Simulation Models for the Performance Evaluation of Spectrum Sharing Techniques in OFDMA Networks

Luca Anchora*, Marco Mezzavilla§, Leonardo Badia*†§, Michele Zorzi†§
* IMT Institute for Advanced Studies, Piazza S. Ponziano 6, 55100 Lucca, Italy
† Consorzio Ferrara Ricerche, via Saragat 1, 44122 Ferrara, Italy
§ Dept. of Information Engineering (DEI), via Gradenigo 6B, 35131 Padova, Italy
luca.anchora@imtlucca.it, {mezzavil,badia,zorzi}@dei.unipd.it *

ABSTRACT

Cooperation in wireless networks is an important means to improve the resource utilization efficiency. It finds an interesting application in the context of spectrum sharing, where multiple wireless users put their licensed frequency bands in common in order to achieve a better resource usage. Due to the complexity of the problem, mathematical analysis is typically focused on simple scenarios. However, we believe that, in order to obtain a concrete proof of concept of the sharing paradigm, it is mandatory to assess its performance in realistic situations, i.e., with a larger number of nodes and a wider range of applications. Therefore, the support of a proper simulation environment is fundamental for high-quality applied research. In this paper we present and evaluate 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. We describe the software architecture that enables the spectrum sharing and, in particular, allows operators to interact in order to agree on a spectrum division. A sample sharing policy is given as well, and a detailed simulation campaign is run to validate the proposed architecture, assess its efficiency, and evaluate the simulation time related to scenarios with an increasing number of nodes.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Network communications, wireless communication; C.2.2 [**Computer Systems Organization**]: Computer-Communication Networks-Network Protocols; I.6.5 [**Model Development**]: modeling methodologies; I.6.8 [**Simulation and Modelling**]: Discrete event

General Terms

Design; Performance; Verification

Keywords

Spectrum sharing; ns-3; LTE; multi-operator cellular network.

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1. INTRODUCTION

The application of game theoretic concepts to wireless networking is becoming widespread within the relevant scientific literature. Several topics related to radio resource management have been approached by means of game theoretic tools which, until few years ago, were considered typical of economics, but have by now become common knowledge among wireless engineers [17]. One of the main reasons for the success of these techniques in the study of wireless networks is that game theory is well suited to approach problems involving both multiple players with different objectives and a general scarcity of resources, characteristics which are often found in radio networks. Actually, spectrum availability problems are due more to the inefficient usage by the licensed users rather than to a real lack of available frequencies [13]. Thus, it is the selfishness of the actors that makes radio resource access problems even more acute, which motivates a proper game theoretic analysis where *egoistic* players are given incentives to *cooperate*.

In particular, early attempts at using game theory within wireless scenarios were mainly considering *cognitive networks*, a model that, since its early characterization [19], involves a distinction between primary and secondary users; these terms are also frequently encountered in game theoretic duopoly analysis à la Stackelberg [21], i.e., involving a player moving first, and another reacting subsequently. A more recent trend of analysis involves a general paradigm of collaborative usage of the wireless spectrum, where different agents are no longer framed as owner or opportunistic unlicensed (i.e., primary and secondary, respectively) users, but rather an egalitarian approach is used. In this context, the focus is more on similarly-minded players, which can be thought of as network operators, which desire to share a portion, or possibly all, of their licensed frequencies for common wireless access, if they envision a gain in doing so, which can be a larger number of users served, a wider network coverage, or any similar benefit. When realistic models for the physical layer are considered, such a collaborative approach is found to be advantageous over competition among operators due to multi-user and frequency diversity [14].

Several studies hinted that spectrum sharing may be beneficial for all the involved players if a collaborative access to the wireless resource is achieved [8, 15, 16]. However, the practical scenario considered in the analysis is often limited to small networks with few transmitter-receiver pairs, most of the times just two, i.e., a total of four nodes. Instead, we believe that a precise performance evaluation of a detailed network is key to get a clear understanding of the usefulness of the sharing concept in wireless scenarios. It is also evident that the performance assessment of a complex system such as a wireless network comprising dozens of nodes cannot be performed through an exact analysis. However, it is fairly common in the scientific community to resort to network simulation instruments; among these, the network simulator-3 (ns-3) tool [4] is well known and is currently considered as one of the most advanced and modular. It is entirely open source and its features span the entire protocol stack, from the physical layer up to the application. Such a modularity has been improved with respect to its previous version ns-2, which, while fairly accurate in the medium access and networking layers, was not sufficiently accurate in the characterization of the wireless channel, at least with the high level of detail required when dealing with spectrum sharing issues. The properties of modularity and entire bottom-up representation of the protocol stack provided by ns-3 are particularly appealing for our purposes, since the analysis of spectrum sharing, while involving physical and datalink layers, implies important consequences in protocol design at higher layers as well, thus being an inherently cross-layer problem. These reasons motivate our choice to employ an existing implementation [20] within ns-3 of the Long Term Evolution (LTE) of the Universal Mobile Telecommunications System (UMTS) [1].

The main contribution of the present paper 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; in particular, as will be discussed in the following, 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 it 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 by the operators when determining the shared portion of the spectrum. In particular, two main sharing meta-policies are available, namely *orthogonal* and *non-orthogonal* sharing. In the former case, the frequencies of the shared pool still remain into exclusive usage of exactly one operator, although not necessarily the one that detains the legal property of the access on that frequency. In the latter, also simultaneous access on the same frequency is possible. In both cases, the arbitrator structure is required to give an abstract representation of every other sharing policy detail, such as priority rules among the operators in case of conflicting assignments. 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 straightforward. Moreover, to simplify the game theoretic analysis, only competitive sharing will be modeled, leaving the issue of identifying efficient and collaborative sharing mechanisms for future work.

Besides introducing the details of the software extensions implemented within ns-3, this paper also provides the results of an extensive simulation campaign meant to assess the effectiveness of the simulator as a benchmark for testing spectrum sharing algorithms. A simple sharing algorithm is used, 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

The availability of a suitable simulation platform for testing protocols and algorithms is quite important, in particular for all those scenarios where the mathematical analysis becomes complex or cannot produce a solution in closed form. One immediate solution, which is often used in the literature, is to develop a basic single-purpose simulator, written from scratch and specific to the scenario under investigation. However, such a solution often violates important requirements in scientific work, i.e., generality and reproducibility of the results. Conversely, several standard code libraries and simulation tools have been developed to support researchers in their work. Some of these instruments are general purpose (e.g., SIMLIB [6], MATLAB [3]) and need customization to the particular context that is to be evaluated; others are more application specific and are meant to simulate the behavior of particular systems, e.g., OMNET++ [5].

For the case of 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 datalink layers. Therefore, many different network scenarios can be created and simulated. One of the last implemented modules realizes LTE cellular networks [20]. The introduced framework enables the creation of Base Stations (called eNodeBs, or eNBs) and user terminals (called UEs) which can communicate with the eNBs. Most of the functionalities of the physical channel and medium access have been implemented, while some of them are still empty or a sample code has been provided, giving the programmer the opportunity to introduce and test new algorithms. This paper aims at extending this basic framework by introducing the multi-cell scenario and allowing eNBs to share part of their frequencies in the downlink direction. This situation is particularly interesting when the eNBs are managed by different cellular network operators.

Although the problems of interference channels and spectrum sharing have been addressed in several papers, e.g., [11, 12], the scenario of inter-cell spectrum sharing has been 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 areas is quite common, it is sensible 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 [7]. 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 [10, 18] the authors introduce the concept of resource sharing in broadband cellular networks and show its impact on achievable capacity and 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 [18] sharing is seen only as a "last resort" solution, in [10] 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 quite far from the implementation that we present in this work, where the resource shared is the band and mobile terminals are always connected to the their home operator.

Another paper where the inter-operator spectrum sharing context is taken into consideration is [9], where a game theoretic analysis is given for a cognitive context where operators are classified into primary and secondary. This is slightly different from the system modeled in our simulator, as described in the next section, where eNBs are not supposed to have sensing capabilities and such a hierarchy is not present.

3. SYSTEM MODEL

We focus on the problem of spectrum sharing in OFDMA networks, with particular reference to the LTE standard [1]. As seen in the introduction, when discussing spectrum sharing policies it is important to clarify the orthogonality of the access scheme in the pool of common frequencies, where "orthogonality" means "impossibility of simultaneous usage by more than one operator." Given that the non-orthogonal approach would require a lengthy discussion about the convergence of the contention for shared frequencies, and the description of a power control mechanism for the users (i.e., the eNBs), we will limit the following discussion to the orthogonal sharing case. Note that, in any event, this choice is made only for the sake of simplicity and is not restrictive as the software modules developed are entirely transparent to the orthogonality property, and they can be promptly extended to work under non-orthogonal sharing almost without any modification. Therefore, from this point on, we will assume that eNBs share orthogonally the pool of common frequencies so that each frequency resource can be assigned to at most a single operator (which, in turn, will use it for one of its UEs) within an allocation time slot, in our case corresponding to the LTE subframe duration, i.e., 1 ms.

Therefore, this work focuses on the definition of a modular framework developed to test different solutions and efficiently evaluate the performance in terms of throughput and execution time, observing scenarios with an increasing number of UEs and sharing percentages. The resulting software can be used as a validation platform for several sharing policies, possibly derived within a game theoretic analysis. In the following, we will show sample results for orthogonal competitive sharing. However, given the modular nature of the simulator, more complex game theoretic approaches can be framed, even resorting to dynamic games, Stackelberg games and so on [17, 21].

The proposed framework can be divided into three parts. First of all, the spectrum usage parameters must be provided, i.e., physical details such as the center frequency, the channel bandwidth, the sharing percentage, and so forth (see Section 3.1). Then, local scheduling and resource allocation algorithms must be executed in each eNB in order to generate an allocation map that represents the proposed serving scheme, as detailed in Section 3.2. Finally, a virtual market is in charge of collecting the local allocation maps and derive the serving schemes that must be adopted by each eNB, according to the chosen contention solving policy, as will be illustrated in Section 3.3.

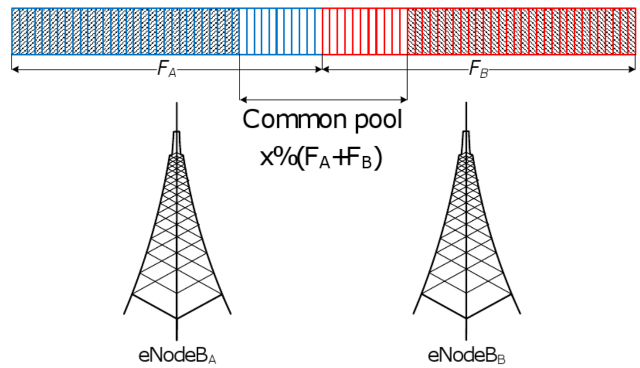

Figure 1: Spectrum sharing

3.1 Spectrum management

Once the physical parameters have been determined, the eNBs select the set of frequencies on which they plan to interoperate. 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 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. Figure 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.

3.2 Intra-cell allocation

The cell capabilities are fully characterized when the physical components have been defined. Then, a joint scheduling and resource allocation algorithm is needed to design a proper downlink transmission scheme. However, the focus of this paper is just on the integration of the proposed spectrum sharing framework for LTE systems into a simulation tool, ns-3. Conversely, the definition and the analysis of efficient game theoretic 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 one hand, *max throughput* represents an allocation scheme for which the resources are allocated to the best UEs, without taking into account fairness among users. On the other hand a fair approach, denominated *fairness*, is proposed: the available system resources are equally distributed among the users, thus lowering the overall throughput, but increasing the average level of satisfaction of each UE. Figure 2 depicts a sample scenario, where 10 UEs and 10 resources, hereinafter referred as resource blocks (RBs), are considered. By selecting the first approach, *max throughput*, all the available resources are allocated to the UEs with the best channel quality indicator (CQI), discussed later in Section 6. Thus, by exploiting multiuser diver-

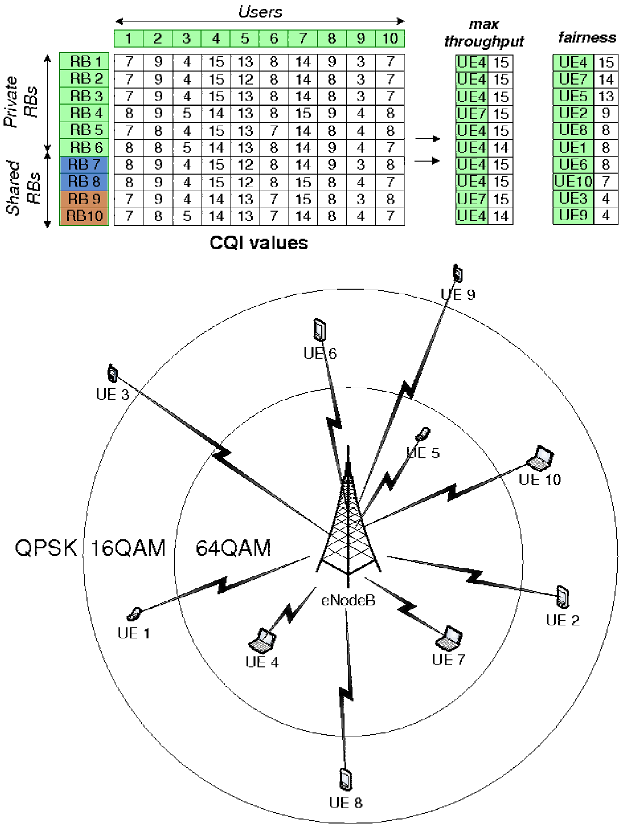

Figure 2: Intra-cell allocation

sity, the system throughput can be very high. However, UEs with lower CQIs will never be served. Therefore, an additional technique has been introduced, i.e., the *fairness* mechanism which, as visible in the figure, will provide service to all the registered UEs. As per the previous case, each RB is allocated to the best UE, but each user cannot get more than a fixed amount of resources. This threshold is given by

$$TH = \left\lceil \frac{N_{RB}}{N_{UE}} \right\rceil, \quad (1)$$

where N_{RB} represents the total number of RBs, and N_{UE} is the number of registered UEs requesting admittance in the system. In the proposed example, from equation (1) the threshold is equal to 1, so all the UEs will be allocated a single RB.

3.3 Inter-cell coordination

The sharing contention policy is implemented in a separate module, here called *virtual market*. The relevant class (we refer to an Object-Oriented Programming, or OOP, paradigm) implements an arbitration rule which defines how the operators bargain the access to the common portion of the spectrum. 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. Each eNB, after generating its own allocation map, sends it to the *virtual market* that gathers all the cells' allocation information and rearranges the allocation map according to the sharing policy. For the sake of simplicity, in this paper we propose immediate implementations of scheduling and resource allocation

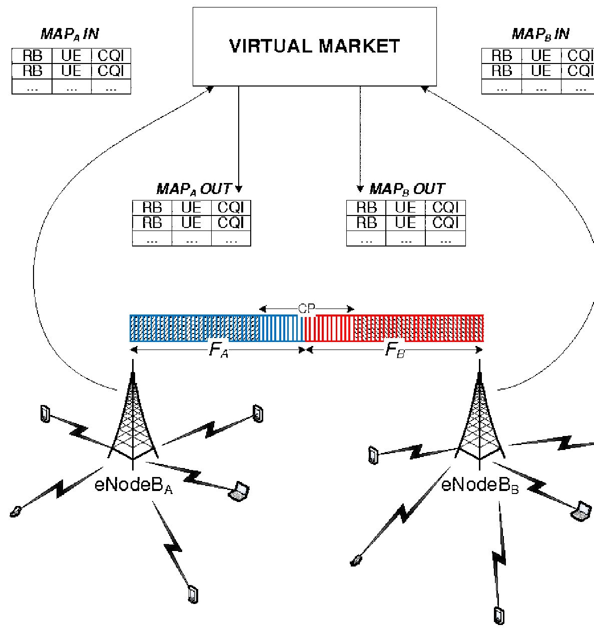

Figure 3: Inter-cell coordination

algorithms, as well as a simple procedure to handle the contentions among operators. Each eNB is assigned a *priority* value per frequency subchannel, defined as

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

where $j \in \{1, ..., m\}$ 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, $F_{eNB_j} = \{RB_{j,1}, ..., RB_{j,n_j}\}$, n_j is the total number of RBs available at eNB$_j$, and $RB_{pool,i} \in F_{eNB_j} \cup ... \cup F_{eNB_m}$. In other words, shared resources are assigned based on these priority levels; obviously, the UEs associated to eNB$_j$ will always have higher priority than all other competing users. In our paper, 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.

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 an intentionally non-optimized (and actually inefficient) policy serves 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. NS-3 LTE EXTENSION

The reference implementation of LTE to which we have applied our modifications is the one presented in [20] and included in the current release of the ns-3 simulator. Our extension introduced two main features, i.e., the implementation of multi-cell multi-operator scenarios and the definition of inter-operator downlink spectrum sharing policies. In this way, we have prepared a framework that can be used as is or extended again to simulate a broader category of scenarios. This is made possible by the extreme modularity of ns-3. It is also worth mentioning that our extension is entirely backward compatible with previous versions of ns-3.

4.1 Multi-cell multi-operator scenario

The definition of a multi-cell scenario requires first of all the definition of a separate object of the class *LteHelper* for each cell. Such an object contains a reference to the eNB and all its UEs and therefore manages the creation and configuration of all the members of a cell (e.g., registration of a UE). Different cells are managed by different *LteHelper*s.

A further modification that was required with respect to [20] regards the management of the time by each eNB. The class *LtePhy* is the base class for modeling eNB and UE physical layer. Then *EnbLtePhy* and *UeLtePhy* are derived classes that implement particular features of the physical layer for the two types of nodes, such as transmission and reception of signals on the wireless channel. The *LtePhy* class has in its private fields two *static* counters, one for the frame index and another for the subframe index within the current frame. 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 multi-cell scenario there are many eNBs, each with its own *EnbLtePhy*, and all these counters need to be incremented. Therefore, two possible solutions are available: either only an eNB increments those counters or each one of them has its own counter and increments it independently. In our implementation we have chosen the latter, thus each eNB has its private view of the time index. In our implementation, they are all synchronized, hence they start each (sub)frame at the same time, but this implementation choice does not prevent further more realistic extensions where the eNBs are non-synchronized.

4.2 Downlink spectrum sharing

Regarding the implementation of the inter-cell downlink spectrum sharing, several modifications to the base model have been written. First of all, we made eNBs aware of the additional subchannels they can use for downlink resource allocation. The original implementation assigns to each *EnbLtePhy* and *UeLtePhy* a vector of subchannels which represents the available resources they can use. In our implementation we have associated to each node an extended vector containing not only the subchannels originally assigned to it, but also those that the other eNBs are willing to share (calculated as a percentage of the original spectrum size) together with the subchannel priority access information. This vector is the set of frequencies that is actually used by the resource allocator of the eNB. The way it is used depends on the scheduling and allocation policy implemented. In particular, to customize these functionalities, it is sufficient to write a new class which extends the *PacketScheduler* class, thereby inheriting its methods, and to override the method *DoRunPacketScheduler*, i.e., the routine called at the beginning of each subframe when a new set of packets must be selected for transmission.

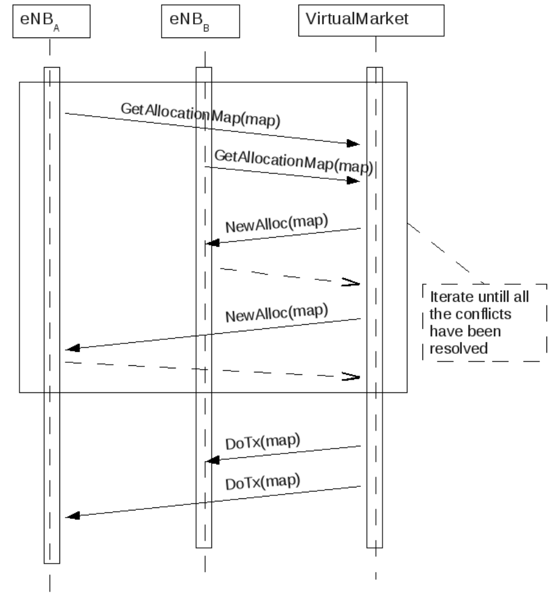

Figure 4: Sequence diagram for allocation conflict resolution

As a further point, we have implemented the communication and trading mechanisms among the eNBs for the sharing of the common pool. Each eNB calculates its allocation map independently, according to an internal scheduling and resource allocation policy. Then, a virtual entity has been introduced to implement the exchange of the maps and the resolution of the conflicts. 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. This virtual entity is an object defined as an instance of the class *VirtualMarket*; at the beginning of each subframe, it receives the resource allocation maps proposed by all the eNBs (competitors) 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 Figure 4 an example of such a communication is shown by means of a sequence diagram, which is also able to catch the temporal dimension of the activity. The particular communication protocol shown is the one described in the previous section for conflict resolution. An iteration is shown since every time a competitor cannot use a subchannel for some UEs (i.e., it loses the contention), it is invited to reschedule those UEs on other free resources (if any).

5. SIMULATION SCENARIO

In order to test the software architecture that we have implemented, and to validate the sample sharing algorithm proposed, we have run some simulations. The aim of this phase is not to test the performance of the algorithm itself since, as already said, the focus of this paper is on the architectural extension of the simulator. The algorithm that we have implemented is meant to be just an example to show how things work, so it is not expected to be the optimal solution. We are more interested in the performance and the usability of the simulator itself. In the following we present the results of a simulation campaign conducted with the extended framework for spectrum sharing in ns-3.

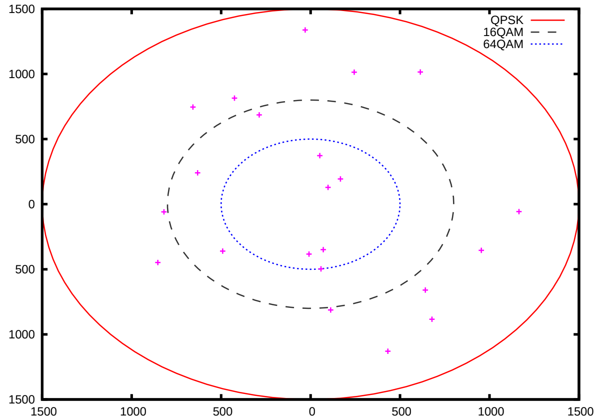

Figure 5: Deployment of the UEs around the eNB

CQI	Modulation	ECR	Spectral Efficiency	TB
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 1: LTE MCS

The scenario consists of two eNBs positioned in the same field, both with a coverage of 1500 m. An increasing number of UEs, characterized by low mobility, are registered to each station, and are uniformly distributed within the associated eNB coverage area. Figure 5 depicts an example of user distribution resulting after the execution of a simulation run with 22 UEs.

As mentioned in the previous sections, each user perceives a different quality of the channel according to its position and other minor factors. Hence, an ideal channel is established between the UE and the eNB, used for the transmission of the CQIs associated to each RB. In fact, thanks to this information, the eNB can select an adequate Modulation and Coding Scheme (MCS). As reported in Table 1, LTE technology provides 15 different option schemes [2], where ECR stands for Effective Code Rate, and represents the robustness of the selected coding scheme. Hence, each MCS determines the transport block (TB) size that results from

$$TB_{CQI} = \frac{RB_{subcarriers} \cdot RB_{OFDMsymbols} \cdot ECR_{CQI}}{TTI}, \quad (3)$$

where $RB_{subcarriers}$, $RB_{OFDMsymbols}$, and TTI, that represent the number of subcarriers per RB, the number of OFDM symbols per RB, and the scheduling time respectively, are provided in Table 2, together with the main system parameters.

Parameter	Value
Center Frequency	2.0 GHz
Channel Bandwidth	10 MHz
Subcarrier Bandwidth	15 kHz
Doppler frequency	200 Hz
$RB_{bandwidth}$	180 kHz
$RB_{subcarriers}$	12
$RB_{OFDMsymbols}$	14
eNodeB TX power	43 dBm
Noise figure (F)	2.5
Noise spectral density (N_0)	-174 dBm/Hz
Macroscopic pathloss	$128.1 + (37.6 \cdot \log_{10}(R))$ dB
Shadow fading	log-normal ($\mu = 0, \sigma = 8$ dB)
Multipath	Jakes model
Wall penetration loss	10 dB
Simulated interval	2000 subframes
Frame duration	10 ms
TTI	1 ms

Table 2: Main system parameters

The simulation campaign is executed to investigate the reliability of the proposed framework, in terms of theoretical capacity, aggregate throughput, and simulation time. In fact, as will be extensively detailed in Section 6, the system performance behavior follows the trend that we expected: on the one hand, increasing the number of UEs in the system corresponds to a throughput increase, while on the other hand 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:

—**Shannon Capacity**, which represents the maximum theoretical throughput in communication systems. It is defined as the maximum of the mutual information between the input and the output of the channel, and is given by

$$C = B \cdot \log_2(1 + SNR). \quad (4)$$

—**System Throughput**, which represents the aggregation of the data rates delivered to all UEs, and is computed as

$$T = \frac{\sum_{i=1}^{N} TB_{RB_i}}{TTI}, \quad (5)$$

where TB_{RB_i} represents the transport block size referred to the ith RB, and N is the total number of RBs available in the system.

—**Simulation time**, which represents the execution time of each set of simulation runs. As expected, it grows with the number of UEs and with the sharing percentage because of the higher computational complexity needed to process a larger number of operations. The reference machine is a desktop computer with a Pentium 4 CPU, 1 GB RAM and running GNU/Linux Ubuntu 10.04 as the operating system.

6. NUMERICAL RESULTS

Figures 6–7 show the performance in terms of capacity and throughput achieved by each cell when the *max throughput* allocation is used. As expected, the actual throughput value is significantly below the channel capacity, which represents the theoretical limit achievable with such a channel condition. The actual amount of data transmitted depends on the ECR and is upper bounded by

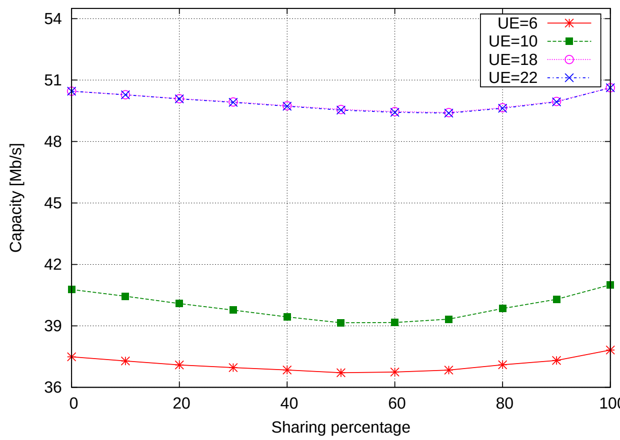

Figure 6: Cell capacity of the *max throughput* allocation

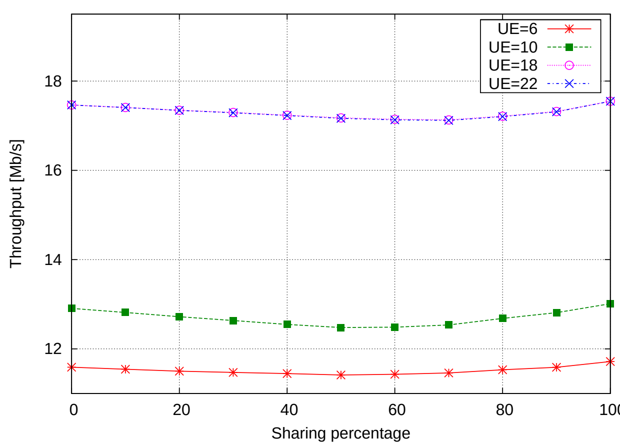

Figure 7: Cell throughput of the *max throughput* allocation

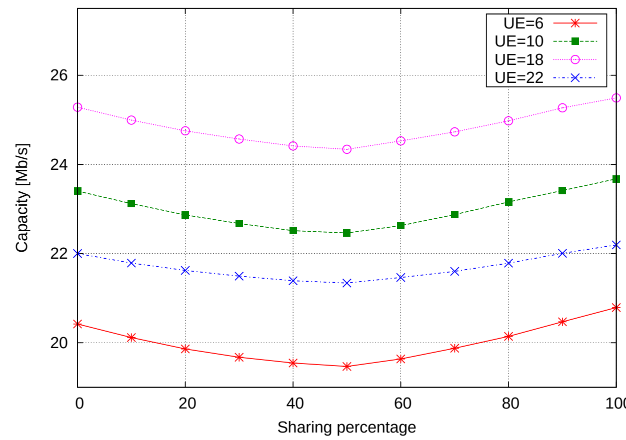

Figure 8: Cell capacity of the *fairness* allocation

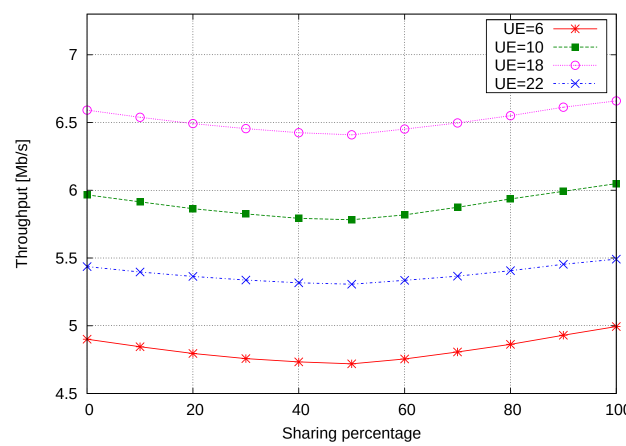

Figure 9: Cell throughput of the *fairness* allocation

the Shannon capacity. However, the behavior of both 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. A first conclusion that might be drawn from these figures is that, if spectrum sharing is performed in a *competitive* manner, there is no gain for the operators in sharing their frequencies. In fact, the higher the sharing percentage, the more likely the resource conflicts. Due to the lack of collaboration among the operators, they simply try to get the best frequencies, whereas other less appealing resources are wasted. This is a typical phenomenon of *non cooperative* game theory, i.e., an inefficient Nash equilibrium as a result of the selfishness of the players [17]. The situation is made worse by the constraint that the private subchannels of one eNB cannot be accessed by the other eNBs, and so some resources might be unsed. These are the main reasons for the convexity of the curves: the presence of a minimum for a 50% sharing indicates the situation of maximum waste. Although the focus of this paper is just on the software framework, we see as a promising extension the identification of efficient game theoretic strategies for inducing the operators to achieve a *collaborative* sharing, thus improving the allocation efficiency. The modularity of our software allows for a prompt insertion of such strategies.

Another important intuition that can be gained from those figures is that both performance indices increase with the number of users. This is an effect of the increased multiuser diversity: the greater the number of UEs, the higher the probability that for each subchannel there is at least one of them with a good CQI. However, this increase is significant only when the number of users is low. When more users are in the system, the marginal improvement due to multiuser diversity becomes lower since for almost all the subchannels there is a user with good CQI. Thus, the curves seem to saturate around 18 users.

To sum up, the results validate the reliability of our model in spite of an inefficient sharing policy, that was not the scope of this paper. 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.

Our framework also enables a comparative analysis among different allocation approaches. Therefore, we can compare the *max throughput* allocation with the other approach, i.e., the *fairness* allocation, that aims at scheduling all the users, not just the best ones. As expected, applying a fair scheduling scheme results in

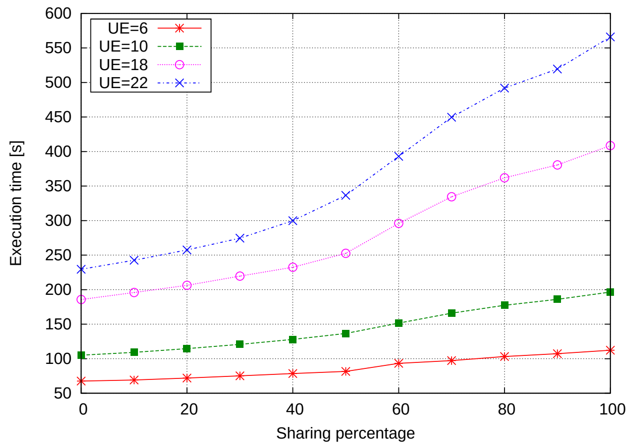

Figure 10: Simulation time

a decrease of the system throughput. This is shown in Figures 8 and 9, where it can be noted that the aggregate data rates obtained are roughly halved with respect to the *max throughput* approach. Moreover, it is highlighted that in the *fairness* allocation both performance indices do not always improve when the number of users increases. In fact, when the number of users is increased, the fairness constraint is harder to satisfy and may actually lead to an overall decrease of the system capacity and throughput.

Finally, the execution time resulting from a wide range of simulations is analyzed. As shown in Figure 10, the obvious complexity increase with respect to the increase of the number of UEs and spectrum sharing percentage is reflected in the graphs. A higher number of UEs requires more memory and computational resources to store and manage all those objects and thus a higher execution time. On the other hand, a greater number of shared resources implies more contention and thus more iterations of the conflict resolution algorithm. Execution times also increase for higher sharing, since the simulator has a higher 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 the normal duration. However, in spite of all these points, the computational complexity scales almost linearly with the number of users, and can thus be considered acceptable for realistic and detailed simulation campaigns.

7. CONCLUSIONS

In this paper we outlined and evaluated a framework for spectrum sharing mechanisms within an LTE implementation of ns-3. The resulting software has been thoroughly tested to evaluate its correctness and reliability in achieving spectrum sharing functionalities. 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.

Future work involves the implementation and exploration of *non-orthogonal* sharing mechanisms, where multiple players are allowed to operate on the shared frequencies. Such an extension implies also the introduction of power control mechanisms to harmonize the transmission among different sources. Finally, submission of the developed software for official release in ns-3 is also planned for the near future.

8. 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] B. Aazhang, J. Lilleberg, and G. Middleton. Spectrum sharing in a cellular system. In *Proc. IEEE ISSSTA*, pages 355–359, 2004.

[8] L. Badia, M. Levorato, F. Librino, and M. Zorzi. Cooperation techniques for wireless systems from networking perspective. *IEEE Wireless Commun. Mag.*, 17(2):89 – 96, Apr. 2010.

[9] M. Bennis, S. Lasaulce, and M. Debbah. Inter-operator spectrum sharing from a game theoretical perspective. *EURASIP J. on Advanc. in Sign. Proc.*, 2009:1–12, 2009.

[10] M. Bennis and J. Lilleberg. Inter base station resource sharing and improving the overall efficiency of B3G systems. In *Proc. IEEE VTC Fall*, pages 1494–1498, 2007.

[11] A. B. Carleial. Interference channels. *IEEE Trans. Inf. Theory*, IT-24(1):60–70, Jan. 1978.

[12] R. Etkin, A. Parekh, and D. Tse. Spectrum sharing for unlicensed bands. *IEEE J. Sel. Areas Commun.*, 25(3):517–528, April 2007.

[13] S. Geirhofer, L. Tong, and B. Sadler. Dynamic spectrum access in the time domain: Modeling and exploiting white space. *IEEE Commun. Mag.*, 45(5):66–72, May 2007.

[14] E. Larsson and E. Jorswieck. Competition versus cooperation on the MISO interference channel. *IEEE J. Sel. Areas Commun.*, 26(7):1059–1069, Sept. 2008.

[15] A. Leshem and E. Zehavi. Cooperative Game Theory and the Gaussian Interference Channel. *IEEE J. Sel. Areas Commun.*, 26(7):1078–1088, Sept. 2008.

[16] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. S. Panwar. CoopMAC: A cooperative MAC for wireless LANs. *IEEE J. Sel. Areas Commun.*, 25(2):340 – 354, Feb. 2007.

[17] A. MacKenzie and L. DaSilva. *Game Theory for Wireless Engineers*. Morgan and Claypool, San Rafael, CA, 2006.

[18] G. Middleton, K. Hooli, A. Tölli, and J. Lilleberg. Inter-operator spectrum sharing in a broadband cellular network. In *Proc. IEEE ISSSTA*, pages 376–380, 2006.

[19] J. Mitola III and G. Maguire Jr. Cognitive radio: making software radios more personal. *IEEE Personal Commun. Mag.*, 6(4):13–18, 1999.

[20] G. Piro, N. Baldo, and M. Miozzo. An LTE module for the ns-3 network simulator. In *Proc. SIMUTools*, March 2011.

[21] J. Zhang and Q. Zhang. Stackelberg game for utility-based cooperative cognitive radio networks. In *Proc. ACM MobiHoc*, 2009.