A Framework for Spectrum Sharing with Beamforming in LTE Networks

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***Abstract*—Growing traffic demands from wireless users are forcing cellular network operators to investigate new forms of efficient usage of the radio resource. A possible solution is represented by spectrum sharing, i.e., multiple network operators that manage neighboring or overlapping cells mutually exchange their available frequencies, so as to form a common pool of resources. In particular, we focus on the so-called non-orthogonal spectrum sharing, where every frequency subchannel can be used by the multiple operators that share it at the same time. Thus, wireless interference arises and therefore the resulting performance may suffer. However, beamforming techniques may be employed by the base stations to counteract interference. This paper aims at evaluating the performance of the resulting sharing scenario, with and without beamforming, for a multi-operator cellular network. We are able to characterize beamforming and provide a practical benchmark to test various allocation schemes and assess the gain, if any, that can be derived on the achievable total cell sum capacity. The performance is also found to be strongly dependent on several key factors, namely, the channel conditions between the users and the base stations, the allocation objective of the operators, and the cell load.**

***Index Terms*—Multicell cooperation; cellular networks; spectrum sharing; beamforming.**

INTRODUCTION

Cellular wireless systems are experiencing a tremendous increase in their transmission rates, thanks to the use of efficient modulation schemes and the exploitation of channel-aware radio resource allocation [1], [2]. Combining these elements, the next generation of cellular networks, i.e., the Long Term Evolution (LTE) of the Universal Mobile Telecommunications System (UMTS) [3] is able to reach “high speed” communication, for example delivering video traffic, through the wireless channel. This result is also achieved thanks to the usage of carefully designed techniques at the physical and data link layers, including the multiple access based on the Orthogonal Frequency Division Multiple Access (OFDMA) technique [5], modern modulation and coding techniques [1], and multi-antenna systems including Space Division Multiple Access (SDMA) [4], [6].

However, this mastery of the transmission technology over the wireless medium has a side effect in the ever increasing traffic demand from the users, making the frequency bands available to the operators insufficient. It becomes then necessary to implement a paradigm change from “exclusive” resource ownership, i.e., each operator using a proprietary frequency band, to more cost-effective solutions which involve an innovative use of the radio spectrum, e.g., based on the operators collaboratively sharing their assigned portions of the wireless spectrum [7].

Many solutions related to this purpose are being actively investigated by a large part of the wireless research community. In particular, several approaches such as Software Defined Radio (SDR) and Cognitive Radio (CR) [8], Coordinated Multi-Point (CoMP) [9], [10], and more in general techniques for cooperative communications [2], [12] have been involved in the effort of identifying practical ways of sharing the wireless spectrum. The resulting schemes involve advanced mathematical tools, e.g., Convex Optimization [1] and/or Game Theory [5], [11], and are investigated by several scientific initiatives and research projects.

Yet, from a practical point of view, it is unclear how much gain is achievable in applying these techniques to cellular networks. Physical layer techniques are often validated in (over)simplified network scenarios with a limited number of nodes, where mutual interference among the wireless terminals can be counteracted through signal processing techniques. Thus, it may be possible, and our evaluations will prove this risk to be concrete, that multiple operators performing a simultaneous allocation of the same frequencies to their users get almost no gain, or even lose capacity. Beamforming techniques, which allow to separate at the physical layer these shared frequency assignments, are key in this respect [6], [13].

Thus, in this paper we investigate beamforming techniques by proposing a simple yet entirely modular framework which enables their quantitative evaluation. In particular, we are interested in determining the conditions under which it is effective for the operators that manage multiple overlapping cells to share their frequencies. We will also explore the parameters that impact on the resulting network performance, and derive practical guidelines for spectrum sharing design.

The main hurdle to this investigation is the difficulty to merge the models describing multiple network layers in a global context. As will be shown, the network performance heavily depends on the characterization adopted for the beamforming, and in particular, when no beamforming is applied, there is very likely no sharing gain. When beamforming is applied, some gain may or may not be present, depending on other factors, such as the number of users and the adopted scheduling policy. Thus, differently from other research studies that just focus on some layers and therefore achieve a partial view of the problem, we frame the problem in a comprehensive study of all the layers. Moreover, even though certain certain physical layer aspects are taken into account through simplified models for the sake of readability, the entire evaluation closely matches the LTE standard [3] on the medium access layer and choice of the numerical parameters, so that our analysis can draw interesting conclusions also from a quantitative perspective.

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SYSTEM MODEL

We consider a scenario with two co-located cells owned by two different network operators, referred to in the following by indices 1 and 2. Each cell is managed by a base station, which in the UMTS and LTE terminology is also called e-NodeB (eNB). Thus, we denote the cells as eNB_1 and eNB_2, respectively. We assume that cell j serves N_j mobile terminals (UEs). As the reference technology, we consider LTE according to Release 10 [3], modeled in a standard-compliant manner. The focus of our investigation is on the downlink communication that uses an OFDMA scheme for user multiplexing. According to the standard, the spectrum is assigned to the operators in chunks, called *subchannels*, consisting of 12 subcarriers with 15 kHz bandwidth, for a total of $b = 180$ kHz. The time axis is also divided into 10 ms frames, which are further subdivided in 10 subframes of 1 ms. With a granularity as fine as a single subframe, the subchannels are allocated to the users. Thus, the atomic unit of resource, called Resource Block (RB), that can be assigned to a user is a time-frequency element of one subchannel for a subframe duration.

The intended resource assignment for multiple cells is an *orthogonal* bundle of frequencies. This means that the bands owned by each operator, denoted with $\mathcal{B}_1$ and $\mathcal{B}_2$, respectively, consist of K_1 and K_2 disjoint subchannels. Thus, the respective bandwidths are $K_1 b$ and $K_2 b$. For the sake of simplicity, we will consider in the following a symmetric scenario where $N_1 = N_2$ and $K_1 = K_2$, the extension to cases where they take different values being straightforward. Therefore, we will drop indices and write N for the number of users and K for the number of subchannels of both base stations.

Even with an orthogonal assignment, it is possible for the operators to actuate some forms of sharing, therefore named *orthogonal sharing*, if the two operators agree on mutually exchanging or borrowing from each other some of their owned subchannels. This may happen on a short-term scale, to track the best channel conditions, or on a long-term scale, for example if the traffic demand to the operators is unbalanced. In any event, an orthogonal sharing procedure involves that any subchannel is used by at most one eNB, regardless of whether it is the original owner of that subchannel or it borrowed it.

This strategy can be beneficial if the network load of the two operators is strongly asymmetric, i.e., some cells are heavily loaded, while others have unused frequencies. In such a case, the sharing benefit simply results from avoiding the waste of resources in some cells and the overload condition in some others. In a symmetric case though, where the improvements should come from the inherent usefulness of orthogonal sharing, the performance gain is very limited, of the order of 10% or less, and heavily depends on the number of users in the system, so that it drops to zero if the cells have many users [7]. The reason is that exchanging allocable subchannels among the cells leads to a better exploitation of frequency diversity. However, when the number of UEs is high, an efficient user allocation performed independently at each cell already achieves a multi-user diversity gain, which makes any further improvement brought by orthogonal sharing very small.

For this reason, it is possible to think of a *non-orthogonal* sharing strategy, where the cells pool some or all of the subchannels which are licensed to them, and use them in the same time subframe. Hence, the same RBs may be simultaneously assigned to multiple users in different cells. Even though this mechanism enables a virtually higher number of RBs, the assignment of the same subchannels to the UEs of multiple co-located cells causes mutual interference. Thus, non-orthogonal sharing increases the *quantity* of allocated resources, at the price of worsening their *quality*. In particular, we will evaluate the effectiveness of the resource allocation with or without sharing by considering the achievable sum capacity, i.e., the theoretical total transmission rate that the eNBs are able to achieve over all the subchannels they use. To keep the approach general, we focus on the capacity quantified through Shannon's formula applied to every assigned RB. It is worth noting that the achievable transmission rate of an LTE downlink can be found to match very well the trend expressed by the system capacity [7]; although some overhead decreases the available rate, the resulting throughput is proportional to Shannon's capacity, which is in turn a logarithmic function of the Signal-to-Noise Ratio (SNR).

Thus, if no sharing is involved, K channels are allocated by each eNB. We denote them as $k = 1 \dots K$ for eNB_1 and $k = K+1 \dots 2K$ for eNB_2. The total capacity C_{tot} allocated by both base stations is

$$C_{tot} = \sum_{k=1}^{2K} C_k \tag{1}$$

and the summation terms are

$$C_k = b \cdot \log_2(1 + \Gamma_k) \tag{2}$$

where C_k is the capacity of the kth channel and Γ_k denotes its SNR. Note that this is a grand total of the capacity allocated by *both* eNBs. The sum capacity of each eNB can be computed just considering a sum from either 1 to K or from $K+1$ to $2K$; as a matter of fact, both base stations share the same physical properties.

Orthogonal spectrum sharing can also be analyzed in this framework with an immediate extension, corresponding to switching some of the indices k and using a similar approach. The improvement brought by orthogonal sharing would therefore lie in the availability of a wider set of channels, so that better SNRs can be achieved. However, the expected gain is marginal, as there is still no simultaneous usage of the same channel.

To evaluate non-orthogonal spectrum sharing, we modify the above formula, depending on the sharing mechanism. With non-orthogonal sharing over the entire bandwidth, each eNB allocates all the $2K$ channels instead of just K. For the sake of simplicity, we focus on this case only, although it would be possible to admit a partial non-orthogonal sharing in which simultaneous usage is admitted for a fraction of the K channels, while the previous formulas describing the non-sharing case are applied to the other subchannels. For all the shared channels, the SNR Γ_k terms must be modified to account for interference. If it is simply summed to the background noise, we can introduce $\Gamma_{j,k}$ as the Signal-to-Interference-plus-Noise Ratio (SINR), achieved by eNB$_j$ on the kth channel. Note that, for each channel k, we have *two* different SINR terms, i.e., one where eNB$_1$ plays the role of the useful signal and eNB$_2$ of the interferer and another with reversed roles. The resulting sum capacity is therefore

$$C_{tot} = \sum_{k=1}^{2K} \sum_{j=1}^{2} C_{j,k} \tag{3}$$

where

$$C_{j,k} = b \cdot \log_2(1 + \Gamma_{j,k}) \tag{4}$$

In other words, we need to modify the capacity evaluation by considering twice as many terms (each channel k gives two contributions) but with decreasing quality, as the SINR is lower than the SNR. In principle, this mechanism can be advantageous as it trades a logarithmic decrease for a multiplicative increase. Moreover, physical layer techniques can be used to further improve the allocation, in particular beamforming can be seen in practice as a way to further improve the SINR, as will be discussed in the next section.

BEAMFORMING MODEL

If the network operators share the whole spectrum in a multicell cooperation fashion, they likely aim at using it in the most efficient way to enhance the total capacity. Treating interference as noise is not very efficient in this respect. The operators may instead exploit physical layer techniques to mitigate the mutual interference and/or improve their own resource usage [1], [12]. In particular, in this paper we assume that the eNBs are able to perform beamforming in transmission [2], [13]. In this way, the interference created on the non-intended receivers is mitigated and the effectiveness of non-orthogonal spectrum access is improved.

For the sake of tractability, we consider the following idealized scenario, represented in Fig. 1. We assume that the cells are perfectly superimposed and the eNBs are co-located and placed in the cell center. Moreover, all the UEs are positioned at the same distance from the center, i.e., on a circle with radius D meters. This is meant to highlight the impact of channel fading and beamforming, while simplifying at the same time every consideration related to the path loss. In fact, removing this assumption would be conceptually straightforward but would also require to weigh the average channel conditions in the allocation of the UEs. Otherwise, a purely channel state dependent selection of the users will most of the times select just the users closest to the center. Therefore, placing the users at the same distance better highlight the effectiveness of spectrum sharing and beamforming techniques, without dwelling into considerations about fairness of the allocation versus the position within the cell, near-far effects, and so on.

Each eNB knows the SINR values perceived by its UEs on all subchannels. This may be obtained, e.g., through a periodic report sent by the terminals at the beginning of each subframe.

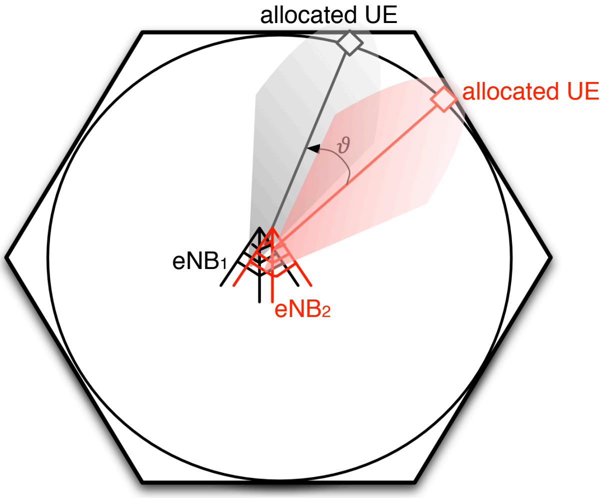

Fig. 1: The multicell scenario with beamforming

Note that, for the sake of realism, we do not assume that the eNB knows the exact positions of the UEs in the cell. If this additional information were known, indeed, an efficient coordination of the beams could be applied, but this would be difficult in a cellular environment with mobile UEs.

However, even a suboptimal selection of the users to allocate may be able to improve the system capacity by means of beamforming [2], [9]. An exact analytical formulation of the beamforming algorithm is not simple, especially when many terminals are considered. In this case, the algorithms known in the literature [12], [13] may not even lead to a closed form solution or may involve optimization problems whose solution is computationally impractical for real-time systems like a base station of a cellular network.

Therefore, we decided to adopt a simplified yet sensible and flexible model for the beamforming technique that enables the evaluation of its effectiveness and limits. We remark that this approach can be quite easily integrated into a system level simulator [7] and used to quickly obtain a quantitative assessment of direct and indirect effects of the application of beamforming on the upper layers, and vice versa.

Based on the model of the previous section, which evaluates capacity as a function of the SINR, we additionally include the property of beamforming to mitigate mutual interference among the terminals. When a transmission is scheduled on a given subchannel, all the non-intended receivers see an interference term that depends on the distance and the spatial separation of the beams. The farther the node from the beam, the lower the interference it receives. From the formulas, a lower interference value implies a greater SINR value and hence a greater capacity.

For our specific scenario, this means that if eNB$_1$ and eNB$_2$ transmit on the same subchannel to UE$_1$ and UE$_2$, respectively, the interference that each terminal experiences is a function of the angle ϑ separating the terminals, as the eNBs are co-located (see Fig. 1). Thus, we summarize the effect of beamforming by defining a coefficient $\alpha(\vartheta) \in [0,1]$, which multiplies the interference term in the SINR computation. Therefore, $\alpha(\vartheta) = 1$ corresponds to omnidirectional antennas where no beamforming is used, whereas $\alpha(\theta) = 0$ represents an ideal situation where the two UEs are perfectly separated.

If a base station, say eNB$_j$, allocates a UE on channel k, at the user's side a useful received power term $P_{j,k}$ will be present, as well as an interference term, due to the other base station, that we denote as $Q_{j,k}$. Thus, the SINR $\Gamma_{j,k}$ used in (4) will be:

$$\Gamma_{j,k} = \frac{P_{j,k}}{Q_{j,k} + \mathcal{N}_0 \cdot b} \qquad (5)$$

where $\mathcal{N}_0$ is the power spectral density of the noise, assumed to be white and Gaussian.

To frame the impact of the beamforming techniques in a simple but modular way, we define an Equivalent SINR (ESINR) $\Gamma'_{j,k}$ as the actual SINR perceived by a terminal when beamforming is used, where the interference term $Q_{j,k}$ is multiplied by the coefficient $\alpha(\vartheta)$ defined above. Therefore, we have

$$\Gamma'_{j,k} = \frac{P_{j,k}}{\alpha(\vartheta)\, Q_{j,k} + \mathcal{N}_0 \cdot b} \qquad (6)$$

and we can replace all terms $\Gamma_{j,k}$ with $\Gamma'_{j,k}$, i.e., the SINR with the ESINR, in the capacity evaluations.

The advantage of this formulation is that the impact of beamforming is summarized in the function $\alpha(\vartheta)$, which can be any meaningful function of choice. The exact specification of $\alpha(\vartheta)$ can obtained either through mathematical analysis or empirically [12]. In this paper, we consider the following linear formulation

$$\alpha(\theta) = 1 - \frac{|\vartheta|}{\pi}, \vartheta \in (-\pi, \pi] \qquad (7)$$

so that interference is 0 when the two UEs form an angle of π radiants, i.e., they are on opposite sides of the cell, while it is equal to 1 when the terminals are on the same position in the cell, i.e., their angle separation is 0 (recall they are also at the same distance from the cell center). To evaluate the effectiveness of this beamforming strategy, we compare it to a situation with omnidirectional radiation, which means $\alpha(\vartheta) = 1$, for all $\vartheta \in (-\pi, \pi]$, i.e., the ESINR coincides with the SINR.

NUMERICAL RESULTS

We run a simulation campaign to evaluate the proposed framework. All the simulations are characterized by a 95% confidence interval with a maximum relative error of 1%.

We consider two superimposed cells belonging to different operators. Each eNB uses K subchannels and manages N UEs, all located at a distance D from the cell center. The channel coefficients between the eNBs and the UEs are determined by considering a fixed path loss and a log-normal shadow fading term, which is independently re-evaluated in every subframe. The numerical values of the parameters are reported in Table I. The physical layer parameters are consistent with the LTE standard [3].

Another important design choice concerns the UE scheduling strategy, which dictates how the UEs are selected and matched with the available channels by the eNBs. Such a decision is made at the beginning of each subframe. All the UEs are assumed to be backlogged. Two allocation policies have been considered, i.e., *max-capacity* and *fair*. The former aims at maximizing the cell sum capacity by always scheduling the best UE possible on each subchannel. In principle, this may even end up in allocating the same UE on all the subchannels. The latter aims at introducing a certain degree of fairness in the allocation by evenly distributing the available subchannels (or equivalently, the RBs) among all the UEs, so that every user must receive at least $\lfloor K/N \rfloor$ subchannels. This means that the allocation procedure follows a waterfilling-like scheme, still aimed at maximizing the total capacity but with the constraint that all UEs must receive an adequate share of RBs.

TABLE I: Main system parameters

Parameter	**Value**
transmission frequency	2 GHz
total bandwidth per eNB	5 MHz
no. of subchannels per eNB K	25
subchannel bandwidth b	180 kHz
noise spectral density ($\mathcal{N}_0$)	-174 dBm/Hz
eNB total transmit power in DL	46 dBm
shadow fading	lognormal ($\mu = 0, \sigma = 10$ dB)
macroscopic path loss at d km	$128.1 + (37.6 \cdot \log_{10} d)$ dB,
frame/subframe duration	10 ms / 1 ms
sharing percentage	100 %

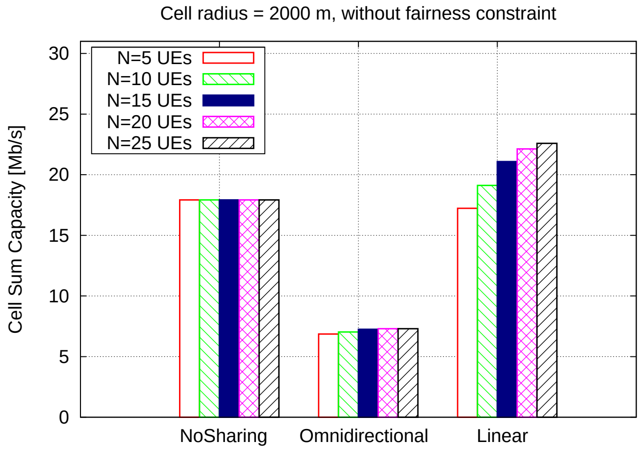

Fig. 2: Spectrum sharing scenarios for users at $D = 2000$ m, max-capacity allocation

However, our investigations also found out that these simple mechanisms are very inefficient in the spectrum sharing case without introducing some additional multicell cooperation. If the eNBs are selfish in their allocation, and just select the users with the best channel, this is also likely to cause severe interference on the allocation of the other cell [5], [8]. For this reason, an additional constraint is added. Whenever an eNB allocates a subchannel which originally belonged to it, i.e., one that would still be available if sharing were not applied, it can simply select the UE with the best channel conditions, and this assignment is prioritized. Upon knowledge of this assignment, the other eNB selects the most favorable assignment in terms

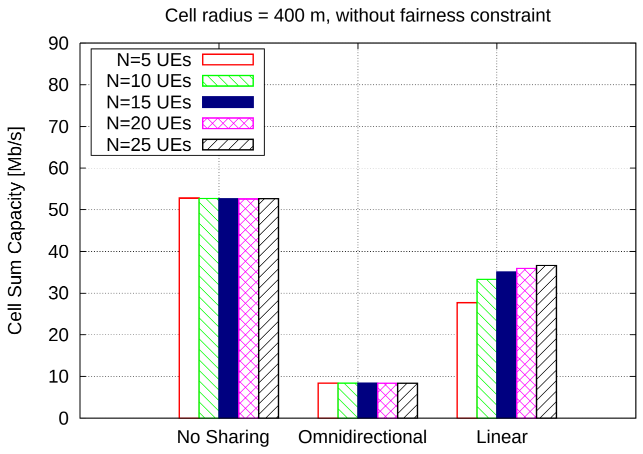

Fig. 3: Spectrum sharing scenarios for users at $D = 400$ m, max-capacity allocation

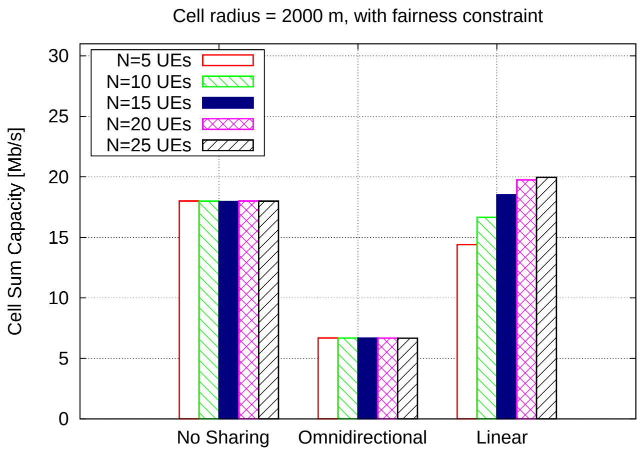

Fig. 4: Spectrum sharing scenarios for users at $D = 2000$ m, fair allocation

of interference, i.e., it chooses that of its UE that generates the lowest interference (or, equivalently, the one with best spatial separation). To sum up, on channels from 1 to K, eNB$_1$ selects its best users (with or without a fairness constraint) and eNB$_2$ tries to limit the interference caused to them. On channels $K+1$ to $2K$ the situation is reversed. Note that this approach requires some kind of communication and policy agreement between the eNBs and is therefore meant to prove that multicell cooperation is necessary to achieve any gain in a spectrum sharing context.

The numerical results are shown in Figs. 2–5. Fig. 2 shows the comparison for a scenario where users are located relatively far from the cell center and the objective of the UE scheduler is to maximize the sum capacity. We compare an allocation without any sharing, a spectrum sharing scenario with omnidirectional transmission from the eNB (i.e., $\alpha = 1$ for every spatial separation of the users) and with the beamforming model discussed in the previous section, labeled "linear" beamforming.

In this scenario, spectrum sharing is able to achieve a certain performance gain with respect to the non-sharing case. However, beamforming is required, as the performance of the omnidirectional eNBs is poorer than in the non-sharing case. Moreover, the gain is visible only if the number of users in the cells is sufficiently high, as the scheduling mechanism can benefit by selecting those UEs which are better separable to allocate them on the same channel. This means that spectrum sharing is beneficial only if a combination of elements is present, whereas if applied without these required conditions it can even decrease the efficiency of spectrum usage.

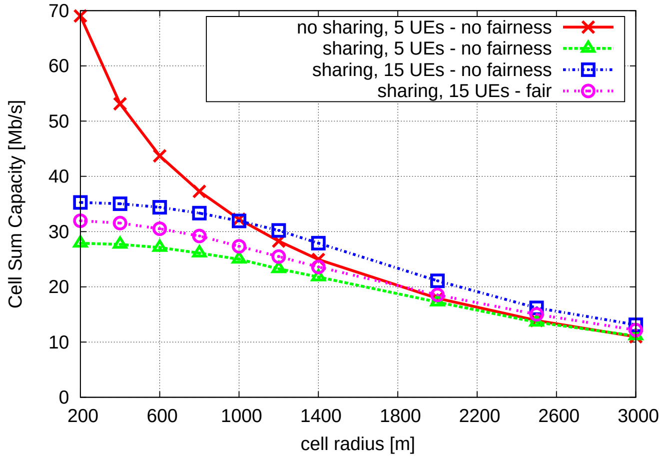

Fig. 5: Comparison of scenarios at variable distances

An example is shown in Fig. 3 where users are moved closer to the cell center. In this case, the average channel conditions are better than those in Fig. 2, and therefore the total capacity increases but at the same time spectrum sharing becomes less effective. In fact, the sharing scenarios (with or without beamforming) appear to be interference-limited, and therefore have a lower improvement than the non-sharing scenario, which is just noise-limited.

Similar reasonings hold for Fig. 4 where instead a fair allocation is applied. The overall capacity is slightly decreased in all the scenarios, but this is more evident with linear beamforming, since the fairness constraint reduces the degrees of freedom of the scheduler in selecting the "best" users (those that bring larger capacity contributions and also lower interference).

It is worth mentioning that the results shown here always consider a situation with cooperating eNBs. More specifically, it is key that at least one of the eNBs, instead of just allocating its best UEs, also tries to limit the interference caused to the UEs of the other cell. In our evaluations, it is the eNB that does not originally "own" the assigned channel that does so. Without such a multicell cooperation mechanism, for example with a selfish allocation of the UEs by both cells, the resulting capacity would be very low.

Finally, Fig. 5 reports the capacity versus the distance. If 15 users are considered, non-orthogonal spectrum sharing with beamforming is able to improve the capacity only after a certain distance, which is around 1000 meters. Such a value depends on the number of users and the specific strategy used for the UE scheduling. Remarkably, when the number of users is limited (see in the figure the curve for 5 UEs) beamforming does not improve capacity. Clearly, the design of an efficient beamforming strategy which gives a higher ESINR even with a limited angular separation can improve this conclusion. However, the capacity problems apparently are due to the difficulty of coordinating the allocation of several users in a network scenario.

IMPLICATIONS AND CONCLUSIONS

Spectrum sharing, i.e., leveraging spatial diversity to use available frequencies more than once in the same geographical area is an important topic in the context of multicell cooperation. Specifically, we investigated the impact of beamforming techniques on non-orthogonal spectrum sharing, which ought to enable spatial reuse higher than one and therefore very high capacity gains. Our numerical results show that, although spectrum sharing and beamforming may improve the transmission performance in simple contexts with a limited number of nodes, their advantage in network scenarios appears to be slim.

In particular, the following conditions must be met to have a perceivable gain. First, beamforming seems to be unavoidable to counteract the interference raise caused by the simultaneous allocation. The definition of efficient beamforming techniques is highlighted as an important further development of the investigations made in this paper. For what concerns our model of linear beamforming, used in the proposed framework to evaluate the ESINR, it ultimately emerges as able to improve performance. However, there are specific situations in which it even fails to provide any gain.

Moreover, a significant number of UE need to be present in the cells, so that the eNBs have enough degrees of freedom to schedule the users that can be coordinated optimally. If the number of users is insufficient, the advantages offered by multi-user diversity cannot be properly exploited.

Finally, it is worth noting that the allocation policies considered in this paper have certain limitations and drawbacks. Power allocation is performed uniformly across all the subchannels. The cell load in terms of UEs or traffic demand is balanced, whereas some asymmetry in this sense would be beneficial for the spectrum sharing scenario, as an overloaded cell could exploit some offloading on the other cell. Also, only pure strategies are considered, i.e., either the two cells share all the subchannels or they do not share any. In light of the numerical results, a mixture of spectrum sharing and exclusive spectrum usage would probably be more advisable. Especially, in a more realistic cellular scenario, also different user placements and mobility could play a role, although they have been left out of the present analysis on purpose, as they would somehow hinder the evaluation of the beamforming technique in an ideal condition.

Nevertheless, we believe that the present results, though simple, provide important insight to understand cross-layer scenarios for multicell cooperation. While advanced physical layer techniques can represent an important foundation for improving the capacity of next generation cellular systems, their applicability to network contexts is still unclear and sometimes may not result in the expected performance improvements. Instead, the resulting capacity may be even decreased. Therefore, a careful application of these techniques is necessary and a comprehensive evaluation of the whole protocol stack may be needed to correctly evaluate the performance of the entire system.

REFERENCES

[1] T. Koike-Akino, P. Popovski, and V. Tarokh, "Optimized constellations for two-way wireless relaying with physical network coding," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 5, pp. 773–787, Jun. 2009.

[2] C. Lu, F. H. P. Fitzek, and P. C. Eggers, "Cooperative spatial reuse with transmit beamforming in multi-rate wireless networks," *Journal of Communications*, vol. 4, no. 1, pp. 26–33, 2009.

[3] *Requirements for further advancements for Evolved Universal Terrestrial Radio Access (E-UTRA)*, TR 36.913 (V9.0.0) ed., 3GPP, Dec. 2009.

[4] A. V. Guglielmi and L. Badia, "Social communication to improve group recognition in mobile networks," *Proceedings IEEE Globecom Workshops*, San Diego, CA, December 2015.

[5] D. Niyato and E. Hossain, "Radio resource management games in wireless networks: an approach to bandwidth allocation and admission control for polling service in IEEE 802.16," *IEEE Wireless Commun. Mag.*, vol. 14, no. 1, pp. 27–35, Feb. 2007.

[6] Z. Lei, C. Yuen, and F. P. S. Chin, "Quasi-orthogonal space-time block codes for two transmit antennas and three time slots," *IEEE Trans. Wireless Commun.*, vol. 10, no. 6, pp. 1983–1991, Jun. 2011.

[7] E. A. Jorswieck, L. Badia, T. Fahldieck, M. Haardt, E. Karipidis, J. Luo, R. Pisz, and C. Scheunert, "Resource sharing improves the network efficiency for network operators," *Wireless World Research Forum 27*, Düsseldorf, Germany, October 2011.

[8] E. G. Larsson and M. Skoglund, "Cognitive radio in a frequency planned environment: some basic limits," *IEEE Trans. Wireless Commun.*, vol. 7, no. 12, pp. 4800–4806, Dec. 2008.

[9] R. Irmer, H. Droste, P. Marsch, M. Grieger, G. Fettweis, S. Brueck, H.-P. Mayer, L. Thiele, and V. Jungnickel, "Coordinated multipoint: Concepts, performance, and field trial results," *IEEE Commun. Mag.*, vol. 49, no. 2, pp. 102–111, Feb. 2011.

[10] E. Jorswieck, L. Badia, T. Fahldieck, E. Karipidis, J. Luo, "Spectrum sharing improves the network efficiency for cellular operators," *IEEE Communications Magazine*, vol. 52, no. 3, pp. 129–136, March 2014.

[11] A. V. Guglielmi and L. Badia, "Bayesian game analysis of a queueing system with multiple candidate servers," *Proceedings IEEE CAMAD*, Guildford, UK, September 2015.

[12] D. Gesbert, S. Hanly, H. Huang, S. Shamai (Shitz), O. Simeone, and W. Yu, "Multi-cell MIMO cooperative networks: A new look at interference," *IEEE J. Sel. Areas Commun.*, vol. 28, no. 9, pp. 1380–1408, Dec. 2010.

[13] R. Mochaourab and E. A. Jorswieck, "Optimal beamforming in interference networks with perfect local channel information," *IEEE Trans. Signal Process.*, vol. 59, no. 3, pp. 1128–1141, Mar. 2011.

[14] L. Badia and A. Botta, "Evaluation of various interference models for joint routing and scheduling in wireless mesh networks," *Proceedings IEEE Globecom*, New Orleans (LA), USA, December 2008.

[15] L. Badia, M. Scalabrin, "Stochastic analysis of delay statistics for intermittently connected vehicular networks," *Proceedings European Wireless*, Barcelona, Spain, May 2014.