Spectrum Sharing Approaches for Machine-Type Communications over LTE Heterogeneous Networks

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Abstract. Machine-type communications (MTC) are expected to be a key enablers in the Internet of Things (IoT) ecosystem by providing ubiquitous connectivity among a new type of small devices (e.g., sensors, wearable devices, smartphone) without (or with minimal) the need of human intervention. In such a scenario, the architecture as well as the radio resource management (RRM) of next-to-come 5G systems needs to be enhanced in order to cope with the exponential growth of low-latency and low-energy MTC traffic. To this end, we propose a dynamic RRM policy which *(i)* exploits an heterogeneous networks (HetNets) deployment aiming to handle massive huge load of MTC devices and *(ii)* adopts a spectrum sharing approach tailored to improve the spectrum utilization in MTC environments. By comparing our proposal with current policies in literature, simulations conducted through the open-source Network Simulator 3 (NS-3) shown that our proposed use of spectrum sharing technique can efficiently improve the performance of MTC traffic in terms of spectral efficiency, power consumption, and fairness.

Keywords: M2M · HetNets · LTE · IoT · Spectrum sharing

1 Introduction

Machine-type communications (MTC) over Long Term Evolution (LTE) and beyond networks represents one on the killer communication paradigms to be exploited by network providers in order to fulfill the requirement of the future fifth generation (5G) wireless networks [1]. In fact, MTC promise to be a value-adds in the exponential growth of the data traffic generated by a new type of devices (e.g., traffic cameras, sensors, wearable devices) in either large- and small-scale environments. MTC open novel scenarios ranging from outdoor to indoor applications, such as smart city solution, for e.g. with intelligent metering, city automation, traffic control, house management, and remote clinical health care (e.g., see Fig. 1) [2]. This allows unprecedented opportunities in different fields (e.g., transport and logistics, smart power grids) belonging to the Internet of Things (IoT) ecosystem [3]. Nevertheless, the huge deployment of MTC devices

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Fig. 1. Smart city scenario

expected in the next years dictates for a more effective network architecture in order to meet the low-latency and low-energy MTC requirements and to mitigate as much as possible the impact of MTC traffic on traditional human-type communications (HTC).

To overcome the above considered issues, a possible solution is given by an enhanced LTE architecture where the extremely dense MTC deployment is supported by the usage of *small-cells*. Indeed, the exploitation of *heterogeneous networks (HetNets)* guarantees low-latency MTC without meaningful additional costs compared to non-3GPP wireless networks and without affecting the performance of HTC traffic.

The concept of HetNets has recently attracted considerable attention in the research community. In contrast to homogeneous networks, designed through a careful planning of the high-power base stations (eNodeBs) guaranteeing wide-area coverage, HetNets are deployed in an uncoordinated manner. The high power nodes (i.e., macro-cells) are jointly integrated with low power small-cells (i.e., pico and femto-cells, relay nodes) that are dynamically arranged and turned on/off directly by the end users according to their own needs [4]. In addition, small-cells, like home-eNodeBs (HeNBs), are *(i)* cheaper compared to macro-cell, *(ii)* plug and play (i.e., they do not need planning by network providers), *(iii)* generally positioned closed to the end user in indoor environment (and this guarantee, in general, improved quality of services to served devices) [5].

Nevertheless, even if MTC devices are managed through the usage of femto-cells, i.e., HeNBs, these exploit the same spectrum bandwidth assigned to the macro-cells eNBs. In such a case, the inter-cell interference can increase significantly thereby degrading the performance in both macro- and small-cells. Therefore, radio resource management (RRM) and scheduling procedures play an key role to efficiently manage the spectrum allocation among macro- and femto-cells with the aim to reduce the *inter-cell interference* and to increase the *spectral efficiency* [6,7].

An emerging approach able to meet such requirements is characterized by the exploitation of *spectrum sharing* policies over HetNets, as reported in [8–10]. Actually, spectrum sharing may be orthogonal, i.e., when an operator exploits a shared resource, this cannot be simultaneously used by other operators. However, this kind of spectrum sharing just achieves marginal gains due to a slight increase in frequency diversity of the system. In this paper we consider a more advanced cooperation representing by the *non-orthogonal spectrum sharing*, where the operators are allowed to simultaneously use the same frequency resources. In this way, we are able to achieve higher efficiency in the spectrum usage and to consequently improve the performance in terms of *capacity* and *throughput* by means of increased *spatial and frequency diversity.*

By considering our HetNets environment, three different spectrum sharing techniques have been investigated in literature [11]:

– *Frequencies separation*: Radio spectrum is divided between the macro-cell and femto-cell in an adjacent manner. In this way, due to the Orthogonal Frequency Division Multiple Access (OFDMA) technique, the inter-cell interference can be neglected.
– *Partial sharing*: macro-cell and femto-cell share only a portion of the spectrum. The non-shared spectrum is exclusively assigned only to macro- or small-cells. Obviously, only the shared spectrum is affected by inter-cell interference.
– *Total sharing*: macro-cell and femto-cell share the overall assigned spectrum. Inter-cell interference needs to be taken into account on the overall spectrum and an efficient RRM policy has to be implemented in order to mitigate this phenomena.

In partial and total sharing, there are two further approaches that allow to share a single radio Resource Block (RB), i.e., the time-frequency unit to be scheduled during the RRM procedure, between the macro-cell and femto-cell [11]: *(i)* orthogonal spectrum sharing policy, where a shared RB is assigned to a given User Equipment (UE) in a mutually exclusive manner; *(ii)* non orthogonal spectrum sharing policy, where two UEs exploit the same RB in the same time.

The aim of the paper is to propose an orthogonal spectrum sharing approach between macro-cell and femto-cell with the aim to improve the overall spectral efficiency and reduce the latency and energy consumption of the MTC devices. Differently from what reported in literature [8], where the shared spectrum is dynamically assigned on portion of bandwidth, in the proposed policy the spectrum is shared on the RB-basis taking into account the channel state variations for each MTC device. Furthermore, two different per-user scheduling algorithms have been proposed and compared with [8] through an exhaustive simulation campaign by using the Network Simulator 3 (NS-3) [12].

The remainder of the paper is organized as follows. In Sect. 2 we briefly discuss the main related work, whereas in Sect. 3 we introduce the proposed resource allocation process. Simulation setting and results are given in Sect. 4, while conclusive remarks and future works can be found in Sect. 5.

2 Related Work

In the last years, several research activities have been conducted with the purpose of addressing the main challenges inherent to the HetNets architecture [5]. In particular, with the aim of improving HetNets performance in terms of efficient radio resources allocation, different RRM techniques have been investigated. Nevertheless, further enhancements could be obtained by introducing the concept of spectrum sharing based on the idea that sharing the same frequency among more eNodeBs can improve the system performance. References [13,14], are two of the earliest works that introduce this concept in wireless networks. In such works shared resources are used as a last resort when private frequencies[1] are not sufficient to handle the normal traffic. While, in [11] spectrum sharing is considered as the main technique for improving spectral efficiency. However, in [11] the spectrum sharing is applied only over a multi-operator scenario, without considering the introduction of low power eNodeBs (i.e., femto-cell) and, hence, of HetNets. In addition, Andrews et al. in [8] efficiently implements spectrum sharing among femto-cell and macro-cell in the HetNets environment. It focuses on the dynamic allocation of portions of bandwidth at the top level of the scheduling users process, selecting the shared bandwidth size, between macro and femto-cells, according to a periodically evaluation of the average inter-cell interference.

The role of small-cells technology and spectrum sharing policies for MTC applications is addressed in [15]. The authors analyze the role of small-range cells and novel technology developed for the current cellular system (e.g., spectrum sharing) in order to provide a comprehensive understanding about the most critical issues and challenges. Dynamic spectrum allocation for Machine-to-Machine (M2M) application is also proposed in [16]. In such a paper, an opportunity access method is utilized to share the spectrum among different newly deployed broadband system and MTC devices for Smart Grid applications. In particular, two novel dynamic spectrum planing algorithms, cognitive single channel assignment(CSCA) and cognitive single channel assignment with look-ahead (CSCA LA) are proposed. Finally, authors in [17] proposed a framework in order to analyze signal-to-interference-ratio distributions and derive efficient resource allocation schemes for spatial multi-group random access in multicell systems, using the Poisson point process model. Using this tool, the

[1] *Private frequencies* are the portion of bandwidth assigned exclusively to a base station.

spectrum-sharing performance of multiple systems are evaluated by considering simultaneous transmissions of MTC devices deployed within the same cell.

3 Resource Allocation Process

We focus on the downlink direction of the Long Term Evolution (LTE) technology [18], where user multiplexing is based on OFDMA. The RB corresponds to the smallest time-frequency resource that can be allocated to a user (12 subcarriers, 0.5 ms) in an Long Term Evolution (LTE) system. For example, a channel bandwidth of 20 MHz corresponds to 100 RB. For the cellular link between the MTC device/cellular user and the eNodeB, a UE in an LTE-A network typically communicates through a macro-cellular link by sending its own data to the eNodeB. In addition, the eNodeB executes the resource allocation every Transmission Time Interval (TTI, lasting 1 ms) by assigning the adequate number of RB pairs to each scheduled UE and by selecting the related Modulation and Coding Scheme (MCS). Scheduling decisions are based on the Channel Quality Indicator (CQI) that is associated to a maximum supported MCS (please, refer to Table 1).

In this paper the scenario illustrated in Fig. 2 is adopted, where a macro and a femto-cell exploit the same radio spectrum. In particular, the macro can totally or partially shares its spectrum with the femto-cell in an orthogonal manner.

Table 1. CQI-MCS mapping [19]

CQI index	Modulation scheme	Code rate x 1024	Efficiency [bit/s/Hz]	Minimum rate [kbps]
1	QPSK	78	0.1523	25.59
2	QPSK	120	0.2344	39.38
3	QPSK	193	0.3770	63.34
4	QPSK	308	0.6016	101.07
5	QPSK	449	0.8770	147.34
6	QPSK	602	1.1758	197.53
7	16-QAM	378	1.4766	248.07
8	16-QAM	490	1.9141	321.57
9	16-QAM	616	2.4063	404.26
10	64-QAM	466	2.7305	458.72
11	64-QAM	567	3.3223	558.72
12	64-QAM	677	3.9023	655.59
13	64-QAM	772	4.5234	759.93
14	64-QAM	873	5.1152	859.35
15	64-QAM	948	5.5547	933.19

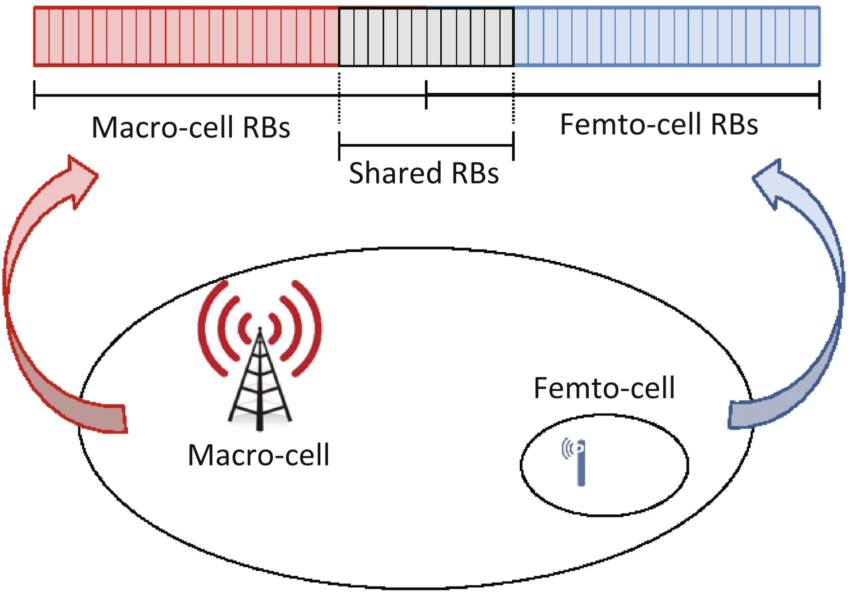

Fig. 2. Adopted scenario

We remark that only the radio spectrum is shared, while users are connected exclusively to their own base station (no infrastructure sharing).

Let $\mathcal{Q}$ be the number of all RBs in downlink direction and $s \in (0, 1)$ the percentage of RBs orthogonally shared between macro and femtocell. We assumed the non shared RBs are equally split between the two eNodeBs. As a consequence, $Q \cdot s = Q\_s$ and $Q\_p = Q - Q\_s$ are the number of shared and private RBs, respectively. It is worth noting that a BS can assigns a private RB only to their own UEs, vice versa a shared RB can be utilized by UEs belonging to both macro and femto-cell. The resource allocation process consists of two phases. During the first one, named *CQI Acquisition*, macro and femto-cells receive the CQI feedbacks from each own UE and sorted in increasing CQI order (highest CQI).

After all CQIs have been collected and properly sorted, the scheduling algorithm is carried out in order to assign efficiently the RBs (shared and not-shared) to all the users belonging to both macro and femto-cell. Two different scheduling algorithms have been proposed in this paper:

- The Fixed Spectrum Sharing (FSS)
- The Dynamic Spectrum Sharing (DSS)

In the FSS policy, the number of the shared RBs Q_s is fixed and does not vary in the time. Each RB is assigned in a mutually exclusive manner to users belonging to both macro and femto-cell according to the sorted list created during the

CQI acquisition phase. The intra-cell interference due to the OFDMA modulation is not taken into account. Differently to FSS, the in the DSS policy the number of the shared RBs Q_s can dynamically vary every TTI. Moreover, each RB is shared between the macro and the femto-cell only if the inter-cell interference achieved is lowest to a given threshold. Otherwise, the RB is privately given to the BS of the user with the highest CQI. In both scheduler policies, in case of collision of two users in the same RB at the same time, the conflict is solved by assigning the RB to the user with the highest CQI. Furthermore, in both FSS and DSS scheduler the private RBs Q_p are assigned following a Max Throughput policy in order to achieve the highest performance. We remark that Max Throughput policy assigns each resource block to the user that achieves the best channel conditions. We compared the proposed algorithms with the dynamic spectrum allocation approach proposed in [8], hereinafter named Dynamic Spectrum Allocation (DSA). The DSA scheduler assigns a priori the shared bandwidth among the macro and the femto-cell based on the average interference achieved by all the system user. Differently, our proposed scheduling algorithms (FSS, DSS) works on the single resource block and not on portion of bandwidth.

4 Simulation Results

Performance evaluation of the proposed algorithms have been conducted through the well-know Network Simulator 3 (NS-3) [12]. We started from an existing NS-3 module thought for implementing the LTE multi-operator spectrum sharing, and we added new functionalities (i.e., new suitable path loss models, low-power nodes, femto-cells, MTC devices, and so on) in order to define a MTC system within an HetNets scenario. The new module allow us to simulate different network behaviors and to set up several system parameters, such as cell coverage, transmitted power, number of MTC devices, number of femto-cells and their position within the macro-cell.

In details, the proposed scenario is characterized by a macro-cell and a femto-cell with different transmitted powers and coverage areas. Different MTC devices are uniformly distributed within the coverage of the macro-cell and femto-cell and a number of cellular users (i.e., HTC traffic) equal to 50 is deployed within the macro-cell. The number of MTC devices varies in the range $[2, 500]$ and the network traffic is modeled through packets with size equal to 100 byte with a time interval of 10s. In addition, each cellular users download through the eNodeB multimedia content with size equal to 500 bytes (constant bit rate, CBR, traffic). The shared spectrum is fixed to a percentage of 100 %, therefore all resource blocks are totally shared between the macro and the femto-cell.

Simulations have been conducted by varying the number of users belonging to both the macro-cell and the femto-cell. Outputs have been achieved by averaging a sufficient number of simulation results in order to guarantee a 95 % confidence interval (Table 2).

In order to evaluate the system performance, we take into account three system parameters: *(i)* average throughput achieved by the MTC devices, *(ii)* average energy consumption, and *(ii)* the well-known Jain's fairness index [20].

Table 2. Main system parameters

Parameters	Value	
Downlink Bandwidth	10 MHz	
Frame duration	10 ms	
TTI duration	1 ms	
TX power	**Macro-cell**	**Femto-cell**
	30 dBm	8 dBm
User TX power	23 dBm	
MTC device TX power	0 dBm	
Pathloss (dB)	**Macro-cell**	**Femto-cell**
	15.6 + (35 * log(R))	38.46 + (20 * log(R))
Wall penetration	7,10,15 dB	
# HTC users	50	
Radius	**Macro-cell**	**Femto-cell**
	500 m	50 m
Interdistance	400 m	

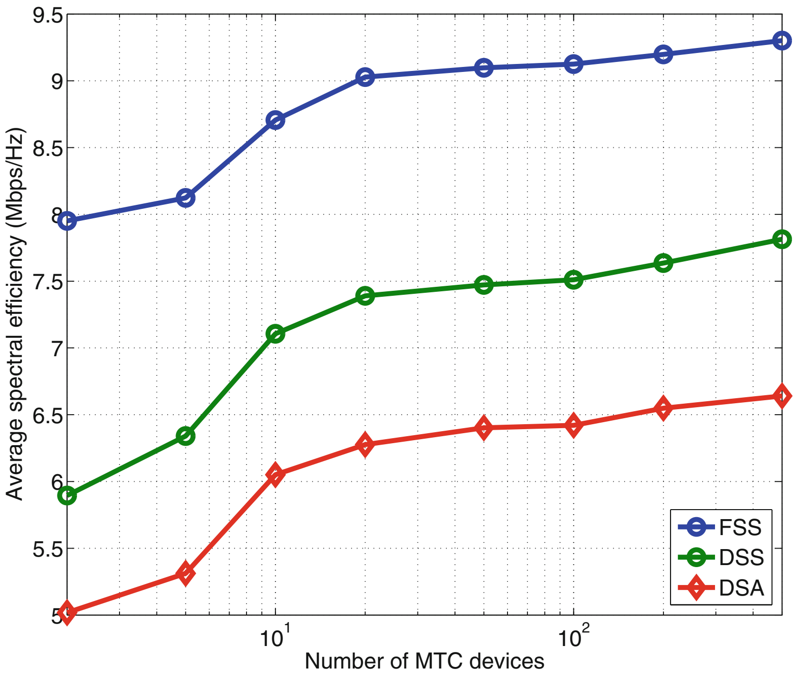

Fig. 3. Average spectral efficiency

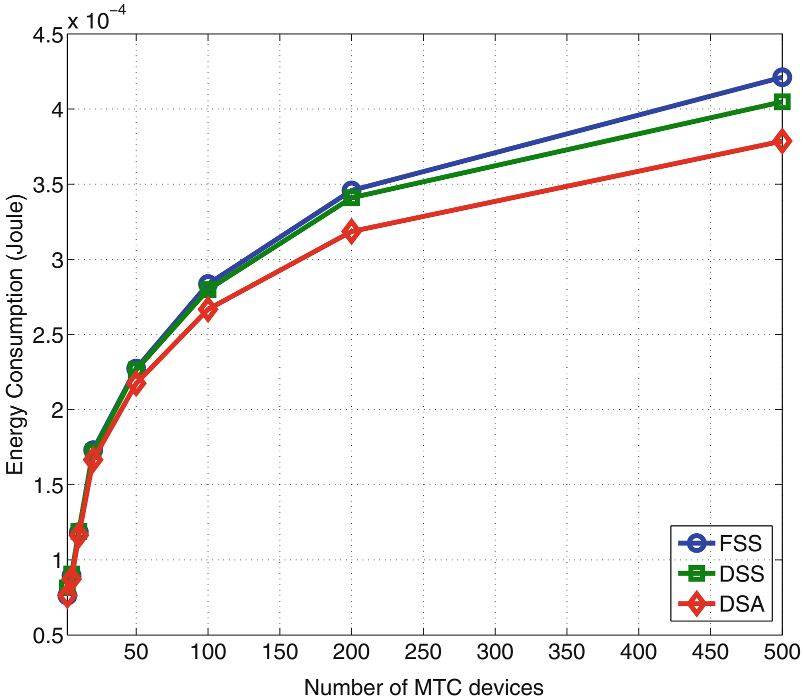

Fig. 4. Average energy consumption

Figure 3 shows the system spectral efficiency by varying the number of MTC devices. DSS scheduler is more performing than DSA. Indeed, in DSA the amount of shared spectrum varies frame-by-frame (i.e., every 10 TTI) depending on the inter-cell interference, whereas in DSS the amount of shared RBs are evaluated on TTI basis taking into account for each RB both the load traffic and the inter-cell interference. It worth noting that FSS is the most performing policy in terms of spectral efficiency. This behavior is due to the fact that in FSS the fixed amount of shared RBs is evaluated assuming negligible the inter-cell interference. Therefore, it represents an ideal case and the obtained result can be considered as an upper bound. In addition, the average percentage gain introduced by the DSS algorithm varies in a range of 20–30%, especially when the traffic load is high. It is due to the increase of the multi-user diversity and the more degrees of freedom in choosing the best users.

The average energy consumption per MTC device is shown in Fig. 4. The energy consumption increases with the traffic load. As we can observe, the DSS policy always performs better compared to the DSA. The slight improvement shown in Fig. 4 is due to the typically low packet size that MTC device has to deliver.

Finally, the fairness achieved using the three different scheduler policies, by varying the number of MTC devices is shown in Fig. 5. We use the *max-min*

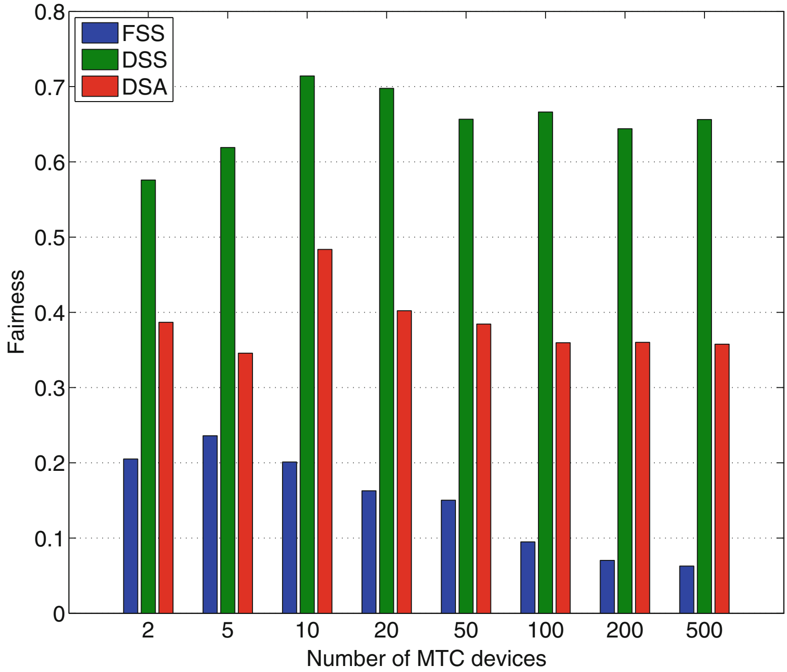

Fig. 5. Fairness index

fairness approach where a feasible allocation of rates is max-min fairness if and only if an increase of any rate within the domain of feasible allocations must be at the cost of a decrease of some already smaller rate. It is worth noting that the RBs are allocated more fairly by considering both the two dynamic allocation of the radio spectrum because only the resources with a lower level of interference are shared among the macro and femto-cell. In particular, the DSS scheduler, respect the DSA scheduler, assigns more fairly the RBs due to the timely response to the traffic load of the base stations. Even though the FSS scheduler achieves the better performance in terms of spectral efficiency and power consumption, it does not provide a good fairness as the RBs are not equally assigned to the macro and femto-cell. As a conclusion, the preliminary results shown in this paper demonstrate that the spectrum sharing techniques are a possible solution to efficiently manage the growing demand of multimedia traffic given by the MTC systems, and that the scheduling algorithms play an important role in the allocation of the shared resource blocks in order to improve the system performance.

5 Conclusion and Future Works

We investigated the spectrum sharing technique for MTC systems over Heterogeneous Networks through simulations by considering spectral efficiency, power consumption and fairness. We integrated our scenario within an existing NS-3 module for LTE spectrum sharing and a simulation campaign varying some the number of MTC devices has been performed. Obtained results show that the dynamic allocation of the radio spectrum (TTI-by-TTI) according to an efficient per-user scheduling process increases the performance of the MTC device with respect to a resource allocation process at top levels (frame-by-frame). Sharing the radio resources on a RB-basis when the the deployment of MTC devices relatively huge allows to achieved high-levels of gain due to the timely response of the proposed algorithms. Therefore, the correct allocation of the shared resource blocks considering the evolution on the system parameter user-by-user plays an important role. As a future work, the same approach can be extended to a scenario with a large number of femto-cells, where an efficient distribution of the radio resources and spectrum sharing techniques is recommended. In fact, efficient approaches in order to manage the spectrum (shared or private) assigned to the femto-cells and macro base stations have to be investigated.

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