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A performance evaluation tool for spectrum sharing in multi-operator LTE networks

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ABSTRACT

Recent advances in wireless networking introduce the concept of resource sharing as one promising way to enhance the performance of radio communications. As the wireless spectrum is a scarce resource, and its usage is often found to be inefficient, it may be meaningful to design solutions where multiple operators join their efforts, so that wireless access of their terminals takes place on shared, rather than proprietary to a single operator, frequency bands. In spite of the conceptual simplicity of this idea, the resulting mathematical analysis may be very complex, since it involves analytical representation of multiple wireless channels. Simulation studies may be extremely useful to obtain a correct performance characterization of wireless networks with shared resources. In this spirit, the present paper introduces and evaluates an original extension of the well known ns-3 network simulator, which focuses on multiple operators of the most up-to-date cellular scenarios, i.e., the Long Term Evolution of UMTS employing OFDMA multiplexing. Spectrum sharing is represented through a proper software architecture, where several sharing policies can be framed. A detailed simulation campaign is run to assess the computational performance of the proposed architecture, and to show its effectiveness in analyzing realistic scenarios.

1. Introduction

Although game theory started as a mathematical formulation of problems mostly belonging to economic and political systems, its application to wireless networking is becoming common practice [22]. Indeed, game theory is well suited to study problems where a scarce resource is contended for by multiple agents (players), as well as situations where these players have contrasting objectives, mostly because they are selfish, i.e., interested in their own good only. Incidentally, these aspects characterize the vast majority of wireless access problems, even though it can be noted that spectrum scarcity is due more to bad frequency planning than to a real lack of available frequencies [17]. In any event, it is the selfishness of the players, i.e., the network operators, that makes the radio access inefficient. This gives a strong motivation for replacing the classic scenario where network users are driven by self-interest with another where they cooperate [27].

A related early attempt at using game theory within wireless scenarios involves *cognitive networks*. In such a model, as defined by [24], two kinds of users co-exist, i.e., primary and secondary. The former are licensed users which access the frequency bands they are entitled to; the latter opportunistically access the sub-channels which are unused by their legitimate owners (the primary users) for a given amount of time. The secondary users can act only after the primary users have made their decision. To some extent, cooperation is present in the sense that the primary users are aware of the secondary, but they let them be; after all, they are not threatening as they only exploit unwanted resources. This situation of cognitive networks is also reminiscent of some game theoretic investigations describing a duopoly situation with an incumbent and an outsider, known as a *Stackelberg game*, which has seen application to wireless networks problems [28].

Actually, an even more general form of collaboration can be thought of, without classifying players into primary or secondary, but rather considering an egalitarian approach, where similarly-minded players desire to use a common resource, or share a portion of their properties with the others. In the wireless network context, this would mean that network operators join their licensed frequencies for common wireless access. As hinted by several studies, such an idea may be beneficial for all the involved players if a collaborative access to the wireless resource is achieved [12,18,20,21]. Possible ways to quantify a gain can be in a larger number of users served, a wider network coverage, a higher network throughput.

However, the main challenge for analyzing this problem is in the adoption of realistic models for the physical layer. In principle, it can be easily argued that certain physical characteristics of the wireless channel, for example multi-user and frequency diversity, make it appealing to share its access, rather than competing for it [19]. Yet, an exact characterization of the wireless channel for

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several players is mathematically difficult. For this reason, the considered scenarios are often limited to small networks with few transmitter–receiver pairs, most of the times just two, i.e., a total of four nodes. We believe that a realistic performance evaluation of larger networks is key to get a clear understanding of the usefulness of the sharing concept in wireless scenarios.

In the scientific community it is quite common to resort to network simulation instruments to assess the performance of large networks which are not easy to tackle exactly. For example, the well known network simulator-3 (ns-3) [4] is currently considered as one of the most advanced and modular software tools to perform this task. The ns-3 simulator is entirely open source and comprises the entire protocol stack, from the physical layer up to the application. Although the focus of network simulation is often on the intermediate layers (data link, network, transport), ns-3 is extremely modular and therefore admits integration with detailed models of the physical layer, especially with the most up-to-date wireless technologies. A bottom-up representation of the protocol stack can be particularly appealing for the analysis of spectrum sharing, that involves both lower and higher layers. These reasons motivate our choice to employ an existing implementation [26] within ns-3 of the Long Term Evolution (LTE) of the Universal Mobile Telecommunications System (UMTS) [1].

The present paper completes the work already presented in [11], whose main contribution is to introduce a novel software extension of this ns-3 version to characterize spectrum sharing scenarios where cooperation is established among multiple operators, each with a considerable number of nodes. To realize this enhancement, original software structures are introduced. First of all, a class describing a virtual *frequency market* has been inserted in the simulator structure. This class implements the functionalities of a virtual arbitrator, and does not represent a physical entity of the network, but rather determines the sharing policy of the frequencies belonging to the common pool. In other words, its role is to abstract the set of rules agreed upon by the operators when determining the shared portion of the spectrum. Moreover, two main sharing meta-policies can be utilized, namely *orthogonal* and *non-orthogonal* sharing. In the former case, the frequencies of the shared pool are used by one and only one operator, although not necessarily the one that detains the legal property of the access on that frequency. In the latter, also simultaneous access of multiple users on the same frequency is possible. In both cases, the arbitrator structure is required to represent in an abstract manner the details of the sharing policy, such as priority rules among the operators in case of conflicting assignments or excessive mutual interference.

It is worth noting that the definition of efficient sharing policies is out of the scope of the present paper. For the sake of simplicity, we focus on orthogonal sharing, which is immediate to describe and does not require to detail any power control policy for shared frequencies. However, as the code developed is entirely modular, an extension to non-orthogonal sharing would be possible. Moreover, only competitive sharing was modeled, leaving the issue of identifying efficient and collaborative sharing mechanisms for a future analysis, possibly with more advanced game theoretic instruments.

Finally, besides introducing the details of the software extensions implemented within ns-3, this paper also provides the results of a simulation campaign meant to assess the effectiveness of the resulting simulator as a benchmark for testing spectrum sharing algorithms. A sample sharing algorithm is employed, and the evaluation of the modified version of the simulator in terms of computational requirements is given as well. The results confirm the ability of such a software instrument to give realistic assessments of the usefulness of spectrum sharing, and at the same time motivate further efforts with game theoretic approaches to implement efficient sharing algorithms where collaborative sharing is sought.

The rest of this paper is organized as follows. In Section 2 we review related works on simulation platforms for spectrum sharing analysis. In Section 3 we describe the system model, detailing the theoretical rationale behind the spectrum sharing characterization, while in Section 4 we discuss the modifications applied to the software architecture. In Section 5 we outline the simulation scenario and in Section 6 we present numerical results to validate our proposed contribution. We finally conclude in Section 7.

2. State of the art

Simulation platforms are a very common reference point to test protocols and assess the network performance, in particular for all those scenarios where the mathematical analysis becomes complex or cannot produce a solution in closed form.

In the literature, most of the works dealing with complex network systems include a performance evaluation part which leans on a simulator. This can be either a single-purpose simulator, specific to the scenario under investigation, or an adapted version of a general-purpose simulator. We believe that the latter alternative better fulfills scientific generality and reproducibility of the results, and enables future developments of individual findings. However, the software instruments chosen by the scientific community to this end are quite heterogeneous, from extremely general software platforms like SIMLIB [6] or MATLAB [3], which are properly customized to the particular context under evaluation, to more application specific tools which refer to particular systems, such as OMNET++ [5].

For what concerns computer networks, one of the most used tools in the research community is the Network Simulator ns [4], whose latest version is ns-3. It is an open source, free software managed by an active community of developers. The whole Internet suite protocol stack is implemented together with the most important protocols at the transport, network, and data link layers. Therefore, many different network scenarios can be created and simulated. One of the last implemented modules realizes LTE cellular networks [26]. The introduced framework enables the creation of Base Stations (called eNodeBs, or eNBs) and mobile terminals (called user equipments, or UEs) which can communicate with the eNBs. Most of the functionalities of the physical channel and medium access have been implemented. In [11], this basic framework has been extended by enabling a multi-cell scenario and allowing eNBs to share part of their frequencies in the downlink direction. Such a scenario is particularly interesting when the eNBs are managed by different cellular network operators. This paper further extends that work and introduces, together with a more detailed description of the system model, a different simulation scenario with an asymmetric cell traffic load.

Although the problems of interference channels and spectrum sharing have been addressed in several papers, e.g., [15,16], the scenario of inter-cell spectrum sharing was considered in a small number of them so far, and even fewer papers have focused on multi-operator networks. However, since in current network deployments the coexistence of multiple operators in adjacent regions is quite common, it makes sense to investigate the efficiency of the spectrum division policies adopted in common practice. The interest in this area has increased during the last years and has been involving not only researchers, but also telecommunication companies and regulatory bodies.

A first simple concept of spectrum sharing has been introduced and analyzed in [8]. Base Stations try to face their incoming requests first by using their initial spectrum, and then by exploiting frequencies not used by the others. Two algorithms for resource allocation are presented and evaluated, but the presence of a centralized network is assumed, together with a coordinating unit that manages the whole network. In [14,23] the authors introduce the concept of resource sharing in broadband cellular networks and show its impact on the achievable capacity and the packet delay. In this case, the resources shared among the different cells are the time slots (time division multiple access is employed), and operators use their allocated slots to transfer data to their mobiles. While in [23] sharing is seen as a "last resort" solution, in [14] a new way of implementing radio networks is explored where mobiles are always connected to the best base station, regardless of whether it belongs to their home operator or not. This point is different from the implementation that we present in this work, where the resource shared is the band and mobile terminals are always connected to their home operators.

Another paper where the inter-operator spectrum sharing context is taken into consideration is [13], where a game theoretic analysis is given for a cognitive context. Here, operators are classified into primary and secondary. This is slightly different from the system modeled in our simulator where, as described in the next section, eNBs are not supposed to have sensing capabilities and such a hierarchy is not present.

3. System model

The focus of this work is on spectrum sharing in OFDMA networks, particularly concerning the LTE standard [1]. As mentioned in the introduction, it is important to clarify the orthogonality of the access scheme in the pool of common frequencies: "orthogonality" means that simultaneous usage by more than one operator is not allowed. Considering that a non-orthogonal approach would require a longer discussion about the convergence of the algorithm for the resolution of contentions on shared frequencies, and the introduction of power control mechanisms for the users (i.e., the eNBs), we will focus on the orthogonal sharing case. Note that, in any event, this choice is made only for the sake of simplicity and, thanks to the modularity of the proposed framework, it can be easily extended to work with non-orthogonal sharing. Therefore, from this point on, we will assume that eNBs share orthogonally the pool of common frequencies, that is each frequency resource can be assigned to at most a single operator within an allocation time slot, in our case corresponding to the LTE subframe duration (1 ms).

We focus on the definition of a modular framework developed to test different solutions and efficiently evaluate the performance in terms of throughput and execution time. The resulting software can be used to validate several sharing policies, possibly derived within a game theoretic analysis. In this work, we will show sample results for orthogonal competitive sharing. However, given the modular nature of the simulator, more complex game theoretic approaches can be studied, even resorting to dynamic games, Stackelberg games and so forth [22,28].

To have a complete system characterization, we need to consider the spectrum management parameters, i.e., physical details such as center frequencies, channel bandwidth, and sharing percentages. In particular, the set of licensed frequencies that the operators are willing to share and the access mechanism must be defined. The policy behind such a cooperation agreement is out of the scope of the present paper, as it is more related to the economic agreement between the operators and to their business models. However, along with different allocation and coordination techniques, it represents an interesting research topic and, thanks to this contribution, various approaches can be quantitatively evaluated. Our choice is to be fully compliant with the LTE standard and to treat OFDMA resource blocks as perfectly fluidic and transferrable entities, subject to licensing constraints (that is, they

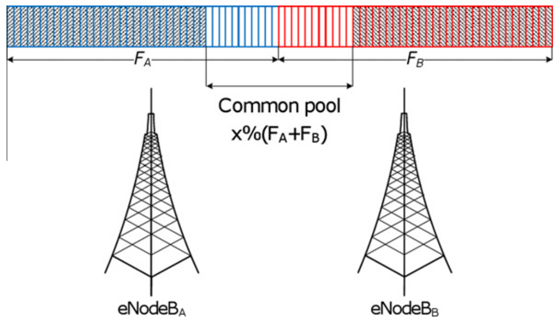

Fig. 1. Spectrum sharing.

can be shared only if the legitimate owner agrees to it). Fig. 1 shows the scheme adopted to define the system sharing capabilities. According to the selected bandwidth percentage to be shared, the eNBs will allow partial access to UEs belonging to other domains.

After there preliminaries, in the following subsections we describe two original parts of our contribution which complete the system description. First, we need to discuss local scheduling and resource allocation algorithms that must be executed in each eNB in order to generate an allocation map, the downlink serving scheme, which will be detailed in Section 3.1. Moreover, we consider a *virtual market* to be in charge of collecting this information and deriving serving schemes that must be adopted by each eNB, according to the chosen contention solving policy, which will be illustrated in Section 3.2.

3.1. Intra-cell allocation

The cell capabilities are fully characterized when the physical components have been defined. Then, we provide a joint scheduling and resource allocation algorithm to properly design a downlink transmission scheme. However, our goal is to integrate the proposed spectrum sharing framework for LTE systems into a simulation tool, ns-3. Conversely, the definition and the analysis of efficient schemes which can be fed to this simulator are not directly investigated here, but are left for future work, possibly within a game theoretic context.

For what concerns the scope of this paper, two basic algorithms have been implemented and compared: on the one hand, *max throughput* represents an allocation scheme for which the resources are allocated to the UEs with the best channel conditions, without taking into account fairness among users. On the other hand, a fair approach, denominated *fairness*, is proposed where the available system resources are distributed among the users, thus reducing the overall throughput. The distribution of the resources, hereinafter referred as resource blocks (RBs), happens in a Round Robin way with the pooling starting from the UEs with the best channel quality and moving to those in a worse condition. Note that, according to the LTE standard [1], channel quality is described by a Channel Quality Index (CQI) value which belongs to a predetermined set of 15 values, which dictates to use different modulation schemes and implies a different spectral efficiency, as will be discussed later.

During the first allocation round, each UE receives a number of RBs equal to

$$TH_{min} = \left\lfloor \frac{N_{RB}}{N_{UE}} \right\rfloor, \quad (1)$$

where N_{RB} represents the total number of RBs, and N_{UE} is the number of registered UEs requesting admission to the system. Once this minimum threshold has been guaranteed to all the users, all the

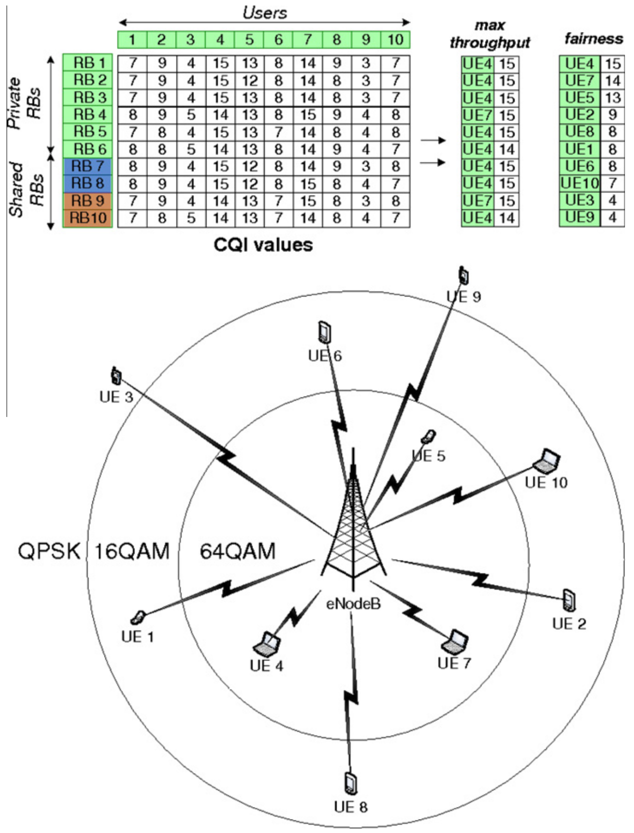

Fig. 2. Intra-cell allocation.

remaining RBs are distributed again by adopting a Round Robin policy and assigning 1 RB per UE starting first from those with better channel conditions. In the proposed example, the threshold in Eq. (1) is equal to 1, so all the UEs will be allocated a single RB. Fig. 2 depicts a sample scenario, where 10 UEs and 10 RBs are considered and both approaches evaluated.

3.2. Inter-cell multi-operator coordination

By enabling sharing mechanisms, base stations belonging to different operators will compete for the same resources. The contention resolution policy is implemented in a separate module, hereinafter called *virtual market*, as shown in Fig. 3. With reference to an Object-Oriented Programming paradigm, we need a *class* implementing the arbitration rule which defines how the operators bargain the access to the common portion of the licensed spectra. Any complex strategy can be implemented within this class, possibly involving further extensions. In particular, this may be the place where to implement, in an entirely modular manner, some procedures inspired by game theoretic principles. After generating its own allocation map, each eNB sends it to the *virtual market* that gathers all the cells' allocation information and rearranges the allocation map according to the sharing policy. In this paper, we propose the implementation of some scheduling and resource allocation algorithms, as well as a simple procedure to handle the contentions among operators. Each eNB is assigned a *priority* value per frequency sub-channel, defined as

$$PR_{eNB_j,RB_{pool,i}} = \begin{cases} p, & RB_{pool,i} \in F_{eNB_j} \\ 1-p, & \text{otherwise} \end{cases}, \tag{2}$$

where $j \in \{1,\ldots,m\}$ represents the eNB identifier, m is the total number of eNBs involved in the sharing process, $p \in [0,1]$ is the priority level given to the eNB, $F_{eNB_j} = \left\{RB_{j,1},\ldots,RB_{j,n_j}\right\}$, n_j is the total number of RBs available at eNB$_j$, and $RB_{pool,i} \in F_{eNB_j} \cup \ldots \cup F_{eNB_m}$. In other words, shared resources are assigned based on these priority levels; obviously, the UEs associated with eNB$_j$ will always have higher priority than all other competing users. In our work, the proposed approach is even simpler: we assume $p = 1$ and $m = 2$, so an eNB will assign to its UEs the shared resources belonging to the *competitor* eNB, referred to as eNB$_c$, only if these are not allocated to UEs belonging to eNB$_c$. Thus, when multiple players request the same resource, only the one with the highest priority will get it. The others end up with no assignment, which is in general inefficient.

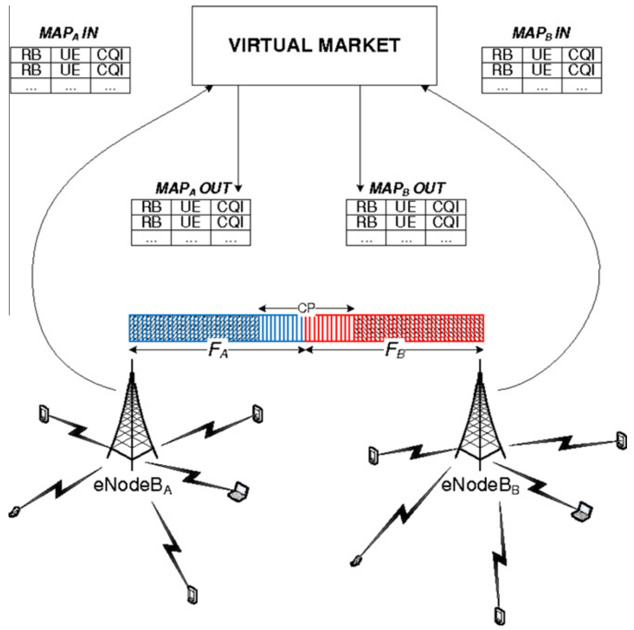

Fig. 3. Inter-cell coordination.

We stress that this general strategy is not given as an optimal allocation, which ought to be derived from a (game) theoretic perspective. Rather, such sub-optimal policies serve to show the effectiveness of our software implementation. Moreover, it can be thought of as a characterization of the inefficient Nash equilibria in the games with *competitive* sharing, while the goal of spectrum sharing should rather be a *collaborative* assignment of frequencies. Thus, our reference allocation policy correctly reflects that, if the whole common pool is shared competitively, in the long run only inefficient and unfair allocations will be achieved. However, we also remark that more efficient solutions derived through game theory, either available in the literature or originally developed, can be tested and validated within the modular framework proposed in this paper, so as to determine the choice that better suits the operator needs.

4. LTE extension for ns-3

In this section we describe the extension of the ns-3 original code that we implemented, with more details than in [11]. The reference implementation of LTE to which we applied our modifications is the one presented in [26] and included in ns-3 starting from the release ns-3.9. That version introduced a basic framework for the simulation of a single-cell LTE network. Several functionalities were only defined but not implemented (e.g., feedbacks from the UEs to their eNB). A simple downlink packet scheduler was provided. All the changes and/or additions made in our code aim at (i) enabling the multi-cell multi-operator LTE scenarios and (ii) defining a flexible architecture for inter-operator downlink spectrum sharing to test sharing policies. In this way, we have prepared a framework that can be used as is or extended again to simulate a broader range of situations. This is made possible by the extreme modularity of ns-3. It is also worth mentioning that our extension is entirely backward compatible with the previous releases of ns-3. The code is publicly available [7].

4.1. Multi-cell multi-operator scenario

The first step for the definition of a multi-cell scenario is the allocation of several objects of the class *LteHelper*, one for each cell. Such an object contains all the information needed to create and manage a cell, including a reference to the eNB and all its UEs.

An important modification that was required with respect to [26] regards the representation of the time axis as seen by each eNB. The PHY layer of eNBs and UEs is implemented in the classes *EnbLtePhy* and *UeLtePhy* respectively, where the operations of signal transmission and reception are managed. Both these classes are derived from the base class *LtePhy*, which contains all the properties and methods common to both types of nodes. Among the others, this class has in its private fields two *static* counters, one for the frame index (*m_nrFrames*) and another for the subframe index (*m_nrSubFrames*) within the current frame (see Fig. 4). They are incremented every time a new frame/subframe is started, a functionality that is implemented by the *EnbLtePhy* class, methods *StartFrame* and *StartSubFrame*, since it is up to the eNB to decide when to start the new frame/subframe. In a certain sense, they represent the timeline for the base station (and for the related cell as well). In a multi-cell scenario there are many eNBs, each with its own *EnbLtePhy*, but the values of the counters are common since they are declared as static. This means that if n eNBs increment the counter, then this will have a value n times greater than what it should have. Two possible solutions are available to solve this problem: either only an eNB increments those counters (a kind of master eNB) or each one of them has its own counters and increments them independently (i.e., the *static* modifier is removed). We have chosen the latter alternative, thus each eNB has its private view of the time index. In our case, they are all synchronized, hence they start each (sub) frame at the same time, but this choice does not prevent further more realistic variations where the eNBs are non-synchronized.

4.2. Downlink spectrum sharing

The implementation of the inter-cell downlink spectrum sharing involved several modifications with the aim to first introduce the spectrum sharing data structures and then develop the support to the conflict resolution mechanisms.

We made eNBs aware of the additional sub-channels they can use for downlink resource allocation by modifying the implementation of the *EnbLtePhy* and *UeLtePhy* classes. Originally, each one of them was assigned a vector of sub-channels which represents the available resources they can use. In our implementation we have associated to each node an extended vector containing not only the sub-channels originally assigned to it, but also those that the other eNBs are willing to share together with the sub-channel priority access information (i.e., a value indicating the level of priority of that node on each sub-channel). The previous data structure has been kept for backward compatibility. A fundamental assumption in this part of the code is that the portions of spectrum licensed to the operators are adjacent, i.e., there are no holes in the whole spectrum. This vector of frequencies is the one actually used for all the allocation, transmission and reception operations. In particular, the (intra-cell) resource allocation is performed by the class *PacketScheduler*. To test some new scheduling and allocation policies it is sufficient to extend it and override the method *DoRunPacketScheduler*, which is the routine called at the beginning of each subframe when a new set of packets must be selected for transmission to the UEs.

Once the support for sharing the frequencies among the eNBs (belonging to different operators) has been implemented, thus enabling them to choose among a broader range of resources, it is necessary to define a software architecture for the communication among the base stations and the synchronization of the access to the common pool. Each eNB determines its allocation map independently, according to an internal scheduling and resource allocation policy. Then, we decided to manage the inter-cell communication (i.e., allocation map exchange) and trading (i.e., conflict resolution) by introducing a virtual entity. In a real system, this phase requires that the eNBs communicate (e.g., through a backhaul) and agree on a final allocation map to which all of them must adhere. In our implementation, this communication is abstracted by such virtual entity, which is an object defined as an instance of the class *VirtualMarket* (see Fig. 3). At the beginning of each subframe, it receives the resource allocation maps

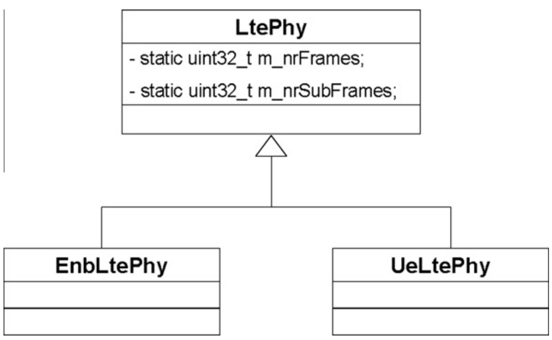

Fig. 4. UML class diagram for the PHY layer in ns-3 LTE.

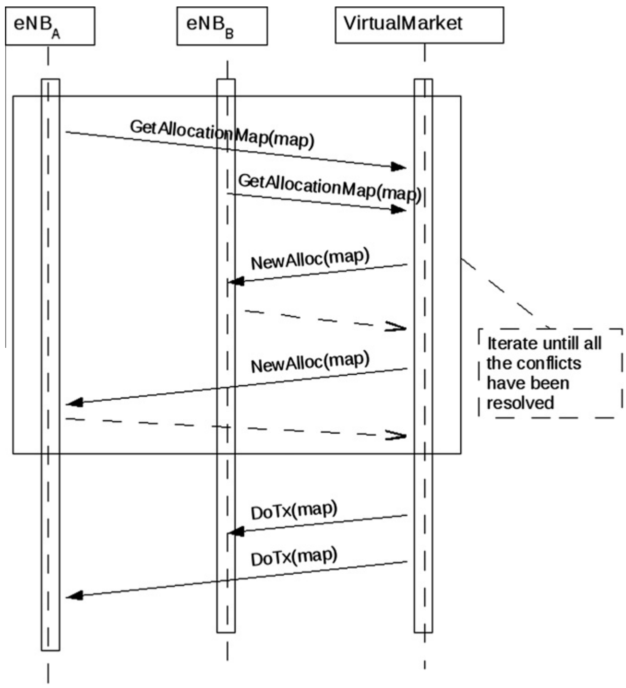

Fig. 5. Sequence diagram for allocation conflict resolution.

proposed by all the competing eNBs and decides the final map according to some policy. Developers can implement whatever policy they need by just modifying that class or extending it and overriding the method that deals with contention resolution, i.e., *GetAllocationMap*. The *VirtualMarket* has a collection of eNB entities, which can communicate with it through its public interface. In Fig. 5 an example of such a communication is shown by means of a UML sequence diagram, which is also able to catch the temporal dimension of the activity. The particular communication scheme shown is the one described in the previous section for conflict resolution, i.e., the priority mechanism. An iteration is indicated since every time a competitor cannot use a sub-channel for some UEs, i.e., it loses the contention, it is invited to reschedule those UEs on other free resources (if any). Of course, this is just an example given to describe how the architecture works.

5. Simulation scenario

In this section we describe the simulation scenarios that we considered to validate the software architecture presented above. We tested the sample sharing algorithms discussed in the previous sections; however, our main focus is on the performance and usability of the extended simulation platform instead of the algorithms themselves.

The scenario consists of two eNBs (i.e., eNB_A and eNB_B) positioned in the same area, both with a coverage of 1500 m. A certain (fixed) number of UEs, characterized by low mobility, are registered to each eNB and generate traffic. The UEs are distributed within the coverage area of the corresponding base station according to a two-dimensional uniform distribution. For the sake of completeness, we considered two types of situations: (i) both cells have the same number of UEs and the same traffic load (*symmetric cell load*), and (ii) the two cells have a different number of UEs and thus a different total traffic load (*asymmetric cell load*). In the former case, the number of UEs, equal for both eNBs, is an independent parameter of the analysis. In the latter, we assume that eNB_A always has 40 UEs to serve while the number of UE managed by eNB_B is an independent parameter. Also, in the latter case, each UE receives a a maximum number of 2 RBs according to a *max throughput* criterion.

As mentioned in the previous sections, each user perceives a different quality of the channel according to its position and other radio propagation related factors. Depending on the Signal-to-Interference-plus-Noise-Ratio (SINR), each UE calculates the CQI for each RB, which can be seen as a partitioning of the SINR values into 15 intervals. The CQI value is sent back to the eNB through a control channel. This information is used for the selection of an adequate Modulation and Coding Scheme (MCS). As reported in Table 1, LTE technology provides 15 different schemes [2], where ECR stands for Effective Code Rate, and represents the robustness of the selected coding scheme. Hence, each CQI determines the number of bits that can be transmitted in a single RB:

$$b_{RB} = RB_{subcarriers} \cdot RB_{OFDMsymbols} \cdot ECR_{CQI} \cdot b_{mod}, \tag{3}$$

where $RB_{subcarriers}$ and $RB_{OFDMsymbols}$, that represent the number of subcarriers per RB and the number of OFDM symbols per RB respectively, are provided in Table 2,, together with the main system parameters, while b_{mod} is the number of bits per symbol, determined by the specific M-ary modulation adopted:

$$b_{mod} = \log_2 M = \begin{cases} 2, & \text{for QPSK}, \\ 4, & \text{for 16-QAM}, \\ 6, & \text{for 64-QAM}. \end{cases} \tag{4}$$

The objective of the simulation campaign is twofold. On the one hand, we measure the performance of the proposed framework in terms of execution time; on the other hand, we used the simulator to analyze some spectrum sharing algorithms for LTE networks, in terms of cell sum capacity and aggregate throughput, thus showing the effectiveness of the proposed software. In fact, as will be extensively detailed in Section 6, the system performance behavior follows the trend that we expected: increasing the number of UEs in the system corresponds to a throughput increase, whereas increasing the sharing percentage induces a smooth decrease of the system throughput, according to the simple conflict resolution approach implemented. More specifically, the performance metrics taken into consideration are:

- **Execution time**, which represents the time required for the execution of a simulation run. We expect an increasing behavior in the number of UEs and in the sharing percentage because of the higher computational complexity needed to perform a greater number of operations. The reference machine is a server with 48 Pentium CPUs, 64 GB RAM and running GNU/Linux Ubuntu 11.04 as the operating system. It must be noted that, even though the number of available processors is considerable, the ns-3 software is inherently non parallel and thus all the runs were always executed on a single processor as if it were a single CPU machine. The only advantage of having more CPUs derived from the possibility to execute several simulations in parallel, one for each different combination of the input parameters (i.e., number of UEs and sharing percentage).
- **Cell sum capacity**, which represents the sum of the Shannon capacity reached in a cell on each sub-channel. It is given by

Table 1
LTE MCS.

CQI	Modulation	ECR	Spectral efficiency	$\mathbf{b}_{RB}$
1	QPSK	0.0762	0.15	24
2	QPSK	0.1172	0.23	40
3	QPSK	0.1885	0.38	60
4	QPSK	0.3008	0.6	100
5	QPSK	0.4385	0.88	144
6	QPSK	0.5879	1.18	196
7	16QAM	0.3691	1.48	248
8	16QAM	0.4785	1.91	322
9	16QAM	0.6016	2.41	402
10	64QAM	0.4551	2.73	452
11	64QAM	0.5537	3.32	554
12	64QAM	0.6504	3.9	654
13	64QAM	0.7539	4.52	756
14	64QAM	0.8525	5.12	856
15	64QAM	0.9258	5.55	936

Table 2
Main system parameters.

Parameter	Value
Center frequencies	2.115 GHz (eNB_A), 2.125 GHz (eNB_B)
eNB downlink channel bandwidth	10 MHz
Subcarrier bandwidth	15 kHz
Doppler frequency	60 Hz
$RB_{bandwidth}$	180 kHz
$RB_{subcarriers}$	12
$RB_{OFDMsymbols}$	14
eNodeB TX power per sub-channel	27 dBm
Noise spectral density (N_0)	−174 dBm/Hz
Pathloss	$128.1 + (37.6 \cdot \log_{10}(R))$ dB
Shadow fading	log-normal ($\sigma = 8$ dB)
Multipath	Jakes model with 6–12 scatterers
Wall penetration loss	10 dB
Simulated interval	10 s
Frame duration	10 ms
TTI	1 ms

$$C = \sum_{i=1}^{N_{UE}} \sum_{j=1}^{N_{RB}} (B \cdot \log_2(1 + SINR_{ij} \cdot \delta_{ij})), \quad \delta_{ij} = \begin{cases} 1, & \text{UE}_i \text{ allocated to } RB_j \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

where N_{RB} is the total number of RBs that can be exploited in the downlink of the cell (i.e., including those shared by the other eNBs), and $SINR_{ij}$ represents the SINR of UE_i on RB_j.

– **Cell sum throughput**, which represents the aggregation of the data rates delivered to all UEs, and is computed as

$$T = \frac{\sum_{i=1}^{N_{RB}} b_{RB_i}}{TTI}, \tag{6}$$

where b_{RB_i} represents the resource block size referred to the ith RB, N_{RB} is the total number of RBs available in the system, and TTI is the transmission time interval (see Table 2).

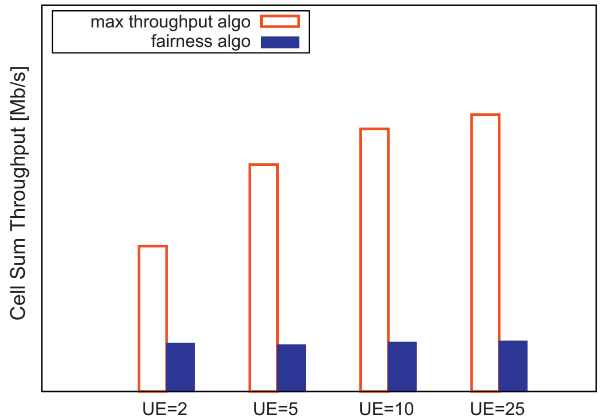

Fig. 7. Comparison of the Cell Sum Throughput for the *max throughput* and the *fairness* allocation algorithms, with a sharing percentage of 100%.

6. Numerical results

Figs. 6 and 7 show the performance in terms of sum capacity and throughput achieved by each cell for both *max throughput* and *fairness* intra-cell allocation algorithms for a different number of cell users. In this case we are considering a symmetric cell load, thus both cells have the same number of UEs and are statistically equivalent. For this reason, only the results for one of them are reported. As expected, the actual throughput value is significantly below the cell sum capacity, as defined in (5), which represents the upper bound on the data rate achievable for a given channel condition. The actual amount of data transmitted depends on the ECR. However, the behavior of both sum capacity and throughput as functions of the sharing percentage for different numbers of users is qualitatively similar, meaning that they differ only by a scaling factor due to the use of real coding and modulation schemes.

In both figures the trade-off between the *max-throughput* and the *fairness* allocation algorithms is clearly shown. The former always makes the system reach a better performance because the application of a fair scheduling policy requires the allocation of RBs also to the UEs with lower CQI. This is true for all values of the number of UEs.

Another important effect that can be noted from Figs. 6 and 7 is the increment of both performance indices with the number of UEs. As expected, this is due to the multiuser diversity effect: the larger the number of UEs, the higher the probability that for each sub-channel there is at least one of them with a good CQI. Of course, this might lead to some (short term) unfairness in favor of the users with a good channel quality. On the contrary, if the fairness constraint must be taken into consideration, then the effect of the multiuser diversity is significantly reduced. That is the reason for which in both figures, the increment of the performance indices for the *fairness* approach is almost negligible. For a possible discussion of this trade-off from a game-theoretic perspective, see [10,9]. Moreover, the marginal increment of efficiency decreases when a certain user density has been reached in the cell. When more users are in the system, then for almost all the sub-channels there is a user with good CQI. Thus, a saturation effect appears.

To sum up, the results validate the reliability of our model. Thanks to the modularity introduced, the contention technique can be adapted to different needs, and in particular to pursue a cooperative sharing, where system capacity and throughput increase when the spectrum sharing percentage becomes higher.

In Figs. 8 and 9 the sum capacity for both cells is shown in the asymmetric load scenario. In this case, since the total amount of traffic is different, the two cells are no longer statistically equivalent. The two figures show the variation of the performance index when several values of sharing percentage (parameter α) are considered. In such a scenario, the spectrum sharing gain can be better appreciated since the overloaded eNB can opportunistically exploit the RBs not used by the other. Of course, when $\alpha = 0\%$ the total capacity achieved in the first cell does not depend on the number of UEs in the second, since it can never use any of the spare re-

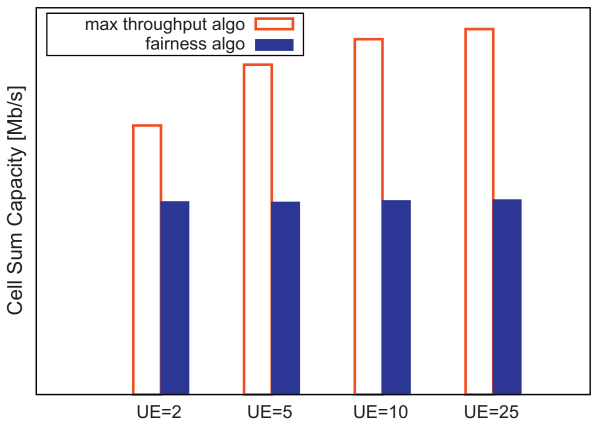

Fig. 6. Comparison of the cell sum capacity for the *max throughput* and the *fairness* allocation algorithms, with a sharing percentage of 100%.

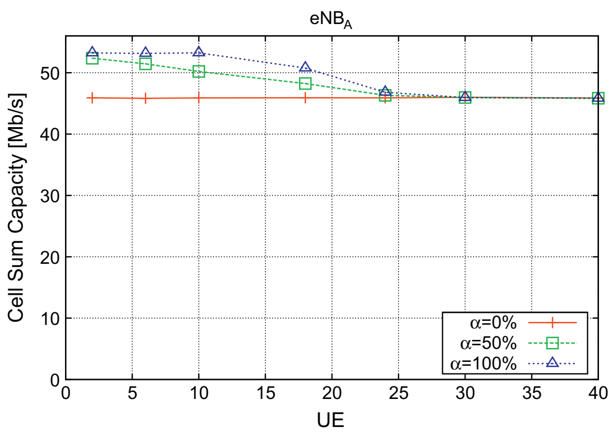

Fig. 8. Cell sum capacity for eNB_A versus the number of UEs in cell B in the asymmetric load scenario.

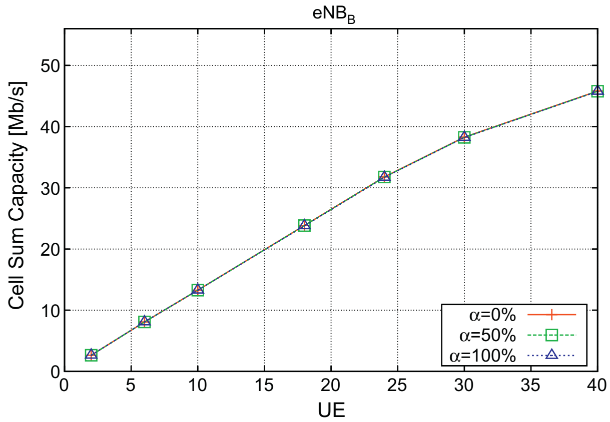

Fig. 9. Cell sum capacity for eNB_B versus the number of UEs in cell B in the asymmetric load scenario.

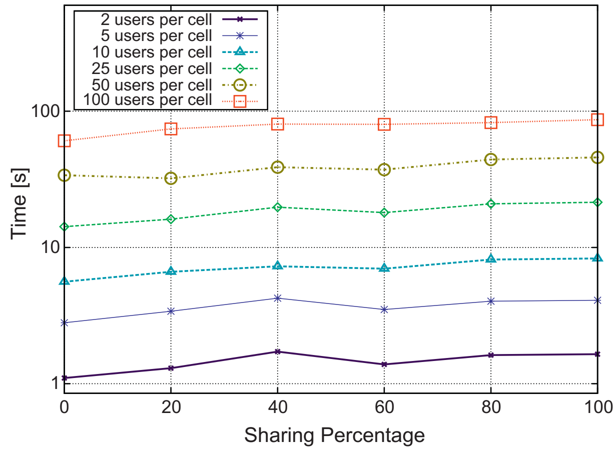

Fig. 10. Execution time.

sources, thus resulting in a remarkable waste of spectrum efficiency. This means that eNB_A cannot serve all its 40 UEs, which would require access to 80 RBs while only 50 RBs are available. On the other hand, when the sharing percentage increases the first eNB is entitled to use some of the resources of the second if it does not need them. This implies an average increment in the total capacity of eNB_A with α. Of course, also eNB_B is entitled to use some of the sub-channels in eNB_A's original pool but, since this one is in saturation, it is very unlikely to find some spare resources and thus it will end up in using mainly its portion of the spectrum. Therefore, the sum capacity in cell B increases with the number of UEs because more users are served but it does not vary significantly with α. It must be noted that the amount of this increment decreases at a certain point, i.e., after $UE = 25$. Indeed, while below such a threshold all the users can be served, beyond that value it is not possible to serve all of them (consider that the other cell is in saturation, so no spare frequencies can be found) and the only degree of freedom that eNB_B can exploit regards the scheduling of a UE instead of another one for the multiuser diversity. Regarding cell A, the total capacity for $\alpha = 50\%$, 100% decreases with the number of UEs in cell B since the larger the load in that cell, the higher the number of required RBs, and thus the lower the number of spare resources that can be accessed by eNB_A. Consider that a priority scheduling policy is adopted, so if eNB_B needs one of its sub-channels it will get it disregarding eNB_A's requests. Also these results validate the software architecture, and at the same time open up the problem of finding an optimal sharing policy, which appears to be an interesting future research direction. A joint gain might be achieved by introducing some coordination between the base stations, according to what stated by cooperative game theory [25].

Finally, in Fig. 10 the execution time resulting from a wide range of simulations is shown. It refers to the symmetric load scenario with a *max throughput* allocation algorithm. There is an obvious increment of the time required to run the simulations as the number of UEs and the spectrum sharing percentage increase. The simulation of more UEs requires more memory and computational resources to store and manage all those objects and thus a larger execution time. On the other hand, a greater amount of shared resources implies more contention and thus more iterations of the conflict resolution algorithm. Execution times also increase for greater sharing percentages since the (intra-cell) resource allocator has a greater number of degrees of freedom. Moreover, we remark that the tracing option was enabled in order to log the performance indices and calculate statistics. Disk accesses are quite time consuming and can slow down the execution by more than 10 times with respect to the normal duration. However, in spite of all these points, the computational complexity increases proportionally with the number of users and the sharing percentage, and can thus be considered acceptable for realistic and detailed simulation campaigns.

7. Conclusions

In this paper we have discussed an extension of the work presented in [11], whose main contribution was the design and implementation of a framework for multi-operator spectrum sharing mechanisms within an LTE implementation of the well-known network simulator ns-3. The aim is to provide the scientific community with an effective and flexible simulation tool that can be easily used, and possibly extended, for the investigation of such a challenging research field. In particular, in the present paper a more detailed description of the implemention is given together with the functional validation in some different and more realistic scenarios than those considered in the former study. The resulting software has been thoroughly tested to evaluate its correctness and reliability in achieving spectrum sharing functionalities. Two different algorithms for intra-cell allocation have been implemented in order to show the flexibility of the architecture and its importance for performance comparisons. Of course, the focus of this phase was on the simulator itself and not on the algorithms, whose performance is not expected to be optimal. However, the results have been satisfactory under all aspects, showing that our proposed extension can serve as a concrete tool to evaluate resource sharing mechanisms in next generation wireless networks. The code has been released and is publicly available [7].

A first important extension of the proposed architecture that can be identified regards the *non-orthogonal* spectrum sharing policy. In this paper, we considered only mutually exclusive access to the common sub-channels. Although simple, this approach might not lead to a full exploitation of the available bandwidth. Interfering transmissions might still be possible provided that the SINR at the intended receivers is above a certain threshold, needed to guarantee a good quality of the received signal. Of course, such a mechanism comes with an additional complexity due to the introduction of power control mechanisms to harmonize the transmission among different sources. Therefore, the investigation of this possibility may be of interest and the availability of a simulation support to the theoretical analysis is a key factor to reach a complete understanding.

8. Acknowledgments

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References

[1] 3GPP Evolved Universal Terrestrial Radio Access (E-UTRA), Overall description; Stage 2, 3GPP TS 36.300.
[2] 3GPP Tech. Specif. Group Radio Access Network; Conveying MCS and TB size via PDCCH, 3GPP TSG-RAN WG1 R1-081483.
[3] Matlab, available at: http://www.mathworks.com/products/matlab/.
[4] ns-3 simulator, available at: http://www.nsnam.org/.
[5] Omnet++ simulator, available at: http://www.omnetpp.org/.
[6] Simlib simulator, available at: http://www.fit.vutbr.cz/~peringer/SIMLIB/.
[7] ns-3 spectrum sharing framework for LTE, available at: http://code.nsnam.org/lanchora/ns-3-lte-SpectrumSharing/.
[8] B. Aazhang, J. Lilleberg, G. Middleton, Spectrum sharing in a cellular system, in: Proceedings of IEEE International Symposium on Spread Spectrum Techniques and Applications, 2004, pp. 355–359.
[9] L. Anchora, L. Badia, M. Zorzi, Joint Scheduling and resource allocation for LTE downlink using Nash bargaining theory, in: Proceedings of International Conference on Communications (ICC)-Workshop on Game Theory for Resource Allocation, June 2011.
[10] L. Anchora, L. Canzian, L. Badia, M. Zorzi. A characterization of resource allocation in LTE systems aimed at game theoretical approaches, in: Proceedings of 15th International Workshop on Computer Aided Modeling, Analysis and Design of Communication Links and Networks (CAMAD), Dec 2010.
[11] L. Anchora, M. Mezzavilla, L. Badia, M. Zorzi, Simulation models for the performance evaluation of spectrum sharing techniques in OFDMA networks, in: Proceedings of ACM International Conference on Modeling, analysis and Simulation of Wireless and Mobile systems (MSWiM), Nov 2011.
[12] L. Badia, M. Levorato, F. Librino, M. Zorzi, Cooperation techniques for wireless systems from a networking perspective, IEEE Wireless Commununications Magazine 17 (2) (2010) 89–96. Apr..
[13] M. Bennis, S. Lasaulce, M. Debbah, Inter-operator spectrum sharing from a game theoretical perspective, EURASIP Journal on Advances in Signal Processing, 2009, pp. 1–12, article No. 4, 2009.
[14] M. Bennis, J. Lilleberg, Inter base station resource sharing and improving the overall efficiency of B3G systems, in: Proceedings of IEEE Vehicular Technology Conference (VTC) Fall, 2007, pp. 1494–1498.
[15] A.B. Carleial, Interference channels, IEEE Transactions on Information Theory 24 (1) (1978) 60–70. Jan..
[16] R. Etkin, A. Parekh, D. Tse, Spectrum sharing for unlicensed bands, IEEE Journal on Selected Areas in Communcations 25 (3) (2007) 517–528. April.
[17] S. Geirhofer, L. Tong, B. Sadler, Dynamic spectrum access in the time domain: Modeling and exploiting white space, IEEE Communications Magazine 45 (5) (2007) 66–72. May.
[18] E. Jorswieck, L. Badia, T. Fahldieck, D. Gesbert, et al., Resource sharing in wireless networks: the SAPHYRE approach, in: Proceedings of Future Network & Mobile Summit, June 2010.
[19] E. Larsson, E. Jorswieck, Competition versus cooperation on the MISO interference channel, IEEE Journal on Selected Areas in Communications 26(7) (2008) 1059–1069.
[20] A. Leshem, E. Zehavi, Cooperative game theory and the Gaussian interference channel, IEEE Journal on Selected Areas in Communications 26(7) (2008) 1078–1088.
[21] P. Liu, Z. Tao, S. Narayanan, T. Korakis, S.S. Panwar, CoopMAC: A cooperative MAC for wireless LANs, IEEE Journal on Selected Areas in Communications 25 (2) (2007) 340–354. Feb..
[22] A. MacKenzie, L. DaSilva, Game theory for wireless engineers, Morgan and Claypool, San Rafael, CA, 2006.
[23] G. Middleton, K. Hooli, A. Tölli, J. Lilleberg, Inter-operator spectrum sharing in a broadband cellular network, in: Proceedings of IEEE International Symposium on Spread Spectrum Techniques and Applications, 2006, pp. 376–380.
[24] J. Mitola III, G. Maguire Jr, Cognitive radio: making software radios more personal, IEEE Personal Communications Magazine 6 (4) (1999) 13–18.
[25] M.J. Osborne, A. Rubinstein, A course in game theory, MIT Press, 1994.
[26] G. Piro, N. Baldo, M. Miozzo, An LTE module for the ns-3 network simulator, in: Proceedings of 4th International Conference on Simulation Tools and Techniques (SIMUTools), March 2011.
[27] V. Srinivasan, P. Nuggehalli, C.F. Chiasserini, R.R. Rao, Cooperation in wireless ad hoc networks, in: Proceedings of IEEE International Conference on Computer Communications (INFOCOM), vol. 2, July 2003, pp. 808–817.
[28] J. Zhang, Q. Zhang, Stackelberg game for utility-based cooperative cognitive radio networks, in: Proceedings of 10th ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc), 2009.