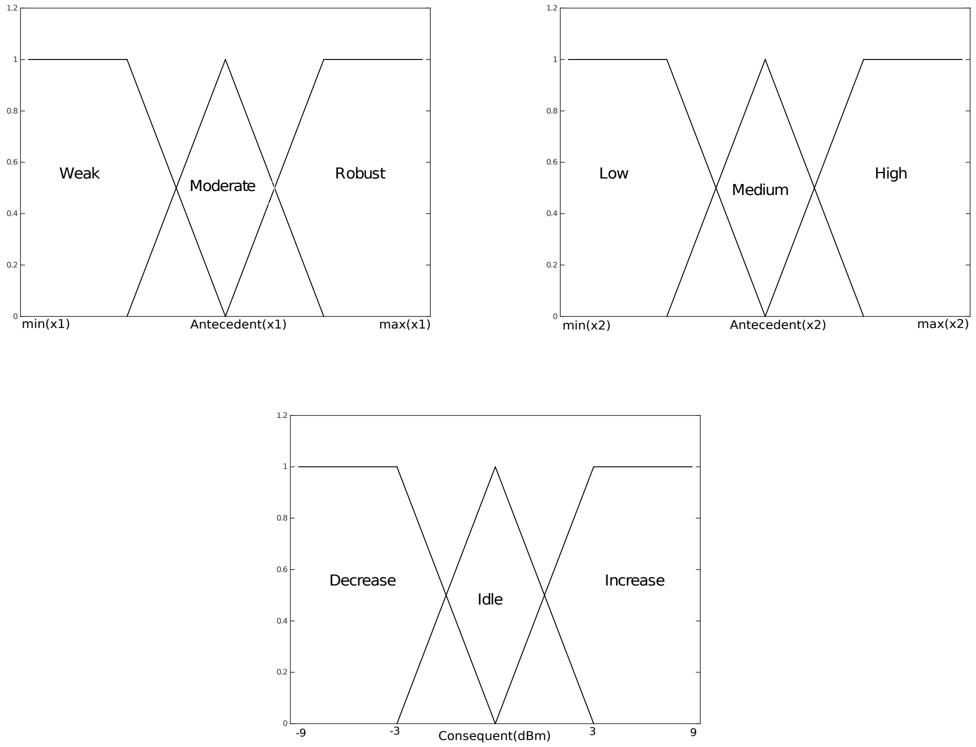


Figure 4.4 – The membership function used to represent the linguistic labels for: (a) Antecedent $x1$, (b) Antecedent $x2$, and the (c) Consequent

Similarly to antecedent (x1), given the UE's interference constraint to maintain the QoS of H2H users, the ratio of the actual interference to the mentioned threshold is used to judge the level of interference. We use the linguistic variable $x2$ that specifies *low*, *medium* and *high*.

$$x2 = \frac{I^{k}_{(D^{l}_{m,t}, eNB)}}{I^{max}_{(D^{l}_{m,t}, eNB)}} \tag{4.14}$$

Consequent: The consequent of this process which is the MTD transmit power control ratio (R^{k}_{pc}), is defined in Eq. 4.11 and the new transmit power level is obtained by multiplying the actual transmit power and the power control ratio derived from the output of fuzzy logic system together. R^{k}_{pc} is expressed in dB domain in Eq. 4.12. The consequent is divided into three levels: *decrease*, *increase* and *idle*. We use trapezoidal membership functions, as it is general enough and widely used [19], to represent the levels of the antecedents x1 and x2 as well as the consequent as depicted in Fig. 4.4(a), 4.4(b) and 4.4(c), respectively.

Table 4.1 – Rule base

Antecedent x1	**Antecedent x2**	**Consequent**
weak	low	increase
weak	medium	increase
weak	high	increase
moderate	low	increase
moderate	medium	idle
moderate	high	decrease
robust	low	increase
robust	medium	increase
robust	high	increase

Fuzzy control rules: After defining the membership functions, we set up the fuzzy rules based on linguistic knowledge from a group of experts. Since there are two antecedents and each antecedent has 3 fuzzy sub-sets, the number of rules is $3^2 = 9$ rules. We establish the fuzzy control rules as shown in table 4.1 following the proposed power control strategies. Finally, the defuzzification is performed using the most popular method, the centroid method.

Then, having properly adjusted the MTD transmit power using the fuzzy logic, we implement the new value of the MTD transmit power, in a similar way to the power control process using the PID controller, in the edge weight assignment phase of algorithm 2 and solve the MWM problem as elaborated in the flowchart depicted in Fig. 4.3.

4.9 Performance evaluation

In order to evaluate the efficiency of the proposed M2M Radio Resource Sharing Algorithms (RRSA), we conduct the following simulations based on the 3GPP LTE system model [80]. The main parameters are summarized in table 4.2. We consider an isolated cell where traditional H2H and M2M communications coexist and can share the RBs for individual data transmission. The system bandwidth is 10 MHz; therefore 50 usable RBs are available per TTI. The channel model accounts for small scale Rayleigh fading and large scale path loss (log-normally distributed). The coverage of the eNB is 500 m radius, and all UEs employ a transmit power of 24 dBm for the uplink. MTDs and UEs in the cell are distributed randomly each TTI. We consider here only one cluster of MTDs. For simplicity and without loss of generality, we assume that at most one RB per TTI is assigned to each H2H user. This assumption is due to the complexity introduced to uplink LTE scheduling algorithms because of the adjacency and power restrictions imposed by SC-FDMA and is beyond the aim of our work. We consider different H2H throughput values. On the other side, one RB is also assumed to be sufficient to fulfill M2M throughput requirements. We also use two well known traditional scheduling algorithms for H2H communications, namely *Round Robin* (RR) and *Proportional Fairness* (PF). The simulation results are obtained through averaging 50 different realizations.

The following performance metrics are measured in order to evaluate the impact of introducing M2M communications on H2H services when using our different proposed M2M radio resource sharing schemes.

- *Network sum-throughput*: This measure represents the network sum-throughput performance in a H2H/M2M coexistence scenario.

- *H2H throughput* and *percentage of M2M devices whose QoS is not met*: These two measures will give an insight into how the H2H throughput get affected due to the introduction of M2M communications as well as into the percentage of M2M devices with violated QoS (QoS is not met).

- *Fairness*: This measure will give us more information about how the fairness policy of H2H scheduling algorithms, namely Proportional Fairness (PF) and Round Robin (RR), are affected due to the emergence of M2M communications. Two fairness metrics are used:

  - **Max-Min**: a qualitative measure of fairness that gives an insight into the gap between devices in the resource allocation process. It is given by:

$$F_{Max-Min} = \frac{\max(R_{U_n})}{\min(R_{U_n})}; n = 1 : N \tag{4.15}$$

Table 4.2 – Simulation parameters

Parameter	**Value**
Cellular layout	Isolated cell
Cell radius	500 m
Mobility: UEs	Random mobility
Mobility: MTDs	Random mobility
Cluster radius	70 m
UEs per cell	N = 80
MTDs per cluster	M =50
Path loss model	UMi in [80]
P_n	24 dBm
P_m^{max}	14 dBm
Noise power spectrum density	-174 dBm/Hz
Carrier frequency	2.5 GHz
Small scale fading	Rayleigh fading coefficient with zero mean and unit variance
Channel bandwidth	W= 10 MHz
Modulation	QAM
K_p, K_d, K_i	0.3
$R_{U_n}^{min}$	$\{64, 128, 256 Kbps\}$
$R_{D_{m,t\rightarrow r}}^{min}$	$9.2Kbps$

- **Jain**: a quantitative measure of fairness that gives insight into the overall system fairness. It is defined as [82]:

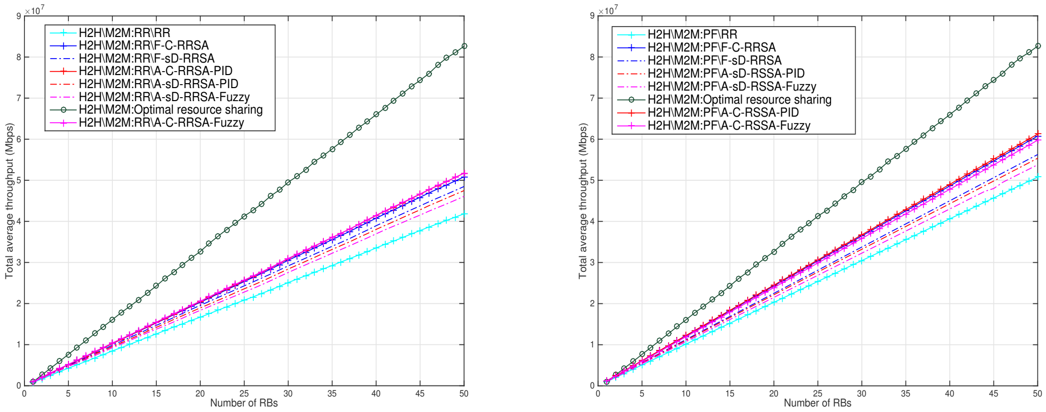
$$F_{Jain} = \frac{(\sum_{n=1}^{N} R_{U_n})^2}{N \sum_{n=1}^{N} R_{U_n}^2} \tag{4.16}$$

- *Probability Density Function (PDF)*: PDF of the distance of MTDs whose QoS is not met with respect to the MTH: This measure will give us some more information regarding where MTDs whose QoS is not met are statistically located.

The nomenclatures, H2H and H2H/M2M mentioned in all figure legends refer respectively to exclusive H2H case and H2H/M2M coexistence case. In the following evaluation process, we use two well known conventional scheduling algorithms for H2H communications: (RR in Subfig (a)) and (PF in Subfig (b)) in an exclusive H2H scenario (*stage 1 of our algorithm*). Then, we assess the impact of introducing M2M communications on H2H performance.

4.9.1 Network sum-throughput

Fig. 4.5 shows the network sum-throughput in a H2H/M2M coexistence scenario as a function of radio resources when using: the optimal resource allocation scheme formulated in Eq. 3.3 through an exhaustive search, one among the conventional resource allocation algorithms for H2H users, namely RR or PF along with one of our proposed fixed and adaptive resource sharing schemes for MTC using either the centralized or the semi-distributed instantiations, or a random resource allocation approach for MTC. It is clearly shown that the proposed interference-aware graph based resource sharing schemes using the centralized instantiation can achieve comparable performance and slightly outperform the interference-aware graph based resource sharing schemes using the semi-distributed instantiation. The best performance obtained when using the optimal resource allocation scheme comes at the expense of a huge computational complexity compared to much lower computational complexity of our proposed two-stage radio resource allocation approach. However, what is important to note here is that the H2H conventional scheduling algorithm has also an impact on the network sum-throughput. For instance, the network sum-throughput is decreased nearly about 40% and 30% compared to the optimal resource allocation scheme when using the proposed adaptive radio resource sharing algorithm with the centralized instantiation along with the RR and PF scheduling algorithms, respectively. Thus, the goal of the reminder here is to show the impact of proposed interference-aware graph based resource sharing schemes for MTC on H2H services.



(a) RR (b) PF

Figure 4.5 – Total average throughput

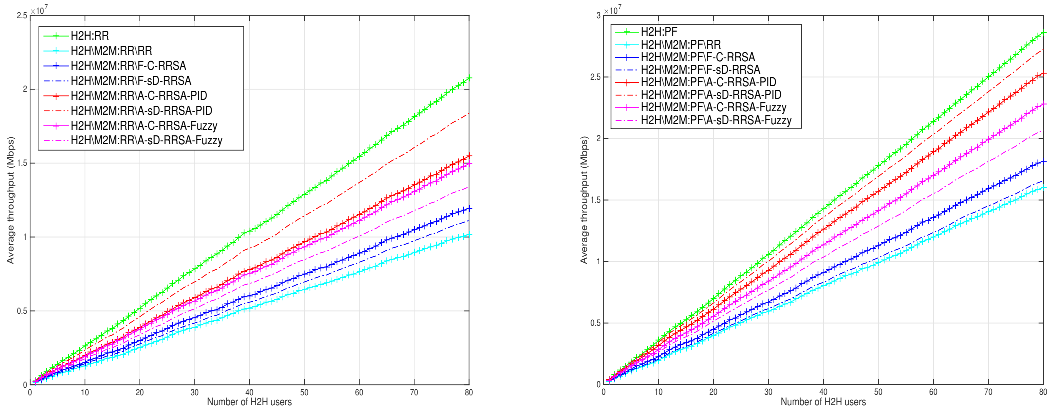
4.9.2 H2H throughput and percentage of MTDs whose QoS is not met

Fig. 4.6 demonstrates the H2H throughput as function of UEs present in the cell when using the three proposed M2M radio resource sharing algorithms: *Fixed Radio Resource Sharing Algorithm* (F-RRSA), *Adaptive Radio Resource Sharing Algorithm using PID controller* (A-RRSA-PID) and *Adaptive Radio Resource Sharing Algorithm using Fuzzy logic* (A-RRSA-Fuzzy) along with their two instantiations, *centralized* (C) and *semi-Distributed* (sD). These latter are also compared to the case where a random M2M radio resource sharing algorithm is used. Concerning H2H scheduling algorithms, the PF algorithm enhances the H2H throughput compared to the RR scheduling algorithm. Indeed, this latter is a channel-blind algorithm that distributes RBs randomly to UEs while the PF scheduling policy tries to handle a trade-off between fairness and throughput. Obviously, the worst performance in a H2H/M2M is obtained when using the random M2M radio resource sharing algorithm where total H2H throughput for 80 UEs is decreased about 50% and 44% compared to the throughput obtained in an exclusive H2H scenario when using RR and PF scheduling algorithms, respectively. Even though, F-C-RRSA achieves better performance compared to the random M2M radio resource allocation in a H2H/M2M coexistence scenario, the H2H throughput remains significantly degraded. For instance, for 80 users, the total throughput is degraded by about 42% and 36% when using F-C-RRSA in RR and PF cases, respectively. In other words, F-C-RRSA achieves approximately a 9% gain over M2M random resource sharing approach. It is seen that the H2H throughput is significantly assured when using A-C-RRSA-PID and A-C-RRSA-Fuzzy. For instance, the total H2H throughput is decreased by about 20% for A-C-RRSA-Fuzzy in both the RR and PF cases while it decreases by about 20% and 11% for A-C-RRSA-PID in RR and PF cases, respectively. This can be explained by the fact that adaptive algorithms, A-RRSA, adjust the M2M transmit power in a way that the QoS of H2H users is guaranteed contrarily to the fixed algorithm F-RRSA, where high interference situations cannot be avoided since the M2M transmit power is fixed.

On the other hand, both A-sD-RRSA-Fuzzy and F-sD-RRSA, i.e. two of the studied semi-distributed instantiations, achieve lower performance compared to their counterpart centralized instantiations. This is due to the fact that the interference power calculation in the semi-distributed instantiation is approximative and not accurate as in the centralized instantiation, resulting in an approximative M2M transmit power adjustment. For example, a gain of about 12% is achieved when using the centralized instantiation over the semi-distributed instantiation which is not significant compared to the communication overhead introduced by the centralized feature. However, A-sD-RRSA-PID outperforms A-C-RRSA-PID by affecting less H2H communications which is quite unexpected. This behavior can be explained by the fact that the MTD transmit power calculated in Eq.

4.12 is low-estimated when using the approximative interference power calculation scheme. In other words, there will be more MTDs with unsatisfied QoS due to the low MTD transmit power estimation as illustrated in Fig. 4.7. This behavior proves that the power control policy when using fuzzy controllers achieves good performance when dealing with less precise inputs in contrast to the PID controller that relies on a quantitative and precise interference data values.

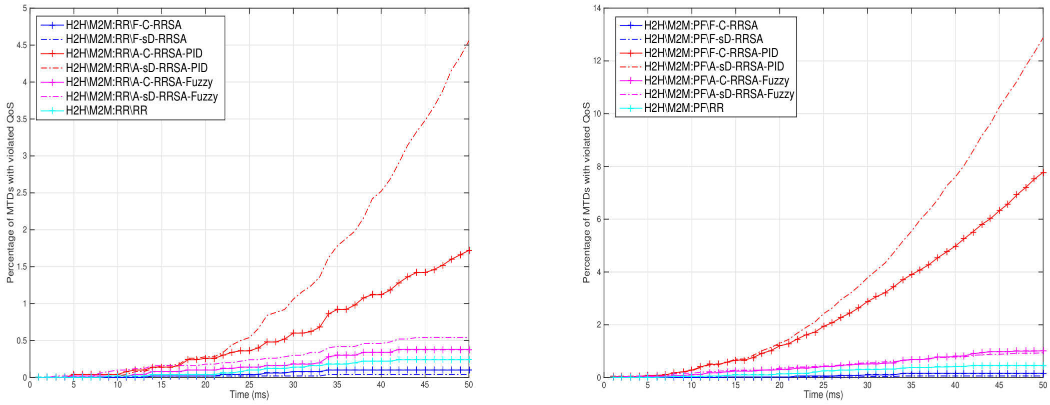
Fig. 4.7 illustrates the percentage of MTDs with unsatisfied QoS as a function of time. The unexpected improvement achieved by A-sD-RRSA-PID over A-C-RRSA-PID in terms of throughput as explained above can be justified by the number of MTDs with unsatisfied QoS. Indeed, the MTD transmit power is low estimated in A-sD-RRSA-PID leading to a rise of the number of unsatisfied MTDs of about 25% at t= 50 *ms* for both cases, RR and PF, compared to A-C-RRSA-PID. The percentage of unsatisfied MTDs of the PF case for all algorithms is higher than the one achieved in RR. This can be explained by the fact that H2H users in the edge of the cell which have been assigned radio resources due to the fairness parameter in the resource allocation process of the PF scheduling algorithm are more sensitive to the interference introduced by M2M communications. Besides, It can be seen that the percentage of MTDs with unsatisfied QoS for F-C-RRSA as well as A-C-RRSA-Fuzzy is negligible. Hence, we can conclude from Fig. 4.6 and 4.7 that adaptive radio resource algorithms using fuzzy logic along with their two instantiations centralized and semi-distributed gives the best compromise by achieving comparable performance to the adaptive radio resource algorithms using PID in terms of guaranteeing H2H throughput while least affecting the M2M services.



(a) RR

(b) PF

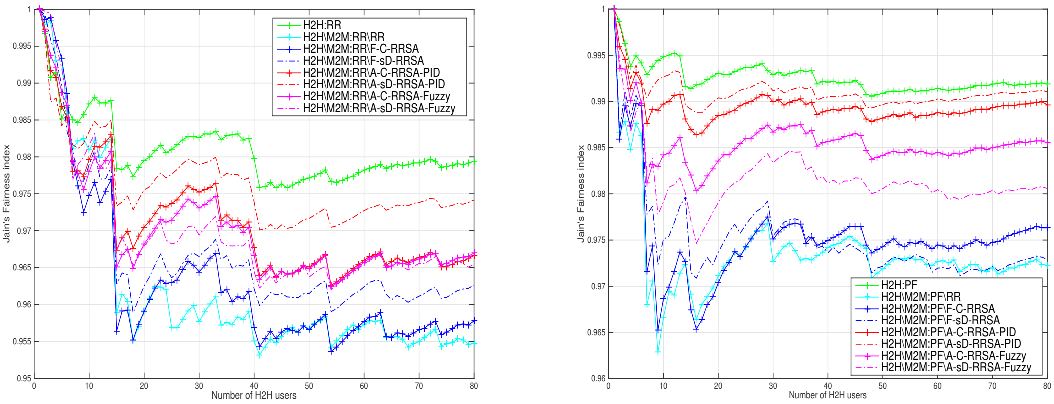
Figure 4.6 – H2H average throughput



(a) RR (b) PF

Figure 4.7 – Percentage of MTDs with unsatisfied QoS

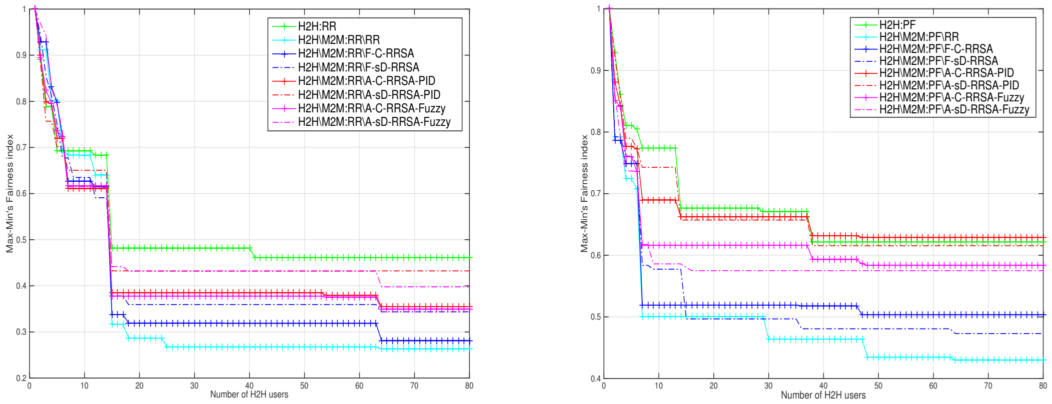
4.9.3 H2H fairness



(a) RR (b) PF

Figure 4.8 – Jain's Fairness Index

Both quantitative and qualitative fairness measures based on throughput are illustrated in Fig. 4.8 and Fig. 4.9, respectively. Obviously, the PF scheduling algorithm used in an exclusive H2H scenario achieves a better level of fairness compared to the RR scheduling algorithm. Indeed, PF assigns RBs to UEs according to the link quality and thus achieves a better throughput while trying to reach a fairness in the distribution of radio resources. The Jain's fairness index shows good level of fairness in this case. This can be explained by the fact that H2H users are all assigned one RB. However, this high level of fairness



(a) RR

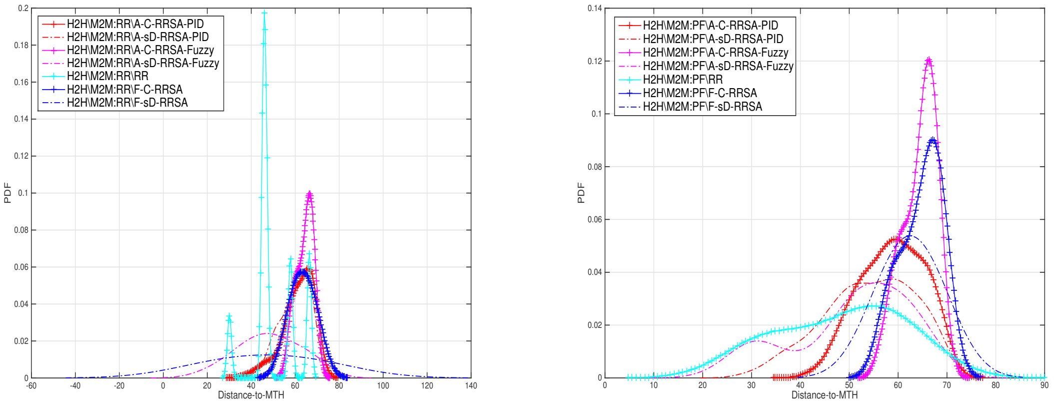
(b) PF

Figure 4.9 – Max-Min's Fairness Index

does not necessarily guarantee that H2H users utilize these equally allocated resources with equal efficiency which is justified with the max-min's fairness in Fig. 4.9. What is quite interesting to note here, however, is that the proposed adaptive M2M radio resource sharing algorithms in a H2H/M2M coexistence scenario with both instantiations, centralized and semi-distributed, maintain the level of fairness of existing RR and PF scheduling algorithms in an exclusive H2H scenario. For instance, Fig. 4.9 (b) illustrates a slight decrease up to 10% for 80 users between the level of fairness achieved in an exclusive H2H scenario and the one achieved using the A-RRSA instantiations in a H2H/M2M coexistence scenario. Thus, we can conclude that adaptive radio resource sharing algorithms for MTC have limited impact on the fairness policy of H2H scheduling algorithms.

4.9.4 PDF of MTDs whose QoS is not met

Fig. 4.10 shows the probability density function (PDF) of the distance of MTDs whose QoS is not met with respect to the MTH using the different proposed M2M radio resource sharing algorithms. We notice that the density of MTDs with unsatisfied QoS for A-C-RRSA-Fuzzy increases the closer they are to the edge of the MTH, from the center of the MTH to which they are attached (since the inter-MTD distance is set to R = 70 m) for both cases PF and RR. It is clearly seen that the density of MTDs with unsatisfied QoS is uniformly distributed when using a random M2M radio resource allocation approach. In addition, we can notice as expected that nodes located in the edge of the cluster for A-C-RRSA-Fuzzy are the ones that suffer the most from QoS deterioration. However, A-sD-RRSA-Fuzzy and A-RRSA-PID with both instantiations show a greater dispersion around the mean compared to A-C-RRSA-Fuzzy. This can



(a) RR

(b) PF

Figure 4.10 – Probability density function of the distance of unsatisfied MTDs-to-MTH

be explained by the approximative interference power calculation in the semi-distributed instantiation. In addition, we can conclude that A-C-RRSA-Fuzzy provides a smooth operation on M2M transmit power and thus is more robust to parameter variations when compared to A-C-RRSA-PID.

4.10 Conclusions

Convinced by the strength of the bipartite graph tool for resolving the resource sharing issue and in order to mitigate the negative effects of M2M communications without sacrificing the QoS of current H2H services, we have introduced in this chapter a novel adaptive power control feature into the proposed fixed interference-aware graph-based resource sharing algorithm. This feature uses one of the two following alternative mechanisms, namely, either PID as the most commonly used controller in process industries or fuzzy logic as a versatile tool that proposes a simpler operation using linguistic information. The main idea behind the power control feature remains in further guaranteeing H2H services and maximizing the M2M spectrum usage through proper M2M transmit power adjustment.

Our evaluation study has clearly shown that adaptive algorithms significantly reduce the negative impact on H2H communications in terms of throughput and protect the level of fairness achieved in an exclusive H2H scenario. The fuzzy logic-based adaptive M2M radio resource sharing algorithm yields the best compromise between guaranteeing H2H performance and satisfying M2M services. Indeed, the fuzzy logic controller provides a smooth operation on M2M transmit power and thus is more robust to parameter variations when compared to the PID controller. Moreover, the semi-distributed instantiation proposed for the adaptive fuzzy-based M2M radio resource sharing algorithm has proved achieving comparable results with the counterpart centralized instantiation. Even though it achieves a decline of 10% in terms of throughput, it also has markedly lower communication overhead.

Throughout this chapter, we have designed an efficient power control strategy with the aim of protecting H2H services and maximizing the M2M efficiency in spectrum usage. We have been interested in solving the uplink resource sharing issue in a H2H/M2M coexistence scenario through centralized or semi-distributed schemes using a bipartite graph methodology. The proposed schemes are suitable for the client-server model of M2M communications, where MTDs are connected to a *Machine-Type-Server* (MTS). However, the proposed solution doesn't address the other communication model available in the M2M realm: the peer-to-peer model. Furthermore, there is a strong need to adopt a fully distributed and energy efficient uplink resource sharing scheme. These are the main purposes of the next chapter.

- CHAPTER 5 -

EFFICIENT TRANSMISSION STRATEGY SELECTION ALGORITHM FOR M2M COMMUNICATIONS

Contents

5.1 Foreword

In the previous chapter, we have proposed a novel adaptive interference-aware graph-based resource sharing scheme for MTC in conjunction with two instantiations, centralized and semi-distributed. We have introduced a power control feature using PID and fuzzy logic in order to guarantee H2H services and maximize the M2M spectrum usage through proper M2M transmit power adjustment. Even though the simulation study has shown that adaptive algorithms significantly reduce the negative impact on H2H services, a centralized approach for resource allocation can be prohibitive since it requires a huge computational complexity due to the heavy information exchange between all MTDs and the eNB. In addition, the proposed semi-distributed graph-based resource sharing instantiation is an approximate approach that is suitable to the client/server model for M2M communications, but not to the peer-to-peer one, as it had been not designed for it. Therefore, there is a strong need to adopt a distributed and energy efficient uplink resource sharing scheme particularly for the peer-to-peer model of M2M communications which is the scope of this chapter.

In this vein, we opt in this chapter, to use game theory as a relevant tool to model situations in which decision makers have to take specific actions that have possible mutual conflicting consequences [71, 41]. More precisely, we model the resource sharing problem using an efficient hybrid-game where MTDs through D2D communications underlying LTE-A compete for radio resources and switch efficiently and in a fully distributed manner between non-cooperative and cooperative games.

To that end, we introduce the context of this work in Section 5.2, followed by the related works in Section 5.3. The system model and problem formulation are presented in Section 5.4. The hybrid-game for M2M transmission strategy selection algorithm is formulated in Section 5.5. While the non-cooperative power control game is described in Section 5.6, the cooperative power control game is formulated in Section 5.7. The performance evaluation of our proposal is drawn in Section 5.8 in a H2H/M2M coexistence scenario followed by the conclusion in Section 5.9.

5.2 Context and motivation

The large scale deployment of M2M devices in LTE-A requires designing efficient resource allocation schemes that tackle scalability and energy efficiency. D2D communications is a key enabler for the multiple radio resource sharing. In other words, multiple D2D pairs can share the same channel and thus enables multiple channel access for IoT. However, the massive number of M2M devices significantly increases the competition on scarce radio resources. Thus, adopting distributed and self organizing M2M resource allocation schemes is required.

In a H2H/M2M coexistence scenario where the wireless channel is shared, game theory represents a relevant tool to model the competition between MTDs and H2H users for the shared radio resources. Consequently, we first propose a group-based operation for M2M links using D2D communications where multiple D2D pairs can use the same sub-channel aiming to assure the desired QoS of H2H users. Then, we design an efficient hybrid-game-based transmission strategy selection algorithm for MTC underlying cellular networks. Indeed, different from existing works that select one category of game theory, cooperative or non-cooperative, before starting to solve the problem, we address the joint issue of transmission strategy for D2D re-use mode (a non-cooperative game or a cooperative game), resource allocation and power control, using a game theoretic framework. Specifically, MTDs sharing the spectrum using D2D re-use mode switch opportunistically from a non-cooperative game strategy to a cooperative game strategy to meet their QoS requirements in terms of rate. Initially, we consider a non-cooperative game scenario due to the selfish behavior of MTDs. A *Mixed Nash Equilibrium* (MNE) is characterized due to the dynamic topology as well as the unpredictability of the link quality. In case the QoS of MTDs is not satisfied, these latter switch in a fully distributed manner to a cooperative game. Here, we use the Shapley value to express the benefit of cooperation of MTDs inside a group and consider two alternatives in the cooperative game. In the first, we quantize the strategy space of each MTD in terms of transmit power into fixed and discrete values. In the second, we make use of the shared information between players inside a group and set adaptively the power level strategy of each MTD combining the output of PID and the fuzzy logic. These mechanisms aim to maximize the efficiency of the M2M spectrum usage and save the energy consumption of MTDs.

We conduct an extensive simulation study to assess the impact of the proposed hybrid-game-based transmission strategy selection algorithm on H2H services in terms of throughput and fairness and evaluate the gain in terms of transmit power consumption.

5.3 Related works

Game theory is a strong tool for modeling different types of interactions, and is widely used to tackle the resource allocation problem in the area of wireless communications. Game theory can be classified into two major branches: non-cooperative and cooperative game theory [54, 88]. While the individual objectives of the players in a non-cooperative game are clearly identifiable and are assumed to be selfish, cooperative game theory represents the study of the behavior of rational players when they cooperate in order to strengthen their positions in the game. Consequently, we divide the existing works that tackle the resource allocation problem for M2M and D2D communications using game theory into two major classes depending on the used approach: non-cooperative game and cooperative game.

5.3.1 Non-cooperative game

A handful of works have considered a non-cooperative game to deal with the resource allocation problem for M2M and D2D communications. For instance, authors in [72] have proposed a resource allocation framework in a H2H/M2M coexistence scenario using game theory. Under this framework, the random access resources are divided into three disjointed pools for H2H, M2M and hybrid H2H/M2M usage. A *Nash Equilibrium* (NE) has been formulated to guarantee the system throughput by adaptively redistributing the traffic load. In [83], authors have designed a non-cooperative dedicated resource allocation framework in a H2H/M2M coexistence scenario. In the proposed framework, M2M devices have three alternatives: (i) being served with unreliable resources in a first come first served manner, (ii) paying for reliable direct access, and (iii) staying idle. In [94], authors have proposed a non-cooperative game-theoretic approach in order to model the distributed competition of radio bandwidth and admission control among M2M devices in home networks. The problem of distributed resource allocation for D2D pairs is formulated as a stochastic non-cooperative game with multiple selfish players in [11]. Even though M2M devices are selfish in nature, the major drawback of considering a non-cooperative approach is that some devices that have been not satisfied by their payoff could be interested to pursue a cooperative action.

5.3.2 Cooperative game

A bunch of works have opted for a cooperative resource allocation framework. For instance, authors in [95] have investigated a cooperative spectrum sharing scheme between D2D users and UEs in the uplink, where a D2D user relays the cellular traffic to get access to the licensed channel in order to improve the QoS through cooperation. In [63], cooperative bargaining solutions for resource allocation over the available component carriers have been investigated. Authors have taken into account the optimal tradeoff between fairness and efficiency, with an ultimate goal to select the most appropriate solution over all of the available carriers. In [97], joint power control for UEs and D2D users has been developed in order to maximize the secrecy capacity of UEs, and a general cooperation scheme has been investigated using a coalitional game. Authors in [91], have proposed a coalition formation game theory to cope with the joint issue of mode selection (either cellular or D2D re-use mode), resource allocation and power control with the primary goal to maximize the available rate. In [70], authors have studied eNB selection and coalition formation for relay transmission in a *Random Access Channel* (RACH) when M2M devices coexist with H2H users. The major drawback of this approach is that all devices or users are considered rational and tend to interact, while M2M devices in real scenarios are selfish and might be not interested in cooperating. In addition, the process of exchange of information in a cooperative game incurs a cost which increases with the size of the group, representing the cooperative users.

5.3.3 Discussion

Assuming that each category of game theory, cooperative and non-cooperative, has its specific features and fits a specific problem, authors in the previous works have selected only one category of game theory before starting to solve the problem. Consequently, the resource allocation issue has been modeled using either a non-cooperative game-theoretic framework for resource allocation or a cooperative game-theoretic framework for resource allocation. We aim in this chapter to model the resource allocation problem for M2M communications using a hybrid-game where MTDs using D2D re-use mode switch opportunistically and in a fully distributed manner between a cooperative game and a non-cooperative game. More precisely, our resource allocation solution can handle both situations: the situation where M2M devices tend to behave initially in a non-cooperative manner as they are selfish, and the situation where some selfish M2M devices have been not satisfied by their payoff and could be interested to pursue a cooperative behavior.

5.4 System model and problem formulation

5.4.1 System model

We consider the uplink scenario of a single cellular network where both H2H and M2M communication links coexist, as illustrated in Fig. 5.1. We assume pairs of MTDs where each MTD transmitter is associated with an MTD receiver. The investigated cellular network consists of one eNB located at the center of the cell that can deliver information to UEs within its broadcasting coverage, N UEs that access the eNB for the information they request, and M pairs of MTDs that communicate with each other. Therefore, there exist in the network N H2H communication links and M M2M communication links, respectively, where $\{n = 1, 2, ..., N\}$, $\{m = 1, 2, ..., M\}$ and $M \geq N$. The MTD transmitter is denoted by $D_{m,t}$ and the MTD receiver is denoted by $D_{m,r}$. Depending on the available bandwidth, the number of RBs, K, ranges from 6 to 110 [5].

To overcome the challenge of spectrum scarcity and improve the spectrum efficiency of the considered cellular network, which consists of both H2H and M2M communication links, we consider a simultaneous access to radio resources using D2D communications. Particularly, traditional cellular communication links have higher priority when accessing the radio resources while M2M communication links communicate through D2D technology, making MTC as an underlay to H2H communications. Thus, efficient interference management schemes should be developed to successfully enable the proposed underlying communication mode. Because the transmit power of UEs is relatively high, resource sharing among different H2H communication links is forbidden in the proposed underlying communication mode. On the other hand, the multiple resource sharing is enabled. More precisely, one or multiple M2M pairs are allowed to share radio resources with H2H users (UEs) since the transmit power of MTDs is relatively low. The key issue here remains in designing novel group-based M2M operation by properly grouping potential M2M communication links able to share the radio resources with a particular H2H user, taking into account the interference among them. We introduce the virtual cluster process for properly grouping pairs of MTDs.

5.4.2 Problem formulation

We consider that radio resources, RBs, are assigned to N traditional H2H users (UEs). At the same time, one or multiple pairs of MTDs seek(s) to re-use RBs occupied by UEs to transmit their data. Specifically, a set of orthogonal sub-channels are assigned to each UE using conventional scheduling algorithms (such as *Proportional Fairness* (PF) or *Round Robin* (RR)) optimally designed for traditional H2H communications. We assume that each sub-channel RB_k is allocated to only one UE, implying that there will be no interference observed from UEs at the eNB. The sub-channels allocated to UEs are fixed for each transmission frame. Then, we propose a novel group-based M2M operation that selects a set of MTD pairs in order to share the spectrum within a particular UE. This group-based operation alleviates significantly the amount of information to be exchanged because of the massive number of IoT devices, and guarantees as well the QoS of H2H users. A set of MTDs is matched to each UE based on cellular rate requirements and the channel information collected by the eNB from the cellular and M2M links, thus forming a virtual cluster. The latter construction is updated each transmission frame. To construct virtual clusters for each cellular link, represented by circles in Fig. 5.1, we require the definition below:

Definition 1: The interference value of a cluster C_n on a radio resource block RB_k, denoted by $v_I^k(C_n)$, is defined as the sum of the interference introduced by L MTD pairs if sharing the sub-channel with a UE, U_n with $n \in N$. Thus, the interference value $v_I^k(C_n)$ can be given as:

$$v_I^k(C_n) = \sum_{m=1}^{L} P_m^k g_{D_{m,t},eNB}^k \tag{5.1}$$

where P_m is the MTD transmit power and $g_{D_{m,t},eNB}$ is the interference link from the MTD transmitter $m \in M$ to the eNB .

The basic idea of the virtual cluster construction is to match iteratively MTD pairs to a particular UE where both access the same sub-channel, and such that the interference value of the cluster should not exceed a given interference threshold that guarantee the QoS of the given UE. Thus, a virtual cluster is composed of L MTDs whose total introduced interference if sharing the RB_k with UE U_n, is equal or below to a given interference threshold, I_{th}^k, of the corresponding UE ; $v_I^k(C_n) \leq I_{th}^k$.

The achievable throughput of UE U_n on RB_k can be expressed as

$$R_{U_n}^k = W.log_2(1 + \frac{P_n g_{U_n}^k}{\sum\limits_{m \in C_n} P_m^k g_{D_{m,t},eNB}^k + \sigma^2}) \tag{5.2}$$

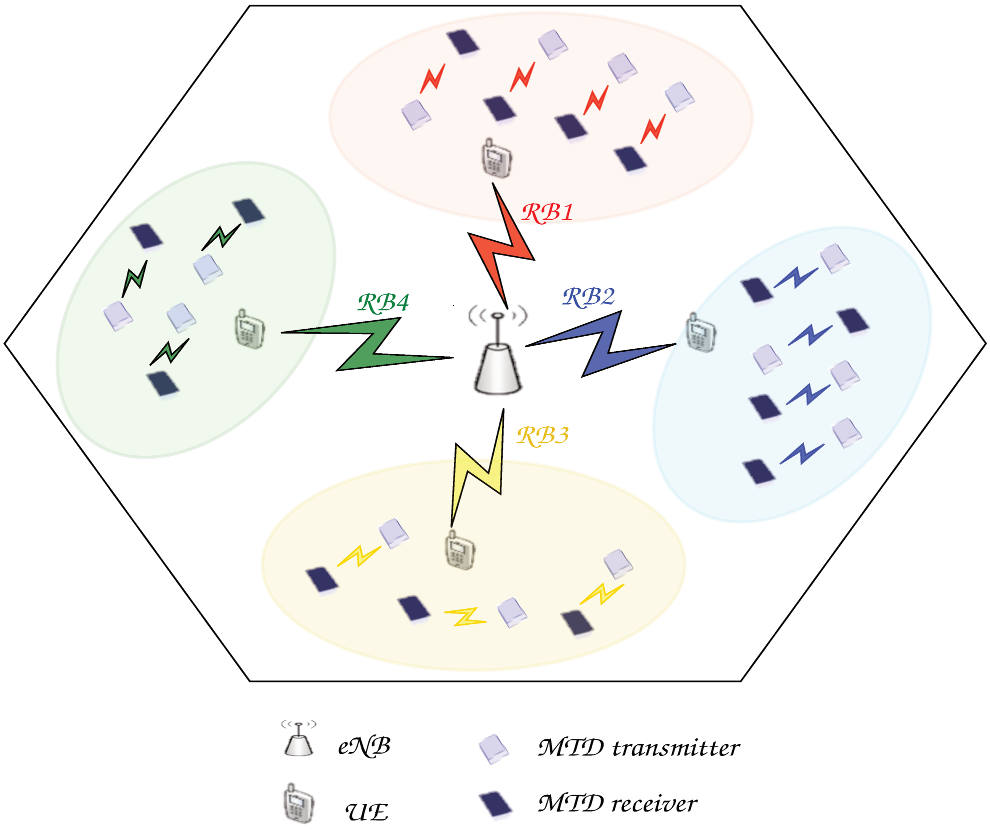


Figure 5.1 – System model under study: inter-MTD within D2D underlying cellular network

where W is the bandwidth, P_n is the UE transmit power and g_{U_n} is the channel gain of the UE from U_n to eNB. The first term in the denominator in Eq. 5.2 represents the interference from MTDs belonging to the same virtual cluster C_n, while the second term represents the variance of the thermal noise, denoted by σ^2 and modeled as an independent Gaussian distribution with zero mean.

Our aim is to satisfy the requirements of all nodes. Hence, to guarantee the QoS of the UE U_n, the achievable throughput for the UE given in Eq. 5.2 should be larger than its rate requirement $R_{U_n}^{min}$ defined as follows:

$$R_{U_n}^{k} \geq R_{U_n}^{min}, \tag{5.3}$$

We evaluate the throughput of MTD pair D_m, on RB_k as

$$R_{D_m}^{k} = W.log_2(1 + \frac{P_m^k g_{D_{m,t},D_{m,r}}^{k}}{P_n g_{U_n,D_{m,r}}^{k} + \sum\limits_{m' \in C_n, m \neq m'} P_{m'}^{k} g_{D_{m',t},D_{m,r}}^{k} + \sigma^2}) \tag{5.4}$$

where $g_{D_{m,t},D_{m,r}}$ is the channel gain of the M2M communications from MTD transmitter $D_{m,t}$ to MTD receiver $D_{m,r}$, $g_{D_{m',t},D_{m,r}}$ is the interference link from $D_{m',t}$ to $D_{m,r}$, and $g_{U_n,D_{m,r}}$ is the interference link from the UE to $D_{m,r}$. The first term in the denominator in Eq. 5.4 represents the interference from UE U_n to the $D_{m,r}$, while the second term represents the intra-cluster interference. This latter represents the interference generated from MTDs of the same virtual cluster when sharing the radio resource, RB_k.

To guarantee the QoS of the MTD pair D_m, the achievable throughput for the MTD defined in Eq. 5.4 should be larger than its rate requirement of $R_{D_m}^{min}$ defined as follows:

$$R_{D_m}^{k} \geq R_{D_m}^{min} \tag{5.5}$$

After properly grouping MTDs, the key issue is to design an efficient transmission strategy selection algorithm for M2M communication links using D2D re-use mode. To grasp the properties and advantages of game theory as a powerful tool for modeling interactions between nodes, we endow MTDs the ability to choose their transmission strategy. Specifically, MTDs can choose in a fully distributed manner between either D2D re-use mode using a non-cooperative game strategy or D2D re-use mode using a cooperative game strategy within the aim to efficiently guarantee the network performance. In the next Sections, we will first introduce our hybrid-game based MTC transmission strategy selection algorithm. Then, we will describe the non-cooperative power control game as well as the cooperative power control game for M2M devices.

5.5 MTC transmission strategy selection algorithm: a hybrid-game

Game theory is a relevant tool to model the competition between players and is widely used to tackle the resource allocation problem in wireless networks. In our model, MTDs are competing in order to access to the radio resources already assigned to H2H users. Consequently, we address the joint issue of transmission strategy for D2D re-use mode (a non-cooperative or a cooperative game), resource allocation and power control using a game theoretic framework. A preference order for the transmission strategy of each M2M pair using D2D re-use mode is established. Hence, for any given M2M pair, re-$use_{NPG} \geq_m$ re-use_{CPG} implies that a MTD pair D_m matched to a UE U_n in a virtual cluster C_n strictly prefers a non-cooperative power control game due to the individual selfish behavior of MTDs over a cooperative power control game. Initially, we assume a non-cooperative game where MTDs are free to act according to their own interests without regard to the overall performance of the virtual cluster as described in Section 5.6. In a non-cooperative game, each MTD transmitter of an M2M pair has the tendency to transmit with its maximum transmit power in order to gain its targeted QoS, which explains the selfish behavior of devices. If the obtained QoS is less than the required QoS, then MTDs belonging to the same virtual cluster C_n whose QoS is not satisfied form a group denoted by S_n called also a grand coalition and switch in a fully distributed manner from a non-cooperative transmission strategy using D2D re-use mode to a cooperative transmission strategy using D2D re-use mode. Algorithm 3 implements the switch rule for the transmission strategy selection of each MTD pair. In the cooperative game, we consider the cost of information exchange inside a coalition and propose two alternative power control strategy spaces as explained in Section 5.7.3. Indeed, we benefit from the shared information inside a coalition in the cooperative game and adapt dynamically the strategy space using PID and fuzzy logic controllers. The dynamic topology as well as the unpredictability of the link quality motivate us to use the mixed-strategy solutions in game theory model to deal with discrete power control issue. A mixed strategy is a probability distribution one uses to randomly choose among available actions in order to avoid being predictable.

Algorithm 3: Transmission strategy selection algorithm

```
for each virtual cluster $C_n$, $n \in N$ do
    Each MTD link $D_m$, $m \in M$, starts to play selfishly in a non-cooperative game using their maximum transmit power
    if MTD's QoS requirement is not satisfied then
        MTDs whose QoS is not satisfied form a coalition $S_n$
        if Cost of information exchange ($\hat{P}_m^k$ in Eq. 5.8) is less than a predetermined threshold ($\tilde{P}_m^k$) then
            MTDs in the coalition switch to a cooperative game
        end if
    end if
end for
```

5.6 Non-cooperative power control game

5.6.1 Payoff function

Let $G = \{L, \{P_m\}, \{\mu_m(.)\}\}$ denote the Non-cooperative Power control Game (NPG) where $L = \{1, 2, ..., L\}$ is the index set for MTDs currently in each virtual cluster C_n, P_m is the strategy set, and $\mu_m(.)$ is the payoff function of a MTD pair D_m. Each user selects a power level p_m such that $p_m \in P_m$. The power vector $\mathbf{p} = (p_1, ..., p_L) \in P$ denote the outcome of the game in terms of selected power levels of all MTDs, where P is the set of all power vectors. The resulting utility level for the mth MTD is $\mu_m(\mathbf{p})$. Let $\mu_m\left(p_m, \mathbf{p}_{-m}\right)$ denote the payoff of a player D_m when playing p_m against $\mathbf{p}_{-m}$ with $\mathbf{p}_{-m}$ is the vector of elements of $\mathbf{p}$ other than the mth element. The latter indicates that the mth MTD has control over its own power, p_m only. The strategy space of all MTDs excluding the mth MTD is denoted by P_{-m}.

To express the payoff function of a MTD, we consider a joint throughput and power control game model. The payoff function of a MTD $D_m, m \in L$, $\mu_m\left(p_m, \mathbf{p}_{-m}\right)$ is composed of an utility function and a cost function, where $\frac{R^k_{D_m}}{R^{min}_{D_m}}$ is the utility function that represents the user's satisfaction in terms of throughput and $\frac{P^k_m}{P^{max}_m}$ is the cost function that depends on the power consumption. α and β are the positive weight constants of the throughput and the price of the transmission cost, respectively.

$$\mu_m\left(p^k_m, \mathbf{p}^k_{-m}\right) = \alpha.\frac{R^k_{D_m}}{R^{min}_{D_m}} - \beta.\frac{p^k_m}{p^{max}_m} \tag{5.6}$$

5.6.2 Mixed Nash Equilibrium

The power level is usually quantized into discrete values in practice [92]. Therefore, the power level of a MTD transmitter $D_{m,t}$ is assumed to be chosen from a finite set. Thus, the strategy space P_m of each MTD is a compact, convex set with minimum and maximum power constraints. The utility level of each MTD depends on both, its own power level strategy and also the choice of the other players' power level strategies, as expressed in Eq. 5.4. In a non-cooperative power control game, each MTD maximizes its own utility in a distributed fashion as:

$$(NPG) \max_{p_m \in P_m} \mu_m\left(p_m, \mathbf{p}_{-m}\right), for\ all\ m \in L \tag{5.7}$$

The transmit power that optimizes individual utility depends on the transmit power of all the remaining MTDs in the virtual cluster. An equilibrium is the operating point that characterizes a set of powers where the users are satisfied with the utility they receive given the power selection of other users.

The dynamic topology as well as the unpredictability of the link quality and the incompletely known opponent's reaction motivate us to use the mixed Nash equilibrium to find the solution of the NPG [38]. By a mixed strategy, we mean that a MTD player $D_{m,t}$ chooses at each scheduling period an action p_m with a given probability. A MNE is defined below.

Definition 2:

Let $\boldsymbol{\delta} = (\delta_1, ..., \delta_L)$ be a mixed strategy profile for an L-player game. For any player $m = 1, 2, ..., L$, let $\boldsymbol{\delta}_{-m}$ represent the mixed strategies used by all the players other than player D_m. Let P_m be the finite set of pure strategies available to player m, and let $\mu_m(p_m, \boldsymbol{\delta}_{-m})$ $p_m \in P_m$ be the payoff to player m when playing p_m against $\boldsymbol{\delta}_{-m}$. Then $\boldsymbol{\delta}$ is a Nash equilibrium $\Leftrightarrow$ the following two conditions hold:

- If $(p_m, p'_m) \in P_m$ are two strategies that occur with positive probability in δ_m, then $\mu_m(p_m, \boldsymbol{\delta}_{-m}) = \mu_m(p'_m, \boldsymbol{\delta}_{-m})$

- If $(p_m, p'_m) \in P_m$ where p_m occurs with positive probability in δ_m, and p'_m occurs with zero probability in δ_m, then $\mu_m(p_m, \boldsymbol{\delta}_{-m}) > \mu_m(p'_m, \boldsymbol{\delta}_{-m})$

5.7 Cooperative power control game

Cooperative Power control Game (CPG) is a rich and flexible tool that studies how the selfish nodes, MTDs whose QoS is not satisfied when using NPG in our case negotiate, interact and cooperate with each other to enhance the performance of the network.

5.7.1 Cost of information exchange

We consider the cost of information exchange inside each grand coalition S_n, which consists of MTDs belonging to the same virtual cluster C_n and whose QoS is not satisfied, in terms of transmit power in order to model the data exchange penalty. Consequently the total power cost for a grand coalition is taken as the sum of the powers required by each MTD transmitter inside the grand coalition, $D_{m,t} \in S_n$, to communicate to the remaining MTD transmitters of the same coalition $D_{m',t} \in S_n$, $m' \neq m$ and can be expressed as:

$$\hat{P}_m^k = \sum_{m' \in S_n, m' \neq m} \frac{\nu_0 . \sigma^2}{(g^k_{D_{m,t}, D_{m',t}})^2} \tag{5.8}$$

where ν_0 is a target average SNR for information exchange, σ^2 is the noise variance and $g_{D_{m,t}, D_{m',t}}$ is the channel gain between MTD transmitters, from $D_{m,t}$ to $D_{m',t}$. The cost of information exchange $\hat{P}_m$ should be less than a given threshold denoted by $\tilde{P}_m$.

5.7.2 Payoff function

In the proposed cooperative game, we are interested in dividing the payoffs of a formed coalition S'_n among its members using the Shapley value. The latter is the most famous fairness criterion since members receive shares proportional to their marginal contribution. The Shapley value is used here in order to divide the payoff of a coalition among its members and measure the benefit of a cooperative game over a non-cooperative one [88]. The payoff portion of each member in a coalition S'_n is given by the Shapley value function as:

$$\Phi_m(v) = \sum_{S_n' \subseteq S_n \setminus \{m\}} \frac{\left|S'_n\right|! \left(|S_n| - \left|S'_n\right| - 1\right)!}{|S_n|!} \left[v\left(S'_n \cup \{m\}\right) - v\left(S'_n\right)\right] \tag{5.9}$$

where the number of members in the formed coalition that represents a subgroup of M2M pairs and the number of unsatisfied MTDs in the grand coalition that represents M2M pairs willing to play cooperatively are denoted by $|S'_n|$ and

$|S_n|$, respectively. We will consider in the simulation a maximum number of 3 for $|S_n|$.

$D_{m,t}$ belongs to a formed coalition S'_n only if

$$\mu_{m_{CPG}} \geq \mu_{m_{NPG}} \tag{5.10}$$

and where the payoff of a MTD player in the formed coalition is calculated as:

$$\mu_{m_{CPG}} = \Phi_m(v) + \mu_{m_{NPG}} \tag{5.11}$$

The worth $v(S'_n)$ of a formed coalition is as follows:

$$v(S'_n) = \sum_{m \in S'_n} \left(\alpha . \frac{R^k_{D_m}}{R^{min}_{D_m}} - \beta . \frac{p^k_m}{p^{max}_m} - \gamma . \hat{P}^k_m \right) \tag{5.12}$$

where α, β and γ are the positive weights constants of the throughput, the price of the transmission cost and the price of information exchange, respectively. Having defined the payoff of MTD players, we calculate the matrix power control game when different $D_{m,t}$ choose multi-power levels and use also the mixed Nash equilibrium to find the equilibrium of the CPG.

5.7.3 Advanced power control techniques in the strategy space

While fixed and discrete power levels with a minimum and a maximum power constraints define the strategy space for each MTD in the non-cooperative game, we benefit from the shared information inside a coalition in the cooperative game and combine the two novel power control schemes, namely PID and fuzzy logic controllers. The goal behind these power control mechanisms is threefold: **(i)** assure the desired QoS of H2H users; **(ii)** maximize the spectrum efficiency of M2M communications and **(iii)** save the battery life of MTDs. In the following, we give a reminder of the M2M transmit power adjustment using the PID or the fuzzy logic introduced in the previous chapter. Our aim here is to use the adaptive M2M transmit power combining the output of the PID and the fuzzy logic in the strategy space of the CPG.

5.7.3.1 Strategy space set using PID controller

The primary goal is to adjust properly the MTD transmit power such that the actual UE throughput, $R^k_{U_n}$ obtained in a H2H/M2M case, converges to its corresponding required QoS in terms of throughput, $R^{min}_{U_n}$. Similarly to Section 4.6.1, the PID controller takes as input the error signal *e(k)* that should be related to the MTD transmit power $P^k_m(k)$. Particularly, *e(k)* represents the gap between the current MTD transmit power and the maximum MTD transmit power. This

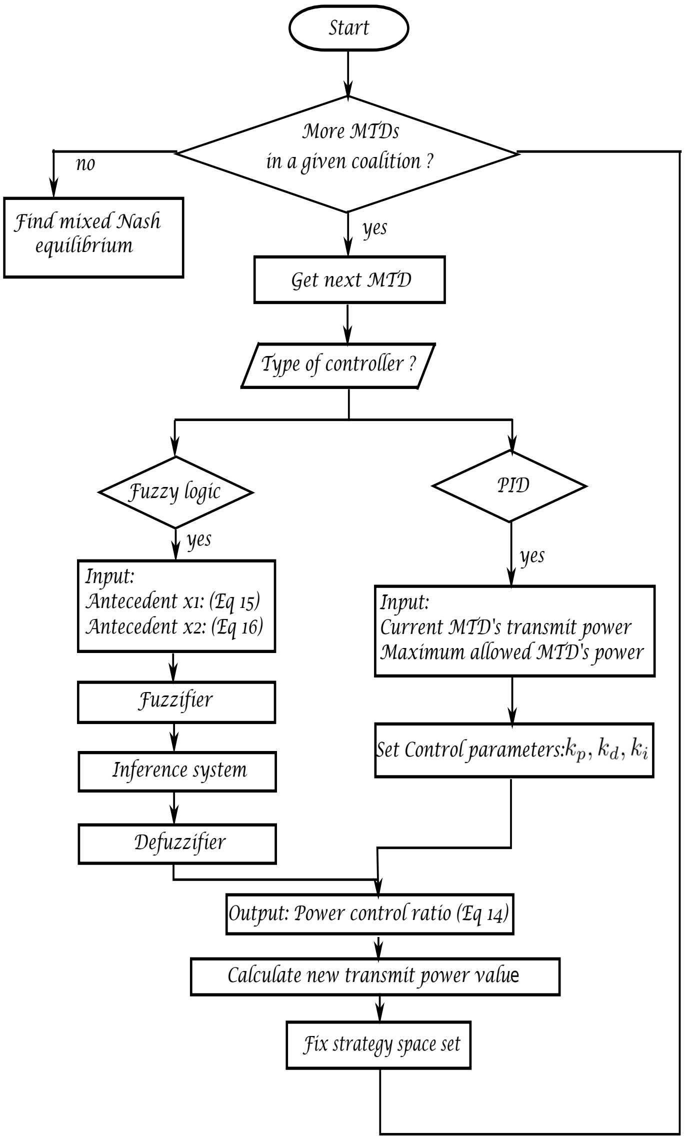


Figure 5.2 – Flowchart of advanced power control techniques in the strategy space

latter is determined given the UE's interference threshold that assure its desired QoS, $R_{U_n}^{min}$ as well as the channel gains of interference links between MTDs and eNB benefiting from the shared information inside a coalition. The PID controller gives as output the power control ratio, *u(k)*, defined in Eq. 4.10. Consequently, by applying the PID controller, the transmit power is limited to assure the desired QoS of H2H users and also to maximize the efficiency of M2M spectrum usage.

5.7.3.2 Strategy space set using fuzzy logic

Different from the PID controller where the MTD transmit power has been adjusted through applying a mathematical model, fuzzy logic is proved to deal with uncertainties (multi-path loss, channel fading) and human perception while approximating the mathematical solution. The basic structure of a fuzzy controller is displayed in the previous chapter in Fig. 4.2. Similarly to Section 4.7.1, we adjust efficiently the MTD transmit power using the fuzzy logic control. This latter consists of four processes. In a first step, measurements of all variables that represent the relevant conditions of the controlled process, called also antecedents (see Eq. 4.13 and Eq. 4.14), are taken. In a second step, the measurements are converted into appropriate fuzzy sets as shown in Fig. 4.4 to express measurements uncertainties which is called the fuzzification process. The third step consists of the fuzzy inference process that uses the fuzzified measurements to evaluate control rules which are shown in table 4.1. The fourth step is the defuzzification process where the output of this evaluation that is a fuzzy set is converted into a crisp value using the centroid method as the most popular method. Therefore, the fuzzy power controller dynamically adjusts the transmit power of the specific MTD in order to assure the QoS of H2H users, maximize the efficiency of the MTD spectrum usage and save the battery life of MTDs.

Fig. 5.2 illustrates the flowchart of advanced power control techniques used in the strategy space of CPG. For each MTD in a given coalition, two adaptive MTD transmit power are determined using either the PID or the fuzzy logic. In case of a PID controller, the new MTD transmit power is determined from the current MTD transmit power and the maximum allowed MTD transmit power. In the fuzzy logic case, the new MTD transmit power is determined based on fuzzy reasoning process. After properly determining the power level of MTD players in the cooperative scenario using PID and fuzzy logic controllers, we set the strategy space combining PID and fuzzy logic. Then, we calculate the payoff matrix when different $D_{m,t}$ choose multi-power levels and solve the mixed Nash equilibrium.

5.8 Performance evaluation

In order to evaluate the efficiency of the proposed hybrid-game-based MTC transmission strategy selection algorithm, we conduct the following simulations based on the 3GPP LTE system model [80]. The main parameters are summarized in table 5.1. We consider an isolated cell where traditional H2H and M2M communications coexist and can share the radio resources, RBs, for individual data transmission. The system bandwidth is $10MHz$; therefore 50 usable RBs are available per TTI. The channel model accounts for small scale Rayleigh fading and large scale path loss (log-normally distributed). We also assume a quasi-static channel model, meaning that the channel coefficients are constant over each transmission frame and change independently from frame to frame. MTDs and UEs in the cell are distributed randomly each scheduling period. For simplicity and without loss of generality, we assume that one RB is assigned to each H2H user per TTI. This assumption is due to the complexity introduced to uplink LTE scheduling algorithms because of the adjacency and power restrictions imposed by SC-FDMA and which is not the aim of our work. On the other side, one RB is assumed to be sufficient to fulfill M2M throughput requirements. We assume two power level strategies for each player $\{P_1,P_2\}$, where $\{13,14\}$ dBm is the proposed fixed discrete strategy space for the non-cooperative game and $\{10,13\}$ dBm is the proposed fixed discrete strategy for the cooperative game. Besides, as suggested in the sub-section 5.7.3, we combine the advanced power control schemes using PID and fuzzy logic, which are defined in details in Section 4.6, in the strategy space of the cooperative game only. We assume that the available power level for each MTD has the same dimension and consider that 3 is the maximum size of the virtual cluster which means that up to 3 M2M pairs can share the sub-channel with a given H2H user. We use two well known traditional scheduling algorithms for H2H communications, *Round Robin* (RR) and *Proportional Fairness* (PF). The simulation results are obtained through averaging 10 different realizations.

The nomenclatures, H2H and H2H/M2M mentioned in all figure legends refer respectively to the exclusive H2H case and the H2H/M2M coexistence case. In the following evaluation process, the performances obtained while the two well known conventional scheduling algorithms for H2H communications are in use, are shown as follows: (RR in Subfig (a)) and (PF in Subfig (b)).

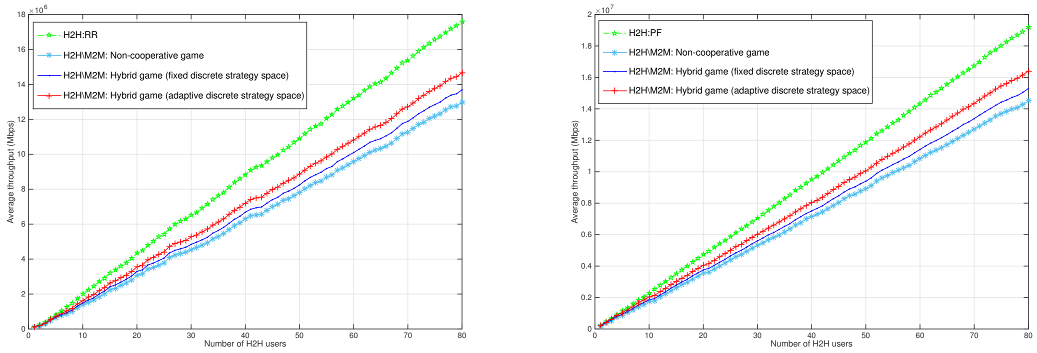
5.8.1 H2H throughput

Fig. 5.3 shows the H2H throughput as function of H2H users in both an exclusive H2H scenario and a H2H/M2M coexistence scenario in order to evaluate the impact of introducing M2M communications on H2H services. We use two alternatives in the proposed hybrid-game for MTC transmission strategy selection algorithm. The first alternative consists of choosing a discrete fixed power level strategy space for the proposed hybrid game (in both non-cooperative and cooperative games). In the second alternative, we choose a discrete fixed power level strategy space for the non-cooperative game and a discrete adaptive power level strategy space in the cooperative game. The proposed hybrid-game with both alternatives is also compared to the case where only a non-cooperative game is used. Concerning H2H scheduling algorithms, PF (Fig. 5.3 (b)) enhances the H2H throughput compared to the RR scheduling algorithm (Fig. 5.3 (a)). Indeed, this latter is a channel-blind algorithm that distributes RBs randomly to UEs while the PF scheduling policy tries to handle a trade-off between fairness and throughput. We observe that the worst performance in a H2H/M2M coexistence scenario is obtained when using a pure non-cooperative game approach

Table 5.1 – Simulation parameters

Parameter	**Value**
Cellular layout	Isolated cell
Cell radius	$500m$
UEs per cell	N = 80
MTDs per cell	N = 150
Path loss model	UMi in [80]
P_n	$23dBm$
D2D range	$250m$
Noise power spectrum density	$-174dBm/Hz$
Carrier frequency	$2.5GHz$
Small scale fading	Rayleigh fading coefficient with zero mean and unit variance
Channel bandwidth	W= $10MHz$
Modulation	QAM
k_p, k_d, k_i	0.3
$R_{U_n}^{min}$	$64Kbps$
$R_{D_m}^{min}$	$\{5Kbps, 9.2Kbps, 12Kbps\}$
α	1
β	0.7
γ	0.7
ν_0	$10dB$
$\tilde{P_m}$	$0.01P_m$

for MTDs sharing the same RB. For instance, the total H2H throughput for 80 UEs, when using a pure non-cooperative game, is decreased about 30% and 27% compared to the throughput obtained in an exclusive H2H scenario in RR and PF cases, respectively. This degradation is justified by the multiple resource sharing despite of the virtual clustering process that allow to partially assure the desired QoS of H2H users. Even though, our proposed hybrid-game transmission strategy selection algorithm when using a fixed power level strategy space achieves better performance compared to the non-cooperative game approach, a slight gain of about 5% is approximately achieved over the non-cooperative game. It is seen that the H2H throughput is significantly assured when using the hybrid-game transmission strategy selection algorithm with an advanced power level strategy in the cooperative game. For instance, the total H2H throughput is decreased by about 16% and 14% in RR and PF cases, respectively. This can be explained by the fact that an adaptive strategy space adjusts the M2M transmit power in a way that the QoS of H2H users is efficiently guaranteed contrarily to a fixed strategy space where high interference situations cannot be avoided since the M2M transmit power is fixed.

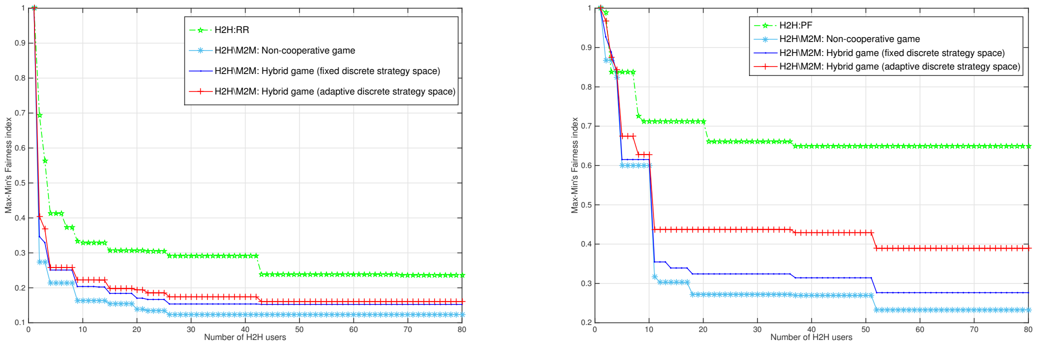


(a) RR (b) PF

Figure 5.3 – Total average throughput

5.8.2 H2H fairness

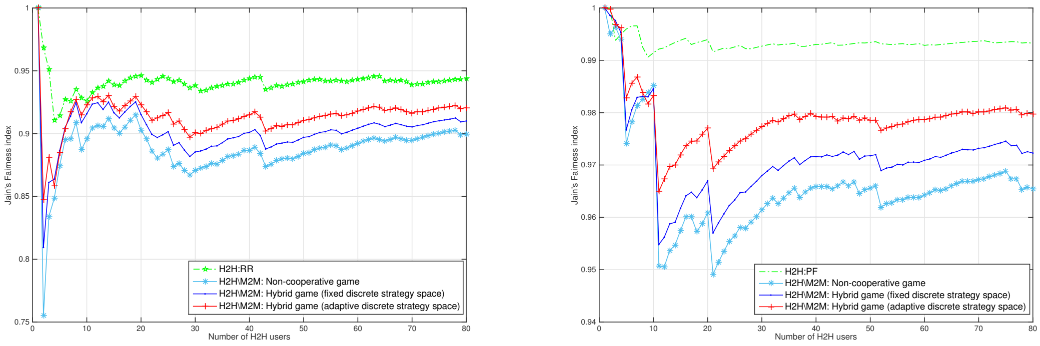
Both qualitative and quantitative fairness measures based on throughput are illustrated Fig. 5.4 and Fig. 5.5, respectively. Obviously, the PF scheduling algorithm used in an exclusive H2H scenario achieves a better level of fairness compared to the RR scheduling algorithm. Indeed, the PF scheduling algorithm assigns RBs to UEs according to the link quality and thus achieves a better throughput while trying to reach a fairness in the distribution of radio resources.



(a) RR (b) PF

Figure 5.4 – Max-Min's fairness index

The Jain's fairness index shows a good level of fairness in this case. This can be explained by the fact that H2H users are all assigned one RB. However, this high level of fairness does not necessarily guarantee that H2H users utilize these equally allocated resources in terms of number with the same efficiency which is justified with the max-min's fairness in Fig. 5.4. The fairness measures show



(a) RR

(b) PF

Figure 5.5 – Jain's fairness index

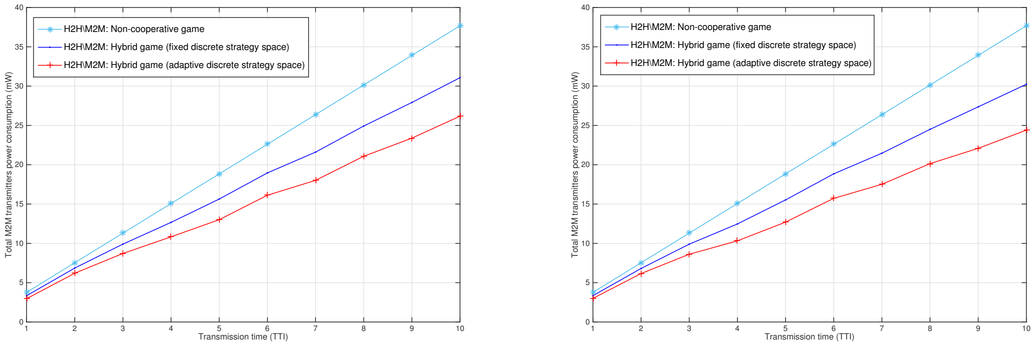
that PF algorithm is more sensitive to the introduction of M2M communications. What is quite interesting to note here, however, is that the proposed hybrid-game for MTC transmission strategy selection algorithm using an adaptive strategy space in the cooperative game, maintains better the level of fairness of existing RR and PF scheduling algorithms. For instance, Fig. 5.4 illustrates a decrease up to 30% and 40% in RR and PF cases, respectively for 80 users compared to the fairness obtained in an exclusive H2H scenario. This decrease can be explained by the multiple resource sharing case in a H2H/M2M coexistence scenario where we consider here that up to 3 MTDs can share radio resources with a given H2H user. Thus, we can conclude that the hybrid-game for MTC transmission strategy selection algorithm using an adaptive strategy space in the cooperative game achieves the best performance in terms of maintaining the fairness policy of H2H scheduling algorithms.

5.8.3 M2M power consumption

Fig. 5.6 shows the total power consumption of MTD transmitters as a function of transmission time. Our proposed hybrid-game for MTC transmission strategy selection algorithm when using an adaptive strategy space for the cooperative game achieves significant reduction in terms of transmit power of about 20% and 40% compared to the proposed hybrid-game when using a fixed strategy space for cooperative game and compared to a pure non-cooperative approach, respectively and hence improves notably the device battery life.

5.8.4 MTDs whose QoS is not met

Fig. 5.7 illustrates the average percentage of MTDs whose QoS in terms of throughput is not met for 10 TTIs. The proposed hybrid-game for MTC trans-



(a) RR (b) PF

Figure 5.6 – Total M2M transmitters power consumption

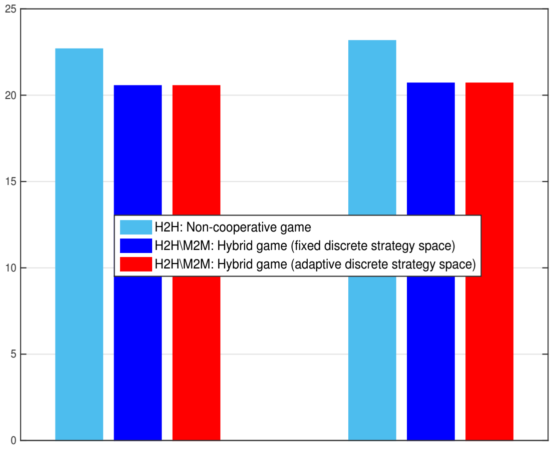


Figure 5.7 – Percentage of M2M pairs whose QoS is not satisfied

mission strategy selection algorithm with both alternatives, fixed or adaptive strategy space in the cooperative game, slightly outperforms the pure non-cooperative game strategy where MTDs are using the maximum transmit power which is quite promising. It is interesting also to note that our proposed hybrid-game for MTC transmission strategy selection algorithm with both alternatives, adaptive and fixed strategy spaces, achieves the same percentage of violated M2M pairs. This proves that the adaptive strategy space used in the cooperative game and which adjusts efficiently the MTD transmit power through combining PID and fuzzy logic allow to maximize the efficiency of M2M communications while achieving a significant gain in terms of transmit power consumption as demonstrated in Fig. 5.6 as well as assuring the desired QoS of H2H users as shown in Fig. 5.3.

5.9 Conclusions

In this chapter, we have focused on designing a scalable multiple access scheme tailored to the scale of M2M devices. We have proposed a novel group-based operation for M2M links using D2D communications underlying cellular networks. Multiple resource sharing is provided where multiple M2M pairs can use the same sub-channel while the desired QoS of H2H users is assured. We have addressed the joint issue of transmission strategy for D2D re-use mode for MTC (either a non-cooperative or a cooperative game), resource sharing and power control using a game theoretic framework. Within this aim, we have developed a novel efficient hybrid-game for MTC transmission strategy selection algorithm underlying cellular networks. Specifically, we have considered initially a non-cooperative game since M2M devices are selfish as they are in practical scenarios. Then, M2M devices whose QoS is not satisfied form a coalition and switch in a fully distributed manner to a cooperative game. To benefit from the information exchange of the cooperative game, we have proposed two alternative power control schemes: a fixed and an adaptive strategy space. In contrast to the former approach that considers a fixed and discrete power levels, the latter approach enables the power levels using a fuzzy logic and a PID controller to be properly set in order to save the battery life of M2M devices while guaranteeing traditional H2H services and maximizing the spectrum efficiency. We have investigated the impact of introducing M2M services on existing H2H services in LTE-A. Our evaluation study has clearly shown that the hybrid-game based M2M transmission strategy selection algorithm avoids significant degradation of H2H services in terms of throughput and maintains the UE's level of fairness compared to the non-cooperative approach. In addition, the adaptive alternative of the hybrid-game allows to save considerably the MTD battery life while maintaining the QoS of M2M links.

- CHAPTER 6 -

CONCLUSIONS AND FUTURE WORKS

In this chapter, we present the conclusions drawn from the results of this dissertation and we highlight the possible future extensions that could be promising to further corroborate our results and achievements.

6.1 Conclusions

Providing adaptive and efficient radio resource sharing schemes for MTC underlying cellular networks is fundamental to enable the massive scale of MTC. By efficient, we mean the design of spectrally and power efficient radio resource sharing schemes. And by adaptive we mean the adaptive utilization of shared available radio resources that allows the network to accommodate M2M services while guaranteeing existing H2H services. To that end, we have split our study into three sub-problems, and thus have answered the questions, Q1-Q3 that we initially addressed in chapter 1. These questions were:

- Q1 How to provide a scalable *Medium Access Control* (MAC) protocol able to handle the massive number of M2M devices?
- Q2 How to have no or limited impact on existing H2H services with the introduction of M2M devices?
- Q3 Considering the selfish behavior of M2M devices, how to provide fully distributed and energy efficient concurrent access for MTC under cellular networks since M2M devices are battery driven and often deployed in remote areas which makes battery replacement hard?

We have first provided in chapter 3 a novel spectrally efficient radio resource sharing scheme for MTC under a H2H/M2M coexistence scenario, and thus we have replied to the question Q1. We have proposed group-based MTDs transmitting traffic through D2D technology. While the group-based operation permits a reduction of the air interface overload, the aggregation of M2M and D2D technology makes it possible to tackle the scalability issue of the massive scale of emerging MTDs. To counter the computational complexity of the sum-rate optimization problem, we have modeled the radio resource sharing problem between H2H users and MTDs as a bipartite graph and have considered a two-stage radio resource allocation approach where H2H users are given higher priority. Then, we have developed an interference-aware graph-based resource sharing algorithm so as to mitigate co-channel interference and thus enhance network efficiency. The goal behind our proposed interference-aware graph-based resource sharing algorithm is to re-assign MTDs one of the available radio resources already assigned to H2H users assuming a fixed M2M transmit power. Furthermore, we have developed a semi-distributed instantiation of the proposed algorithm in order to reduce the high communication overhead of the centralized approach. Our simulation results under a static scenario in the context of LTE have shown that the proposed Fixed Centralized Radio Resource Sharing Algorithm (F-C-RRSA) achieves approximately a gain of 15% over the proposed Fixed semi-Distributed Radio Resource Sharing Algorithm (F-sD-RRSA) in terms of network sum-rate. However, the proposed F-sD-RRSA has lower communication overhead. We have also shown that the inter-cluster interference is not significant due to the low MTD transmit power.

Convinced by the strength of the bipartite graph methodology to provide low computational complexity sub-optimal solution of the radio resource sharing issue between H2H users and MTDs, we have empowered in chapter 4 the proposed interference-aware graph-based algorithm with an adaptive power control feature in order to address the question Q2. The goal behind the power control feature is to further enhance the protection of H2H services under a H2H/M2M coexistence scenario by efficiently adjusting the MTD transmit power. Therefore, we have provided a joint spectrally and power efficient framework. We have used one of two alternative power control mechanisms: the Proportional Integral Derivative (PID) controller, as the most well known controller that requires a rigorous mathematical knowledge of the system, and the fuzzy logic, as a simple tool that uses linguistic information. Our evaluation study under a mobile scenario has clearly shown that the adaptive algorithms significantly reduce the negative impact on H2H communications in terms of throughput and protect the level of fairness achieved in an exclusive H2H scenario. The fuzzy logic-based adaptive M2M radio resource sharing algorithm yields the best compromise between guaranteeing H2H performance and satisfying M2M services. Indeed, the fuzzy logic controller provides a smooth operation on M2M transmit power and thus is more resilient to parameter variations when compared to the PID controller.

Our third contribution in chapter 5 is about designing a joint fully distributed and energy efficient radio resource sharing scheme for MTC, and thus we have replied to the question Q3. We have proposed a novel group-based operation for M2M links and have enabled multiple resource sharing where multiple M2M pairs can use the same sub-channel while the desired QoS of H2H users is assured. Convinced by the strength of game theory as a relevant tool to model situations in which decision makers have to take specific actions that have possible mutual conflicting consequences, we have developed a novel efficient hybrid-game for an MTC transmission strategy selection algorithm underlying cellular networks. We have set a preference order for the transmission strategy of each M2M pair using D2D re-use mode. Specifically, we have considered initially a non-cooperative game since M2M devices are characterized by a selfish behavior as they are in practical scenarios. Then, M2M devices whose QoS is not satisfied form a coalition and switch in a fully distributed manner to a cooperative game. To benefit from the information exchange of the cooperative game, we have proposed two alternative power control schemes: a fixed and an adaptive strategy space. In contrast to the former approach that considers a fixed and discrete power levels, the latter approach enables the power levels using fuzzy logic and PID controller to be properly set in order to save the battery life of M2M devices. We have conducted an extensive simulation study under a mobile scenario to assess the impact of the proposed hybrid-game-based transmission strategy selection algorithm on H2H services in terms of throughput and fairness and have evaluated the gain in terms of power consumption. Simulation results have shown that the proposed hybrid-game using the adaptive strategy space in the cooperative approach is the one that achieves the best compromise by guaranteeing H2H performance in terms of throughput and fairness while at the same time maximizing the efficiency of M2M spectrum usage. In addition, the battery life of MTDs is significantly extended with a gain of up to 40% compared to a pure non-cooperative game approach.

6.2 Future works

Though this study addresses several of the requirements that are significant for enabling the massive scale and specific requirements of MTC, there are still many opportunities to extend this work.

We have considered that MTD traffic is sent through the radio resources allocated to H2H users in order to cope with the spectrum scarcity. However, a fundamental question arises: why should H2H users share their allocated sub-channels with M2M devices which lead to a degradation of their performance. Developing strategies and incentives to encourage resource sharing between H2H users and MTDs, as a two-sided-market, and using them in our model would be interesting. New methodologies for conducting the costs/benefits ratio in a given sharing scenario can be formulated to address the incentive issue. For example, MTDs may provide monetary compensation to H2H users in spite of sharing the latter spectrum. The cost of using underlying D2D technology should be well studied, so that MTDs involved in D2D communication should not be charged more than using the services of a BS. In addition, incorporating a level of trust into incentive mechanisms is of great relevance. Indeed, since both H2H users and M2M devices are exchanging information (distance, channel information ...), involving a mutual reputation reward in the incentive mechanism that reflects the performance and reliability of each node will render the resource sharing vitreous and thus would enhance the spectrum sharing.

Another perspective could be the extension of our proposed adaptive and efficient radio resource sharing framework for MTC underlying cellular networks to security system design problems. Due to the specific features of M2M communications benefiting from D2D technology, unique security threats are exposed to M2M services. Different from traditional infrastructure-based communication, the direct communication between devices is more vulnerable. M2M devices are semi or fully self managed and characterized by a limited computational capacity of devices which may hinder successful deployment of MTC. While monitoring has been suggested for a long time as a relevant solution for securing the network and detecting intrusions by a centralized entity, it cannot be the convenient solution to handle the massive number of MTC. Consequently, focusing on facilitating the design of security and privacy solutions for M2M communications by developing novel security operations that compensate the power consumption and computational capacity for limited capacity M2M devices is a challenging issue.

Also, in chapter 5, we have proposed a novel efficient and fully-distributed hybrid transmission strategy selection algorithm taking into consideration the selfish behavior of M2M devices. Integrating the hybrid transmission strategy selection algorithm with an Evolutionary Game Theory (EGT) modeling is promising. EGT focuses on the dynamics of the strategy adaptation in the population. In contrast to our proposed hybrid transmission strategy selection algorithm where the utility function has been designed based on multiple parameters and a sufficient amount of available information, we are interested in studying network scenarios where nodes do not possess enough information to construct detailed utility functions. The idea is to focus on how node behavior evolves, through identifying situations where nodes are involved in a non-cooperative game or in a cooperative game. An interesting aspect of EGT compared to classical game theory is that it provides a way to understand how node strategies can thrive even when such behavior is not rational in terms of received payoffs.

As a final comment, one should note that we have addressed throughout this thesis the problem of uplink energy-efficient resource sharing algorithms for MTC underlying cellular networks. Different from works that have proposed resource allocation algorithms within a primary objective to maximize the aggregate throughput under a H2H/M2M coexistence scenario, we have considered the energy efficiency as the main requirement and have used different power control strategies to assure the desired QoS for H2H users and to maximize the spectrum usage. Including the delay requirement to our proposed solutions is possible and can completely characterize the H2H/M2M co-existence scenario. This proposed open issue as well as extending our solutions to handle other system design requirements such us load balancing, handover ... would also contribute to pave the way for a successful deployment of massive MTC.

PUBLICATIONS

International Journals

S. Hamdoun, H. Tembine, A. Rachedi and Y. Ghamri-Doudane, “Efficient Hybrid-Game for MTC Transmission Strategy Selection Algorithm in D2D-based 5G Networks’, IEEE Elsevier Ad hoc Networks, *submitted*, 2017.

S. Hamdoun, A. Rachedi and Y. Ghamri-Doudane, “A Graph-Based Radio Resource Sharing Scheme for MTC in D2D-based 5G Networks’, IEEE Transactions on Vehicular Technology, *submitted*, 2016.

International Conferences

S. Hamdoun, A. Rachedi, H. Tembine and Y. Ghamri-Doudane, “Efficient Transmission Strategy Selection Algorithm for M2M Communications: An Evolutionary Game Approach’, IEEE NCA, Cambridge, MA USA, November 2016.

S. Hamdoun, A. Rachedi and Y. Ghamri-Doudane, “A Flexible M2M Radio Resource Sharing Scheme in LTE Networks within an H2H/M2M Coexistence Scenario’, IEEE ICC, Kuala Lumpur, Malysia, May 2016.

S. Hamdoun, A. Rachedi and Y. Ghamri-Doudane, “Radio Resource Sharing for MTC in LTE-A: An Interference-Aware Bipartite Graph Approach’, IEEE Globecom, San Diego, CA, USA, December 2015.

National Conferences

S. Hamdoun, A. Rachedi and Y. Ghamri-Doudane, “Gestion adaptative des ressources radio dans un scénario de coexistence M2M/H2H’, IEEE CoRes, Bayonne, France, May 2016.

S. Hamdoun, A. Rachedi, and Y. Ghamri-Doudane, “Partage des ressources radio pour MTC dans LTE-A: Une approche basée sur le graphe biparti’, IEEE CFIP NOTERE, Paris, France, July 2015

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