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Spectrum Sharing Improves the Network Efficiency for Cellular Operators

Eduard A. Jorswieck, Leonardo Badia, Torsten Fahldieck, Eleftherios Karipidis, Jian Luo

ABSTRACT

The article describes the potential gain by spectrum sharing between cellular operators in terms of network efficiency. The focus of the study is on a specific resource sharing scenario: spectrum sharing between two operators in cellular downlink transmission. If frequency bands are allocated dynamically and exclusively to one operator — a case called orthogonal spectrum sharing — significant gains in terms of achievable throughput (spectrum sharing gains between 50 percent and 100 percent) and user satisfaction are reported for asymmetric scenarios at link and system level as well as from two hardware demonstrators. Additionally, if frequency bands are allocated simultaneously to two operators — a case called non-orthogonal spectrum sharing — further gains are reported. In order to achieve these, different enablers from hardware technologies and base station capabilities are required. However, we argue that all requirements are fulfilled in 3GPP and newer mobile standards. Therefore, the results and conclusions of this overview particle encourage to seriously consider the inter-operator spectrum sharing technologies.

INTRODUCTION

Important physical resources in wireless communications systems are spectrum, infrastructure, and energy. In general these resources are scarce because of either natural limitations and costs or environmental and regulation constraints. Focusing on spectrum, efficient usage of spectrum is required since 7 trillion devices will serve 7 billion people 24 hours 7 days a week until 2017 as formulated in the wireless world research forum (WWRF) vision [1].

In current wireless communications, radio spectrum is typically used such that interference is avoided or reduced by exclusive or careful allocation of frequency bands. This report demonstrates how equal-priority spectrum sharing in cellular networks improves spectral efficiency, enhances coverage, increases user satisfaction, leads to increased efficiency for operators, and decreases capital and operating expenditures. In the SAPHYRE[1] project, inter-operator spectrum sharing is analyzed. An initial overview of the approach without technical results was reported in [2].

The traditional way of handling spectrum for cellular wide and metropolitan area networks arose about 90 years ago based on the capabilities of radio transceivers and the regulatory requirements. Spectrum divided in chunks of certain bandwidth is exclusively licensed to operators by public auctions [3] for one decade or more. Furthermore, one Radio Access Technology (RAT) is assigned to the spectrum bands, e.g. Global System for Mobile communications (GSM), Universal Mobile Telecommunications Standard (UMTS), Long Term Evolution Advanced (LTE/A), or High Speed Packet Access (HSPA) as UMTS evolution. This situation is illustrated in Fig. 1a. Two operators (yellow and blue) own certain parts of the spectrum, which is again subdivided into three smaller frequency bands each assigned to one RAT. In this example, we focus on 3GPP RAT [4], however, the principle can be extended to 3GPP2 as well as to other IEEE 802 standardized RATs. International Mobile Telecommunications Advanced (IMT/A) is a placeholder for these RATs satisfying the IMT/A requirements.

The first step to flexible radio spectrum usage for a single operator is intra-operator spectrum sharing, which includes the dynamic allocation of RATs, as well as the movement of users, within the operator's spectrum bands, as illustrated in Fig. 1b. In a number of European countries the adaptive assignment of RATs to licensed spectrum is allowed by the regulatory bodies [5] enabling the flexible application of Software Defined Radio (SDR) technology. This trend to more flexible use of spectrum is supported by novel developments in radio technology.

In *orthogonal inter-operator spectrum sharing* the users can be moved over the spectrum bands of both operators. However, at any time instance, one spectrum band is still exclusively assigned to one operator,[2] so that no additional interference is created, as illustrated in Fig. 1c. In different time slots, parts of the spectrum — shared bands — owned by the yellow operator are assigned to the blue operator and vice versa.

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[1] *This work has been performed in the framework of the European research project SAPHYRE, which is partly funded by the European Union under FP7 ICT Objective 1.1 – The Network of the Future. SAPHYRE studies Sharing Physical Resources Mechanisms and Implementations for Wireless Networks. For more details see www.saphyre.eu.*

[2] *Roaming could be seen as a special case of orthogonal inter-operator spectrum sharing. In the general case, two co-existing operators adaptively assign parts of the spectrum to each other but do not exchange data on their backhaul networks.*

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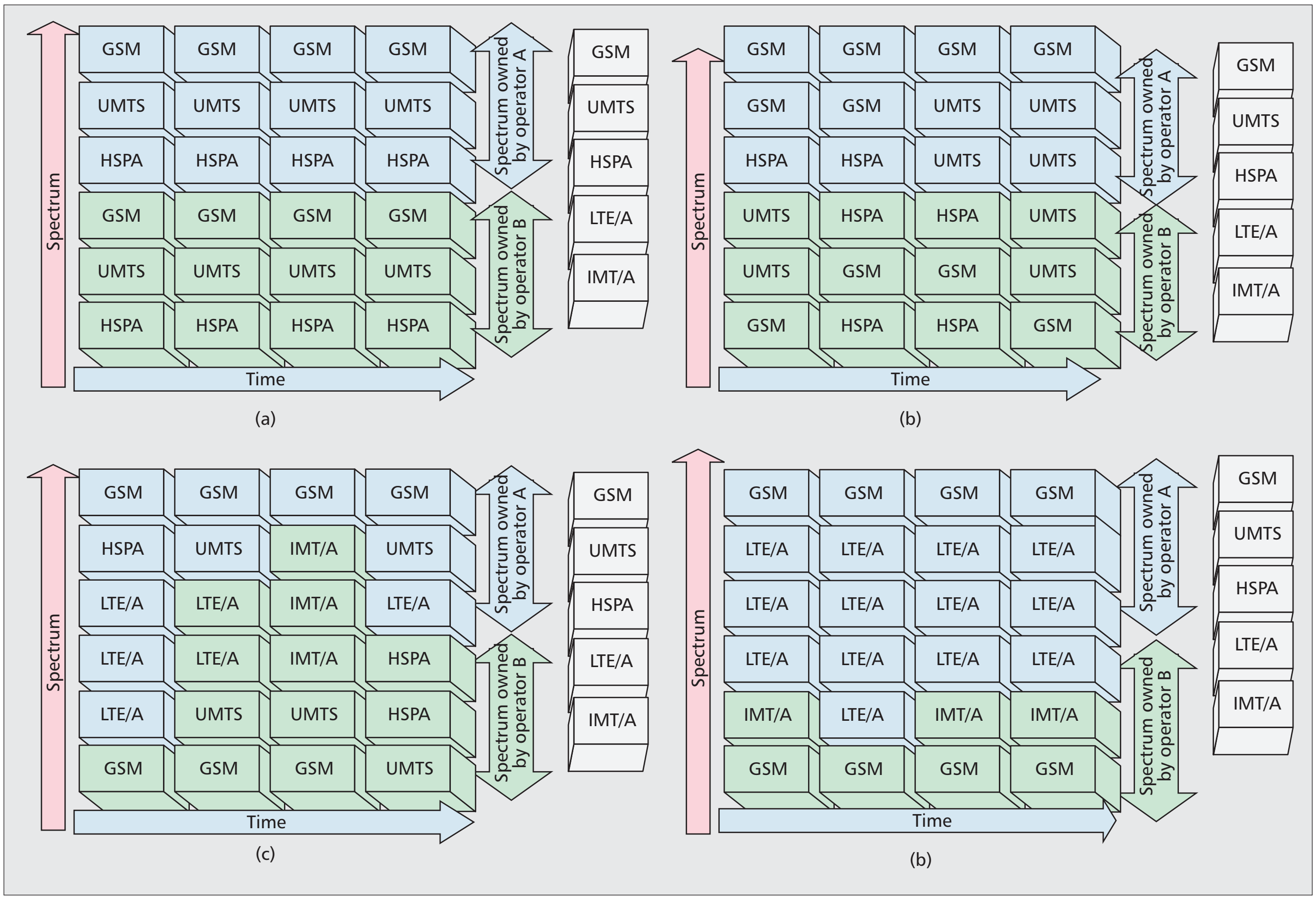

Figure 1. *Classification of spectrum sharing methods: a) no spectrum sharing; b) Intra-operator spectrum sharing; c) inter-operator orthogonal spectrum sharing; and d) inter-operator non-orthogonal spectrum sharing.*

The most flexible way of spectrum sharing is *non-orthogonal inter-operator spectrum sharing*, illustrated in Fig. 1d, where the shared bands can be assigned to more than one operator indicated by the green color of frequency blocks. The protected bands are still reserved for QoS guarantees. Consider the first time slot in Fig. 1d: There, two legacy GSM bands are protected for exclusive use and three bands are shared between two operators using LTE/A as RAT. This type of sharing creates interference on the PHysical laYer (PHY). However, by clever transceiver optimization, and user selection, spectrum sharing gains in terms of spectral efficiency are reported, e.g., in [6].

We define the gain by inter-operator spectrum sharing as the net improvement in spectral efficiency, measured in [Mb/s/Hz]. On link level, we define the spectrum sharing gain as the ratio of the sum rate achieved by cooperative beamforming over Time-Division Multiple Access (TDMA). On system level, the gain is computed in terms of total capacity. Please note that the idea of spectrum sharing can be extended to different network scenarios, e.g., Private Mobile Networks (PMN) or communications for Public Protection and Disaster Relief (PPDR).

Cooperative MultiPoint (CoMP) is viewed as the key technology for LTE/A [7] and has been proposed since Release 9 of LTE. Multiple base stations cooperate to improve the data rates and reliability. It exploits the intercell interference in order to increase the spectral efficiency. In contrast to inter-operator orthogonal and non-orthogonal spectrum sharing, it is currently limited to a single operator, and coordinated beamforming requires the exchange of Channel State Information (CSI) as well as (usually) user data via high-data backbone connections. Thereby, specific reference signals are required to obtain global CSI and perform the joint precoding and transmit optimization. It improves the cell edge user data rate and spectral efficiency by cooperation between sectors or different sites of the same operator. CoMP uses frequency reuse factor one in multiple cells, which is similar to the spectrum sharing setting.

Fractional Frequency Reuse (FFR) is applied in Mobile WiMAX, based on IEEE 802.16, and in LTE to increase the spectral efficiency. Users close to the cell center are allowed to reuse frequency bands from neighbor sectors — frequency reuse one — whereas users close to the cell edge are assigned exclusive frequency bands. The difference to inter-operator spectrum sharing is that FFR is applied within one operator and the decision on the frequency band assignment is usually based on the average received power, i.e., Signal-to-Interference-plus-Noise Ratio (SINR) threshold.

Cognitive Radio (CR) and SDR can be seen as enablers for inter-operator spectrum sharing:

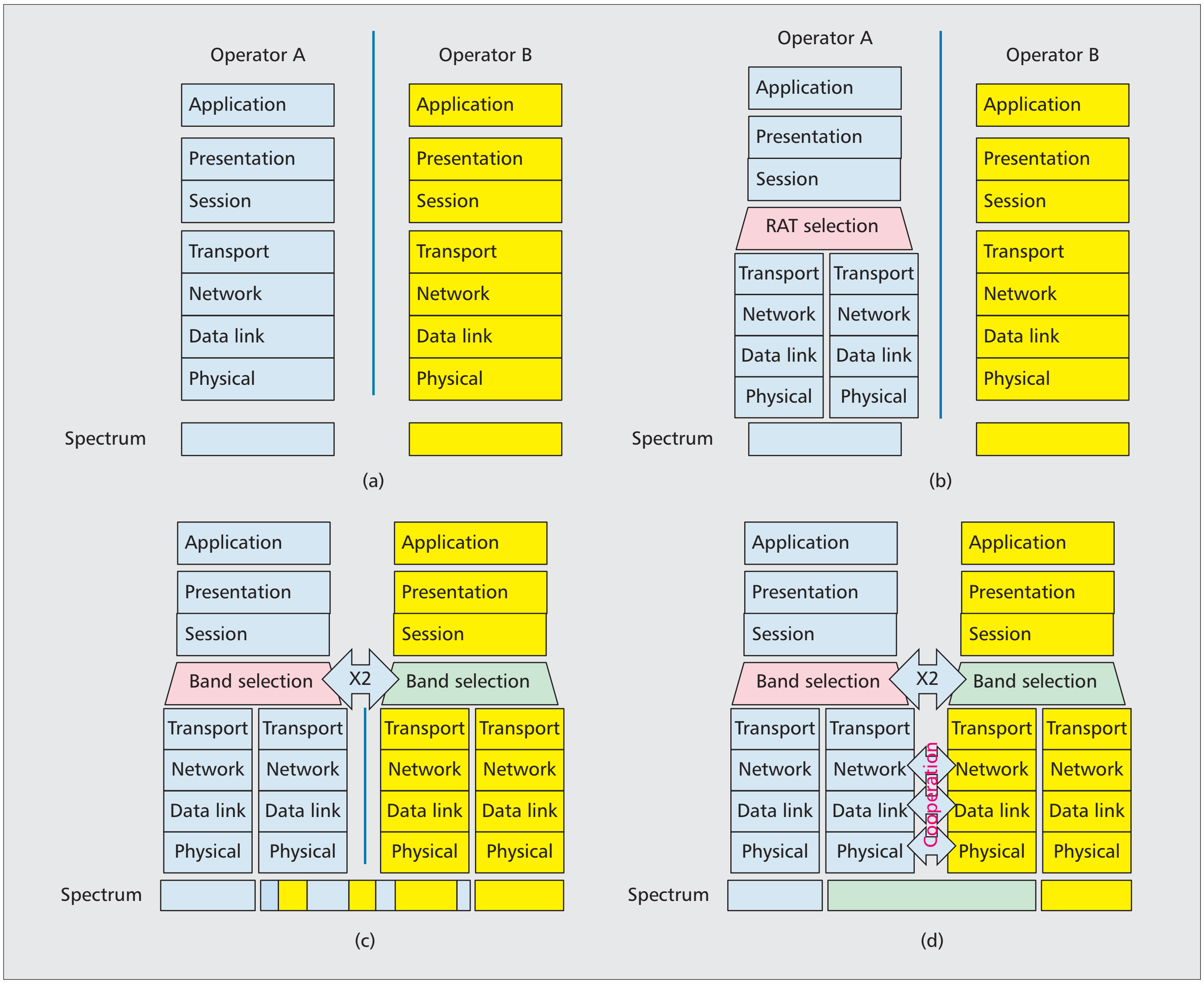

Figure 2. *Architectural implications of spectrum sharing: increased overhead on the technology-dependent layers, additional requirements for signalling and increased complexity due to cooperation: a) no spectrum sharing; b) intra-operator spectrum sharing; c) orthogonal inter-operator spectrum sharing; and d) non-orthogonal inter-operator spectrum sharing.*

In CR, nodes sense their environment, decide on opportunities for successful data transmission and flexible use of spectral, temporal, and spatial resources. In the broad sense of CR networks, inter-operator spectrum sharing benefits from cognitive and flexible transceivers and SDR clearly increases the flexibility and adaptivity in terms of spectrum and RAT assignment.

For orthogonal inter-operator spectrum sharing a large number of different approaches are proposed in the literature [8]. Since the flexible allocation of spectrum between two or more operators results in conflicting interests, systematic tools from game theory are often applied.

ENABLERS AND REQUIREMENTS

The different types of spectrum sharing influence the system architecture as illustrated in Fig. 2. In Fig. 2a the state-of-the-art architecture is shown. All layers at the two different operators are implemented separately and no interaction is required because both operators access their own licensed spectrum. In Fig. 2b the proposed architecture for intra-operator spectrum sharing is illustrated. Still there is no need to have interoperability between operators. However, a RAT selection needs to be implemented on top of the technology layers. In Fig. 2c the proposed architecture for orthogonal inter-operator spectrum sharing is shown. In addition to the RAT and band selection on top of the technology layers, there exists an interface (e.g. the X2 interface) which is utilized to coordinate the band selection process among operators. In Fig. 2d our envisioned architecture for non-orthogonal inter-operator spectrum sharing is illustrated. In addition to the interface for band selection, cooperation between the lowest three technology layers is required and the inter-operator traffic is significantly increased. However, we will explain below that the signalling overhead can be realized.

Spectrum sharing impacts several additional requirements on the BS architecture.

Spectrum size: Increased spectrum usage

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[3] *Note that spectrum sharing gains by non-orthogonal spectrum sharing are obtained even by a 2 × 1 Multiple-Input-Single-Output (MISO) configuration.*

requires increased spectrum capability for the BSs, either as broader carrier or as carrier aggregation. The extension of the spectrum range leads to increased requirements of processing power on the lower layers of the protocol stack of the wireless interface especially in the PHY. The required processing complexity on PHY increases approximately linearly with the spectrum size.

Backbone interface throughput: The required throughput of the backbone interface of a BS is impacted by the effective throughput of the radio interface and increases approximately linearly with the user traffic. Furthermore, the collaborative use of shared radio resources among different BSs impacts additional control traffic. To perform cooperative optimization of PHY and Medium Access Control (MAC) layers, the BSs have to exchange control data like CSI via the backbone. The following example roughly estimates the expected additional CSI which has to be exchanged between neighbor sites assuming:
- Size of jointly used spectrum 2 × 10 MHz (50 resource blocks per operator),
- Report periodicity of 1 Transmission Time Interval (TTI), e.g., 1 ms in LTE,
- CSI size of 8 bits, i.e., 4 In-phase (I) and 4 Quadrature (Q) bits [9]
- 2 transmit antennas per BS and 1 receive antenna per User Terminal (UT)
- Information exchange between neighboring cells
- 3 BSs per site
- 4 neighbor BSs from other sites,
- 10 UTs per cell [4].

Hence, the inter-site CSI traffic is 8 bits × 50 (resource blocks per operator) × 2 (channels per link) × 4 (neighbor BSs) × 3 (BSs) × 10 (UTs)/ 0.001 s = 96 Mb/s. The practical backhaul rate for a dense urban deployment is about 100 Mb/s for one cell and 300 Mb/s for one site respectively, so the additional control traffic is comparable to a typical current backhaul rate.

Spectrum sharing enabled BSs have to fulfill several additional requirements mainly in terms of increased spectrum, number of end users, additional processing power, and enhanced backbone capacity. A raw assertion about the requested capability can be done by analyzing the capabilities of current and future BS implementations. BSs which will be available on the market in the next few years have to be compliant to 3GPP Rel-10 and subsequent releases. Some key requirements of 3GPP Rel-10 are spectrum ranges up to 100 MHz, carrier aggregation and 8 × 8 Multiple-Input-Multiple-Output (MIMO) capabilities. A BS which fulfills these requirements may be enabled for sharing scenarios regarding spectrum ranges and beamforming capability.[3] Moreover, spectrum sharing has the same requirements on synchronization as CoMP. Finally, the hardware and software requirements to compute the spectrum sharing algorithms and methods highly depend on the BS architecture and particular hardware and software components. Considering the evolution path of LTE, 3GPP Rel-11 [4] will provide CoMP. BSs which fulfill the requirements for performing CoMP methods provide sufficient hardware and software resources to perform spectrum sharing methods.

Non-Orthogonal Spectrum Sharing: Signal Processing and Implementation

We envision that future cellular networks will achieve higher spectral efficiency if the operators decide to share parts of the spectrum that has hitherto been exclusively licensed to them. Inter-operator spectrum sharing can be realized in an orthogonal manner as shown in Fig. 1c, e.g. by applying a TDMA scheme. However, the utmost gain is expected when the operators share the spectrum non-orthogonally. The major impairment that has so far prevented such a development is the interference caused by co-channel transmissions. Consider this simple setup: Two neighboring base stations BS1 and BS2 of different operators transmit towards UT1 and UT2 respectively and the UTs receive a combination of the transmissions. We claim that reliable and fast communication can be achieved in both links by applying advanced signal processing techniques.

The most prominent of these techniques is called transmit beamforming and is enabled by the availability of multiple antennas at modern BSs. By appropriately scaling the transmitted signal in each antenna, the overall effect is to steer the transmission power towards the intended UT and away from the other UT. That is, interference is managed by effectively separating the transmissions in space, rather than in time — like in the orthogonal sharing scheme TDMA — or in frequency — like legacy with no sharing. This scenario is the MISO Interference Channel (IC), whose capacity region (maximal achievable transmission rates) is yet unknown in general. However, it is possible to find practically-relevant achievable rate regions. Figure 3a illustrates one achievable rate region for an instance of Rayleigh-fading channels (in one resource block), assuming that local CSI is perfectly known at the BSs and the UTs treat the interference as additive noise. The rates R_1 and R_2 are achievable for UT1 and UT2, respectively. The triangular region achieved by orthogonal (TDMA) sharing lies inside the non-orthogonal sharing region. Hence, there is a multitude of operating points that yield high-rate to both links, which can only be achieved by non-orthogonal spectrum sharing.

The MISO IC also models the intercell interference problem in a single-operator cellular network with aggressive frequency reuse, but there are some important distinctions to this setup. First, the interference level can be significant, since the cells of different networks overlap each other and the corresponding BSs might even be co-located, especially in dense urban environments where the need of sharing is more prominent. Second, since the BSs belong to different operators, they do not share the user data and cannot use the joint processing family of CoMP techniques that turn intercell interference into an advantage. However, coordinated beam-

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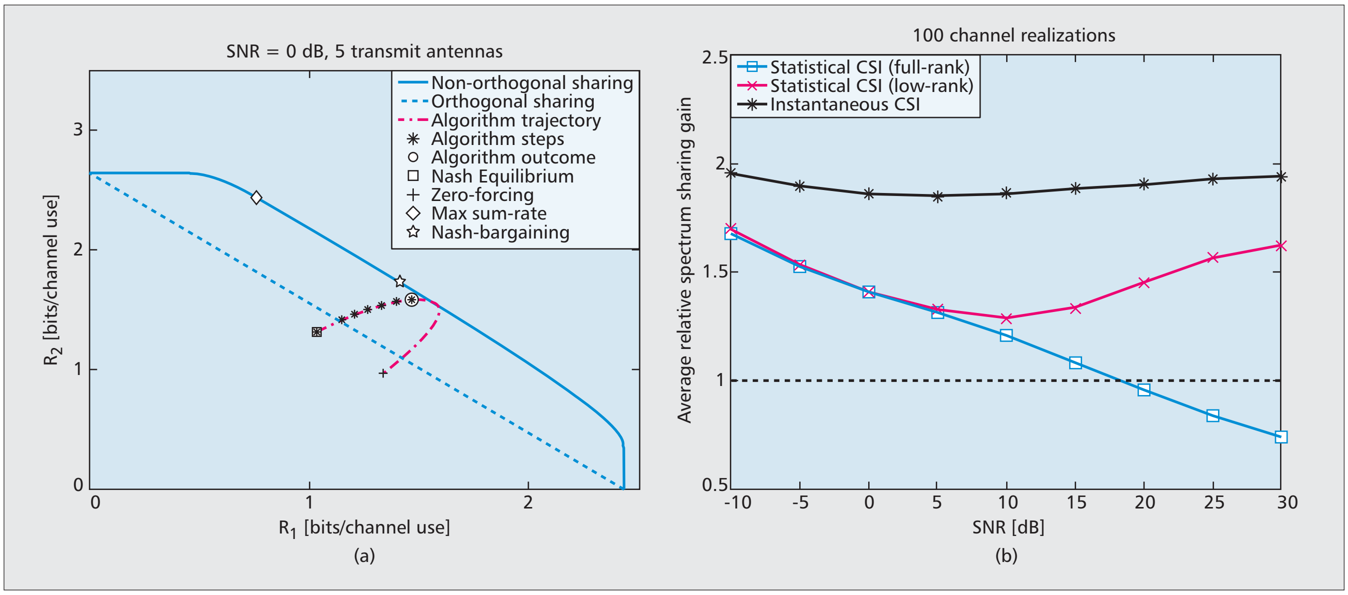
[4] *The SAPHYRE hardware demonstrators have received the award "Best Demonstration Stand" at the Future Network and Mobile Summit 2012 in Berlin.*



(a) (b)

Figure 3. *Non-orthogonal spectrum sharing enabled by transmit beamforming: a) example of MISO IC achievable rate region and important operating points; and b) average relative spectrum sharing gain for various CSI scenarios.*

forming may be applicable, provided that the BSs share CSI, via an appropriate inter-operator backbone interface. Only local CSI is required, i.e., the channels from one BS to the UTs in its vicinity. Third, the beamforming design needs to be adapted, since the objectives of the operators are conflicting; each wants to optimize the QoS of a different UT using the same resources. Possible solutions of this multicriterion optimization can be motivated by fundamental game-theoretic concepts. One extreme approach is that the BSs do not coordinate and selfishly use the Maximum-Ratio Transmission (MRT) without bounding the created interference; the other extreme is to altruistically ensure that no interference is caused. The former leads to a Nash Equilibrium (NE) and the latter to a Zero-Forcing (ZF) operating point. As evidenced in Fig. 3a, both of them are in general inefficient, since they lie far inside the rate region. Pareto-optimal operating points are efficient operating points on the boundary of the rate region, e.g., the illustrated max Sum-Rate (SR) and Nash Bargaining Solution (NBS) ones, can be achieved by a compromise amongst the extreme designs. The key is to allow each BS create controlled levels of interference that can be tolerated. This situation also resembles the underlay CR paradigm, in which a secondary network can operate aside the primary (licensed) one, provided that it does not cause detrimental interference. We claim that both operators can achieve more gain by equally sharing their spectrum and cooperating in the design of their transmissions.

Inter-operator cooperation enabling coordinated beamforming may be achieved by simple schemes provided that they are mutually beneficial. Consider for example an iterative beamforming algorithm, which uses as design parameter the interference temperature, i.e., the interference that each BS generates towards the UT of the other operator. In every iteration, as long as both rates continue increasing, the BSs decrease the interference temperature. Each BS designs its beamforming vector in a distributed manner by maximizing the signal power received by its UT, but without exceeding the chosen interference temperature. Figure 3a shows the operating points achieved at each iteration and it is evidenced that the algorithm outcome is close to Pareto optimal. The algorithm can be applied when the BSs have either instantaneous or statistical CSI. In Fig. 3b, the average relative spectrum sharing gain, computed over 100 channel realizations, is reported for various Signal-to-Noise Ratio (SNR) levels. We see that for instantaneous CSI, the sum rate with cooperative beamforming is approximately doubled with respect to TDMA. For statistical CSI with low-rank channel covariance matrices, the sum rate is increased by approximately 50 percent. With full-rank channel covariance matrices, the gain linearly decreases with SNR and at 18dB it becomes loss. We evidence that accurate CSI increases the spectrum sharing gain.

The proposed downlink spectrum sharing approaches have been implemented and demonstrated using two hardware demonstrators.[4] The first one is a "Hardware In the Loop" (HIL) demonstrator shown in Fig. 4 and consists of two broadband wireless experimental devices and a channel emulator device (EB Propsim®F8). The implemented scenario contains two operators, each having 1 BS and 1 UT. The two BSs can exchange information via Ethernet. The downlink signals were transmitted through the channel emulator, where measured urban LTE channels were loaded. In the no-sharing case, each operator owns 10 MHz spectrum and uses MRT. In the non-orthogonal spectrum sharing case, both operators share 20 MHz spectrum and apply a cooperative transmit beamforming technique described above [6]. The measured sum rate in Fig. 4 shows significant gains achieved by non-orthogonal spectrum sharing.

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[5] *E. A. Jorswieck* et al., *"Resource Sharing Improves the Network Efficiency for Network Operators," 27th Meeting of the Wireless World Research Forum (WWRF), Oct. 2011.*

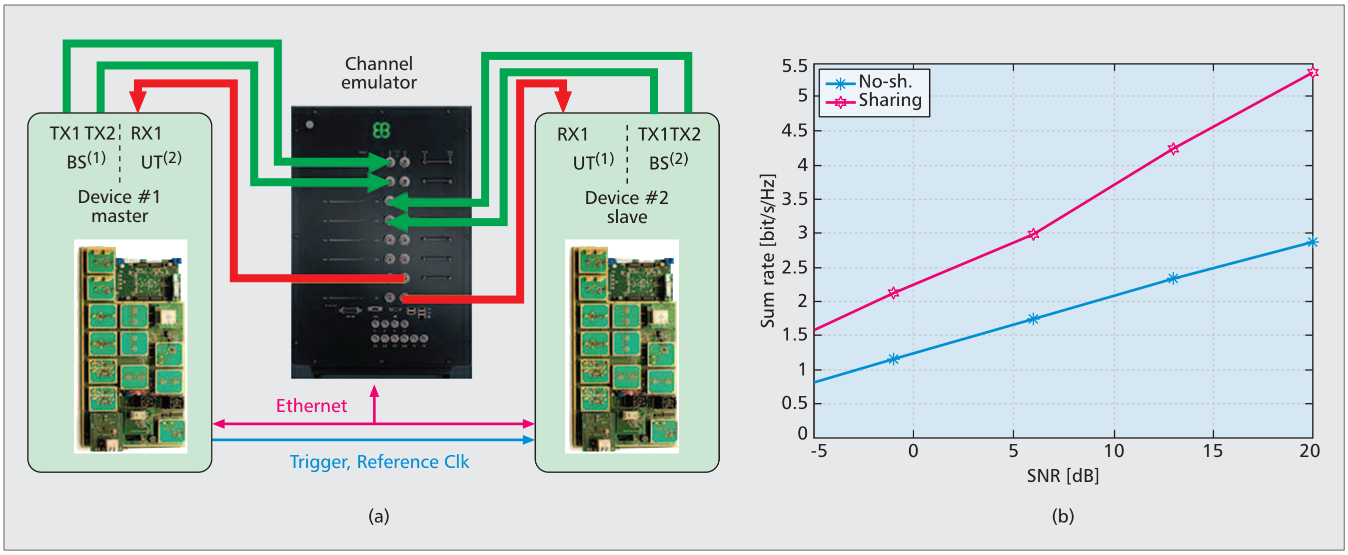

Figure 4. *The HIL demonstrator and the measured throughput results: a) system diagram of the HIL demonstator; and b) sharing gain of system sum rate over SNR.*

ORTHOGONAL SPECTRUM SHARING: SYSTEM LEVEL ASSESSMENT AND LTE/A DEMONSTRATION

The spectrum sharing gain can be extended through a proper resource allocation mechanism in the medium access, up to the higher layers. We focus on resource sharing by LTE operators covering the same physical area and possibly sharing some of their licensed frequency bands. The evaluation presented in the following refers to an orthogonal spectrum sharing case.

The evaluation scenario consists of two LTE operators covering approximately the same region, where BSs and mobile users are distributed following a grid structure of 3 × 3 hexagonal cells wrapped onto itself. The BS of one operator is placed exactly 50 meters apart from the corresponding BS of the other. Both operators can utilize a 10 MHz band, in which they have, according to the LTE standard, 50 resource blocks of 12 subcarriers. The two bands are adjacent, so the operators can share a portion of their spectrum. In this specific case, a resource sharing of x percent means that x resource blocks are orthogonally shared, i.e., they may be used by either operator, but only one at a time. LTE resource allocation is simulated through ns3 network simulator for a duration of 2000 subframes of 10 ms. The propagation model considers a frequency-selective channel with pathloss and fast fading. In the specific simulation results discussed below, a macroscopic pathloss equal to $138.1+(37.6 \cdot \log_{10}(R))$ dB is included, to which a log-normal Rayleigh fading with parameter $\sigma = 8$ dB and a Jakes' model with Doppler frequency of 50 hertz is superimposed. Transmission power is 43 dBm and the noise spectral density is –174 dBm/Hz. An additional noise figure of 4 dB at the receiver is considered.

For the user-generated traffic flows, the operators apply a scheduling policy that aims at maximizing the system throughput, which results in opportunistically allocating the user with higher Channel Quality Indicator (CQI) value for each resource block. The resulting allocation will not be fair user-wise. This is done intentionally, as the selection of a specific scheduling policy is out of the scope of this analysis. Besides, introducing some fairness among the users would possibly achieve very poor results in terms of the achieved total throughput. On the other hand, we expect that in a setup where fairness issues are also considered, the gain achieved by a collaborative physical resource sharing would be much higher.

The allocation schemes that we consider for the operators to share their common portion of the spectrum are meant as theoretical bounds to performance achieved by orthogonal sharing in the best and worst case, respectively. First of all, a theoretical *upper bound* is identified by considering the two operators as perfectly collaborating entities. This means that the operators behave as a matter of fact as a single entity, i.e., there is a single decision block that allocates resources to the users of both operators, so as to maximize the total joint throughput of both operators.

A second allocation policy which works as a *lower bound*, starts by considering the same resource allocation that would happen without resource sharing. This results in both operators using only their licensed frequencies. Then, the resource allocator checks if a user of a given operator can achieve a higher throughput if allocated on a resource block belonging to the shared pool that is currently allocated to the other operator. Pairwise exchanges are identified, that is, if the resource allocator identifies a symmetrical occurrence of this situation for both operators (i.e., they both have a user that could be allocated on a resource presently allocated to the other), the allocation is switched. If the situation is unbalanced, i.e., only one operator gains in the exchange, no switch occurs. Although this policy respects the theoretical principle of improving the allocation without making either

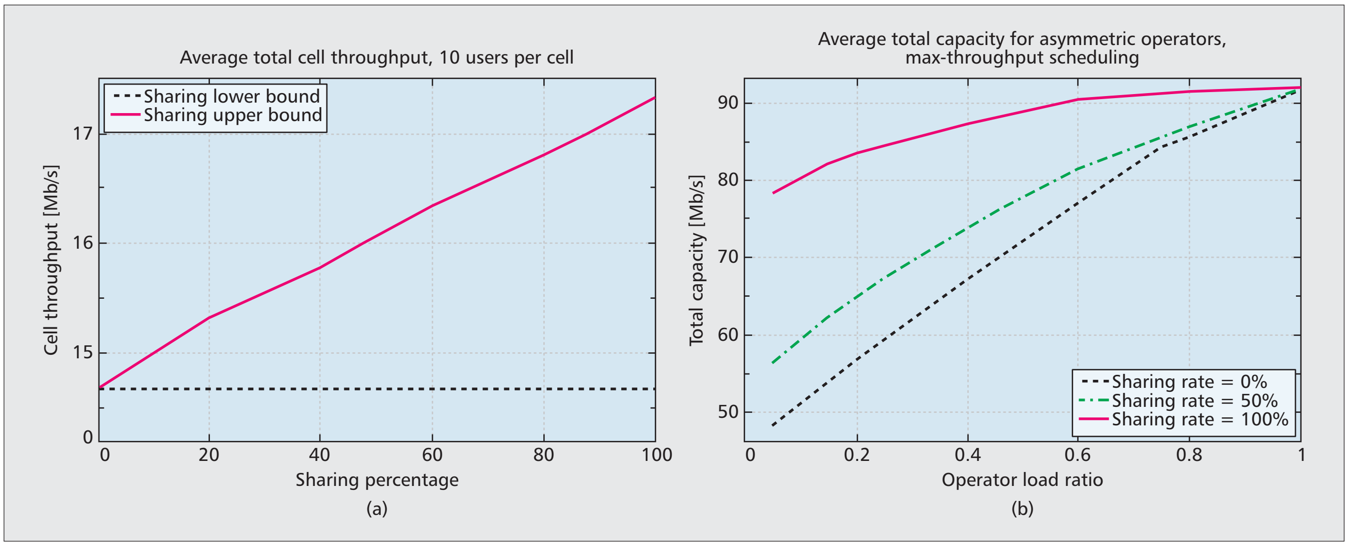

Figure 5. *Performance evaluation of orthogonal sharing, for* maximal throughput *schedulin: a) Cell throughput as a function of the sharing percentage, 10 users per cell,* maximal throughput *scheduling; and b) total capacity as a function of the load unbalance of operator 2, 40 users per cell for operator 1,* maximal throughput *scheduling.*

of the operators worse, we expect the number of exchanges to be actually often limited.

Figure 5a shows the throughput per cell achieved by each operator. Note that we performed evaluations of the system capacity in Shannon sense, quantified as the mutual information between the input and the output of the channel, which is a useful upper bound. The results for this metric are in line with those of the throughput, although the value of the throughput is around 1/3 of the Shannon upper bound.

Several conclusions can be drawn from the figure. First of all, the overall theoretical spectrum sharing gain achievable by purely *orthogonal* sharing is about 12 percent. This is not an impressive gain, but it comes only at the price of a tightly coordinated scheduling, it is just a matter of better exploiting the available resources. Note that the lower bound almost always falls to the trivial Nash equilibrium of not sharing any resource.

Figure 5b shows instead the network capacity achievable by means of orthogonal sharing in the context of an unbalanced network scenario. Here, the load of the first operator is kept fixed at 40 users/cell, while the load of the second operator is changed from almost no users to the same amount of operator 1. Differently from the previous evaluation, it is assumed that each user is satisfied when it receives two full LTE resource blocks (if this assumption were not made, the users will simply eat up the available capacity no matter how many they are). Yet, operator 1 is always unable to satisfy its own users, as the available capacity of 50 resource blocks is enough for just 25 of them. However, should the band of operator 2 be unused, spectrum sharing would allow to manage additional traffic. Note that, although the gain is obviously maximal when operator 2 is almost unloaded, we achieve some sharing gain even when both operators fully exploit their bands thanks to frequency diversity which enables a better selection of the resource blocks for the users. Finally, it is worth noting that the gain when the band is entirely shared (100 percent) is more than proportionally higher than the partial sharing of 50 percent, thanks to the combined effect of frequency diversity and resource sharing.

The orthogonal spectrum sharing is demonstrated in an LTE/A demonstrator shown in Fig. 6, which consists of 2 BS devices and 6 UTs, and have the LTE physical layer and MAC layer implemented in real-time. This demonstrator operates at 2.6 GHz carrier frequency with fading channels (generated in an isolated metal device). This setup corresponds to a scenario with two operators, each having 3 UTs, sharing 20 MHz spectrum in an orthogonal manner. Both operators jointly allocate the resource in the shared spectrum to exploit traffic dynamic and multi-user diversity. In the live demonstration, it was shown that with spectrum sharing, the maximum UT traffics that can be adopted by an operator is significantly increased compared to the case with exclusive spectrum usage (see Figure 6, where an operator 1 with 3 active UTs can use spectrum of operator 2 who has only 1 active UT).

CONCLUSIONS

This article presents a holistic view on spectrum sharing between operators in a cellular wireless network. The gain by sharing spectrum heavily depends on the chosen network scenario and the parameter setting. Therefore, it is important to understand the potential reasons and requirements and their tradeoff for the gain. We report spectrum sharing gains in the range between 10 and 100 percent. In orthogonal spectrum sharing, the diversity and asymmetry of users increases the gain whereas for non-orthogonal spectrum sharing, the correlation or similarity the spatial signatures between channels to the mobile stations is more important. The results indicate that current cellular standards and base station hardware may support and benefit from spectrum sharing.

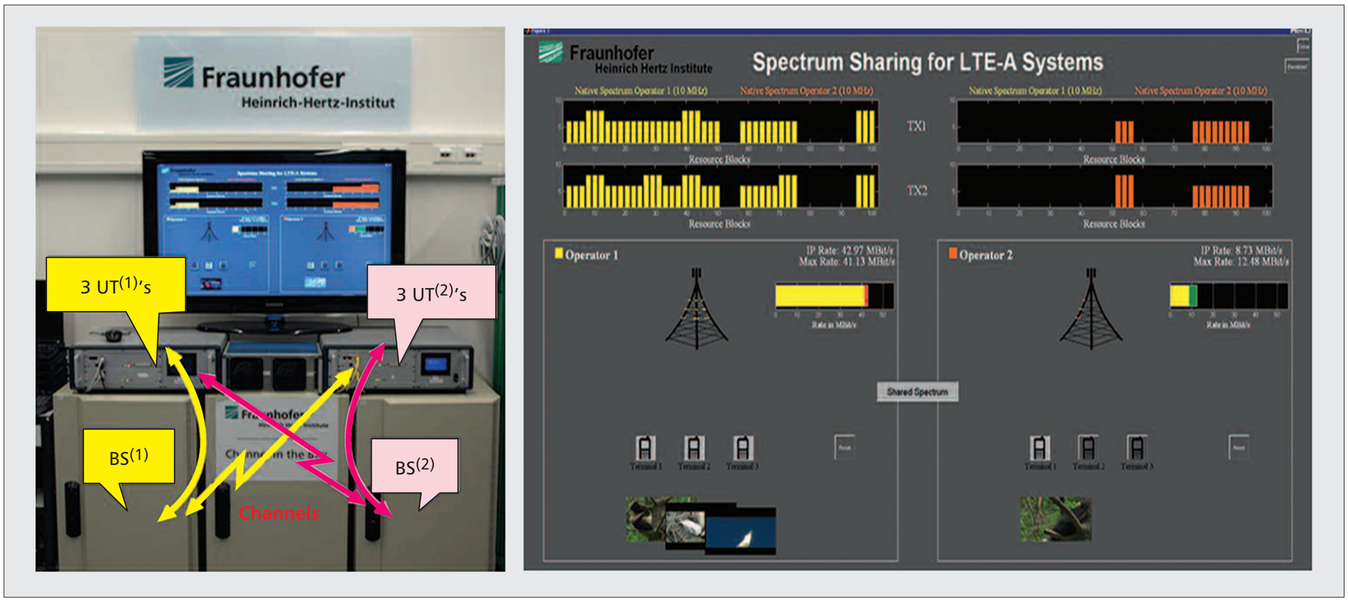

Figure 6. *The LTE-advanced inter-operator orthogonal spectrum-sharing demonstrator.*

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BIOGRAPHIES

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