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Safa Hamdoun, Abderrezak Rachedi, Yacine Ghamri-Doudane. Graph-Based Radio Resource Sharing Schemes for MTC in D2D-based 5G Networks. *Mobile Networks and Applications*, 2020, 25, 10.1007/s11036-020-01527-1 . hal-02518521

HAL Id: hal-02518521

<https://hal.science/hal-02518521>

Submitted on 21 Jun 2023

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Graph-Based Radio Resource Sharing Schemes for MTC in D2D-based 5G Networks

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Received: 07/12/2019 / Accepted: date

Abstract Apart from the the increasing demand of smart-phones in *human-to-human* (H2H) communications, the introduction of *machine-to-machine* (M2M) devices poses significant challenges to wireless cellular networks. In order to offer the ability to connect billion of devices to propel the society into a new era of connectivity in our homes, offices and smart cities, we design novel radio resource sharing algorithms in a H2H/M2M coexistence case to accommodate M2M communications while not severely degrading existing H2H services. We propose group-based M2M communications that share the same spectrum with H2H communications through *device-to-device* (D2D) communication, as one of the technology components of 5G architecture. First, we formulate radio resource sharing problem as a sum-rate maximization, problem for which the optimal solution is non-deterministic polynomial-time hard (NP-hard). To overcome the computational complexity of the optimal solution, we model the resource sharing problem as a bipartite graph, then propose a novel interference-aware graph-based resource sharing scheme using a fixed M2M transmit power. To further enhance the protection of H2H services, we introduce an adaptive power control mechanism into the interference-aware graph-based resource sharing scheme. M2M

transmit power is efficiently adjusted using one among the two following alternative controllers, namely, either the *proportional integral derivative* (PID) or the fuzzy logic. The latter is proposed within the aim to assure the desired *quality-of-service* (QoS) of H2H users and increase the efficiency of M2M spectrum usage. In both cases (fixed and adaptive), a centralized and a semi-distributed instantiations are given. Simulation results show that adaptive M2M radio resource sharing scheme using fuzzy logic is the one that achieves the best compromise. In fact, it guarantees H2H performance in terms of throughput and fairness while maximizing the efficiency of M2M spectrum usage. Simulation results also show that in spite of its quite good performance, the semi-distributed M2M resource sharing instantiation achieves them with a decline of up to 10% in terms of H2H throughput compared to the centralized instantiation. This is achieved through a markedly lower communication overhead.

Keywords M2M communications, H2H communications, D2D technology, radio resource sharing, PID controller, Fuzzy logic

1 Introduction

Machine-to-machine (M2M) communication is an evolving paradigm that enables the ubiquitous connectivity between billions of devices with limited or no human intervention. The autonomous connection and proliferation of smart devices, embedded in the streets to traffic control systems cars or little drones (both terrestrial and aerial) and beyond, facilitates the emergence of a wide range of intelligent M2M applications such as pollution mitigation, farming, and emergency rescue operations. These more demanding large-scale M2M applications are the key enabler for the *internet of things* (IoT)[1,2] and flying and driving networks [3,4] as a new potential market .

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Two major scenarios can characterize M2M communications. The first one is the client/server model which consists of the communication between *machine-type-devices* (MTDs) and one or more *machine-type-servers* (MTSs). Most M2M applications, such as health monitoring, water, gas, or power metering adopts client/server scenario. Group-based operation in such scenario is a promising solution to offload the *base station* (BS). The second scenario adopts an alternative model of communication where MTDs are communicating directly through *peer-to-peer* (P2P) communications [5].

With the pervasive coverage, efficient support of user mobility as well as high data rates, cellular networks have been considered the key enabler for M2M communications[6]. The *third generation partnership project* (3GPP) has named M2M communication as *machine-type-communication* (MTC). As cellular networks has been optimally designed for *human-to-human* (H2H) communications [7], significant researches from release 10 and beyond in 3GPP have considered enhancements to support MTC.

Different from H2H services, M2M applications have their own requirements such as energy efficiency and small data transmission. These characteristics render traditional uplink scheduling algorithms designed for H2H communications not suitable for MTC communications. Traditional LTE scheduling schemes have been dedicated for broadband applications with high data rates [8]. Thus, existing LTE uplink scheduling algorithms cannot cater to M2M requirements because of their associated complexity and high signaling overload.

device-to-device (D2D) technology, introduced in LTE release 12 and beyond, is seen as a key enabler for M2M communications mainly for its high spectral efficiency. D2D enables a direct communication between two users without traversing the BS. Indeed, same radio resources can be shared between D2D and *cellular user equipments* (UEs) links. Therefore, designing novel radio resource sharing algorithms that mitigate the co-channel interference is of fundamental importance .

In our previous work [9], we investigated from a MAC layer perspective the radio resource sharing problem in a H2H/M2M coexistence scenario where group-based MTC underlying cellular network transmit traffic through D2D technology. The novelties and main contributions of this paper are summarized as follows:

- First, we consider that M2M communications are underlying H2H communications, and formulate the radio resource sharing issue as a sum-rate maximisation, problem for which the optimal solution is non-deterministic polynomial-time hard (NP-hard).
- We model the radio resource sharing problem for M2M underlying H2H communications as a bipartite graph to overcome the high computational complexity of the op-

timal solution, where a two-stage radio resource allocation mechanism. In order to assure higher priority to H2H communications, traditional LTE scheduling algorithms are used, in first step, to assign radio resources to H2H communications. Then, we develop an interference-aware graph-based resource sharing scheme for M2M communications underlying cellular networks.

- We introduce a novel adaptive power control mechanism that we integrate into our interference-aware graph-based resource sharing approach to further guarantee H2H applications and maximizing the efficiency of M2M services. We use one among two alternative mechanisms to adjust efficiently the M2M transmit power: either *proportional integral derivative* (PID) controller or fuzzy logic controller.
- We develop a centralized and a semi-distributed instantiation for each of our interference-aware graph-based resource sharing schemes: fixed (with a fixed M2M transmit power) as both adaptive features (with an adaptive M2M transmit power using either PID or fuzzy logic).
- Finally, we address a numerical assessment study to compare our proposed graph-based radio resource sharing schemes and evaluate their impact on H2H services in terms of fairness and throughput.

The rest part of this paper is organized as follows: Section 2 introduces the background, involving the benefits of group-based MTC underlying cellular networks as well as an overview of two well-known controllers in the control field: PID and fuzzy logic mainly used in our work to adjust efficiently MTC transmit power. Section 3 presents related works. This is followed by a formulation of the resource sharing problem in a H2H/M2M coexistence scenario as an optimization problem, then we model the resource sharing problem as a novel interference-aware bipartite graph. In Section 5, we develop two instantiations for the fixed graph-based radio resource sharing schemes: a centralized and a semi-distributed one. In Section 6, we integrate an adaptive radio resource sharing feature, using either a fuzzy logic or a PID along with their centralized and semi-distributed instantiations. Section 7 presents our numerical assessment study. Finally, the conclusion and future perspectives are given in Section 8.

2 Background

In this section, we first give the merits of group-based MTC using D2D technology. Then, we introduce briefly two major controllers namely PID and fuzzy logic that we integrate into our proposed adaptive power control-based radio resource sharing scheme to adjust M2M transmit power.

2.1 Group-based MTC using D2D technology

The ultimate goal behind grouping MTDs remains in reducing the number of communications through the BS. D2D communication offered in LTE-A is an emerging technology that allows devices to communicate among themselves without traversing the BS [10]. Consequently, transmitting MTC traffic through D2D links is a promising motivation and the benefits are twofold: **(a)** MTDs in a cluster can communicate to the cluster head called *machine type head* (MTH) through D2D technology, reducing the number of connections between devices and the BS and countering the *radio access network* (RAN) overhead. **(b)** The power consumption is reduced as nearby devices can communicate directly without necessarily traversing the BS. Based on the spectrum usage of inband D2D communications, which occurs on the cellular spectrum, existing works can be classified into two categories: inband underlay D2D and inband overlay D2D. While D2D and cellular links are allocated each dedicated cellular resources in the latter category [11, 12], they share the same resources in the former case [13, 14]. Obviously, inband underlay D2D improves the efficiency of the cellular spectrum. Thus, novel radio resource sharing algorithms should be designed to address the mitigation of co-channel interference.

2.2 Overview of PID controllers and Fuzzy Logic

PID and fuzzy logic are considered the two major controllers in the control field that are widely used to address many problems in different application areas such as leveling security services or managing the radio resources in wireless networks [15–18]. While PID controllers require a rigorous mathematical knowledge of the system, fuzzy logic is a versatile tool that introduces a simpler language through linguistic information, which render it easier and cheaper to implement. Fuzzy logic is considered a strong tool for many applications where mathematics are not the appropriate conceptual model to characterize the imprecision of the real world. In our work, we integrate either PID or fuzzy logic aiming at controlling efficiently the M2M transmit power in order to mitigate the co-channel interference in a H2H/M2M coexistence scenario [6].

2.2.1 PID

The Proportional Integral Derivative (PID) controller is a very well known feedback controller in the control field. Its basic concept consists of keeping a measured process variable close to a desired value regardless of the variation of the process dynamics. Fig. 1 illustrates the PID feedback control system. The input of PID controller is the error signal, $e(k)$, that represents the difference between the measured process

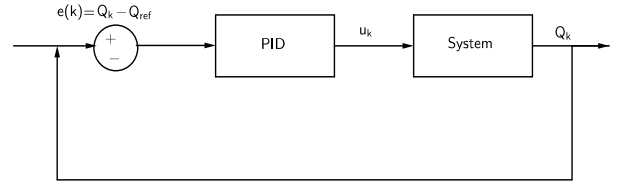


Fig. 1: A PID-controller based system

variable Q_k and a reference value Q_{ref} . The control variable u_k is the output of the PID controller. Three types of control actions describes the PID controller:

- **Proportional to the error (P part):** The P part reacts immediately to the sensed error.
- **Proportional to the integral of the error (I part):** The I part integrates the history of the error.
- **Proportional to the derivative of the error (D part):** The D part predicts the immediate future and then makes corrections based on the estimated error.

The three types of control actions can be combined or used separately [19].

2.2.2 Fuzzy Logic

Fuzzy logic, in control field, adopts a linguistic representation to model the process to be controlled [20]. Different from PID controller that relies on a precise data value to generate a specific output based on a mathematical model, the fuzzy theory deals with imprecision and is easier to prototype. The fuzzy logic decision making process is composed of three consecutive steps as illustrated in Fig. 2:

- **Fuzzification:** A crisp set of input data are gathered and converted to a fuzzy set using predefined *membership functions* (MBFs). MBFs are a set of fuzzy regions that define control variables in the fuzzy model.
- **Fuzzy inference system:** Fuzzy numbers or input variables are fed into a predefined fuzzy control rules which tie the input values to the output model properties.
- **Defuzzification:** The output of the fuzzy set is converted into a crisp value. The most popular method of defuzzification is the centroid, where the center of area of the fuzzy set is determined and used as the defuzzified output.

Unlike PID controllers that require a mathematical knowledge of the system to be controlled, fuzzy logic is considered a powerful method for its computational simplicity. We are motivated in this paper to integrate one among PID and fuzzy logic controllers into our adaptive interference-graph based radio resource sharing scheme with the aim to guarantee H2H services and maximize M2M spectrum usage.

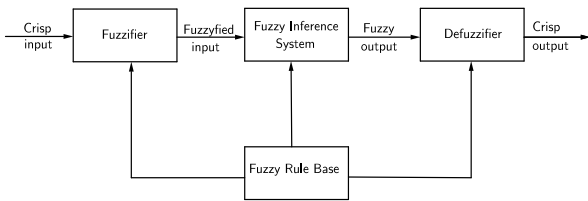


Fig. 2: A fuzzy system

3 Related Works

Different from traditional human-centric communications where the research efforts are in downlink (DL) and uplink (UL), MTC applications are usually uplink-centric. LTE has been initially designed for broadband applications, and thus is able to only handle traditional H2H communications [8, 21, 22]. However, the specific features of M2M communications characterized by the small amount of data to forward and the massive scale of MTDs render existing UL radio resource allocation algorithms prohibitive to cater to M2M scenarios. Hence, designing new UL radio resource allocation schemes in LTE network and beyond that well-accommodate MTC is crucial.

A handful of works [23, 24] have recently investigated the radio resource allocation algorithms in a H2H/M2M co-existence scenario for LTE. A mixed scheduler has been proposed in [23], where MTDs have been classified based on their delay tolerance. While higher priority has been given to UEs, the rest of radio resources have been allocated to MTDs. The best radio resources in terms of channel quality have been assigned to the least delay tolerant MTD. Authors in [24] have proposed a mixed scheduler for H2H and M2M communications. Radio resources have been assigned to UEs in a first step, then residual resources have been adaptively assigned to MTC communications with the aim to minimize the rejection upon incoming connection of MTDs. However, the problem of starvation for MTDs remains the major drawback of these works in case of a heavy H2H traffic scenario. In addition, the quite good obtained performance comes at the expense of a huge signaling load due to the centralized feature. The latter consists of sending reports to the *evolved Node B* (eNB) individually per MTD.

In order to face the challenge of spectrum scarcity due to the massive scale of MTC, many authors have opted to use random access procedure as an appropriate method to enable the multiple access. A group-based M2M radio resource allocation scheme has been proposed in [25, 26] to handle massive M2M communications. MTDs sharing the same QoS requirements have been grouped logically into clusters according to their allowed jitter. Then, fixed access grant time interval (AGTI) has been periodically assigned to each cluster. Within an allocated AGTI, a fixed number

of time-frequency domain radio resources has been given to support MTDs in each cluster. The major limitation is that only constant-rate traffic patterns are considered by the authors contrarily to the randomness of real M2M traffic and the radio spectrum is not efficiently used. Furthermore, the impact of this mechanism on traditional H2H users has not been discussed. On the other hand, authors in [27] have opted to use a classical *time-division multiple access* (TDMA) scheme to enable the multiple access for MTC. Particularly, MTDs have been matched to a particular UE and assigned the radio resources originally occupied by UEs in a TDMA manner to transmit their traffic. Nevertheless, authors here have not considered the QoS guarantees for UEs. Moreover, the TDMA scheme leads to low spectral efficiency.

Underlay D2D communication is considered an efficient alternative to enable the multiple access for MTC. Indeed, D2D users here can re-use the cellular spectrum, and communicate directly while remaining controlled by the BS. The original motivation for exploiting underlay D2D communication has been to increase the spectral efficiency and reduce the communication delay [28, 29]. However, the prominent issue to solve in an underlay D2D communication mode is the co-channel interference due to the orthogonality loss. In [14], authors have proposed an interference limited area control scheme to prevent cellular user equipments located in a predefined area from sharing radio resources assigned to D2D users. A widely used technique in literature to avoid the interference situations in D2D underlying cellular networks is to control the transmit power of D2D and/or cellular links. For instance, previous works in [30–32] have considered the joint optimization of power allocation and resource scheduling for D2D communications underlying a cellular infrastructure. The proposed scheduling algorithms in these works have been based on centralized mathematical models using mixed-integer programming. However, the corresponding solution methods might be cumbersome for a MTC scenario. In [28], authors have given the eNB the ability to adapt the transmit power of a cellular user. Indeed, the transmitter of cellular links underlying D2D links can increase its transmit power to mitigate the interference created by D2D links. However, traditional H2H users have higher priority which motivate us in this work to guarantee H2H services through assuming that MTDs are required to adapt their transmit power in a H2H/M2M co-existence scenario. Graph theory is a strong tool for modeling different type of interactions, and is widely used to tackle the resource management problem. Authors in [33] have formulated the interference relationships for D2D communication links underlying cellular communication as an interference-aware graph. A low computational complexity resource allocation scheme has been proposed to maximize the network sum-rate. However, only the downlink is investigated. Be-

Table 1: Acronyms

<i>M2M</i>	Machine-to-machine communications
<i>MTC</i>	Machine-type-communications
<i>H2H</i>	Human-to-human communications
<i>D2D</i>	Device-to-device communications
<i>UE</i>	User equipment
<i>MTD</i>	Machine-type-device
<i>MTH</i>	Machine-type-head
<i>eNB</i>	evolved Node B
<i>RB</i>	Resource block
<i>TTI</i>	Transmission time interval
<i>BG</i>	Bipartite graph

sides, QoS requirements of D2D and cellular links are not considered.

Convinced by the strength of the graph theory, we propose a novel interference-aware-graph-based radio resource sharing scheme for M2M. We enable M2M to transmit traffic through D2D technology, making MTC an underlay to traditional cellular communications. Different from previous works, we consider a two-stage resource allocation approach where H2H users have higher priority. Thus, in a first step, traditional scheduling algorithms optimally designed for H2H services are carried out. In a second step, we introduce a low computational complexity interference-aware graph-based resource sharing scheme for M2M that efficiently re-assign MTDs one of the available radio resources already allocated to H2H users. Then, we introduce an adaptive power control feature into the interference-aware graph-based resource sharing scheme with the aim to guarantee the performance of H2H services while overcoming the limitation of the above mentioned related work. Indeed, none of the mentioned works, proposing radio resource sharing algorithms for MTC underlying cellular networks, jointly and successfully considered the impact on H2H services as well as spectrum usage efficiency.

4 System Model and problem formulation

4.1 System description

We focus on the uplink LTE networks in a multi-user M2M/H2H coexistence scenario and consider a single cell, as illustrated in Fig. 3. In the proposed system model, the eNB is located at the center of the cell. Machine-type-devices (MTDs) here communicate through D2D communications, rendering MTC 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 performs the role of a cluster head. The acronyms used in this paper are summarized in Table 1.

In LTE networks, the radio resources are distributed in both time and frequency domains. In the time domain, radio

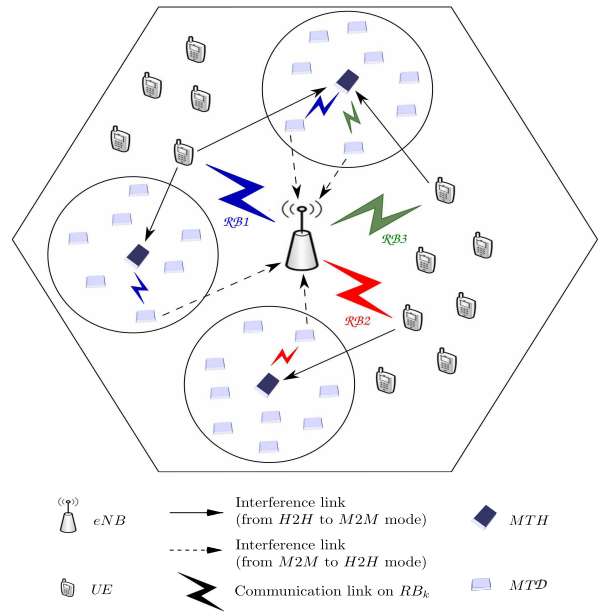


Fig. 3: System model under study: inter-MTD within D2D underlying cellular network

resources are distributed every Transmission Time Interval (TTI) that consists of two slots and has a duration of 1 ms. 20 slots or 10 TTIs constitute one LTE frame. In the frequency domain, the available bandwidth is divided into a number of sub-channels each including 12 subcarriers. Each subchannel has a bandwidth of 180 kHz and along with 7 symbols in the time domain constitutes a RB. Depending on the available bandwidth, the number of RBs can vary from 6 to 110. Further, we

In LTE networks, the radio resources are distributed in time and frequency domains. Radio resources, in the time domain, are distributed every transmission time interval (TTI), 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 sub-carriers with 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). This latter is the minimum unit of the resource allocation process. The number of available RBs ranges from 6 to 110[34] depending on the bandwidth.

To increase spectrum usage efficiency, we assume that MTDs are sharing radio resources with H2H users (UEs) through D2D technology. Specifically, we assume that UEs are not allowed to share RBs due to their high transmit power. Consequently, no interference is generated between UEs. Besides, we suppose that MTDs are allocated at most one RB due to their small data transmission. MTDs of the same cluster cannot share the radio resource RB. On the other side, radio resource sharing among UEs and MTDs as well

Table 2: Notations

Notation	Description
$\mathcal{K} = \{1, 2, \dots, K\}$	Set of sub-channels
$\mathcal{M} = \{1, 2, \dots, M\}$	Set of MTDs
$\mathcal{N} = \{1, 2, \dots, N\}$	Set of UEs
$\mathcal{L} = \{1, 2, \dots, L\}$	Set of clusters
β	Bandwidth
P_n^k	UE transmit power over k^{th} RB
P_m^k	MTD transmit power over k^{th} RB
U_n	Traditional UE
C_l	Cluster l
$D_{m,t}^l$	MTD transmitter m that belongs to C_l
$D_{m,r}^l$	MTH or MTD receiver of C_l
R^k	Throughput on k^{th} RB

as among MTDs of different clusters is not forbidden owing to the MTD's low transmit power. In this paper, we focus on the intra-cell interference, particularly the interference from MTDs to the eNB (*interference from M2M mode to H2H mode*) and from UEs to MTHs (*interference from H2H mode to M2M mode*).

Similarly to [9], we determine the channel gains of different communication and interference links from the *path loss* (PL) and the small scale fading, as listed in Table 3. The different notations are defined in Table 2. A frequency flat fading on each RB is considered where the small scale fading for a certain communication link is independent, but remains the same on each RB.

Table 3: Channel gains

Channel gain on RB_k	from \Rightarrow to
$g_{U_n}^k = PL_{U_n} h_{U_n}^k$	UE \Rightarrow eNB
$g_{D_{m,t}^l, D_{m,r}^l}^k = PL_{D_{m,t}^l, D_{m,r}^l} h_{D_{m,t}^l, D_{m,r}^l}^k$	MTD \Rightarrow MTH
$g_{D_{m,t}^l, eNB}^k = PL_{D_{m,t}^l, eNB} h_{D_{m,t}^l, eNB}^k$	MTD \Rightarrow eNB
$g_{U_n, D_{m,r}^l}^k = PL_{U_n, D_{m,r}^l} h_{U_n, D_{m,r}^l}^k$	UE \Rightarrow MTH

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

$$R_{U_n}^k = \beta \log_2 \left(1 + \frac{P_n^k g_{U_n}^k}{\sum_{l \in \mathcal{L}} \sum_{j \in \mathcal{M}} I_{(D_{j,t}^l, eNB)}^k + \sigma^2} \right) \quad (1)$$

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 the thermal noise, denoted by σ^2 and modeled as an independent Gaussian distribution with zero mean.

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

$$R_{D_{m,t-r}^l}^k = \beta \log_2 \left(1 + \frac{P_m^k g_{D_{m,t}^l, D_{m,r}^l}^k}{\sum_{i \in \mathcal{N}} I_{(U_i, D_{m,r}^l)}^k + \sum_{l' \in \mathcal{L}, l' \neq l} \sum_{j \in \mathcal{M}} I_{(D_{j,t}^{l'}, D_{m,r}^l)}^k + \sigma^2} \right) \quad (2)$$

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 . Throughout this paper, we consider that inter-cluster (inter-D2D) interference is negligible since MTD transmit power is relatively low.

4.2 Radio resource sharing optimization problem

Let us as a next step, after describing our system model, investigate the uplink resource sharing problem for group-based MTDs underlying cellular network through D2D technology. The goal is to maximize the sum of the Shannon capacity within the network in a H2H/M2M coexistence scenario. Let $S_{(N+L \cdot M) \times K} = \begin{pmatrix} X_{N \times K} \\ L \cdot Y_{M \times K} \end{pmatrix}$ 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

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

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

$$S_{opt} = \arg \max_{S_{(N+L \cdot M) \times K}} \sum_{k=1}^K \frac{1}{K} \left[\sum_{n=1}^N R_{U_n}^k \alpha_{n,k} + \sum_{l=1}^L \sum_{m=1}^M R_{D_{m,t-r}^l}^k \beta_{m,k} \right] \quad (3)$$

subject to

$$\begin{cases} \sum_{n=1}^N \alpha_{n,k} \leq 1, \\ \sum_{m=1}^M \beta_{m,k} \leq 1, \\ \sum_{k=1}^K \beta_{m,k} \leq 1, \\ R_{U_n}^k \geq R_{U_n}^{min}, \\ R_{D_{m,t-r}^l}^k \geq R_{D_{m,t-r}^l}^{min}. \end{cases} \quad (4)$$

where $R_{U_n}^k$ and $R_{D_{m,t-r}}^k$ are given respectively by (1) and (2). Note that the first constraint in (4) guarantees that traditional H2H users occupy exclusively the radio resource, RB. The second constraint in (4) guarantees that an RB cannot be re-used by MTDs belonging to a same cluster. The third constraint in (4) ensures that at most one RB can be assigned to a MTC communication link. The last two constraints represent the minimum required throughput of cellular and D2D users, respectively.

4.3 Complexity analysis

An exhaustive search for all $\alpha_{n \times k}$ and $\beta_{m \times k}^l$ in each group subject to the constraints in (4) is required to obtain the optimal RB assignment S_{opt} solution in (3). The computational complexity to assign a set of RBs to N H2H users (UEs) considering all the possible choices while assuming the first constraint in (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 MTD group subject to the second and third constraint in (4) can be computed in $\mathcal{O}(M^{LK})$. Hence, the total computational complexity of the optimal RB assignment solution is given by:

$$\mathcal{C}_{S_{opt}} = \mathcal{O}\left(\sum_{k=0}^K \frac{N!}{(N-k)!k!} \cdot M^{Lk}\right) \quad (5)$$

Thus, the computational complexity obtained in (5) is exponential. From [33,35], the optimization problem of (3) is a non-deterministic polynomial-time hard (NP-hard) combinatorial optimization problem with non linear constraints.

4.4 Interference aware bipartite graph modeling

Considering the high computational complexity of solving the optimization problem of (3), we propose a *bipartite graph* (BG) based radio resource allocation approach as a sub-optimal solution for the radio resource sharing scenario in a H2H/M2M coexistence case. The fundamental paradigm shift from a single-user to a multi-user communication system with the emergence of *orthogonal frequency-division multiple access* (OFDMA) in LTE, drives us to model the resource sharing problem as a bipartite graph. In fact, unlike 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 sub-carriers at any given time, OFDMA and *Single Carrier-Frequency Division Multiple Access* (SC-FDMA) provide multiple users the ability to transmit simultaneously on different sub-carriers per OFDM symbol. Thus, the bipartite graph is a powerful tool to model radio resource sharing

problem in a H2H/M2M coexistence scenario. Indeed, available radio resources can be assigned to MTDs which is a bipartite graph matching problem.

We propose a H2H/M2M coexistence scenario where M2M communications are underlying cellular network through D2D technology. Traditional cellular communications (H2H communications) are given higher priority. Consequently, we propose a two-stage radio resource allocation approach in order to guarantee H2H services and maximize M2M spectrum efficiency. We first assume that radio resource, RBs, are assigned to traditional H2H users. Then, MTDs seek to re-use RBs occupied by UEs to transmit their data. *In the first stage*, radio resources are assigned to H2H users exclusively using conventional schedulers (*proportional fairness* (PF), *round robin* (RR)) [36] optimally designed for H2H users. *In the second stage*, we model the resource sharing problem as a weighted BG, then we develop different alternative graph-based radio resource sharing schemes for MTC as illustrated in Fig. 5.

Let us model the MTD resource sharing assignment problem as a BG. Our goal is to re-assign RBs already allocated to UEs, to MTDs in a way to maximize the total throughput. 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 traditional H2H resource allocation algorithms, U_m^l represents the set of MTDs, $U_m^l = \bigcup_{t=1}^{S_l} D_{m,t}^l$ 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, nodes in subset U_m are divided into L clusters, $U_m = \bigcup_{l=1}^L U_m^l$. 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 $i = 1, 2, \dots, N$ and $j = 1, 2, \dots, M$. The set of edges of G are denoted by:

$$E = \bigcup_{l=1}^L E^l = \bigcup_{l=1}^L e_{i,j}^l \mid u_i \in U_{n,k}, u_j \in U_m^l \quad (6)$$

We represent the weight assigned to edges by the sum of the potential throughput of H2H and M2M communications. An example of G in a network with $U_{n,k} = 4$, $U_m = 5$ and $L = 2$ is illustrated in Fig. 4a.

5 Fixed Radio Resource Sharing Algorithms (F-RRSA)

After modeling radio resource sharing problem in a H2H/M2M coexistence scenario as a bipartite graph, we first propose a fixed radio resource sharing set of algorithms (V in Fig. 5). We introduce two instantiations, in this Section, of the fixed

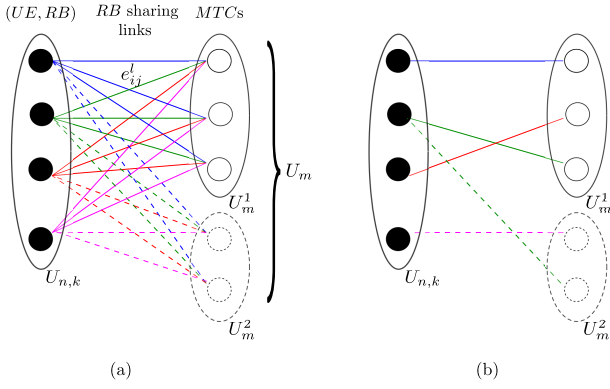


Fig. 4: Exemplary of a bipartite graph and its matching $U_m = 5$, $U_{n,k} = 4$

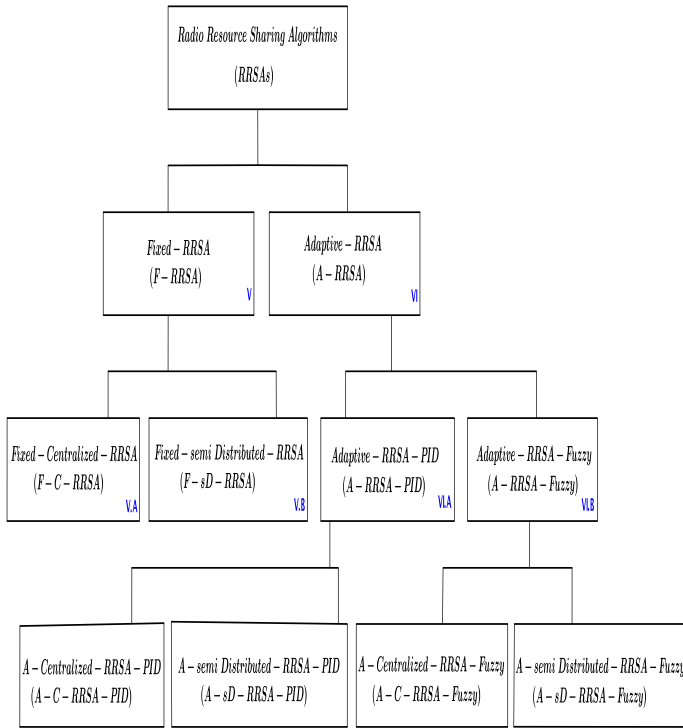


Fig. 5: Proposed M2M Radio Resource Sharing Algorithms

radio resource sharing approach: centralized (V.A in Fig. 5) and semi-distributed (V.B in Fig. 5). These algorithms are denoted as fixed since the M2M transmit power is set to a fixed value.

5.1 Fixed Centralized Radio Resource Sharing Algorithm (F-C-RRSA)

F-C-RRSA 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 weighted matching (MWM) problem in BG. These two steps are described in the following.

5.1.1 Edge weight assignment

Based on the knowledge of the path loss and fading for the potential interference links on each RB_k , the eNB 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 (1) and (2). The mutual interference identified in (1) and (2) is calculated as follows:

(i) Interference power caused by M2M mode on H2H mode, $I_{(D_{m,t}^l, e_{NB})}^k$ in (1), is replaced by (7)

$$I_{(D_{m,t}^l, e_{NB})}^k = P_m^k g_{D_{m,t}^l, e_{NB}}^k \quad (7)$$

and

(ii) Interference power caused by H2H mode on M2M mode, $I_{(U_n, D_{m,r}^l)}^k$ in (2), is replaced by (8)

$$I_{(U_n, D_{m,r}^l)}^k = P_n^k g_{U_n, D_{m,r}^l}^k \quad (8)$$

5.1.2 Solving MWM

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

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

For each MTH ($D_{m,r}^l$), we obtain a matching M^l (see Fig. 4b). M^l consists of the subset of the edges in G where each pair of edges in U_m^l has no common ends.

Given the following optimization function

$$W^l = \sum_{e_{i,j}^l \in M^l} w_{e_{i,j}^l} \quad (9)$$

The maximum weighted matching (MWM) satisfies that:

$$W_{opt}^l = \max \sum_{e_{i,j}^l \in M^l} w_{e_{i,j}^l}, l \in \mathcal{L} \quad (10)$$

where $w(e_{i,j}^l) = (1) + (2)$

$$W_{opt}^l = \arg \max_{M^l} W^l \quad (11)$$

Kuhn Munkres (KM) algorithm is then adopted to achieve MWM for BGs [37]. In this case, an 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 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).

5.2 Fixed semi-Distributed Radio Resource Sharing Algorithm (F-sD-RRSA)

Different from the centralized feature, presented in Section 5.1, that requires to gather in a single point, eNB, all accurate CSI of communication and interference links leading to a significant communication overhead, only the positions of MTDs belonging to its cluster are required for each MTH (cluster head), in semi-Distributed feature, which is not greedy in terms of resources. The interference calculation remains the key parameter to determine the scheduling operator, eNB for the centralized feature and MTHs for the the semi-distributed feature of radio resource sharing algorithm.

5.2.1 Edge weight assignment

A path loss model is adopted to calculate the interference power without requiring any accurate interference channel informations. 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 (1) and (2). The mutual interference identified in (1) and (2) is calculated as follows:

(i) *Interference power caused by M2M mode on H2H mode*, $I_{(D_{m,t}^l, eNB)}^k$ in (1), is replaced by (12)

$$I_{(D_{m,t}^l, eNB)}^k = c(d_{D_{m,t}^l, eNB})^{-\alpha} P_m^k \quad (12)$$

and

(ii) *Interference power caused by H2H mode on M2M mode*, $I_{(U_n, D_{m,r}^l)}^k$ in (2), is replaced by (13)

$$I_{(U_n, D_{m,r}^l)}^k = c(d_{U_n, D_{m,r}^l})^{-\alpha} P_n^k \quad (13)$$

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.

Algorithm 1 Centralized MTC Resource Allocation approach

```

1: Input :  $G(U, E)$ ,  $\bar{\alpha}$ , CSI
2: while  $l \leq \mathcal{L}$  do
3:   for each  $M^l \subseteq E^l$  do
4:     Calculate  $w(e_{i,j}^l)$  as  $w(e_{i,j}^l) = (1) + (2)$ ;  $i \in N$ ,  $j \in M$ 
       with  $I_{(D_{j,t}^l, eNB)}^k = (7)$  and  $I_{(U_i, D_{j,r}^l)}^k = (8)$ 
5:     Calculate  $W^l$  by (9)
6:   end for
7:   Find the solution  $\mathbf{W}_{\text{opt}}^l$  of (10)
8: end while

```

Algorithm 2 semi-Distributed MTC Resource Allocation approach

```

1: Input :  $G(U, E)$ ,  $\bar{\alpha}$ , MTDs' locations
2: while  $l \leq \mathcal{L}$  do
3:   for each  $M^l \subseteq E^l$  do
4:     Calculate  $w(e_{i,j}^l)$  as  $w(e_{i,j}^l) = (1) + (2)$ ;  $i \in N$ ,  $j \in M$ 
       with  $I_{(D_{j,t}^l, eNB)}^k = (12)$  and  $I_{(U_i, D_{j,r}^l)}^k = (13)$ 
5:     Calculate  $W^l$  by (9)
6:   end for
7:   Find the solution  $\mathbf{W}_{\text{opt}}^l$  of (10)
8: end while

```

5.2.2 Solving MWM

In the semi-Distributed feature, each MTH acts as a scheduling operator. An MTH collects the communication requests from MTDs of the same cluster, then announces the RB allocations to MTDs of the corresponding cluster through solving the MWM problem as explained in Section 5.1.2 (see algorithm 2).

5.3 Complexity analysis

The computational complexity of the proposed two-stage resource assignment approach consists of the sum of the complexity of both algorithms performed in each stage. In the first stage, the complexity of H2H radio resource allocation depends on the algorithm used. For instance, PF algorithm performs a linear search on the users for assigning RBs in order to maximize a given utility function. Hence, the total complexity of the PF algorithm is $\mathcal{O}(N^2K)$. 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. As a consequence, the proposed two-stage resource allocation scheme achieves a fairly lower computational costs comparing to the optimal method (see 4.3).

6 Adaptive Power Control-Based Radio Resource Sharing Algorithms (A-RRSA)

To further prevent the degradation of H2H services due to M2M spectrum sharing, we introduce an adaptive power control feature into the fixed interference-aware graph-based resource sharing algorithm. The basic idea behind is to efficiently adjust the M2M transmit power in order to protect the QoS of H2H users. Two power control options are designed based respectively on (i) *PID controller* and (ii) *fuzzy logic controller*.

6.1 Adaptive Radio Resource Sharing Algorithm using PID Controller (A-RRSA-PID)

In this subsection, we will first explain the proposed power control strategy using a PID controller (VI.A in Fig. 5). The difference between centralized and semi-distributed instantiations remains in the interference calculation. Please refer to Sections 5.1.1 and 5.2.1 for more details about interference calculation in centralized and semi-distributed instantiations, respectively.

6.1.1 Power control and edge weight assignment

Having modeled the resource sharing issue into a BG, we propose to integrate into the radio resource sharing process a novel power control mechanism which uses as a first option a PID controller. Specifically, we prioritize H2H users by driving MTDs to adjust their transmit power aiming at guaranteeing H2H services. The primary goal is to drive the actual UE throughput, $R_{U_n}^k$, to converge to its corresponding required QoS in terms of throughput, $R_{U_n}^{min}$. Through adjusting appropriately MTD transmit power, not only the QoS of H2H users is assured, but also the efficiency of 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's transmit power and the maximum MTD's 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:

$$u(k) = u(k-1) + k_p \left(1 + \frac{T}{T_i} + k_p \frac{T_d}{T} \right) e(k) - k_p \left(1 + 2 \frac{T_d}{T} \right) e(k-1) + k_p \frac{T_d}{T} e(k-2) \quad (14)$$

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 . They are equal to (k_p/k_i) and (k_d/k_p) , respectively.

In each scheduling period (TTI), the new MTD transmit power is determined by multiplying actual MTD transmit power with 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:

$$R_{pc}^k = \frac{(P_m^k)^{new}}{(P_m^k)^{actual}} \quad (15)$$

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:

$$R_{pc}^k(dB) = 10 \log_{10} \frac{(P_m^k)^{new}}{(P_m^k)^{actual}} = (P_m^k)^{new}(dBm) - (P_m^k)^{actual}(dBm) \quad (16)$$

Therefore, through using PID controller, the MTD 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, we implement the result of the power control process in the edge weight assignment process for each MTH and solve the MWM problem as shown in flowchart in Fig. 6.

6.2 Adaptive Radio Resource Sharing Algorithm using Fuzzy Logic (A-RRSA-Fuzzy)

Unlike MTD transmit power control process using a PID controller where a specific and a precise output is given through adopting a mathematical model, fuzzy controllers approximate the mathematical solution and hence require less computational complexity, making the prototyping process and implementation easier. In addition, the fuzzy logic has the capability to benefit from the human knowledge into a machine-based decision process. Similarly to Section 6.1, we only introduce here the novel power control scheme using fuzzy logic along with their two instantiations centralized and semi-distributed (VI.B in Fig. 5). Please refer to Sections 5.1.1 and 5.2.1 for the details of the interference calculation in the centralized and semi-distributed features, respectively.

6.2.1 Power control and edge weight assignment

We design a fuzzy power controller to dynamically adjust MTD transmit power in order to assure the QoS of H2H users as well as to maximize the efficiency of the MTD spectrum usage. The desired UE throughput given by equation (1) should be greater than a predetermined threshold given by the fourth constraint in (4). From equation (1), we notice

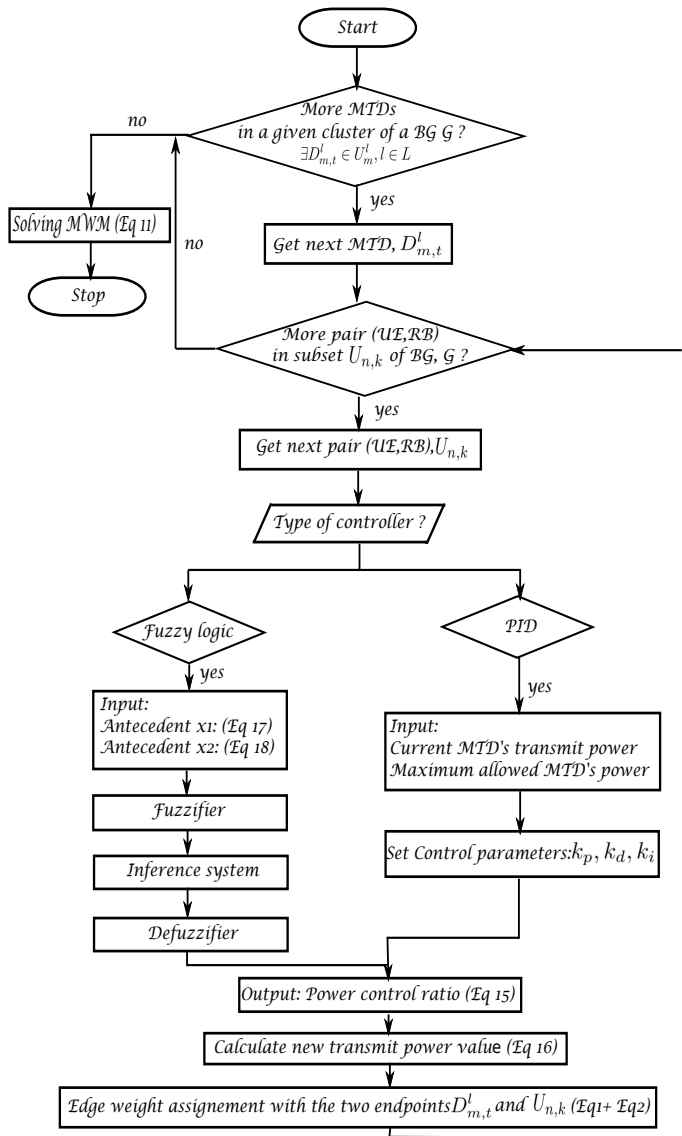


Fig. 6: Flowchart of adaptive power control-based radio resource sharing algorithms

that the MTD transmit power is influenced by the following two parameters called antecedents in the fuzzy logic.

Antecedent x_1 : The UE's throughput level in a H2H scenario. Indeed, the UE's throughput given by equation (1) with $I_{(D_{m,t}^l, eNB)}^k = 0$ 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 (x_1) is the ratio of the throughput of a UE in an exclusive H2H scenario to the corresponding QoS. It is given by:

$$x_1 = \frac{R_{U_n}^k}{R_{U_n}^{\min}} \quad (17)$$

The linguistic variable x_1 characterizes the transmission state of the H2H link with the term set: *robust*, *weak* and *moderate*.

Antecedent x_2 : 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).

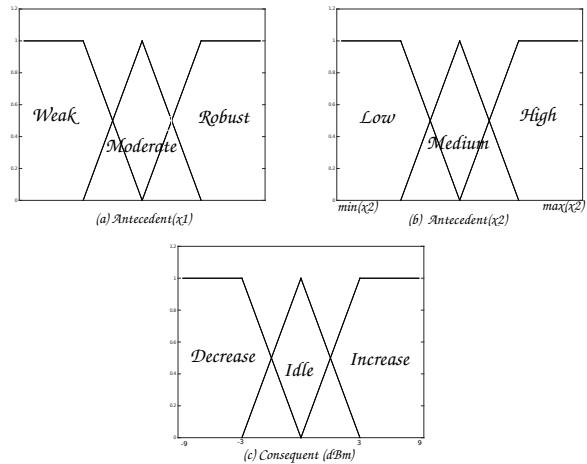


Fig. 7: The membership function used to represent the linguistic labels for: (a) Antecedent x_1 , (b) Antecedent x_2 , and (c) the Consequent

Similarly to antecedent (x_1), 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 x_2 that specifies *low*, *medium* and *high*.

$$x2 = \frac{I_{(D_{m,t}^l, eNB)}^k}{I_{(D_{m,t}^l, eNB)}^{max}} \quad (18)$$

Consequent: The consequent of this process which is the MTD transmit power control ratio (R_{pc}^k), is defined in (15) and the new transmit power level is obtained by multiplying the actual transmit power and the power control ratio derived from the output of the fuzzy logic system together. R_{pc}^k is expressed in dB domain in (16). The consequent is divided into three levels: *decrease*, *increase* and *idle*.

We use trapezoidal membership functions to represent the levels of the antecedents $x1$ and $x2$ as well as the consequent as depicted in Fig. 7.

Table 4: 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: Having defined membership functions, we set up the fuzzy rules from a group of experts based on linguistic knowledge. 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 following the proposed power control strategies. Finally, the defuzzification is performed using the most popular method, the centroid method.

Then, having properly adjusted the transmit power using fuzzy logic, we implement the result of the power control process, similarly to the adaptive feature using PID controller, in the edge weight assignment process for each MTH and solve the MWM problem as illustrated in the flowchart in Fig. 6.

7 Performance Evaluation

7.1 Simulation setup

We consider in the following simulations, to assess the efficiency of the proposed M2M radio resource sharing algorithms (RRSA), an uplink single cell based on 3GPP LTE[38]. The main parameters are summarized in Table 5. Traditional H2H and M2M communications coexist and can share RBs

for individual data transmission. The system bandwidth considered 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. The MTDs of each cluster 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 the SC-FDMA scheme and which 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 requirement. Two major traditional scheduling algorithms, *round robin* (RR) and *proportional fairness* (PF), are assumed for H2H communications. We apply the 9 rules listed in Table 4 when using the fuzzy logic scheme. Simulation results are obtained through averaging 50 different realizations using MATLAB. In order to evaluate the impact of introducing

Table 5: Simulation parameters

Parameter	Value
Cellular layout	Isolated cell
Cell radius	500 m
Mobility:UEs	Random
Mobility: MTDs	Random
Cluster radius	70 m
UEs per cell	$N = 80$
MTDs per cluster	$M = 50$
Path loss model	UMi in [38]
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 $Kbps$ }
$R_{D_{m,t-r}}^{min}$	9.2 $Kbps$

M2M communications on H2H services using the different proposed M2M radio resource sharing schemes, the following performance metrics are measured:

- *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 in-

roduction 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 schedulers, namely PF and RR, are affected due to the emergence of M2M communications. Two fairness metrics are then used.
 - **Max-Min**: a qualitative measure of fairness that gives an insight into the gap between devices in the resource allocation process and is given by:

$$F_{Max-Min} = \frac{\max(R_{U_i})}{\min(R_{U_i})}; i = 1 : N \quad (19)$$

- **Jain**: a quantitative measure of fairness that gives insight into the overall system fairness and is defined as [39]:

$$F_{Jain} = \frac{(\sum_{i=1}^N R_{U_i})^2}{N \sum_{i=1}^N R_{U_i}^2} \quad (20)$$

- *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 schedulers 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.

7.2 Network sum-throughput

Fig. 8 illustrates 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 (3) and (4) 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 outperforms 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. Hence, the goal of our work here is to assess the impact of the proposed interference-aware graph based resource sharing schemes for MTC on H2H services.

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

Fig. 9 demonstrates the H2H throughput as function of UEs present in the cell when using the three proposed M2M radio resource allocation 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 are also compared to the case where a random M2M radio resource allocation algorithm is used. Concerning H2H schedulers, the PF scheduler enhances the H2H throughput compared to the RR scheduler. Indeed, this latter is a channel-blind scheduler 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 allocation algorithm where the 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 schedulers, 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 the RR and PF schedulers cases, respectively. In other words, F-C-RRSA achieves approximately a 9% gain over the M2M random resource allocation. It is seen that the H2H throughput is significantly assured when using the 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 the adaptive algorithms adjusts the M2M transmit power in a way that the QoS of H2H users is guaranteed contrarily to the fixed algorithm

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 in semi-distributed (sD) instantiation achieve lower performance compared to the centralized instantiation. This is due to the fact that the interference calculation in the semi-distributed instantiation is approximative and not accurate as in the centralized instantiation, this leads to an approximative M2M transmit power adjustment. For example, a gain of about 12% is achieved for 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 algorithm performance outperforms the A-C-RRSA-PID by affecting less the H2H communications which is quite unexpected. This behavior can be explained by the fact that the MTD transmit power calculated in Eq (16) is low-estimated when using the approximative interference calculation scheme. In other words, there will be more MTDs with unsatisfied QoS due to the low MTD transmit power estimation as shown in Fig. 10. 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. 10 illustrates the percentage of MTDs with unsatisfied QoS as a function of time. The unexpected improvement achieved by A-C-RRSA-PID over A-sD-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 in the PF case for all algorithms is higher than the one achieved in RR. Indeed, 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 scheduler 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. 9 and 10 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.

7.4 H2H fairness

Both quantitative and qualitative fairness measures based on throughput are illustrated in Fig. 11 and Fig. 12, respec-

tively. Obviously, the PF scheduler used in an exclusive H2H scenario achieves a better level of fairness compared to the RR scheduler. Indeed, the PF scheduler 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 does not necessarily guarantee that the H2H users utilize these equally allocated resources with equal efficiency which is justified with the max-min's fairness in Fig. 12. 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 the existing RR and PF schedulers in an exclusive H2H scenario. For instance, Fig. 12 (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 in a H2H/M2M coexistence scenario.

7.5 PDF of MTDs whose QoS is not met

Fig. 13 shows the probability density function 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. This indicates 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, the A-sD-RRSA-Fuzzy and A-RRSA-PID show a greater dispersion around the mean compared to the A-C-RRSA-Fuzzy. This can be explained by the approximative interference calculation in the semi-distributed instantiation and the sensitivity to the parameters variations for the PID controller. It is clearly seen that the density of MTDs with unsatisfied QoS is uniformly distributed when using a random M2M radio resource allocation.

7.6 Discussion

Our evaluation study showed 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

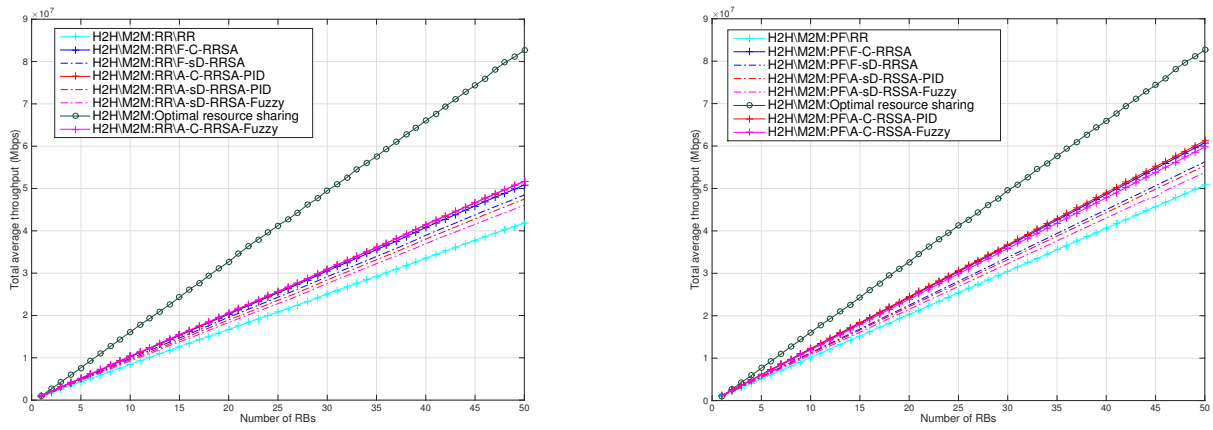


Fig. 8: Total average throughput

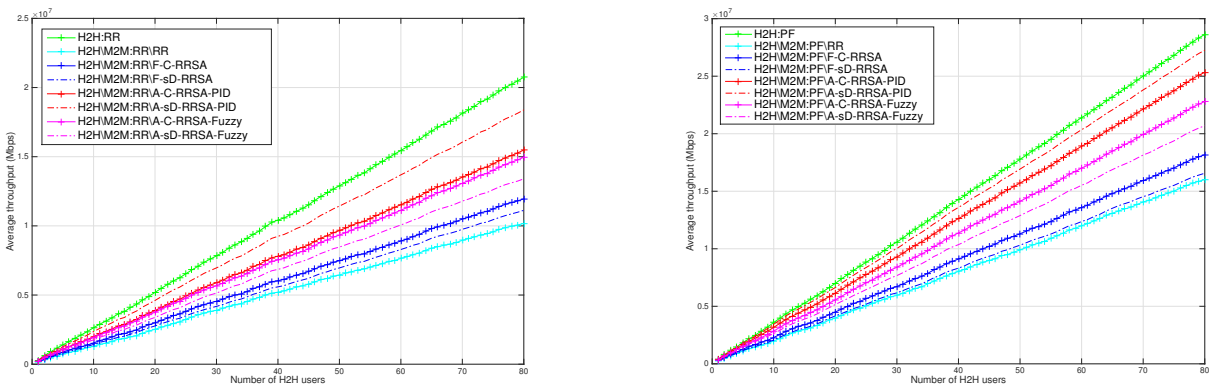


Fig. 9: H2H average throughput

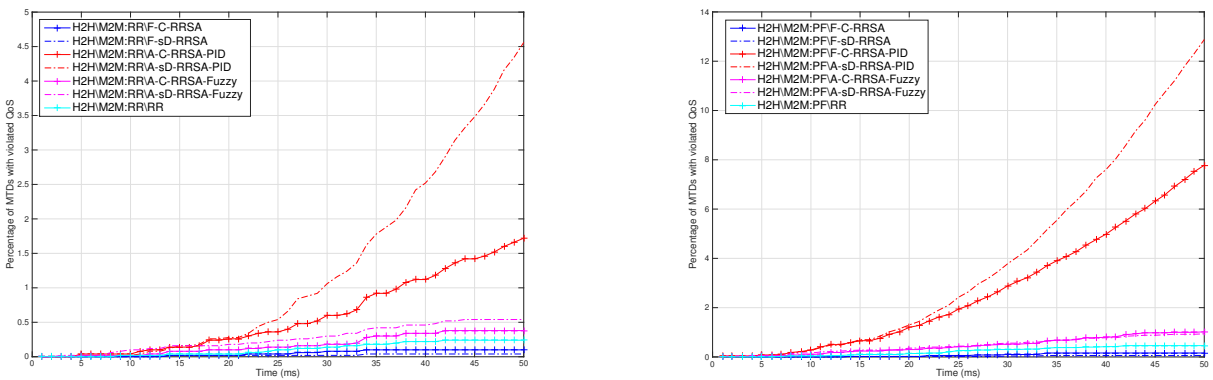


Fig. 10: Percentage of MTDs with unsatisfied QoS

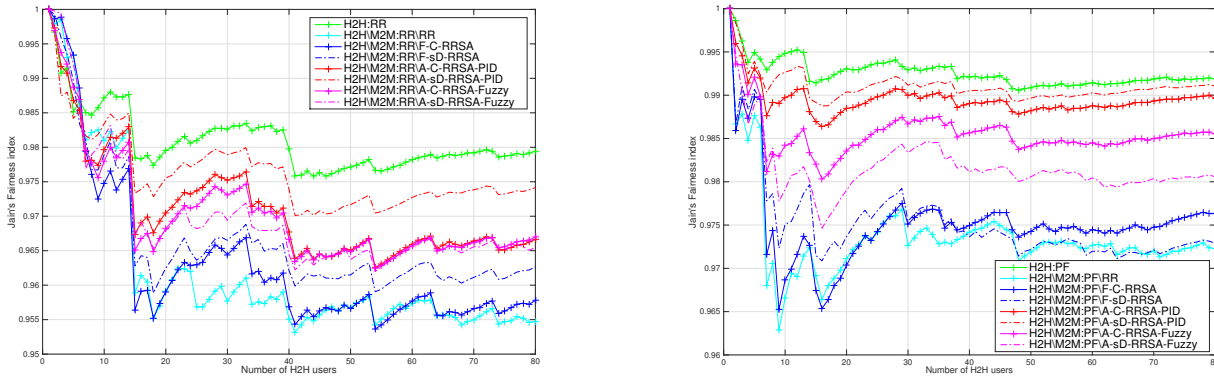


Fig. 11: Jain's Fairness Index

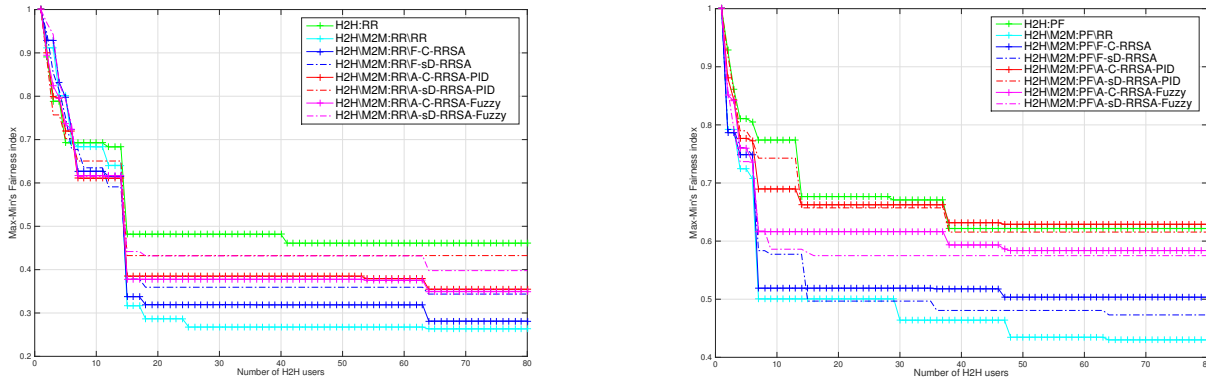


Fig. 12: Max-Min's Fairness Index

and satisfying M2M services. Indeed, the fuzzy logic controller provides a smooth operation on M2M transmit power and thus is more robust to parameters variations compared to PID controller. Moreover, the semi-distributed instantiation of M2M radio resource sharing scheme proved to achieve comparable results with the centralized instantiation. Even though it achieved a decline of 10% in terms of throughput, it also has markedly lower communication overhead.

8 Conclusion

In this paper, we investigated the radio resource sharing problem in a H2H/M2M coexistence scenario. We first proposed a novel fixed interference-aware graph-based resource sharing algorithm where the M2M transmit power is set to a fixed value. To further guarantee H2H services while maximizing the efficiency of M2M communications, we introduced a novel adaptive power control feature using one among the two following alternative mechanisms, namely, either proportional integral derivative (PID) or fuzzy logic controllers and integrate it into our interference-aware graph-

based resource sharing algorithm. For each of the proposed algorithms (fixed and adaptive), we developed a centralized and a semi-distributed instantiation. Our evaluation study clearly showed 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. Moreover, the semi-distributed instantiation achieves comparable results with the centralized instantiation with a markedly lower communication overhead. For future work, we propose to combine fuzzy logic with other intelligent methods such as minimum variance and predictive strategies in order to further improve the performance of our adaptive radio resource sharing scheme. Besides, we propose to consider a multiple-cell scenario as we referred to a single-cell one in our simulations.

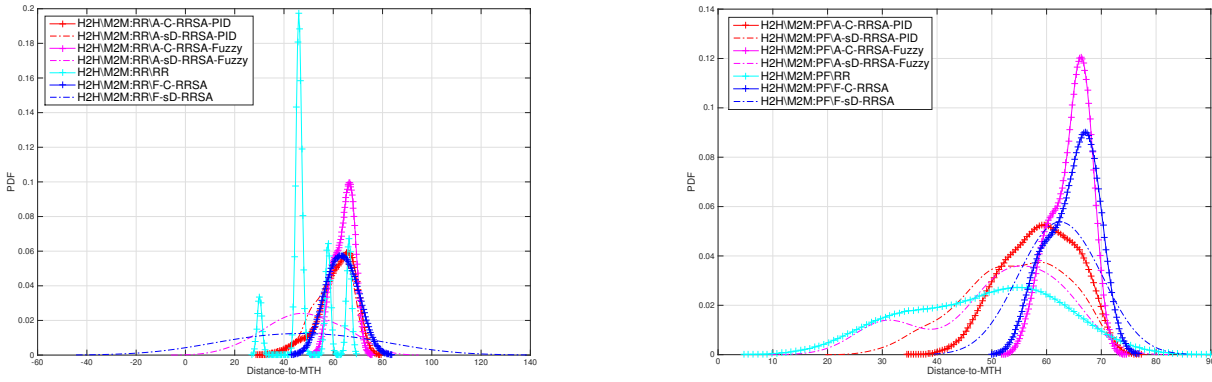


Fig. 13: Probability density function of the distance of unsatisfied MTDs-to-MTH

Appendix

Kuhn-munkres algorithm to solve maximum weighted matching problem

Step 0

For each cluster, start with an arbitrary feasible vertex labeling $f^l = f_0^l$, determine the equality subgraph G_{f^l} .

Step 1

Choose an arbitrary maximum matching M^l in G_{f^l} . If M^l is perfect for G^l , then M^l is optimal. Stop. Otherwise, there is some unmatched $U_i \in U_{n,k}$. Set $S = \{U_i\}$ and $T = \emptyset$

Step 2

If $J_{G_{f^l}} \neq T$, go to **step 3**. Otherwise, $J_{G_{f^l}} = T$. Find

$$\alpha_f^l = \min_{U_i \in S, U_j \in T^c} \{f^l(U_i) + f^l(U_j) - w(e_{i,j}^l)\}$$

Where T^c denotes the complement of T in U_i , and construct a new labeling $f^{l'}$ by

$$f^{l'} = \begin{cases} f^l(u_i) - \alpha_1, & u_i \in S \\ f^l(u_i) + \alpha_1, & u_i \in T \\ f^l(u_i), & \text{otherwise} \end{cases}$$

Note that $\alpha_1 > 0$ and $J_{G_{f^{l'}}} \neq T$. Replace f^l by $f^{l'}$ and G_{f^l} by $G_{f^{l'}}$

Step 3

Choose a vertex $U_j \in J_{G_{f^{l'}}}(S) \setminus T$. If U_j is matched in M , say with $U_k \in U_i$, replace S by $S \cup U_k$ and T by $T \cup U_j$, and go to **step 2**. Otherwise, there will be an M-alternating path from U_i to U_j , and we may use this path and a larger matching $M^{l'} \in G_{f^{l'}}$. Replace M^l by $M^{l'}$ and go to **step 1**.

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