SAPHYRE

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Abstract

This deliverable describes the potential gain for network operators by resource sharing between wireless cellular operators in terms of network efficiency. Both orthogonal (exclusive frequency allocation) and non-orthogonal (simultaneous allocation) spectrum sharing scenarios were studied. The results and conclusions encourage to seriously consider the inter-operator spectrum sharing technologies and businesses.

Keywords

Spectrum sharing, inter-operator, business model, relay nodes, sharing.

Contents

Abbreviations

3GPP	3rd Generation Partnership Project
4G	4^{th} Generation
AF	Amplify and Forward
BB	Baseband
BD	Block Diagonalisation
BS	Base Station
BW	Bandwidth
CoMP	Cooperative Multi-Point
CPU	Central Processing Unit
CQI	Channel Quality Indicator
CR	Cognitive Radio
CSI	Channel State Information
DAC	Digital to Analog Converter
DCA	Direct Conversion Architecture
DF	Decode and Forward
DL	Downlink
DSA	Dynamic Spectrum Access
FFR	Fractional Frequency Reuse
FlexCoBF	Flexible Coordinated Beamforming
GSM	Global System for Mobile communications
HDF	Hierarchical Decode and Forward
HSPA	High Speed Packet Access
IC	Interference Channel
IF	Intermediate Frequency
LO	Local Oscillator
LPF	Low-Pass Filter
LTE/A	Long Term Evolution / Advanced
MAC	Medium Access Control
MAN	Metropolitan Area Networks
MCIFS	Multi-Carrier IF Signal

MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MNO	Mobile Network Operator
MOD	Modulator
MRC	Maximum Ratio Combining
MVNO	Mobile Virtual Network Operator
NBS	Nash Bargaining Solution
NUE	Network Utility Equipment
PHY	Physical layer
QoS	Quality of Service
RAT	Radio Access Technology
RBD	Regularised Block Diagonalisation
RF	Radio Frequency
RS	Relay Station
Rx	Receive
SDR	Software Defined Radio
SINR	Signal to Interference and Noise Ratio
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access
TTI	Transmit Time Interval
Tx	Transmit
UMTS	Universal Mobile Telecommunications Standard
UT	User Terminal
WAN	Wide Area Networks
WIMAX	Worldwide Interoperability for Microwave Access
WWRF	Wireless World Research Forum

1 Executive summary

The paper describes the potential gain for network operators by resource sharing between wireless cellular operators in terms of network efficiency. It is called SAPHYRE gain. Within this deliverable, a specific resource sharing scenario is studied, which is spectrum sharing between two operators in cellular downlink transmission.

If frequency bands are allocated dynamically and exclusively to one operator – so called orthogonal spectrum sharing – significant gains in terms of achievable throughput and user satisfaction are reported for asymmetric scenarios on link as well as on system level. Additionally, if frequency bands are allocated simultaneously to two operators – so called non-orthogonal spectrum sharing – further gains are reported. In order to achieve these, different enablers from hardware and base station capabilities are required. However, all requirements are fulfilled in 4G and future mobile standards. Furthermore, the corresponding business opportunities for spectrum sharing exists in various configurations, including virtual mobile operators. Therefore, the results and conclusions of the paper encourage to seriously consider the inter-operator spectrum sharing technologies and businesses.

2 Introduction

In current wireless communications, radio spectrum and infrastructure are typically used such that interference is avoided by exclusive allocation of frequency bands and employment of base stations. The paper will demonstrate how equal-priority resource sharing in wireless networks improves spectral efficiency, enhances coverage, increases user satisfaction, leads to increased revenue for operators, and decreases capital and operating expenditures.

This deliverable is based on the first SAPHYRE position paper, which is the first out of a three papers series and it focuses on spectrum sharing between two operators in a representative cellular downlink scenario.

2.1 Basic idea and definitions

In the first stage we explain the idea and provide definitions of resource sharing with special emphasis on spectrum sharing. The differentiation to other common and important types of sharing including cooperative multipoint (CoMP) and fractional frequency reuse (FFR) is clarified. Related projects and a brief state-of-the-art overview is provided.

Important physical resources in wireless communications systems are spectrum, infrastructure and energy. In general these resources are scarce because of either natural limitations, costs or environmental 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].

The traditional way of handling spectrum for cellular wireless wide area networks (WAN) and metropolitan area networks (MAN) 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 [2] for a decade or more duration. 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). This situation is illustrated in Figure 1-a). 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. Economists have long argued that market mechanisms should also be applied to radio spectrum [3]. This trend to more flexible use of spectrum is supported by novel developments in radio technology.

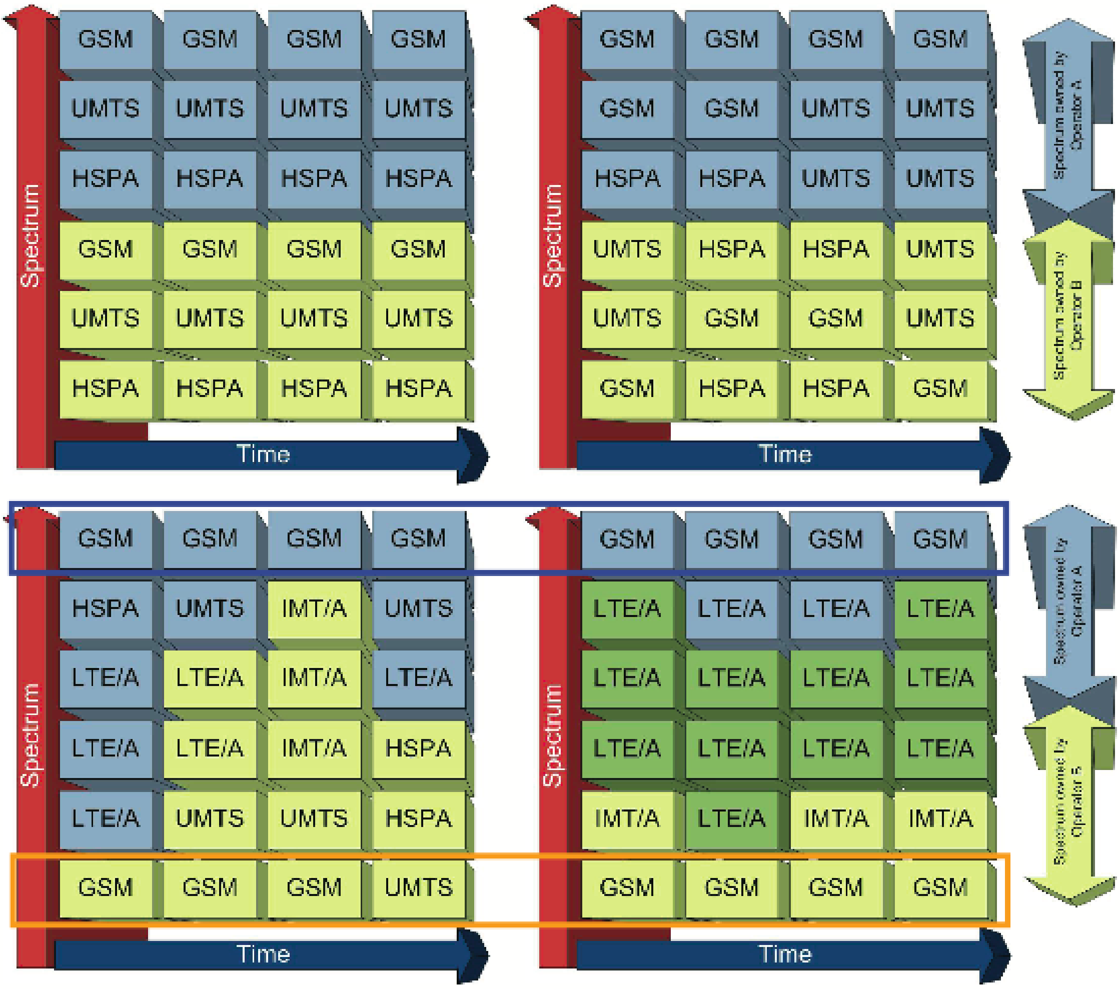

Figure 1: Classification of spectrum sharing methods: a) upper left: no spectrum sharing, b) upper right: intra-operator spectrum sharing, c) lower left: inter-operator orthogonal spectrum sharing, d) lower right: inter-operator non-orthogonal spectrum sharing.

The first step to flexible radio spectrum usage for a single operator is intra-operator spectrum sharing [4] which includes the dynamic allocation of RATs within the spectrum blocks of one operator as well as the movement of users between bands. The first adaptation is illustrated in Figure 1-b). 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.

In orthogonal spectrum sharing the users can be moved over the spectrum bands of both operators. However, one spectrum band is still exclusively assigned to one operator. No additional interference is created by orthogonal spectrum sharing as illustrated in Figure 1-c). In different time slots parts of the spectrum – shared bands – owned by the yellow operator are assigned to the blue operator and vice versa. Both operators keep some part of the spectrum – protected bands: blue and orange boxes in Figure 1-c) and Figure 1-d) – in order to satisfy their quality-of-service (QoS) guarantees for their customers. Gains by orthogonal inter-operator spectrum sharing in terms of spectral efficiency and throughput are reported in [6].

The most flexible way of spectrum sharing is non-orthogonal inter-operator spectrum sharing. Illustrated in Figure 1-d) the shared bands can be assigned to more than one operator indicated by the green colour of frequency blocks. The protected bands are still reserved for service guarantees. Consider the first time slot in Figure 1-d): 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 optimisation, user selection, SAPHYRE-gains in terms of spectral efficiency are reported in [7].

We define the gain by inter-operator spectrum sharing as the SAPHYRE-gain. Depending on the context it is measured in spectral efficiency [Mbit/sHz] or feasibility with respect to signalling and control overhead, business and regulation. After a brief section on related techniques and recent results, the following sections will report on the assumptions and SAPHYRE-gain results.

2.2 Related techniques and state-of-the-art

CoMP is viewed as the key technology for LTE/A. It exploits the intercell interference in order to increase the spectral efficiency [8]. In contrast to inter-operator orthogonal and non-orthogonal spectrum sharing, it is limited to a single operator, it requires the exchange of channel state information (CSI) as well as user data via high-data backbone connections. Thereby, specific reference signals are required to obtain global CSI and perform the joint precoding and transmit optimisation. CoMP [9] has been proposed in the long term evolution (LTE) beyond Release 9. It improves the cell edge user data rate and spectral efficiency by cooperation between sectors or different sites of the same operator. CoMP uses the frequency reuse factor one in multiple cells, which is similar to the SAPHYRE setting. However, there are essential differences between these two concepts. A detailed comparison is listed in Table 1.

FFR is applied in Mobile WIMAX (based on IEEE 802.16) in order to increase the spectral efficiency. Users close to the cell centre are allowed to reuse frequency bands from neighbour 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 SINR threshold.

Cognitive radio (CR) and SDR can be seen as enablers for inter-operator spectrum sharing: In the broad sense of CR networks, inter-operator 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. Since the flexible allocation of spectrum between two or more operators results in conflicting interests, systematic tools from game theory are often applied. In [10], auctions and an entity termed spectrum broker is proposed to assign resources to operators.

A microeconomic model for bandwidth sharing in dynamic spectrum access (DSA) networks is studied in [11].

	CoMP	**SAPHYRE**
Major objective	Combat inter-cell interference and improve spectral efficiency for the cell edge user of a single operator	Improve the operators' revenue as well as user experience via cost, spectrum and energy efficient physical resource sharing
Application scenario	Intra-Operator (intra-Site and inter-Site)	Inter-Operator
Shared resources	Data & CSI sharing	CSI sharing only
Downlink	• Coordinated scheduling / beamforming (no data sharing) • Joint processing CoMP (data sharing)	• Centralised / decentralised (CSI sharing / no CSI sharing) processing between operators using game theory • Relay assisted communications
Signalling and overhead	• Synchronisation between base stations • Backhaul with low latency and high bandwidth • Channel estimation and efficient feedback • Clustering and multisite scheduling	• Synchronisation between base stations • Backhaul with low latency and high bandwidth • Channel estimation and efficient feedback • Information exchange mechanism between operators

Table 1: Comparison of CoMP and SAPHYRE.

3 Enablers and requirements

This section describes requirements and constraints from the base station perspective. The enablers of spectrum and infrastructure sharing in terms of hardware technologies are described.

3.1 General base station requirements and constraints

This section discusses the additional requirements which are necessary for base stations to perform the here proposed resources sharing methods.

Spectrum pooling is defined as a scenario where different operators pool their licensed spectrum to a broader collaborative used spectrum. This scenario impacts several additional requirements on the base station architecture:

a) Spectrum size: A collaborative spectrum usage requires an increased spectrum capability for the base stations, either as broader carrier or carrier aggregation. The extension of the spectrum range leads to increased need of processing power on the lower layers of the protocol stack of the wireless interface respectively in the physical layer. If the spectrum is doubled, the number of subcarriers doubles and in the result the functional blocks in the physical layer have to process Fourier transformations of double size during the same constant TTI which request a doubled number of mathematical operations. Similar conditions exist in the other functional blocks within the physical layer like turbo encoder and decoder. Basically the required processing power on physical layer increases approximately with the spectrum size.

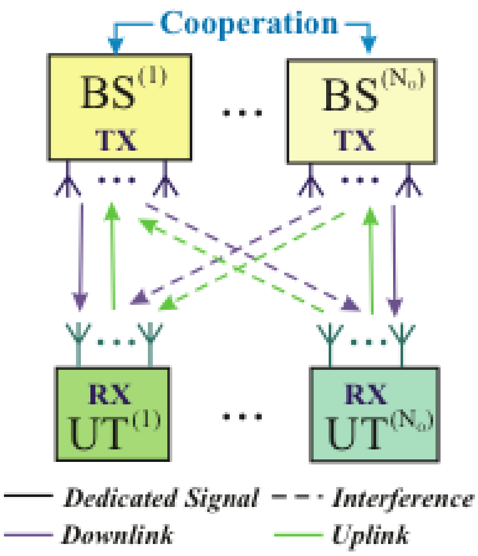

Figure 2: Cooperation in spectrum sharing scenario.

b) Backbone interface throughput: The required throughput of the backbone interface of a base station is impacted by effective throughput of the radio interface and increases approximately linear with the user traffic. Furthermore, the collaborative use of shared radio resources among different base stations impacts additional control traffic. The base stations have to exchange data like channel state information via the backbone as shown in Figure 2. The following example estimates the expected additional control traffic which has to be exchanged between neighboured base stations for methods like “Co-operation for Joint MAC-PHY Optimisation / Power Control”:

- Jointly used spectrum size of 20 MHz,
- Report periodicity of 1 TTI, e.g. 1 ms in LTE,
- Channel state information size of 8 bit, i.e. 4 bit I and 4 bit Q [12],
- Channel state information for 2 transmit antennas per base station NBS and 1 receive antenna per user NUE each, information exchange between neighboured cells as in Figure 2,
- 3 sectors per site,
- 4 NBS neighbour base stations from other sites as in Figure 3,
- 1 BS has 6 neighbours, i.e. 4 NBS from other sites and 2 NBS from the same site,
- 10 users per cell [13],
- Inter-site traffic:

$$\text{8 bit CSI} \times \text{2 NBS} \times \text{1 NUE} \times \text{4 NBS} \times \text{3 BSS} \times \text{10 UE} = \text{0,001 s TTI} = \text{1,92 Mbps} \quad (1)$$

The practical backhaul rate for a dense urban deployment is 100 Mbps [14] for one cell and 300 Mbps for one site respectively, so the additional control traffic is small compared to a typical backhaul rate of about 1 % and hence can be neglected.

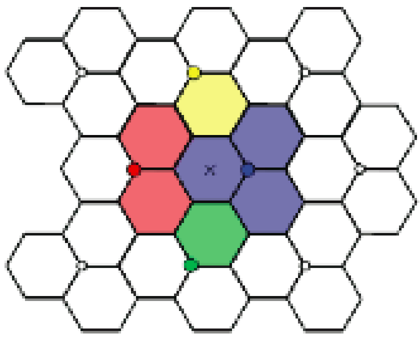

Figure 3: Cooperation cluster.

SAPHYRE enabled base stations have to fulfil several additional requirements mainly in terms of increased spectrum, number of end user, additional processing power and enhanced backbone capacity. Analysing the capabilities of current and future base station implementations can do a raw assertion about the requested capability. Base stations, which will be available on the market in the next few years, have to be compliant to 3GPP Rel-10 [15] and subsequent releases. Some key requirements of 3GPP Rel-10 are spectrum ranges up to 100 MHz, carrier aggregation and 8×8 MIMO. A base station, which fulfils these requirements, may also be enabled for sharing scenarios regarding spectrum ranges and multi-carrier as proposed in SAPHYRE. Furthermore MIMO provides prerequisites to perform beamforming to support methods like “Co-operation for Joint MAC-PHY Optimisation / Power Control”. The hardware and software requirements to compute the SAPHYRE algorithms and methods highly depend on the base station architecture and particular hardware and software components. Considering the evolution path of LTE, 3GPP Rel-11 [16] will provide coordinated multi-point operations CoMP. Base stations, which fulfil the requirements for performing CoMP methods may also provide sufficient hardware and software resources to perform SAPHYRE methods.

3.2 Enablers from hardware technology

Generally, to enable flexible resource sharing, three key enablers should be applied: SDR technology, direct conversion architecture (DCA) and frequency agile broadband RF- and baseband (BB) components. With these enablers, efficient switching of the transmission frequency is allowed. We first consider a spectrum-sharing-only scenario with two operators. The BS of each operator transmits signals both in his own band and in a shared band. Moreover, we consider the downlink (DL) case as shown in Figure 2, since its throughput is a significant performance criterion.

If the shared band is sufficiently close to the own band, e.g. within several hundred MHz difference, the signals in both bands can be transmitted via a single RF chain, which includes digital-to-analog converters (DAC), low-pass filters (LPF), modulators (MOD) and antennas. In the BS, the signal streams for both bands can be generated simultaneously in the digital BB and converted to two intermediate frequency (IF) bands digitally. Such a signal is called multi-carrier IF signal (MCIFS). The IF frequency and the LO frequency of the MOD should be chosen so that the signal streams will be on the desired bands after up-conversion. For the generation and transmission of MCIFS, broadband DACs, LPFs, MOD and antennas are required. Moreover, to apply advanced precoding techniques, multiple antennas as well as the corresponding analog components are required.

If the shared band is quite far away from the own band, e.g. one on the 2.6 GHz band and one on the 800 MHz band for LTE, separate RF chains are required to up-convert the two signal streams. For both cases, if the maximum single user rate is not assumed to be increased, no BW enhancement is required at the UT. Otherwise, if the user should be able to receive signals from both own- and shared bands, BW enhancement and multiple Rx RF-chains may be necessary.

Similar principles apply for both infrastructure-only and full sharing scenarios. For infrastructure-only sharing, signals of orthogonal bands of different operators are transmitted via one RAN. The requirements for the BW and the analog components

are generally the same. In most of the state-of-the-art BSs e.g. [17], SDR techniques, DCA as well as broadband RF- and BB analog components have been successfully deployed. Thus, resource sharing can be realised.

4 LTE downlink spectrum sharing

In this section, we describe for the LTE downlink scenario:

a) fundamental principles of spectrum sharing between operators,
b) the signal processing and resource allocation algorithms,
c) system level assessments reporting SAPHYRE gains, and
d) a feasibility study with regards to business and regulation.

4.1 Principles of non-orthogonal spectrum sharing

SAPHYRE envisions 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. As discussed in Section 2.1, inter-operator spectrum sharing can be realised in an orthogonal manner as shown in Figure 1-c), e.g. by applying a time-division multiple access (TDMA) scheme. However, the utmost gain is expected when the operators share the spectrum non-orthogonally, i.e. they concurrently use the same frequency bands in the same geographical location like shown in Figure 1-d). The major impairment, that has so far prevented such a development, is the interference caused by co-channel transmissions. Figure 4 depicts the simplest setup for the downlink mode of the non-orthogonal spectrum sharing scenario: two neighbouring base stations BS1 and BS2 of different operators transmit towards their user terminals UT1 and UT2 respectively and the UTs receive a combination of the transmissions. SAPHYRE advocates that reliable and fast communication can be achieved in both links by applying advanced signal processing techniques as given in Section 4.2 to mitigate the interference caused by sharing.

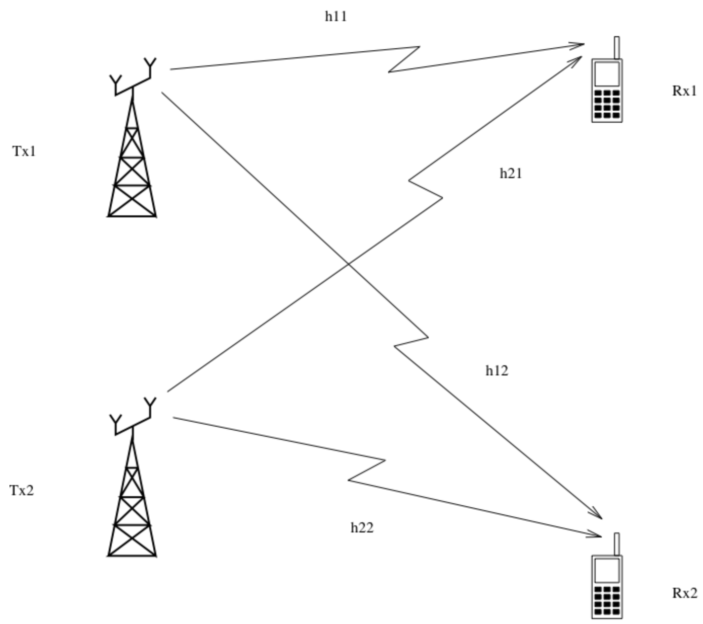

Figure 4: Two-user MISO interference channel.

The most prominent of these techniques is called transmit beamforming and it is enabled by the availability of multiple antennas at modern base stations. By applying appropriate scaling of 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, the 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. Transmit beamforming techniques have been well-studied in the context of single cell downlink scenario, which is modelled by the multiple-input multiple-output (MISO) broadcast channel. They enhance spectral efficiency by enabling spatial multiplexing. Extending these techniques to the scenario interest in Figure 4, so-called MISO interference channel (IC), is non-trivial. The capacity region of the MISO IC is yet unknown in general. However, it is possible to compute practically-relevant achievable rate regions. Figure 5 illustrates such an achievable rate region for an arbitrary instance of Rayleigh-fading channels, assuming that they are perfectly known at the BSs and that the UTs treat the interference as additive noise. The triangular region achieved by orthogonal sharing (TDMA) is also depicted in Figure 5 and it is evidenced that it 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. This is particularly true when there are many degrees of freedom (transmit antennas) for the beamforming design or when the spatial signatures of the direct and the crosstalk channels of each UT are very different.

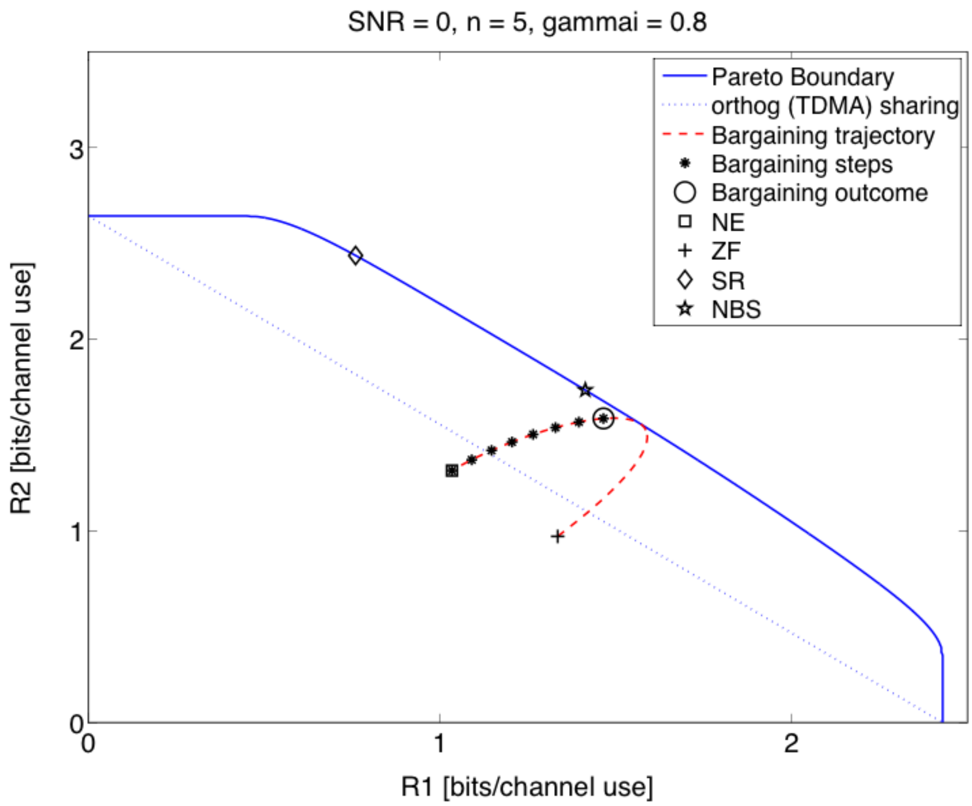

Figure 5: Exemplary achievable rate region and important operating points.

The spectrum sharing scenario of Figure 4 resembles the problem of intercell interference management in modern cellular networks with aggressive frequency reuse, but there are some important distinctions. First, the interference level can be significant, since the cells of different networks overlap each other and the 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 hence cannot use CoMP techniques to turn intercell interference into an advantage. What they need to share, via an appropriate inter-operator backbone interface, is only CSI: each BS needs to know the channels towards all UTs in its vicinity in order to enable efficient transmit beamforming design. Third, the objectives of the operators are conflicting since they want to optimise the communication experience of different UTs using the same resources. This calls for decentralised designs, that can be motivated by fundamental game-theoretic concepts. One extreme approach is that the BSs selfishly maximise the rate of their own UT disregarding the interference caused to the other UT: the other extreme is to altruistically maximise own rate while ensuring that no interference is caused to the other UT. The former approach leads to the so-called Nash equilibrium and the latter to the so-called zero-forcing operating point. As evidenced in Figure 5, both of them are in general inefficient, since the lie far inside the rate region. SAPHYRE research has shown that the efficient operating points, on the boundary of the rate region, can be achieved by a compromise amongst the aforementioned extreme designs. The key is that each BS allows leakage of specific levels of interference that can be tolerated from the other UT. This is similar to another non-orthogonal spectrum sharing paradigm, that of cognitive underlay networks, in which a secondary network can operate aside the primary (licensed) one, provided that it does not cause detrimental interference. SAPHYRE claims that both operators can achieve more gain by equally sharing their spectrum and by cooperating in the design of their transmissions.

4.2 Signal processing and resource allocation algorithms

In this section, we introduce the signal processing algorithms which are developed to tackle the challenges introduced by non-orthogonal spectrum sharing. One of the signal processing tasks in wireless communications is to exploit additional degrees of freedom in multi-user and multi-network environments. In the following, several efficient signal processing algorithms in the spectrum sharing models defined in SAPHYRE are presented.

4.2.1 Cooperative beamforming

One of the algorithms proposed by SAPHYRE is an iterative distributed beamforming algorithm which uses as design parameter the interference temperature, i.e. the interference that each transmitter generates towards the receiver of the other user. It enables cooperation among the base stations in order to increase both users' rates by lowering the overall interference. In every iteration, as long as both rates keep on increasing, the transmitters mutually decrease the interference temperature. They choose their beamforming vectors distributively, solving the constrained optimisation problem of maximising the useful signal power for a given level of generated interference. The algorithm is equally applicable when the transmitters have either instantaneous or statistical channel state information (CSI). The difference is that the core optimisation problem is solved in closed-form for instantaneous CSI, whereas for statistical CSI an efficient solution is found numerically via semidefinite programming. The outcome of the proposed algorithm is approximately Pareto-optimal.

In order to evaluate the gain of the cooperative beamforming algorithm over the orthogonal (TDMA) spectrum sharing scenario, we illustrate in Figure 6 the sum-rate as a function of the SNR. The respective sum rates are also provided for the Nash equilibrium, zero-forcing, Nash bargaining, and maximum sum-rate operating points. For each SNR value, the results depicted are averages over 100 channel realisations.

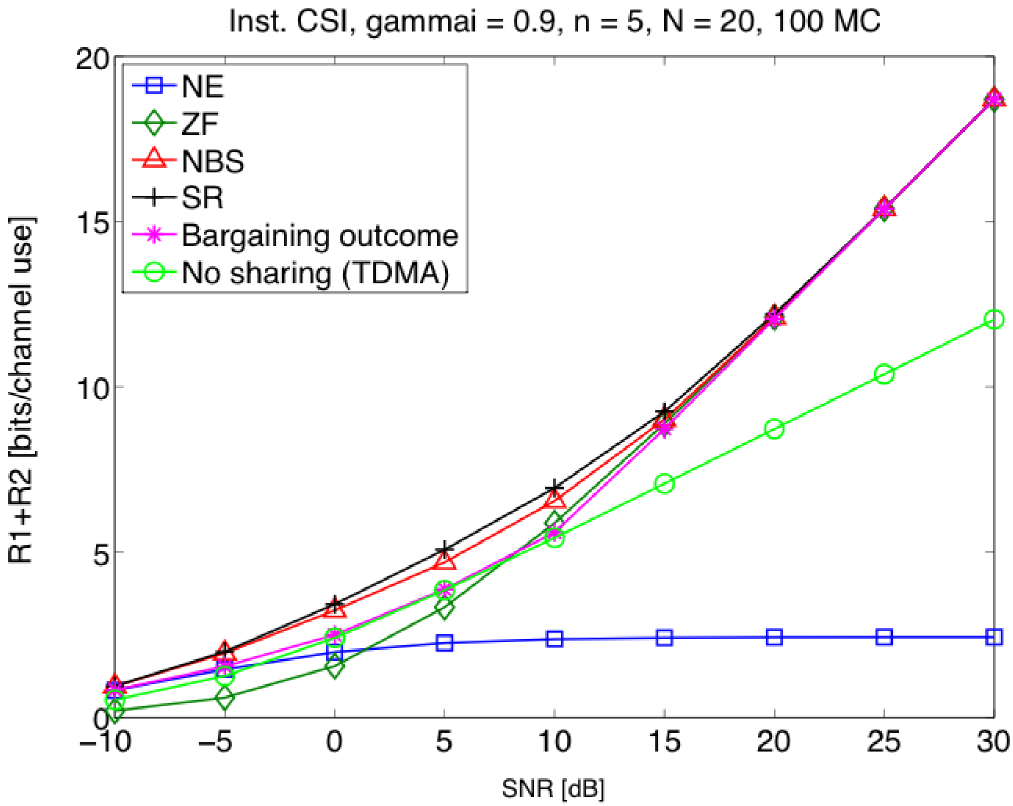

Figure 6: Sum rate of various beamforming schemes.

We define the SAPHYRE gain as the ratio of the sum rate achieved by cooperative beamforming over TDMA. In Figure 7, we see that for instantaneous CSI, the sum rate is approximately doubled. For statistical CSI with low-rank covariance matrices, the sum rate is increased by approximately 50%. For statistical CSI with full-rank covariance matrices, the gain linearly decrease with SNR and at 18 dB it becomes loss. We evidence that accurate CSI increases the SAPHYRE gain.

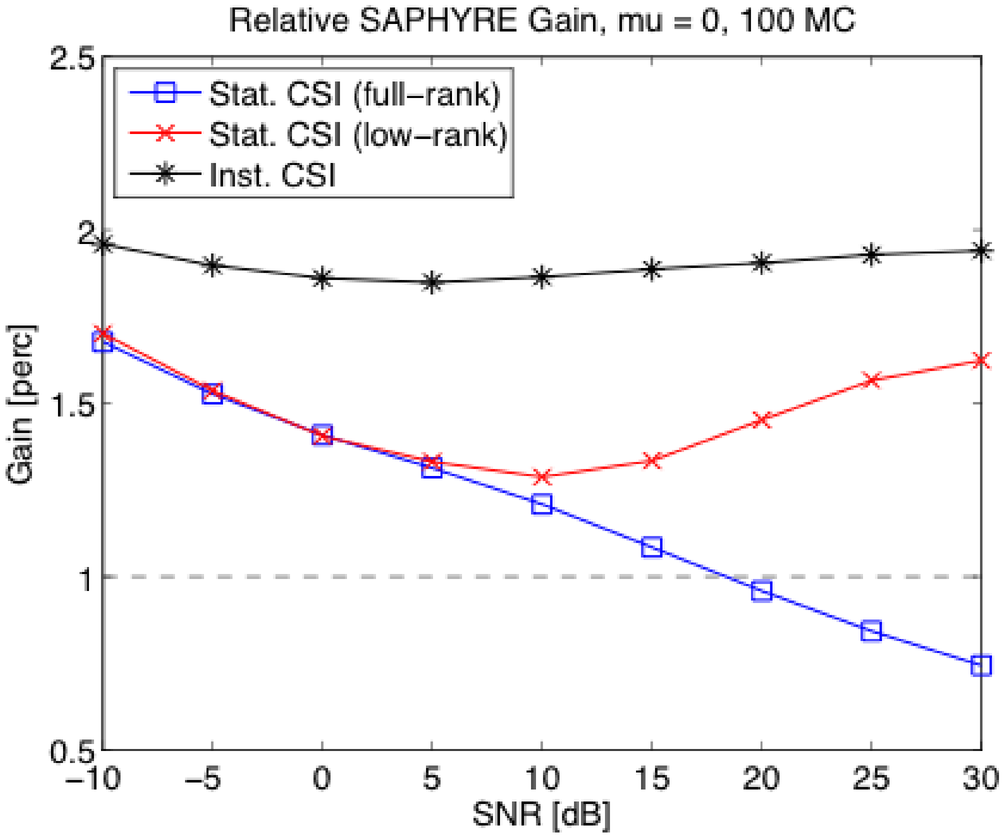

Figure 7: Spectrum sharing gain for various CSI scenarios.

4.2.2 Flexible multi-cell coordinated beamforming

Flexible coordinated beamforming for the interference channel (IC FlexCoBF) is a low-complexity suboptimal transceiver scheme which is designed for the single-stream transmission in the two-user MIMO IC. It aims at maximising the sum rate without any dimensionality constraint on antenna configurations. Inspired by [18], the IC FlexCoBF has been designed to iteratively suppress the inter-user interference utilising either block diagonalisation (BD) [19] or regularised block diagonalisation (RBD) [20] at the transmitter, combined with maximum ratio combining (MRC) at the receiver. To start, the receive filters are randomly initialised. By defining the equivalent interference channel as the multiplication of the receive filter with the interference channel, the precoder at each TX is designed by applying the BD method to the equivalent interference channels to completely remove the interference or by utilising RBD to minimise the power of interference plus noise for each RX. Then the MRC receive filters are updated using the obtained TX precoders to strengthen the desired signals. The procedure continues iteratively until the stopping criterion is fulfilled, i.e. the power of the interference plus the noise is below a predefined threshold. There is no dimensionality constraint on the number of antennas compared to CoZF [21].

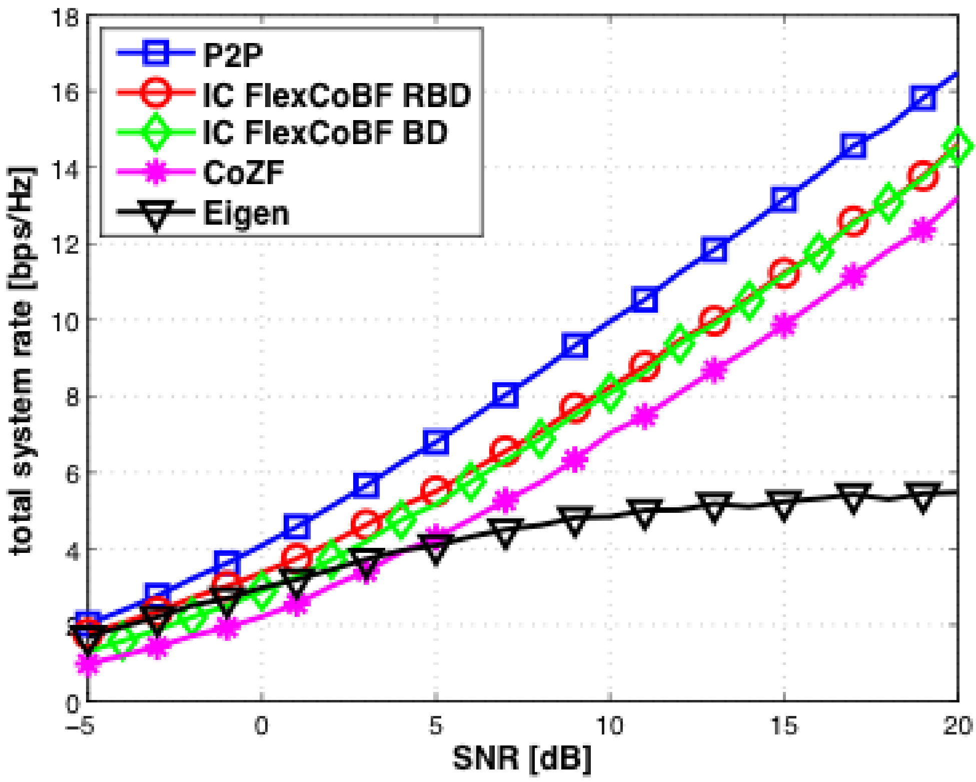

Figure 8: System sum rate for the transmitters and receivers equipped with two antennas.

The system sum rate performance of the IC is given in Figure 8. Both transmitters and receivers are equipped with two antennas. We assume that perfect link adaptation and perfect synchronisation can be achieved. Each element of all channel matrices is a zero mean circularly symmetric complex Gaussian random variable with unit variance. The transmit power of each TX is set to P_T and the SNR is defined as P_T/σ_n^2 with σ_n^2 denoting the noise variance at a single antenna. We include an upper bound as a comparison, which is an ideal point to point transmission while taking no interference into account. Using eigen-beamforming for both links treating all the interferences as noise also includes a reference scheme, called Eigen. It is observed that IC FlexCoBF with either RBD or BD performs much better than CoZF within all SNR ranges. Especially at low SNRs, CoZF performs even worse than Eigen. IC FlexCoBF RBD improves the sum rate compared to BD because it allows some residual interferences to balance with the noise enhancement. Figure 9 displays the sharing gain, which is defined as the ratio of the system sum rate obtained by the use of the shared spectrum between the transceivers over that obtained by two ideal point to point transmissions accessing the spectrum exclusively. The sharing gain becomes larger as the SNR increases for IC FlexCoBF BD while there is even an improvement at low SNRs for IC FlexCoBF RBD due to the regularisation of RBD. To conclude, the spectrum sharing is more advantageous compared to the orthogonal use of the spectrum in a time division multiple access manner.

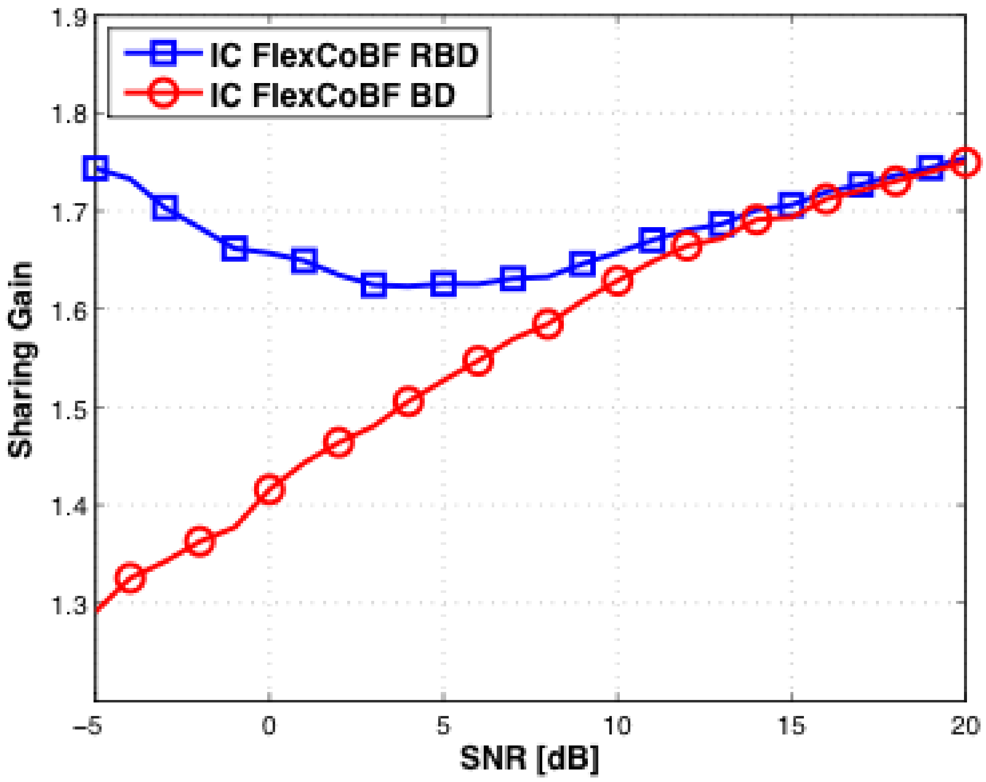

Figure 9: Sharing gain: the ratio of the system sum rate obtained by sharing the spectrum over that by exclusive use of the spectrum.

4.2.3 System-level investigations

The sharing gain can be extended through a proper resource allocation mechanism in the medium access, up to the higher layers. It becomes interesting to evaluate how multiple operators can coordinate to achieve a better resource usage; in particular, 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-sharing* case. For a non-orthogonal sharing case, we expect the gains to be much higher, but also to require a more complex signalling exchange. The performance improvement we present in the following come instead almost without any added complexity for the involved operator.

The evaluation scenario consists of two LTE operators covering approximately the same region, where eNodeBs and mobile users are distributed following a grid structure of 3×3 hexagonal cells wrapped onto itself. Each eNodeB of one operator is placed exactly 50 meters apart from the corresponding eNodeB of the other. Both operators can utilise 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 $2x$ resource blocks are orthogonally shared, i.e. they may be used by both operators, but only one of them at a time. LTE resource allocation is simulated through ns3 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

$$138{,}1+(37{,}6 \cdot \log_{10}(R))\ [\text{dB}] \tag{2}$$

is included, to which a log-normal Rayleigh fading with parameter σ = 8 dB and a Jakes' model with Doppler frequency of 50 Hz 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.

Two scenarios are considered: in the former, which represents a case where the operators have *balanced load*, 10 users per cell are considered for both operators. This result is further relaxed in the second scenario, where operator 1 has a fixed traffic with 40 users per cell, where the traffic of operator 2 is variable. For the resulting user-generated traffic flows, the operators apply a scheduling policy that aims at maximising the system throughput, which results in just allocating the user with higher Channel Quality Indicator (CQI) value for each resource block. It is worth mentioning that 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 degree of fairness among the users would possibly achieve very poor results in terms of the achieved total throughput. On the other hand, we also 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 considered to determine how the operators share their common portion of the spectrum are to be 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 maximise the total joint throughput of both operators. This results in what we refer to as *single operator upper bound*. It is worth remarking that this upper bound, besides being unrealistic in a context where different operators are competitors, will also achieve throughput gains at the price of a decreased fairness between the operators. In fact, the shared resource blocks are allocated to the best users of either operator, so in principle one operator can get exclusive usage of the shared spectrum portion if its users have a better CQI.

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

However, it is important to notice that the lower bound ends up in a Nash equilibrium (which is also Pareto efficient) for the resource sharing problem. The single operator upper bound instead, which is based on mandatory collaboration between the operators, is not guaranteed to be an equilibrium, and therefore to be achievable in practice in a game theoretic sense (i.e. if the operators are driven by their own profit).

Figure 10 show the throughput per cell achieved by each operator. Note that we also 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.

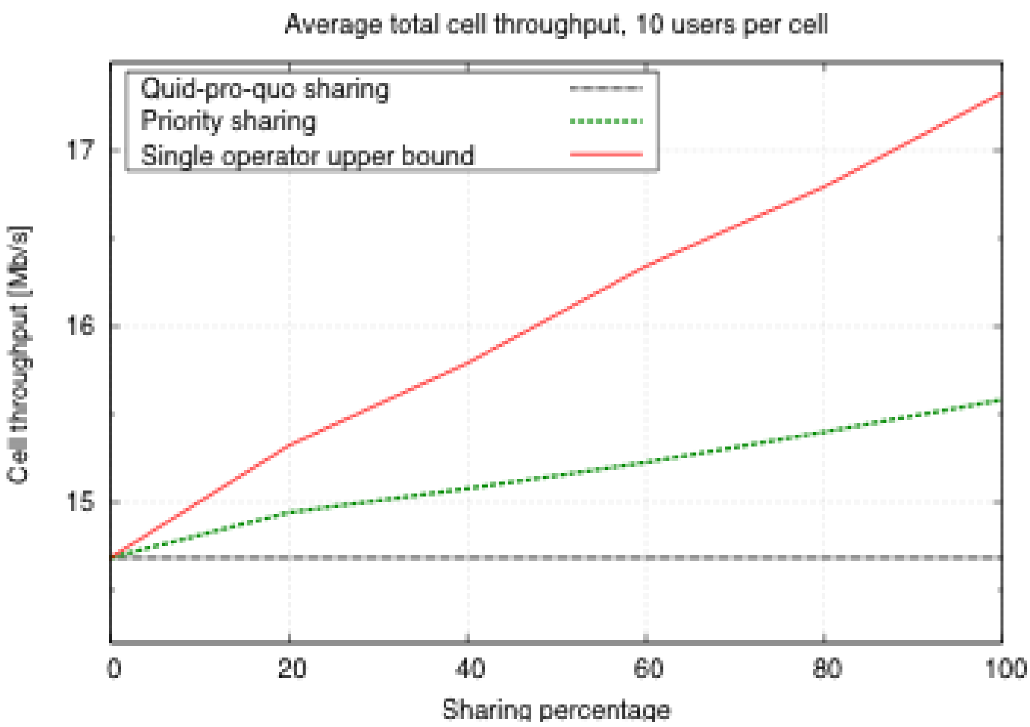

Figure 10: Cell throughput as a function of the sharing percentage, 10 users per cell, maximal throughput scheduling.

Several conclusions can be drawn from the figure. First of all, the overall theoretical sharing gain achievable by purely *orthogonal* sharing is about 12%. This is not an impressive gain, but it comes at almost no price, 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. This means that simple solutions based on standard non-cooperative game theory are not really helpful to boost the throughput in the orthogonal sharing case.

Finally, although it is not visible from the figure, the higher gain achieved by the upper bound does not always correspond to a Nash equilibrium, as the overall capacity of the system is indeed increased but the individual total throughput values of the operators are not. In particular, it can be seen that there is no longer a gain for *both* operators when the sharing percentage is roughly above 35%. Since the overall gain at that point is around 6%, this may justify that the priority scheme is already close to the ceiling of the achievable gains in such a setup (if we consider not only the absolute system gain, but also a Pareto efficiency criterion that both selfish operators want to gain from sharing resources).

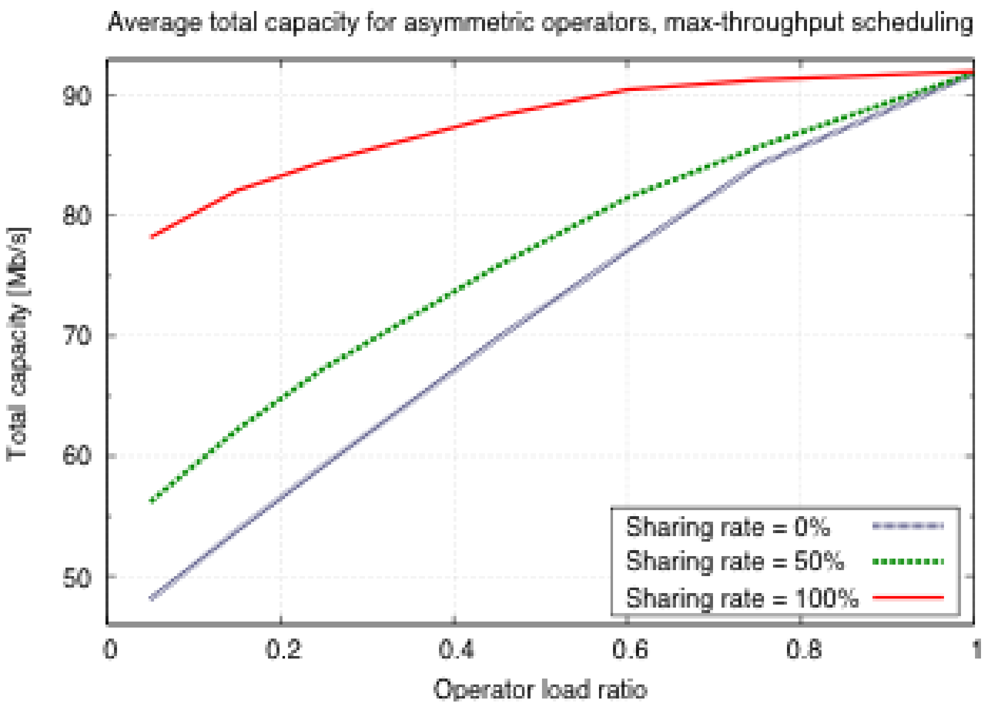

Figure 11: Cell throughput as a function of the load unbalance of operator 2, 40 users per cell for operator 1, maximal throughput scheduling.

Figure 11 shows instead the network capacity achievable by means of orthogonal sharing in the context of an unbalanced network scenario. Here, the load of operator 1 is kept fixed at 40 users/cell, while the load of operator 2 is changed from almost no users to the same amount of operator 1. Differently from the previous evaluation, it is also 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%) is more than proportionally higher than the partial sharing of 50%, thanks to the combined effect of frequency diversity and resource sharing.

4.2.4 Feasibility study with regards to business and regulatory

As mentioned in introduction, the traditional way of handling spectrum for cellular wireless area networks come into being about 90 years ago and is based on the concept of spectrum divided in chunks of certain bandwidth exclusively licensed to operators for a decade or more duration [2]. Caused by limitations of the technical infrastructure of beginning of the last century deeply influenced the current market of the civil mobile telecommunication:

- Constituting a triple of attributes – access to spectrum, possessing of infrastructure, delivery of services to the end customer, i.e. basic elements of service delivery chain – exclusively describing the activities of a mobile network operator,
- Establishing an entry barrier for newcomers,
- Promoting entities delivering all services to all customers, making market strategy based on specialisation hardly possible,
- Giving the regulatory bodies a set of tools to motivate mobile network operators to develop the infrastructure with coverage not only focused on areas generating the highest revenue.

The exponential growth of the demand on the mobile services over the last years causing growth of demand on spectrum of similar dynamic, turned spectrum to be the critical asset in the service delivery chain. It's limited accessibility requires new technology, braking the main constraint, making possible new definition of the business models and regulatory policy.

Taking into account the business relations between MNOs and regulatory body, the main stakeholders participating in the spectrum sharing, three types of spectrum allocation, in the case of spectrum sharing, could be defied:

- Intra-operator sharing, i.e. spectrum allocation type where MNO shares acquired spectrum resources between different access technologies, braking fixed assignment of radio access technology to spectrum resources,
- Cooperative sharing, i.e. a spectrum allocation type where two or more MNOs share spectrum that was licensed to them in the traditional way,
- Spot-market scenario, i.e. a spectrum allocation type where the regulatory body does not assign spectral resources to MNO exclusively, for long period of time – current model – but allows sharing between MNOs and charges for the used quanta of spectrum.

The SAPHYRE Project focuses on cooperative sharing delivering solutions supporting orthogonal and non-orthogonal sharing and analyses the spot – market scenario. From the business perspective following scenarios are taken into consideration:

- Inter-operator cooperative spectrum sharing with legacy networks: In this scenario each operator involved in the cooperative spectrum sharing agreement can dynamically share part of its own channel in real-time and in a fully operator-controlled way so that it can also be used by other operators inside a given transmission standard. Different access policies are possible.
- Cooperative spectrum sharing in an additional dedicated band: In this scenario, there is an agreement between operators for sharing a spectrum, however, each operator involved in the spectrum sharing process still keeps the right to exclusively use the frequency band it has been assigned, while the shared frequency band is an additional spectrum that no operator involved in the spectrum sharing process was licensed to use before the sharing agreement was signed.
- Spectrum trading with separate networks, i.e. spectrum broker: In this scenario, two or more operators access the same part of the spectrum resources they have usage rights for. The spectrum is owned by a reseller. Each operator deploys his own network and does not share any infrastructure. The distribution of the shared spectrum resources is done in real-time by trading entity, by whom the access to the shared spectrum channels at a particular location is sold.

The main business criterion differentiating the scenarios is a different approach to investment risk. Our analysis has shown that in all cases there is a need on the market for an entity responsible for market organisation – a broker. Also a secondary spectrum market should be considered.

The results of system level simulation show that the technical concepts, being the subject of the SAPHYRE, make possible the novel approach to the market organisation.

5 Further developments

In addition to spectrum other physical resources are available to be shared in certain scenarios. In particular infrastructure like active, passive, base stations, relays are promising candidates for sharing. Therefore full RAN sharing – spectrum and infrastructure – and relay sharing – spectrum and infrastructure – are currently under investigation, too. In the following, the basic motivation for these cases are briefly described.

5.1 Full RAN sharing

In a full sharing scenario a base station within a shared radio access network RAN has to fulfil following additional requirements.

Enhanced spectrum range: Like in the spectrum sharing scenario the base station have to operate on an increased spectrum size with the requirements as describe before.

Increased number of user: If two operators share the same radio access network RAN, this RAN respectively the base stations have to perform the end users of two operators. Assumed a single operator has a given number of end users, a base station which have to serve the end users of both operators requires the capability to serve the double number of end users. The number of end users has mainly impact on the MAC and higher layers of the protocol stack of the radio interface and on the processing within the control plane. With increasing number of users the number of data flows and corresponding connection contexts increases. The scheduler has to schedule and enlarged number of traffic flows per TTI. Every logical connection has an instantiations management effort, so the total processing effort of the control plane increases proportional with the number of traffic flows impacted by the number of end users.

Increased backbone capability: According to an enhanced throughput on the wireless interface the base station has to provide appropriate backbone capability.

Enhanced operator management: If a base station is used by two or more operators, addition management functionality has to be implemented. This can be done by a legacy approach like MVNO where additional software functionality is required to perform enhanced policy and billing mechanisms among the different operators. A more progressive approach is use of base station virtualisation where a physical base station hosts two or more virtual base stations, one virtual base station per operator. This approach requests additional resources for hardware like more CPU power and increased memory and additional software functionality like a virtual machine monitor and virtualised network components.

5.2 Two-way relaying and spectrum sharing

Relaying, as a mean of reducing the deployment cost, enhancing the network capacity and mitigating shadowing effects, has attracted intensive interests not only from academia but also from industry, e.g. 3GPP standard one-way decode and forward (DF) relaying under the half-duplex constraint is considered. In SAPHYRE, we investigate more advanced relaying techniques and combine them with the resource sharing concepts to provide more efficient relaying systems, e.g. the relay assisted resource sharing using two-way relaying together with digital amplify and forward (AF) relays. The motivation is that two-way relaying technique uses the radio resources in a particular efficient manner compared to the one-way relaying [22]. Meanwhile, the AF strategy yields much less delay and has a lower complexity than the DF strategy. Moreover, when applied to a resource sharing scenario more advantages can be obtained. For instance, a relay-assisted communication scenario (depicted in Figure 12) in which multiple operators use one relay terminal (possibly owned by another operator/ virtual operator) to bidirectionally exchange information using the same spectrum is presented in [23]. Such a scenario involves spectrum as well as infrastructure (relay) sharing. It is demonstrated that this form of voluntary cooperation uses the physical resources even more efficiently and can provide a significant gain in terms of the system sum rate compared to the conventional exclusive approach. Additionally, the use of the AF strategy can avoid complex signalling (a relay does not need to acquire signalling knowledge of different operators). Since the operators do not need to share their data and QoS criteria (modulation and coding formats, etc.), these lead to more independence of the operators. Other relaying techniques such as the hierarchical decode and forward (HDF) strategy which is inspired by wireless network coding are also novel PHY techniques which are introduced to allow the sharing of the wireless medium [24]. Due to the space limitations, we will not describe these techniques in details in this paper.

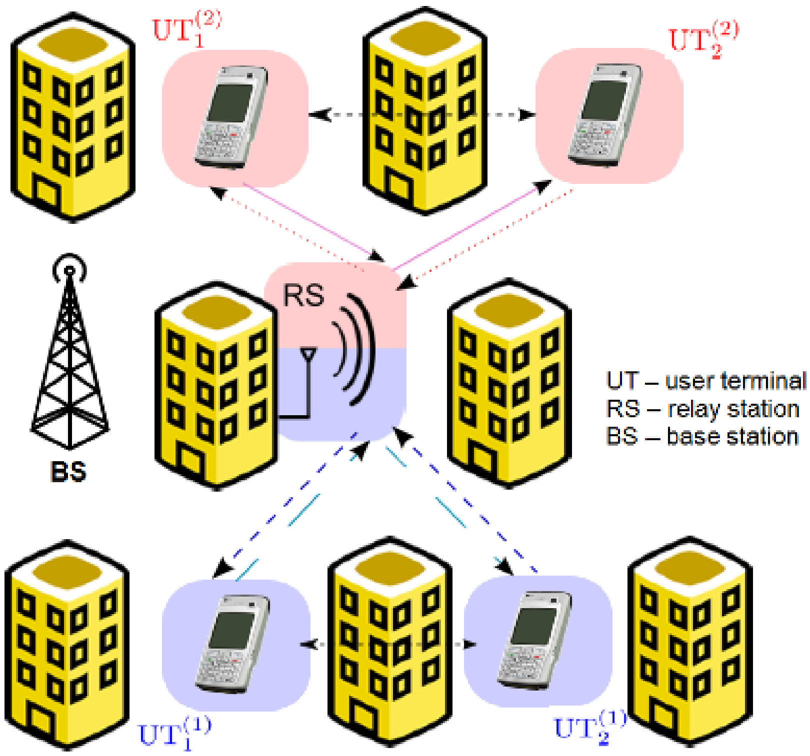

Figure 12: A relay-assisted resource sharing where users of two operators share the relay and the spectrum in a metropolis.

6 Conclusions

This paper presents a holistic view on spectrum sharing between operators in a cellular wireless network. The gain by sharing spectrum, called SAPHYRE gain, heavily depends on the chosen network scenario and the parameter setting. Therefore, it is important to understand the potential reasons and requirements and their trade-off for the gain. In orthogonal spectrum sharing, the diversity and asymmetry of users increases the SAPHYRE gain whereas for non-orthogonal spectrum sharing, the correlation or similarity the spatial signatures between channels to the mobile stations is more important. In conclusion, the paper showed that it is in general possible to realise gains by sharing spectrum for both operators. Furthermore, these gains can materialise in terms of revenue gains by appropriate business models.

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