

Capacity Gains due to Orthogonal Spectrum Sharing in Multi-Operator LTE Cellular Networks

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Abstract—Static spectrum allocation leads to resource wastage and inter-operator spectrum sharing is a possible way to improve spectrum efficiency. In this work, we assume that two cellular network operators agree upon sharing part of their spectrum, which can then be dynamically accessed by either of them in a mutually exclusive way. Our goal is to numerically assess the gain, in terms of cell capacity, due to such orthogonal spectrum sharing. Hence, we propose a centralized algorithm that performs coordinated scheduling, in order to numerically evaluate an upper bound on the achievable sum capacity. The algorithm is centralized and exploits complete information on both networks to perform the optimum allocation. The simulation results illustrate the impact of the multiuser diversity and the asymmetry in the traffic load among the networks on the overall achievable gain.

Index Terms—Spectrum sharing, resource allocation, OFDMA, LTE downlink, multi-operator networks, multiuser diversity.

I. INTRODUCTION

IN the last decade, cellular networks have been receiving an ever increasing attention from the market. Their permanent availability in most locations made them a fundamental means for the realization of the *anywhere anytime* communication paradigm. Currently, such networks are not used only for phone calls but also as access networks to the Internet. Therefore, most of the traffic is generated by applications such as web, e-mail, file transfer, streaming audio and video. The exponentially increasing traffic load and the high Quality-of-Service (QoS) requirements are the main challenges. The scarcity of resources with respect to the high demand and their cost implies the need for efficient use. In general, the term *resource* can be referred to spectrum, power, infrastructure, etc. In this work, we focus on the spectrum licensed to network operators. Herein, we consider the downlink mode of the cells, where Orthogonal Frequency Division Multiple Access (OFDMA) is the reference technology, according to the Long Term Evolution (LTE) of the UMTS standard [1].

In most countries, each cellular network operator is licensed by the regulator a separate portion of the spectrum. The operator then manages this spectrum trying to minimize inter-cell interference. In this process, it does not need to take into consideration other operators' choices since the orthogonality

of the spectrum licensing guarantees inter-operator interference avoidance. Although effective, this approach leads to inefficient use of spectrum. First, if a cell of an operator is underloaded for a certain period of time, then a part of the spectrum will be wasted, while it could have been exploited by adjacent cells of other operators experiencing high traffic. Second, the gains due to multiuser diversity that a Base Station (BS) can exploit during resource allocation are bounded by the size of the spectrum portion allocated to the cell. If larger spectrum chunks can be accessed, then higher data rates can be guaranteed to the users.

In order to overcome the aforementioned problems, we consider a scenario where several operators decide to share with each other a part of their spectrum [2]. However, this choice requires coordination of the access to the shared resources in order to avoid another resource wastage due to the so called “Tragedy of the commons” [3]. Many algorithms can be proposed, belonging to two main categories: *orthogonal* and *non-orthogonal*. The former considers mutually exclusive access to the shared spectrum and hence does not tolerate any interference. The latter allows several BSs to use the same transmission frequency at the same time, provided that the level of interference at the intended receivers is below a desired threshold. All of them have pros and cons and enable different gains for the operators. In this paper, we quantify an *upper bound* on the achievable gain when an orthogonal sharing policy is considered. To do so, we propose a centralized algorithm which exploits perfect channel information and performs the optimal allocation in a coordinated manner. Even though it is not directly amenable to practical implementation, due to the conflicting operator interests, this solution aims at calculating an upper bound on the sum capacity that can be reached in each cell.

The structure of the paper is the following. In Section II the status of current research activities on this topic is reported. In Section III the system model forming the basis of this work is given. The description of the coordinated scheduling algorithm is presented in Section IV, while Section V contains the description of the simulation campaign we have executed and the presentation of part of the results we have obtained. Finally, in Section VI conclusions are drawn and future research directions are outlined.

II. STATE OF THE ART

In the recent literature many researchers have started to focus on multi-operator spectrum sharing in cellular networks as a possible way to face the increasing demand. In current network deployments, the coexistence of multiple operators in adjacent areas is quite common; thus, the interest in this particular scenario has been increasing during the last years from both academic and industrial points of view. The issue of spectrum licensing and the high cost associated with it are boosting factors for research activities.

One of the first papers that introduced spectrum sharing in cellular networks is [4], where several operators share a set of resources and try to take advantage of the fluctuations of the incoming traffic for an opportunistic allocation of the unused resources. The goal is the minimization of the call blocking probability. Each BS uses the common spectrum only when its private portion is not sufficient to satisfy all the users' requests ("sharing as a last resort"). The solutions proposed require centralized operations. Time Division Multiple Access (TDMA) is considered in [5], [6], where each operator is allocated a separate time-slot in a common super-frame. Also in this case, operators resort to the shared resources only when their private ones are not sufficient. Moreover, in [6] infrastructure sharing is considered, also for non-co-located BSs. Specifically, the mobile users are always connected to the best BS, regardless of the operator. In [7] a comprehensive comparison of all these algorithms is made in terms of service probability. In particular, the solutions "sharing as a last resort", "always connected to the least loaded" and "sharing as a secondary user" are evaluated and compared with the non-sharing case. The first one is that considered in [5], [6]; the second one mandates that each terminal always connects to the BS with more unused resources, regardless of it is its home operator or not. The third one introduces a classification of the users into primary and secondary depending if they are connected to their home operator or not, and more priority in the allocation is given to the formers. The analysis shows that all the algorithms lead to a performance gain, in particular the second one. In our work we consider a different scenario, where the only resource shared is the spectrum and mobile terminals are always connected to their home operator.

Another paper on inter-operator spectrum sharing is [8] that uses game theory in a Cognitive Radio (CR) context, where operators are classified as primary and secondary. This is different from our system model, as described in the next section, where BSs are not supposed to have sensing capabilities and such a hierarchy is not present. In [9], a more complex CR environment is considered, where a CR network operates in the coverage area of three Primary Network Operators (PNO) and is subject to some rate and interference constraints. PNOs take advantage of the relaying capabilities of the secondary operator, which accepts to cooperate as long as it is granted access to the spectrum it needs.

In [10], the authors consider a scenario with interfering femtocells belonging to different network operators. Each operator decides to share its spectrum, thus femtocells belonging to an operator are entitled to use the spectrum of any other.

To reduce mutual interference, a dynamic frequency selection strategy is proposed, according to which each femtocell can select the best operating frequency among those available, regardless of the original owner. In this way, an automatic redistribution of the minimum frequency reuse distance is realized and the spectrum sharing gain (calculated from the number of active femtocells) increases significantly. The main difference with our work is that we do not consider a femtocell scenario, but only adjacent macrocells; moreover, in our case the sharing gain is evaluated in terms of the achievable channel capacity.

III. SYSTEM MODEL

We consider two LTE mobile networks, operating in the same geographical region, i.e., having adjacent cells. In particular, for the sake of simplicity we consider the case of two cells. However, all considerations can be promptly extended to a more general case. We assume that the network operators own adjacent portions of the spectrum and agree upon sharing a part of them.

In LTE networks, the downlink of a cell is organized according to a TDMA/OFDMA scheme. Time is divided into 10 ms frames, each consisting of 10 sub-frames of 1 ms. The spectrum is divided into bundles of adjacent sub-carriers, called *sub-channels*, each assigned to a single user for an entire sub-frame. Thus, the resources to be allocated by the BS managing the cell are represented by the sub-channels, and the allocation decision is made on a frame basis. The choice of which user to allocate on each sub-channel depends on the scheduling and resource allocation policy adopted, i.e., on the utility functions that are to be optimized by the allocation entity.

Let \mathcal{K} be the set of available sub-channels for the downlink, split into two subsets \mathcal{K}_1 and \mathcal{K}_2 , where \mathcal{K}_j is assigned to operator j . Denote with $K = |\mathcal{K}|$, $K_j = |\mathcal{K}_j|$ and with $\alpha \in [0, 1]$ the sharing percentage, i.e., the fraction of spectrum each operator decides to share. For the sake of simplicity, we assume $|\mathcal{K}_1| = |\mathcal{K}_2| = K/2$ and indicate it as k . The extension to the general case is straightforward. The k sub-channels are split into a part $k^s = k\alpha$ that is shared, and a part k^p that remains private to the operator, with $k = k^s + k^p$. In this way, each operator has a final set of k^F available sub-channels that is made of its initial k plus the k^s shared by the other,

$$k^F = k(1 + \alpha). \quad (1)$$

We denote with k^c the number of sub-channels which compose the common pool (i.e., $k^c = 2k^s$). In this work we consider the case of *orthogonal spectrum sharing*, so that the access to the common resources is mutually exclusive. Therefore, coordination for the usage of such resources is needed.

We remark that, since OFDMA is used for the downlink access of multiple users, no interference occurs among different sub-channels and thus the transmit power on each one of them can be set to the maximum possible. The performance metric taken into consideration for operator m is the cell sum capacity, i.e., the sum of the Shannon capacities achievable on

each sub-channel allocated, defined as

$$C_m = \sum_{i=1}^{N_{UE}} \sum_{j=1}^{k^F} B \log_2(1 + SINR_{ij} \cdot \delta_{ij}),$$

$$\delta_{ij} = \begin{cases} 1, & \text{UE}_i \text{ allocated to sub-channel } j \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

where B and N_{UE} are, respectively, the sub-channel bandwidth and the number of User Equipments (UEs) in the cell, while $SINR_{i,j}$ is the Signal-to-Interference-and-Noise Ratio (SINR) perceived by UE i on sub-channel j . Note that the actual cell throughput is lower than the capacity and depends on the modulation and coding scheme chosen for each sub-channel based on the corresponding SINR.

IV. COORDINATED SCHEDULING ALGORITHM

At first, each BS runs independently its internal resource allocation procedure; then, the trading for the common pool usage starts. Therefore, two phases can be identified: (i) the proposal of a resource allocation and (ii) the contention resolution.

For every allocation opportunity, each BS belonging to an operator decides which are the sub-channels, among those it is entitled to use, that will be used in that allocation period and the UE the resource will be assigned to. We call the set of pairs $\langle \text{sub-channel}, \text{UE} \rangle$ as *channel allocation map*. We assume that the BS manages a different flow for each UE registered to it, and these flows are always backlogged, so that every time a flow is selected there is always a packet to transmit. Another fundamental assumption that we make is regarding the internal scheduling policy adopted by each BS. When not otherwise specified, we suppose that short-term fairness among the flows is not taken into consideration, thus the only objective of the allocator is the maximization of the cell capacity. This may lead to situations where some users get multiple resources while others get none. If fairness were taken into consideration, then the total throughput reached by a BS would be reduced, since the allocator could be forced to make sub-optimal choices, as discussed in depth in [11].

The problem of selecting the channel allocation map that maximizes the capacity is combinatorial in nature and thus with a high computational complexity. In a more formal way, each UE has a Channel Quality Indicator (CQI) for each sub-channel. We denote $CQI_{i,j}^l$ the CQI value of user j , served by BS i , for the sub-channel l . Each BS selects, for each sub-channel l , the user u_i^l with the largest CQI so as to maximize the sum capacity. In other words,

$$u_i^l = \arg \max_j CQI_{i,j}^l, \quad l = 1, \dots, k^F, \quad (3)$$

$$CQI_i^l = \max_j CQI_{i,j}^l, \quad l = 1, \dots, k^F. \quad (4)$$

In this way, BS i constructs the proposed allocation vector $\mathbf{u}_i = [u_i^1, u_i^2, \dots, u_i^k, u_i^{k+1}, \dots, u_i^{k^F}]$. If the resources that BS i can allocate are $p < k^F$, then it selects the best p elements according to the value of CQI, $[u_i^{m_1}, u_i^{m_2}, \dots, u_i^{m_p}]$, where $m_s \in \mathcal{K}$, $s = 1, 2, \dots, p$.

When each BS has determined its proposed resource allocation, the trading phase starts in order to solve all the

possible contentions for resource access and determine the final allocation maps. Many algorithms can be proposed to take care of the conflicts, each of them having pros and cons and reaching different performance. In this paper, we propose such an algorithm, without considering the implementation aspects of it, for the purpose of establishing an upper bound on the cell capacity achieved in total by both operators. Such a centralized algorithm, even though not meant as a practical scheme, can be used to benchmark the performance of any other strategies. In particular, the proposed solution aims at maximizing the total cell capacity. To do so, the operators behave as if they were a single entity, a kind of *monopolist* having complete information on both cells, and allocate each sub-channel to the best UE, i.e., the one having the largest Channel Quality Indicator (CQI), without taking into consideration any fairness constraints amongst operators. The resulting capacity is hence the theoretical limit, i.e., the maximum achievable by full coordination. Of course, when deciding the allocation of the common sub-channels, the UE can belong to any of the involved operators. On the other hand, when allocating the sub-channels private to a certain operator, then only its UEs can be taken into consideration. The pseudo-code for the algorithm is given hereafter.

Algorithm 1 Coordinated Scheduling Algorithm

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1: for all sub-channels  $j \in \mathcal{K}$  do
2:   if ( $j \in \mathcal{K}^c$ ) then //it is a common sub-channel
3:     if ( $CQI_{1,u_1^j}^j > CQI_{2,u_2^j}^j$ ) then
4:        $w^j = u_1^j$ ;
5:     else
6:        $w^j = u_2^j$ ;
7:     end if
8:   else//it is private sub-channel
9:      $w^j = u_s^j$ ; //s is the owner of sub-channel  $j$ 
10:  end if
11: end for

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In this way, the final allocation vector $\mathbf{u} = (u^k)_{k \in \mathcal{K}}$ is constructed and contains the indication of which UE to allocate on each sub-channel.

V. NUMERICAL RESULTS

We run an extensive simulation campaign to assess the performance of the coordinated scheduling algorithm. To better appreciate the sharing gain achievable by orthogonal spectrum sharing, we considered two different scenarios: (i) symmetric load scenario, and (ii) asymmetric load scenario. We consider two partially overlapping disk-shaped cells and random user distribution. Table I contains the main system parameters common to both scenarios. In particular, those related to the PHY layer are taken directly from the LTE standard. The simulations were run by using the network simulator ns-3 [12] with the extension defined in [13] for the support of multi-cell multi-operator LTE networks with spectrum sharing.

Symmetric load scenario. Both cells are under saturation (i.e., all the UEs have an infinite number of packets to transmit) and each BS tries to use as many sub-channels as possible, i.e., k^F .

Parameter	Value
Center frequencies	2.115 GHz (BS0), 2.125 GHz (BS1)
Downlink channel bandwidth	10 MHz
Subcarrier bandwidth	15 kHz
Doppler frequency	60 Hz
Sub-channel bandwidth	180 kHz
Number of downlink sub-channels	50
Subcarriers per sub-channel	12
OFDM symbols per sub-carrier	14
TX power per sub-channel	27 dBm
Noise spectral density (N_0)	-174 dBm/Hz
Pathloss	$128.1 + (37.6 \cdot \log_{10}(d))$ dB (d is the BS-UE distance in km)
Shadow fading	log-normal ($\sigma = 8$ dB)
Multipath	Jakes model with 6 to 12 scatterers
Wall penetration loss	10 dB
Frame duration	10 ms
TTI	1 ms
Cell radius	1500 m
Distance between BSs	1000 m

TABLE I: Main system parameters

The two cells are statistically equivalent and thus the average performance achieved by both coincides.

Asymmetric load scenario. In this scenario, the two BSs have different traffic load and the one with higher traffic can opportunistically exploit the shared resources not used by the other one. In order to model this scenario, we assume that each BS guarantees to each UE no more than two sub-channels at each allocation opportunity. The UEs are always allocated according to their CQI, so as to exploit multiuser diversity as much as possible. In particular, each BS tries to give 2 time-frequency resources to each of its users, as long as there are free sub-channels in the part of the spectrum it can access. Therefore, the asymmetric load is generated by varying the number of users. Cell 1 is overloaded and has 40 UEs to serve; thus, it needs 80 sub-channels. For cell 2 we considered a varying number of UEs, ranging from 2 up to 40. When the sharing percentage is 0%, BS1 cannot use more than 50 sub-channels, regardless of the load of cell 2. This may lead to large resource wastage when the latter is underloaded. When the sharing percentage increases, BS1 is entitled to using more sub-channels of the other operator and thus a larger number of UEs can be served. Therefore, the performance of BS1 is limited by the sharing percentage and by the load of cell 2, which needs some of the available resources to satisfy its users. When both cells have the same load, also the respective achievable channel capacity is the same because they are statistically equivalent.

All the results are characterized by a 95% confidence interval with a maximum relative error of 5%. Fig. 1 shows the sum capacity reached by each cell in the symmetric load scenario, for various numbers of UEs, when the sharing percentage increases. Since both cells are statistically equivalent (for number of UEs, channel state, traffic load), also the

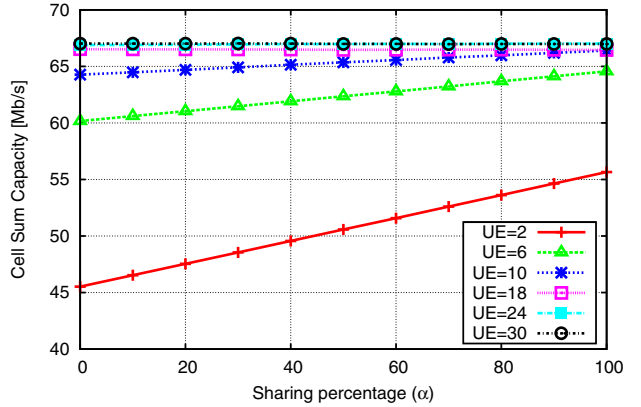


Fig. 1: Cell sum capacity versus sharing percentage for various number of UEs and symmetric load

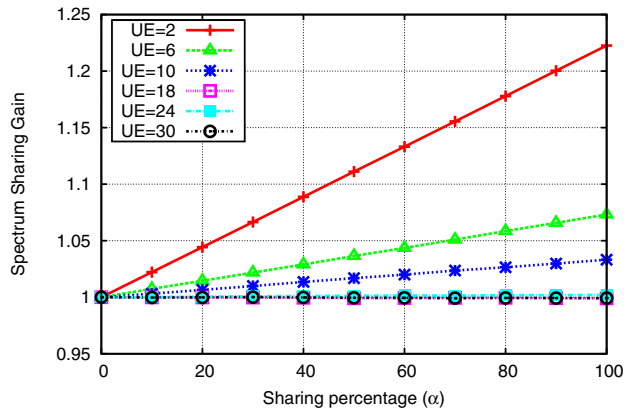


Fig. 2: Spectrum sharing gain versus sharing percentage for various UEs and symmetric load

respective final outcome is the same. First of all, a clear increment of the capacity with the number of UEs can be noted, which is a direct consequence of multiuser diversity. The larger the number of UEs, the higher the probability that for each sub-channel there is at least one UE with good channel quality, particularly for the common pool because the number of candidate UEs is doubled. However, the marginal increment of the total capacity decreases in the number of UEs since for almost all the sub-channels there is at least one user in good situation. The second important observation that can be made is that a *spectrum sharing gain* can be identified. The cell sum capacity increases with the sharing percentage, thus there is an incentive for the network operators to share part of their frequencies. Fig. 2 shows such a gain as the ratio between the cell capacity achieved with and without spectrum sharing. For small number of UEs and full sharing, 20% gain can be reached over the non-sharing case. As discussed previously, the sharing gain is greater for scenarios with few UEs, and tends to reduce for situations with more users, because additional (due to spectrum sharing) multiuser diversity yields diminishing returns. This aspect is more evident in Fig. 3, where the total (i.e., over the two cells)

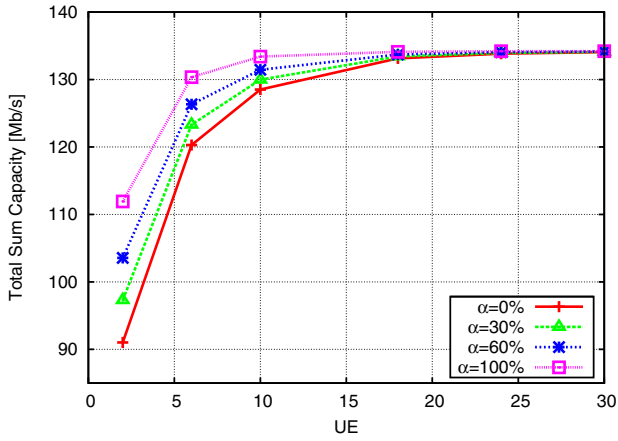


Fig. 3: Total sum capacity versus the number of UEs per cell for various sharing percentages and symmetric load

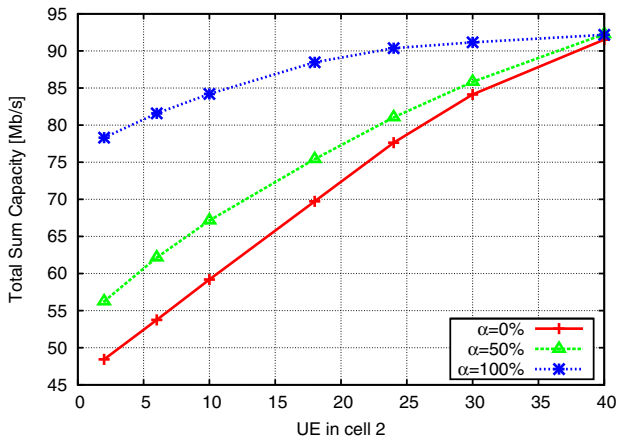


Fig. 4: Total sum capacity versus the number of UEs in cell 2 for various sharing percentages and asymmetric load

sum capacity is depicted as a function of the number of UEs in each cell. In this case, the saturation effect for cells with more users is more evident: after 18 UEs the improvement of the capacity is almost negligible, as discussed above.

Fig. 4 depicts the corresponding total sum capacity for the scenario with asymmetric traffic, as a function of the number of UEs in cell 2. Three values of the percentage α of spectrum sharing have been considered, i.e., 0, 50 and 100%. For the reference case of no sharing ($\alpha = 0\%$), the curve increases due to the increasing number of UEs that are served in cell 2 (remember that for cell 1 the capacity is constant since all the 50 resources are always allocated). For the sharing case ($\alpha > 0$), the total capacity still increases with the number of UEs for the same reason. Moreover, there is additional increase, due to the fact that BS1 is entitled to use a higher portion of the spectrum and thus can serve more UEs. It should be noted that after a certain number of UEs in cell 2 has been reached (in this case 25 since the number of initial sub-channels per cell is 50), there are no free resources that BS1 can exploit from cell 2. Any additional increment in the total sum capacity is only due to multiuser diversity, which still yields some benefits from the increase in the number of

users, even though the additional improvement decreases for networks with more users.

The capacity results and sharing gains also depend on the radio propagation environment. The larger the frequency diversity, the higher the interest that an operator might have in accessing the spectrum of its competitors because it might contain sub-carriers of better quality for it. Also, the allocation policy adopted by the BS plays an important role. In this numerical study, we do not consider fairness among flows for the symmetric load scenario and for each sub-channel the best UE is always chosen. By introducing some fairness, the curves would change significantly, in particular the capacity values will decrease.

VI. CONCLUSIONS

We considered multi-cellular networks of different operators, serving the same geographical area. Motivated by the need to assess the potential of orthogonal spectrum sharing, we proposed a coordinated scheduling algorithm that enabled us to numerically quantify an upper bound on the total achievable capacity. Simulation results have shown that, at least for the considered setting, there exist performance gains. We have seen that the number of end users and the asymmetry in the traffic conditions influence the sharing gains. The importance of this work is twofold: not only do the gains motivate further research for the development of efficient distributed algorithms for coordinated scheduling in this context, but the upper bounds can be used to benchmark their performance.

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