Resource Allocation and Management in Multi-Operator Cellular Networks with Shared Physical Resources

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***Abstract*—In this paper, we focus on next-generation cellular networks and discuss physical resources sharing among the operators. This implies cooperative usage of the available radio frequencies and also infrastructure sharing. In particular, we analyze the *spectrum sharing gain* achievable at different time scales and the main factors impacting on it. Then, we move towards a wider idea of resource sharing and consider a joint spectrum and infrastructure sharing (full sharing). We describe a two-layer resource management architecture that enables operators to reduce costs while still guaranteeing a good service level. The main findings of our investigations are to quantify the effectiveness of resource sharing and open up new perspectives for the operators of next-generation networks.**

***Index Terms*—Resource allocation; spectrum sharing; infrastructure sharing; cross-layer optimization.**

I. Introduction

NEXT generation cellular networks are required to support an ever increasing traffic with a good Quality of Service (QoS) [1], [2]. Besides the classical voice service, currently, most of the burden is due to multimedia applications, which are expected to represent the main portion of (wireless) Internet traffic in the near future [3]. High bandwidth, low latency and delay jitter are the main requirements of such applications. The scarcity and the cost of the available radio resources require an efficient management of them, to avoid wastes and save money. A possible solution for network operators is to share their resources with each other and use them dynamically, according to their needs [4], [5], [6]. Hereinafter, we use the term *resource* to denote both licensed spectrum and network infrastructure.

For what concerns spectrum management, in most countries network operators are currently assigned pre-determined and separate portions of the licensed spectrum and use them independently. Although effective in interference avoidance, this method is inefficient since (i) frequencies not used by an underloaded operator cannot be used by anyone, and (ii) possible multiuser diversity effects are limited to the portion of band an operator has been assigned. If operators agrees upon sharing a percentage of their spectra, then these drawbacks may be overcome. Two methodologies are possible to coordinate frequency allocation in a shared context: *orthogonal* (i.e., mutually exclusive) and *non-orthogonal* [6]. In the former, simultaneous multiple access to the same frequency is not allowed. In the latter it is, provided that total interference is low enough to still guarantee a good signal-to-interference-plus-noise-ratio (SINR) at the intended receivers. In both cases, the fundamental challenge is represented by the arbitration of the conflicts that may arise when several operators try to access the same resource at the same time.

Another important point is the time granularity at which the allocation is performed. Short, intermediate and long-time scale policies are possible, with some inherent advantages and drawbacks. As the time scale becomes shorter, the flexibility increases in adapting to channel variations. On the other hand, very frequent allocations introduce significant overhead and require fast-converging algorithms. In this work, we explore orthogonal sharing on all the aforementioned time-scales and quantify the achievable gain and the main factors impacting on it, encompassing different application scenarios and evaluation methodologies.

Regarding infrastructure sharing, in this case operators share the physical devices of the radio access network (e.g., antennas, masts) in order to reduce the costs of installation and maintenance. Typically, these investments are rather significant and represent a barrier for companies which want to enter this market. Therefore, small firms can benefit from this opportunity. The shared infrastructure can span from the single antenna to the whole site. Also in this case, the challenge is represented by the allocation of resources to the involved players (i.e., the base stations) in a fair yet efficient way. Moreover, it is important to take into consideration the needs of operators to differentiate their services from each other.

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In this paper, we propose a two-layer architecture for a full sharing scenario (both spectrum and network infrastructure): first, allocation is done among the users belonging to the same operator, subsequently a multi-operator joint allocation occurs.

The remainder of the work is organized as follows. Section II pictures the current state of the research. In Section III spectrum sharing is thoroughly discussed and numerical results are given for the short, intermediate and long time-scale. Then, in Section IV the infrastructure sharing is discussed. Finally, in Section V conclusions are drawn.

II. State of the Art

A first simple idea of spectrum sharing in a cellular radio system is introduced in [7]. The authors propose two simple yet effective algorithms to redistribute excess users to spectrum bands with available capacity, thus enabling some operators to serve more users than they could if spectrum were used exclusively. The performance is measured in terms of call block probability and a significant gain is showed. In [8], the authors derive the ideal maximum load that a network can handle without excessive delay, and claim that the gain achievable with spectrum sharing is limited by geographical and physical layer constraints. Unlike our work, where a frequency division is considered, in that paper the authors consider a time division system where each operator is allocated a time slot in a common super-frame, while the sharing algorithm attempts to schedule packets that cannot be accommodated by their home operators. In [9], a step ahead is made and the network infrastructure is considered with roaming of the users. A theoretical analysis on the capacity region of a cellular network with spectrum sharing is given in [10], where a game theoretic model is proposed for networks where a primary and secondary operator can be identified. In our work, we do not introduce such a distinction and consider all the operators as peer entities in the game of resource access. An analysis is carried out by using the auction theory. Other recent works focusing on spectrum sharing are described in [6] and [11]. The former considers a non-orthogonal sharing scenario, modeled as a MISO IC (Multiple Input Single Output Interference Channel), and proposes the technique of transmit beamforming for the mitigation of the sharing interference. The latter considers non-orthogonal sharing as well and evaluates the sharing gain among two operators under different traffic loading conditions. In addition, soft handover and signaling overhead are considered.

In recent years, infrastructure sharing has received an ever increasing interest as well. As stated in [12], this is a good opportunity for operators to reduce both capital expenditure (CAPEX) and operational expenditure (OPEX). In that paper, besides presenting a survey on the state of the art, the authors present a list of requirements for 4G networks and propose a framework which fulfills them. A virtualization-based technique is exploited, where a virtual network is built on top of those of each operator. Technical and business perspectives of this proposal are discussed together with some open issues. In [13], a mathematical model is proposed for the benefit-cost analysis by considering the Chinese telecommunication market as a reference scenario, where the three main firms signed an agreement for infrastructure sharing. In [14], a quantitative analysis is conducted as well, but a simulative approach is used instead. In all the scenarios considered (e.g., site sharing, shared RAN, full sharing), performance improvements are shown. In our work, we propose a two layer resource management for combined infrastructure and spectrum sharing (full RAN sharing).

III. Spectrum Sharing

In the following subsections, we consider short, intermediate and long time-scale allocation schemes for spectrum sharing. The analysis is carried out for different types of cellular network technologies and traffic conditions to emphasize, for each scheme, the main factors impacting on it and on the achievable sharing gain. Moreover, we us highlight the independence of the sharing schemes from any particular technology. We remark that we consider here only single-input single-output (SISO) systems. The extension to more advanced physical layers with multiple inputs [15] or multiple packet reception capabilities [16] can be considered as further extensions.

A. Short time-scale spectrum sharing

A fine-grained allocation allows the exploitation of channel fluctuations due to channel fading. Consider a network with two neighbor cells belonging to two different operators that share adjacent bands in an LTE (Long Term Evolution) [17] system. The time is divided into 10 ms frames consisting of 1 ms sub-frames. The spectrum is split into sub-channels which bundle sub-carriers of total bandwidth equal to 180 kHz and are allocated to the operators in every sub-frame. The Base Station (BS) managing each cell performs, in the downlink, channel-aware scheduling and resource allocation to its users (UE - User Equipment), to exploit the multiuser diversity (*intra-cell* allocation).

Once each BS has decided its optimal allocation of the channels, all the possible conflicts for the access to the common part of the spectrum need to be solved. We propose a centralized approach to evaluate the upper bound on the sharing gain. Even though it is meant as a theoretical performance, not as a practical algorithm, it can serve as a comparison term. In particular, we have implemented a *Monopoly-like upper bound algorithm* that maximizes the total cell sum capacity. The operators behave as if they were a single (monopolist) entity, without any balance consideration. Each sub-channel is always assigned to the UE with the best channel. The resulting capacity is the maximum achievable, a theoretical upper bound.

We report the results obtained from a simulation campaign, where a customized version of the ns-3 network simulator [18] was used. Among the main simulation parameters we have: transmission frequency of 2110 MHz, 20 MHz of total bandwidth, average UE speed of 30 km/h. The radio propagation model includes path loss, 10 dB of wall penetration loss, log-normal shadowing with average 0 dB and log-standard deviation 8 dB, multipath fading modeled according to Jakes'

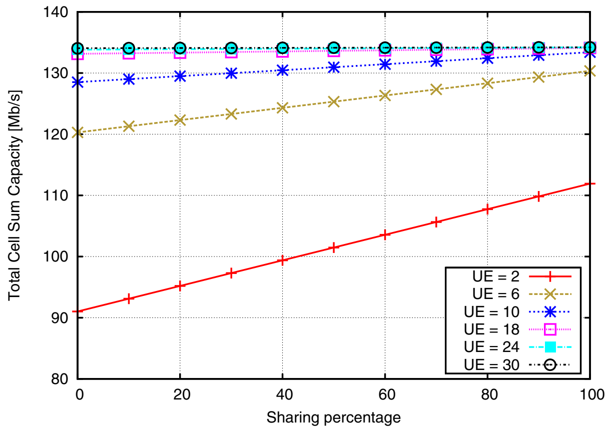

Fig. 1: Upper bound on the total cell sum capacity for short time-scale allocation

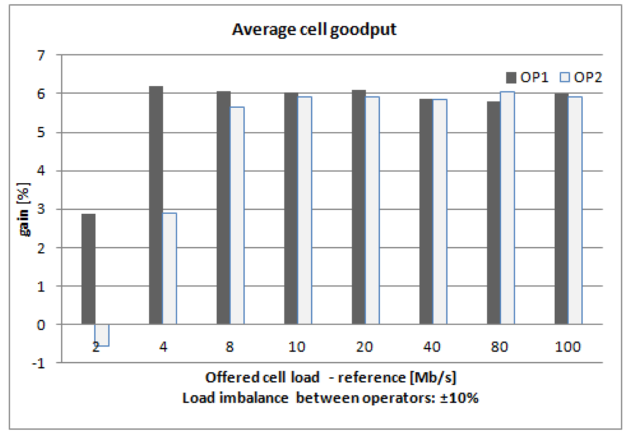

Fig. 2: Average cell goodput gains in sharing scenario (low load imbalance)

model [19]. The downlink transmission power at the eNB is 43 dBm. All the UEs are assumed to be backlogged.

Fig. 1 presents the results of a first simulation campaign. First of all, an increase in the capacity with the number of users can be noted, as a direct consequence of the multiuser diversity. The greater the number of UEs, the higher the probability that for each sub-channel there is at least one UE with good channel quality. However, for a higher user density, the improvement is low because for almost all the sub-channels at least one user experiences a good channel quality. A second important observation is that there is a neat *sharing gain*, since the sum capacity increases with the sharing percentage. For a small number of UEs a 20% gain can be reached over the no-sharing case. The decrease of the gain with the number of UEs is still a consequence of the reduced multiuser diversity.

However, it is important to remind that these values were obtained for a scenario under saturation. In the case of low load, BSs can opportunistically exploit most of the unused resources, as showed also in the forthcoming subsections. Therefore, we can consider the results in Fig. 1 as the worst-case upper bound.

B. Intermediate time-scale spectrum sharing

For the analysis of the intermediate time-scale spectrum sharing we used the generalization of a second price Vickrey-Clarke-Groves (VCG) auction [20] to dynamically allocate radio resources from the shared spectrum pool to operators in a High-Speed Downlink Packet Access (HSDPA) [21] network. Each operator employs a Dual-cell HSDPA (DC-HSDPA) network and agrees to assign one carrier to the commonly shared pool. The objective function is the buffer size for the BS in each cell. It considers the amount of profit a particular operator expects from using a certain number of resources in the next time period.

For this scenario, consider a network of 19 three-sectored, homogeneous cells. Two co-located operators provide coverage over the same geographical area and serve their own subscribers only. The spectrum available for the auctioning game is merged into a single pool of HSPA carriers, which are available at each cell and can be used by any operator in TDMA mode, depending on the auction outcomes in each cell. Therefore, this is an orthogonal spectrum sharing model.

The traffic model is seen as a crucial aspect. We evaluate the system performance by considering partially correlated and varying load balance among operators, introducing tolerance on top of the reference offered cell load. The traffic model is defined based on the packet burst size. The number of the active and randomly located UEs using high data rate service is fixed and constant for both operators. Uncorrelated valuations are forced by the unbalanced packet bursts sizes. Resource allocation grants for the pooled carriers is repeated in periodic time intervals Δ (set equal to 200 ms). The decision of which resources can be used by each operator for a particular time period is taken by the virtual Auctioning Unit (AU). Each AU decision is valid for a time period of Δ, after which the Auctioning Process must be repeated and a new resource allocation scheme shall be provided. We assume that the carriers are of same value for the operators, thus the decision refers to the number of carriers to be allocated to each operator.

It was found that, depending on the load balance among auction players, the sharing gains change among the operators. Due to the valuation function used, in extreme load imbalance cases the gains are exploding for the most loaded operator, at the expense of the less loaded one. In Fig. 2, OP1 has a higher quantity of traffic to deal with, and thus it benefits more from spectrum sharing since it can opportunistically exploit the resources of OP2, which gets a reduced performance. However, this reduction is less significant when the average cell load increases because all the cells approach the saturation.

C. Long time-scale spectrum sharing

In this case, the timescale is of the order of seconds. For the analysis we consider an heterogeneous network, where operator A has only macro-cells and operator B owns hotspot cells (pico-/micro- cells) in the same area [22]. It is assumed that operator A owns all the subscriptions, although all the terminals can access the hotspot cells and their spectrum based on an agreement among the operators. A user close to a hotspot cell may receive from it a stronger signal than from the macro cells, and thus might be better served by the hotspot cell if there is sufficient capacity available. Thus, it may be appropriate to assign more spectrum to hotspot cells when the traffic is highly concentrated around them. With spectrum sharing, the sub-bands owned by both operators will be dynamically assigned to the two networks. Users of operator A will be served by both.

Regarding the access technology, we suppose operator A has an LTE network with 12 sectored sites arranged in a hexagonal layout with an inter-site distance of 1 km, overlaid with operator B's LTE network consisting of 3 hotspot cells (evenly located) per coverage area of each macro-cell. Each operator owns 10 MHz in the 2100 MHz band. In each macro-cell the directional antenna pattern given by [17] is considered, with an effective antenna gain of 11.5 dB and a maximum transmit power of 46 dBm, while each hot-spot cell has omni-directional antennas with a maximum transmit power of 30 dBm. The path loss is given by $138.5+32.225\log(d)$ and by $127 + 30\log(d)$ for macro- and hotspot-cells respectively (d is the distance in km). The radio propagation model also includes log-normal shadow fading with log-standard deviation 8 dB, and a 17 dB indoor penetration loss. The traffic flows represent the download of files with a log-normally distributed size with average 1.0 Mb and log-standard deviation 1.5 Mb. Flows are generated according to a Poisson process with average arrival rate λ. With probability K the location of a generated flow is sampled in the service area of the hotspots, while with probability $1-K$ it is uniformly sampled over the entire coverage area. For each initiated flow, the serving cell is selected based on the received pilot strength. The spectrum is assigned to the networks with a granularity of 6 physical resource blocks of 180 kHz at a time scale of 60 seconds, according to the time-averaged traffic loads (with averaging window of 60 seconds) served by macro- and hotspot cells. At any time, the available radio resources in each cell are evenly shared by the served flows.

Simulations have been performed for the daily profile of K showed in Fig. 3a with $\lambda = 122$ flows/s and the maximum value of K, K_{max}, varying between 0 and 1. Fig. 3b shows that spectrum sharing allows the operators to increase their average throughput with respect to the no-sharing case. In particular, the greater K_{max}, the greater the gain in the average throughput. This is due to the fact that with a larger K_{max} the traffic is more concentrated around the hotspots, which are assigned more spectrum and offer better radio connection than the macro cells.

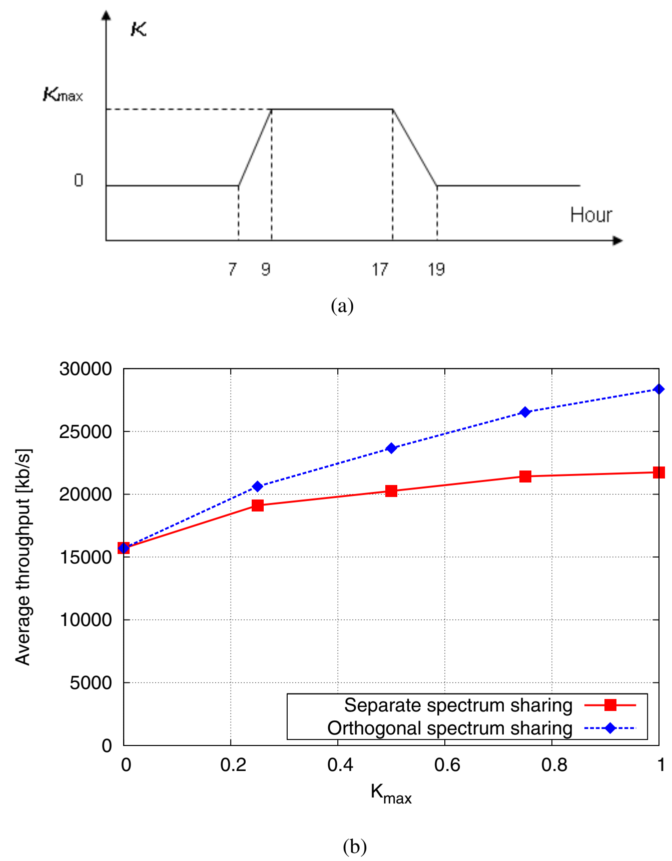

Fig. 3: Sample daily traffic profile (a) and gain of spectrum sharing over separate spectrum assignment for different traffic profiles (b)

IV. Two-Layer Resource Management for Full Sharing Scenario

In the full sharing scenario, two or more operators share one radio access network, as well as their licensed spectrum. The aim is to increase the efficiency of the radio resources usage by a collaborative access to the pooled spectrum and to decrease the capital and operational expenditure by a collaborative usage of the radio access network.

From a technical point of view, the full sharing scenario can be seen as a legacy scenario (one RAN, one operator). The shared usage of the pooled spectrum leads to several performance improvements, like statistical multiplexing gain and improved frequency-selective scheduling due to the increased spectrum range, as showed in the previous sections. However, some drawbacks are possible as well. According to the physical channel conditions of the air interface, the relationship between achieved throughput and used radio resources differs and this may lead to unfair assignments of radio resources from the operators' perspective. Furthermore, equipment sharing forces different operators to use the same hardware and software with the same feature set. To overcome these problems, we have defined an architecture based on a two-layer resource management. This consists of one or more instances of an upper-layer resource manager (URM), one per operator, and a unique lower-layer resource manager (LRM) (Fig. 4). The URM performs resource allocation among all end-users data flows of one operator. It allocates the radio resources according to the quality of service constraint of the data flows and abstract channel quality identifier (ACQI). The LRM schedules the data coming from different URMs according to the abstract priority indicators (API), the physical channel conditions and the resource assignment algorithms. The coupling between the URM entities and the LRM is performed by the exchange of APIs, generated by the URM, and of the ACQIs, generated by the LRM. The LRM also incorporates resource assignment algorithms, which reflects

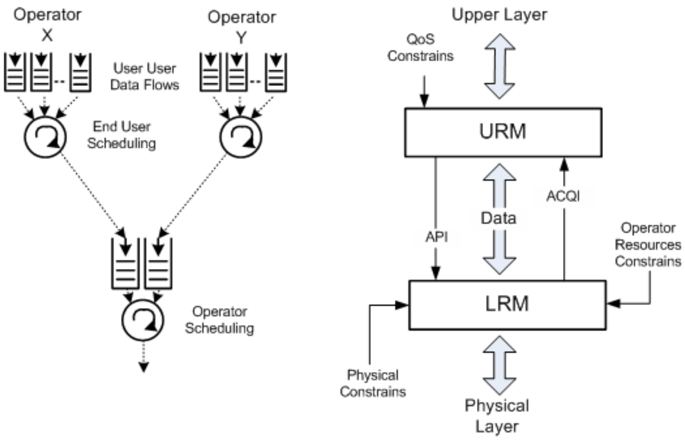

Fig. 4: Two-layer resource management

the business relationships and the spectrum ownerships of the different operators. These algorithms deal with percentages of physical resource blocks (PRB). This credit-based resources assignment can be flexibly adapted to any given spectrum partitioning.

The two layered resource management provides a better decoupling of the end user and operator resource management. Furthermore, the existence of a dedicated higher layer resource management per operator gives them the opportunity to implement their individual resource management algorithms for a better support of the specific service classes offered to their end users. This enables a better service differentiation among competing operators and may improve the acceptance of the full sharing.

V. Conclusions and Future Developments

In this paper, we have investigated the potential of physical resource sharing strategies in future cellular networks. Both spectrum and infrastructure sharing have been discussed. In the former case, we have analyzed the achievable gain under various time allocation schemes. The simulation results show that a sharing gain can be obtained in every case. We also highlighted the factors impacting on such a gain, i.e., traffic and user load unbalances. In the latter case, we have proposed an architecture that considers both business constraints and physical issues. The proposed architecture is flexible enough to guarantee service diversification among the operators.

Possible future extensions of this work include the evaluation of more advanced physical layer signal processing algorithms for spectrum sharing and relay-assisted physical resource sharing.

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