Resource sharing between operators

White Paper

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Foreword

Future wireless cellular systems are experiencing a rapid growth of data rate demands from the users; thus, it becomes key for the network operators to pursue an efficient exploitation of the wireless medium, both in the sense of using advanced physical layer techniques and also to seek coordination among each other.

This White Paper represents the outcome of SAPHYRE, an ambitious research project supported by the European Commission dedicated to exploring the economic potential of resource sharing between operators for the European mobile communications sector.

SAPHYRE is dedicated to paving the way for paradigm change from exclusive resource allocation to voluntary physical resource sharing. The vision of the SAPHYRE project is:

- to show how voluntary sharing of physical and infrastructure resources enables a fundamental, order-of-magnitude gain in the efficiency of spectrum utilisation;
- to develop the enabling technology that facilitates such voluntary sharing; and
- to determine the key features of a regulatory framework that underpins and promotes such voluntary sharing.

The first part addresses the potential gain for network operators achieved by resource sharing between wireless cellular operators in terms of network efficiency, which is called SAPHYRE gain. For this, a specific resource sharing scenario is studied: spectrum sharing between two operators in cellular downlink transmission. If frequency bands are allocated dynamically and exclusively to one operator – a so called orthogonal spectrum sharing – then 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 – a 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 exist in various configurations including virtual mobile operators.

The second part gives an overview about physical layer coding and processing techniques that utilises relays in multi-user and multi-operator networks to share the spectrum resources. The spectrum sharing considered is the non-orthogonal one, meaning that the signals from different users interact in the same time, same frequency and the same location. The umbrella physical layer technique used to achieve this is called Wireless Network Coding. It comprises a number of variants, some of them based on Network Coded Modulation with various relay decision and decoding functions, some of them based on analogue linear signal processing. In all cases, we show that the physical layer processing properly utilising the network knowledge (network aware) turns the signal interactions into a “friendly” interference that helps to improve the coverage and efficiency against the classical orthogonal sharing.

The third part investigates resource sharing among the operators as a cooperation paradigm that drives the radio resource management and improves the exploitation of the available wireless frequencies. More specifically, it explores the concepts of spectrum sharing among different operators, based on their licensed frequency bands, which are considered as (partly or fully) available for joint and coordinated utilisation, and also infrastructure sharing, i.e. collective utilisation of their transceiver equipments. This rationale leads to the proposed concept of full resource sharing, which is envisioned as a viable approach to future wireless networks.
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Resource sharing between operators
### Abbreviations

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<th>Description</th>
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<td>2-SRN</td>
<td>2-source relay network</td>
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<td>2-WRC</td>
<td>2-way relay channel</td>
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<td>3GPP</td>
<td>3rd generation partnership project</td>
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<tr>
<td>AF</td>
<td>amplify and forward</td>
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<tr>
<td>BB</td>
<td>baseband</td>
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<td>BC</td>
<td>broadcast channel</td>
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<td>BD</td>
<td>block diagonalisation</td>
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<td>BS</td>
<td>base station</td>
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<td>C-SI</td>
<td>complementary side-information</td>
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<td>CF</td>
<td>compute and forward</td>
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<td>CFO</td>
<td>common frequency offsets</td>
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<td>CoMP</td>
<td>cooperative multipoint</td>
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<tr>
<td>CP</td>
<td>cyclic prefix</td>
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<td>CQI</td>
<td>channel quality indicator</td>
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<td>CR</td>
<td>cognitive radio</td>
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<td>CsF</td>
<td>compress and forward</td>
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<td>CSI</td>
<td>channel state information</td>
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<tr>
<td>DAC</td>
<td>digital-to-analogue converters</td>
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<td>DCA</td>
<td>direct conversion architecture</td>
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<tr>
<td>DF</td>
<td>decode and forward</td>
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<td>DL</td>
<td>downlink</td>
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<tr>
<td>E-UTRA</td>
<td>evolved universal terrestrial radio access</td>
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<tr>
<td>eNB</td>
<td>enhanced NodeB</td>
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<td>FFR</td>
<td>fractional frequency reuse</td>
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<td>FlexCoBF</td>
<td>flexible coordinated beamforming</td>
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<tr>
<td>GSM</td>
<td>global system for mobile communications</td>
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<td>GWCN</td>
<td>gateway core network</td>
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<tr>
<td>HCF</td>
<td>hierarchical compress and forward</td>
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<tr>
<td>HDF</td>
<td>hierarchical decode and forward</td>
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<tr>
<td>HNC</td>
<td>hierarchical network code</td>
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<tr>
<td>HSPA</td>
<td>high speed packet access</td>
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<tr>
<td>HXA</td>
<td>hierarchical eXclusive alphabet</td>
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<tr>
<td>HXC</td>
<td>hierarchical eXclusive code</td>
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<tr>
<td>IC</td>
<td>interference channel</td>
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<td>ICF</td>
<td>inverse compute and forward</td>
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<td>IPR</td>
<td>intellectual property rights</td>
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<td>IF</td>
<td>intermediate frequency</td>
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<td>IN</td>
<td>interference neutralisation</td>
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<tr>
<td>JDF</td>
<td>joint decode and forward</td>
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<tr>
<td>LPF</td>
<td>low-pass filters</td>
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<tr>
<td>LTE/A</td>
<td>long term evolution advanced</td>
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<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>MAC</td>
<td>multiple access channel; media access control</td>
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<td>MCIFS</td>
<td>multi-carrier IF signal</td>
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<td>MIMO</td>
<td>multiple-input multiple-output</td>
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<td>MISO</td>
<td>multiple-input single-output</td>
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<tr>
<td>MNO</td>
<td>mobile network operator</td>
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<tr>
<td>MOD</td>
<td>modulator</td>
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<td>MRC</td>
<td>maximum-ratio combining</td>
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<td>MRT</td>
<td>maximum-ratio transmission</td>
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<td>MU</td>
<td>multi-user</td>
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<tr>
<td>MVNO</td>
<td>mobile virtual network operator</td>
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<td>NBS</td>
<td>neighboured base station</td>
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<tr>
<td>NC</td>
<td>network coding</td>
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<tr>
<td>NCM</td>
<td>network coded modulation</td>
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<tr>
<td>OFDM</td>
<td>orthogonal frequency-division multiplexing</td>
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<tr>
<td>OFDMA</td>
<td>orthogonal frequency-division multiple access</td>
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<tr>
<td>OPEX</td>
<td>operational expenses</td>
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<tr>
<td>PA</td>
<td>power amplifier</td>
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<tr>
<td>PHY</td>
<td>physical layer</td>
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<tr>
<td>ProBaSeMO</td>
<td>projection based separation of multiple operators</td>
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<tr>
<td>QoS</td>
<td>quality-of-service</td>
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<tr>
<td>QPSK</td>
<td>quadrature phase shift keying</td>
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<tr>
<td>R-D</td>
<td>relay-to-destination</td>
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<tr>
<td>RAT</td>
<td>radio access technology</td>
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<tr>
<td>RAN</td>
<td>radio access network</td>
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<tr>
<td>RBD</td>
<td>regularised block diagonalisation</td>
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<td>RF</td>
<td>radio frequency</td>
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<td>RN</td>
<td>relay node</td>
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<tr>
<td>SDR</td>
<td>software defined radio</td>
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<tr>
<td>SIMO</td>
<td>single-input multiple-output</td>
</tr>
<tr>
<td>SINR</td>
<td>signal-to-interference-plus-noise ratio</td>
</tr>
<tr>
<td>SISO</td>
<td>single-input single-output</td>
</tr>
<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
</tr>
<tr>
<td>SR</td>
<td>sum rate</td>
</tr>
<tr>
<td>SU</td>
<td>single user</td>
</tr>
<tr>
<td>SWOT</td>
<td>strengths, weaknesses, opportunities and threats</td>
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<tr>
<td>TDD</td>
<td>time-division duplex</td>
</tr>
<tr>
<td>TDMA</td>
<td>time-division multiple access</td>
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<tr>
<td>TTI</td>
<td>transmission time interval</td>
</tr>
<tr>
<td>UT</td>
<td>user terminal</td>
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<tr>
<td>WiMAX</td>
<td>world-wide interoperability for microwave access</td>
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<tr>
<td>WNC</td>
<td>wireless network coding</td>
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<tr>
<td>WWRF</td>
<td>wireless world research forum</td>
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<tr>
<td>ZF</td>
<td>zero-forcing</td>
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# Spectrum sharing improves the network efficiency for network operators

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Resource sharing between operators
1. Spectrum sharing improves the network efficiency for network operators

1.1. 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 report 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 part focuses on spectrum sharing between two operators in a representative cellular downlink scenario. In the second part, relays are utilised to enable sharing of the spectrum resources.

1.1.1. 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.

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
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, an 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 a 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.

The first step to flexible radio spectrum usage for a single operator is intra-operator spectrum sharing [4] which includes the dynamic allocation of RAT 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 RAT to licensed spectrum is allowed by the regulatory bodies [5] enabling the flexible application of software defined radio technology.

In the SAPHYRE project, inter-operator spectrum sharing is analysed. 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 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. As 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, the spectral efficiency is increased by transceiver optimisation and channel aware user selection. We call this gain achieved by inter-operator spectrum sharing SAPHYRE gain [7]. Depending on the context it is measured in spectral efficiency [Mbit/s-Hz] or feasibility with respect to signalling and control overhead, business and regulation. After a brief introduction on related techniques and recent results, the following sections will report on the assumptions and SAPHYRE-gain results.
1.1.2. Related techniques and state-of-the-art

CoMP is considered 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 to perform the joint precoding and transmit optimisation. CoMP [9] has been proposed in 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 LTE and 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 neighboured 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. the signal-to-interference-plus-noise (SINR) threshold.

<table>
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<tr>
<th>CoMP</th>
<th>SAPHYRE</th>
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<tr>
<td>Major objective</td>
<td>Combat inter-cell interference and improve spectral efficiency for the cell edge user of a single operator</td>
</tr>
<tr>
<td>Application scenario</td>
<td>Intra-operator (intra-site and inter-site)</td>
</tr>
<tr>
<td>Shared resources</td>
<td>Data and CSI sharing</td>
</tr>
</tbody>
</table>
| 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
Cognitive radio (CR) and software defined radio (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 increase the flexibility and adaptivity in terms of spectrum and RAT assignment.

For orthogonal inter-operator spectrum sharing a large number of different approaches is 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].

1.2. 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.

1.2.1. General base station requirements and constraints

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

a) Spectrum size: A collaborative spectrum usage requires for the base stations (BS) an increased spectrum capability, 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 and on the physical layer, respectively. If the spectrum is doubled then the number of subcarriers doubles, too, and in the result the functional blocks in the physical layer have to process Fourier transformations of double size during the same constant transmission time interval (TTI) which requests 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 approx. with the spectrum size.

![Figure 2: Cooperation in spectrum sharing scenario](image-url)
Spectrum sharing improves the network efficiency for network operators

\textit{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 neighbour 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 neighboured base station (NBS) and 1 receive antenna per UT;
- Information exchange between neighbouring cells as in Figure 2;
- 3 base stations (BS) per site;
- 4 NBS 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 of 8 bit CSI × 2 NBS × 1 UT × 4 NBS × 3 BS × 10 UT/0.001 s TTI = 1.92 Mbps.

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.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{cooperation_cluster.png}
\caption{Cooperation cluster}
\end{figure}

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. A raw assertion about the requested capability can be done by analysing the capabilities of current and future base station implementations. 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 fulfil 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 in order 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.

1.2.2. 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-analogue converters (DAC), low-pass filters (LPF), modulators (MOD), power amplifiers (PA) 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). Both 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 DAC, LPF, MOD, PA and antennas are required. Moreover, to apply advanced precoding techniques, multiple antennas as well as the corresponding analogue 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 bandwidth enhancement is required at the user terminal (UT). Otherwise, if the user should be able to receive signals from both own and shared bands, bandwidth 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 radio access network (RAN). The requirements for the bandwidth and the analogue components are generally the same. In most of the state-of-the-art BS, e.g. [17], SDR techniques, DCA as well as broadband RF and BB analogue components have been successfully deployed. Thus, resource sharing can be realised.

1.3. LTE downlink spectrum sharing

In this section, we describe for the LTE downlink scenario: (i) fundamental principles of spectrum sharing between operators, (ii) the signal processing and resource allocation algorithms, (iii) system level assessments reporting SAPHYRE gains, and (iv) a feasibility study with regards to business and regulation.
1.3.1. 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 1.1.1, 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 set-up for the downlink mode of the non-orthogonal spectrum sharing scenario: two neighboured base stations BS1 and BS2 of different operators transmit towards their respective user terminals UT1 and UT2 and the UT 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 1.3.2 to mitigate the interference caused by sharing.

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 single-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 BS and that the UT 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.

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 BS might even be co-located, especially in dense urban environments where the need of sharing is more prominent. Second, since the BS 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 UT 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 UT using the same resources. This calls for decentralised designs, that can be
motivated by fundamental game-theoretic concepts. One extreme approach is that the BS 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 they lay 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.

1.3.2. 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.

a) 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, in order to solve 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

![Figure 4: Two-user MISO interference channel](image)

![Figure 5: Exemplary achievable rate region and important operating points](image)
the core optimisation problem is solved in closed-form for instantaneous CSI, whereas for statistical CSI an efficient solution is found numerically by 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.

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 6: Sum rate of various beamforming schemes](image)

![Figure 7: Spectrum sharing gain for various CSI scenarios](image)

b) **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 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 coordinated zero-forcing [21].
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 $P_T/\sigma_n^2$ with $\sigma_n^2$ 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 the no interference into account. A reference scheme, called Eigen, is also included by using eigen-beamforming for both links treating all interference as noise. It is observed that IC FlexCoBF with either RBD or BD performs much better than CoZF within all SNR ranges. Especially at low SNR, CoZF performs even worse than Eigen. IC FlexCoBF RBD improves the sum rate compared to BD because it allows some residual interference 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 SNR 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.

1.3.3. 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 eNB and mobile users are distributed following a grid structure of $3 \times 3$ hexagonal cells wrapped onto itself. Each eNB of one operator is placed exactly 50 meters apart from the corresponding eNB 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 $138.1 + (37.6 \cdot \log_{10}(R))$ dB is included, to which a log-normal Rayleigh fading with parameter $\sigma = 8$ 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 first, 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, while 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 set-up 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) then 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.

![Graph](image)

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

Figure 10 shows 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.

Several conclusions can be drawn from Figure 10. 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 Figure 10, the higher gain achieved by the upper bound does not always correspond to a Nash equilibrium, as the overall capacity of the
Spectrum sharing improves the network efficiency for network operators.

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 set-up (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).

![Graph showing cell throughput as a function of the load unbalance of operator 2, with 40 users per cell for operator 1, maximal throughput scheduling.](image)

**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 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.

1.3.4. **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. Its 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 MNO and regulatory bodies, which are the main stakeholders participating in the spectrum sharing, three types of spectrum allocation could be defied:

1. Intra-operator sharing – a spectrum allocation type where an MNO shares acquired spectrum resources between different access technologies, braking fixed assignment of radio access technology to spectrum resources;
2. Cooperative sharing – a spectrum allocation type where two or more MNO share spectrum that is licensed to them in the traditional way;
3. Spot-market scenario – a spectrum allocation type where the regulatory body does not assign spectral resources to MNO exclusively, for long period of time – the current model – but allows sharing between MNO 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 parts 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, the operators involved in the spectrum sharing process still keep the right to exclusively use the frequency band, which has been assigned to them, 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
Spectrum sharing improves the network efficiency for network operators own network and does not share any infrastructure. The distribution of the shared spectrum resources is done in real-time by a 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.

1.4. 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 is briefly described.

1.4.1. Full RAN sharing

In a full sharing scenario a base station within a shared 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 users:* If two operators share the same radio access network, this RAN respectively the base stations have to process 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 an increasing number of users the number of data flows and corresponding connection contexts increases, too. The scheduler has to schedule an 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 proportionally 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, additional management functionality has to be implemented. This can be done by a legacy approach like a mobile virtual network operator (MVNO), where additional software functionality is required to perform enhanced policy and billing mechanisms among the different operators. A more progressive approach is the 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 processing power and increased memory and additional software functionality like a virtual machine monitor and virtualised network components.
1.4.2. 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. the 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 the 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 then 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 bi-directionally 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). The operators do not need to share their data and QoS criteria (modulation and coding formats, etc.), which leads 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 detail.

![Figure 12: A relay-assisted resource sharing where users of two operators share the relay and the spectrum in a metropolis](image)
1.5. Conclusions

This first part of the White Paper presented a holistic view on spectrum sharing between operators in a cellular wireless network. The gain achieved 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 report 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.
Resource sharing between operators
2. Infrastructure and spectrum sharing in interference relay networks

2.1. Basic idea of spectrum sharing using relays

Spectrum sharing is a general term describing a wide range of techniques where the given spectrum bandwidth is shared for multiple purposes, typically for multiple users and/or operators. A major distinguishing point is however form and granularity of such sharing. An orthogonal slicing of the spectrum, e.g. OFDM sub-carriers, complemented with various multi-user/operator resource management techniques assigning those slices for users/operators already found its way into practical systems. This report focuses on a more elaborated form of sharing – non-orthogonal sharing. All participating users/operators use the signal at the same time, the same location and the same frequency. Their transmitted signals superpose one on each other. The information theory predicts that this superposition form of propagation medium sharing has much higher efficiency in multi-terminal and multi-node networks than the classical one with orthogonal physical resource slicing and traditional routing protocols. However a particular forms of coding and processing achieving this goal and even the fundamental limits for such scenarios are still open research problems.

All accidental or unavoidable signal “overlaps” – the interference – is traditionally understood as harmful and something that should be avoided. We will show that smart construction of signals, codes and processing can turn the signal interaction into friendly interference that can improve the performance. This “smart” use of signal interactions strongly relies on incorporating additional nodes (relays) in the network and in designing network structure aware coding and processing.

A main message of the report can be formulated as follows. The spectrum sharing is achieved by adding additional nodes (relays) which allow active processing at physical layer improving the efficiency of the information transfer over the wireless medium. We are adding additional “active intelligence” where otherwise the signal would only passively “propagate and superimpose”. Relay nodes actively process the signals but have only a fractional complexity and limited required signalling compared to the full functional base station.

To some extent, we can think about relay based communications (non-orthogonal) as of the system with pro-active propagation environment with own intelligence, which uses the knowledge of the network structure to improve the performance rather than a simple network of links with some added nodes. The form of the pro-active relay functionality can vary widely. It can range from linear-only signal space operations to the use of full decoding and re-encoding of some function of the source data. Wireless network coding (WNC) is a general umbrella term for all of these techniques involving signal-space operations in multi-terminal and multi-node networks which use non-orthogonal spectrum sharing.

Current state-of-the-art in WNC stands on, although quite recent but steadily growing, a set of conceptual works. A representative set covering various angles of view includes [25]–[29]. Due to the space limitations, we skip a detailed analysis of these works, but we encourage the reader to refer to these papers and the references therein to get a more detailed picture.
2.2. System scenario, classification and constraints

2.2.1. Topology and scenario

In order to study the benefits, a realistic performance and fundamental limits of the relay based system, we need a system scenario and topology model. It should capture all important aspects and, at the same time, it should be simple enough to allow the required analysis.

The ultimate scenario is supposed to be close to a practical deployment scenario and it is supposed to model all relevant phenomena. The multi-terminal and multi-node PHY using the WNC approach is in fact a network structure aware modulation and coding, which is inherently (i) cooperative; (ii) distributed; (iii) sharing relay nodes, and (iv) allowing separate utility metric groups.

Performance (throughput) of the WNC based system is substantially improved directly at PHY, compared to a traditional point-to-point PHY role. But on top of this, there is a wide potential for an additional gain. WNC systems allow a wider resource, e.g. game theory, management. It directly operates over the shared PHY coding, signal processing, and the shared PHY directly provides input for performance utility metric groups.

The ultimate system scenario is shown in Figure 13. The network elements are nodes. The data source and destination nodes are called terminals. Apart from the source and destination nodes, there are also the relay nodes which are neither source nor destination.

![Figure 13: Ultimate scenario with wireless signal space links](image)

The processing at the relay nodes which respects complete network structure is called a hierarchical one. The hierarchical relay processing handles hierarchical data symbols which uniquely represent (a function) the individual data from source A and B only.
when combined with the side-information on the complementary data at the final destination. We call this strategy generally a hierarchical strategy, e.g. hierarchical decode and forward (HDF). A reason for using the name hierarchical is that the relay decodes symbols hierarchically composed from the original two source symbols. The relay does not care about these individual symbols and treats them as one container. The PHY of the node utilises the network structure knowledge in a hierarchy. In a more complicated network topology, this encapsulation would occur in hierarchical levels. Example #1: There are two sources A and B. The relay operates with a hierarchical symbol (AB) and the mutual structure knowledge of A+B composite is required. Example #2: There are sources AB (the result of the previous hierarchical operation) and C. The relay operates with a hierarchical symbol ((AB)C) and the mutual structure knowledge of (AB)+C composite is required. It is however required only at the highest hierarchy level (()+) at the given node.

There are three types of signals. The hierarchical information signal carries (among others) the information about the desired data. The complementary side-information (C-SI) signal does not carry the information about the desired data, but it carries the information about other parameters or data that helps the receiver to decode the data from the hierarchical signal. It is in fact a friendly interference. The last signal type is a classical harmful interference. More detailed definitions will be provided later.

In all our systems, we assume the half-duplex constraint where a simultaneous Tx and Rx operation of given node is impossible due to the technological reasons. This is reflected by multiple stages of the network operation.

The Butterfly network – a 2-source relay network (2-SRN), see Figure 14 – can be seen as a simplified scenario, which captures the phenomena of multiple sources, a shared common node, partial (imperfect) C-SI and two separate utility metrics. The 2-way relay channel (2-WRC) is a special case with perfect C-SI. The half-duplex constraint is respected. The 2-SRN will be used to investigate a particular PHY sharing technique with WNC coding strategy. It is hierarchical decode/compress and forward (HDF/HCF) strategy which uses hierarchical exclusive code (HXC) or hierarchical exclusive alphabet (HXA). It uses two stages (phases): hierarchical MAC and hierarchical BC. The HDF strategy requires C-SI at the destination. It can be both, the perfect C-SI or partial (soft) C-SI.

Figure 14: Butterfly network – 2-source relay network with partial C-SI
2.2.2. Classification of the WNC technique

We start with the classification of the strategies according to the role of the node in the network.

a) Strategy at source terminals: A strategy at the source terminals refers to the codebook construction. The codebook is a multi-source codebook and it must respect the presence of the other sources in the network and the way how the codewords are combined at relay nodes and what form of information is available at the destinations.

![AF relay strategy](image1)

*Figure 15: AF relay strategy (equivalent model): 2-WRC scenario from the A-data perspective*

![DF relay strategy](image2)

*Figure 16: DF relay strategy (equivalent model): 2-WRC scenario from the A-data perspective*

b) Strategy at relay: A strategy at relay nodes refers to the operation performed on incoming signals to produce the relay output. The operation must respect the level of complementary side-information at the destination. The strategies can be classified into following classes: (1) amplify and forward (AF), (2) decode and forward (DF) (joint/hierarchical), (3) compress and forward (CsF).

1. AF relay strategy: The AF relay strategy (Figure 15) is a linear processing only. It applies linear scaling to maximise the signal to noise ratio (or other target performance criteria) at the destination. It is effectively equivalent to a single hop MAC channel, when the C-SI is added at the destination. The bottleneck on R-D channels results from the added noise on that channel.

2. DF relay strategy: Any decode and forward strategy (Figure 16), of arbitrary variant, makes full decisions at the relay. The decisions can be made on a symbol, a bit, or a codeword. The decisions themselves can be based on various demodulation decision region mappers. This creates various variants of DF strategy. The major variants are the following:

   - Joint DF – the joint simultaneous separate decoders (symbol demappers) decode symbols from A and B separately.
   - Hierarchical DF – the hierarchical codeword (symbol) is decoded by a specific decision region mapper. All xDF strategies have independent MAC
and BC phase bottlenecks. The particular MAC and BC throughputs depend on the strategy variant.

(2a) JDF relay strategy: The joint decode and forward (JDF) is a variant of DF strategy where the relay decoder provides joint simultaneous separate decisions (symbol demappers) on A and B from the MAC stage (Figure 17). Then the individual decision can be used for example to form the discrete network coding (NC) coded BC phase symbol. The JDF exists in two subvariants depending on how the individual decisions were made. They can be done either by decoders with a separate marginalised metric or by composite hypothesis decoders but regardless of this, in both cases, providing separate estimates $[\hat{d}_A, \hat{d}_B]$.

(2b) HDF relay strategy: The hierarchical decode and forward (HDF) differs from JDF in the fact that the relay does not provide both individual source node symbols but only and directly the hierarchical symbol (see Section 2.3.1). The decision on the hierarchical symbol is done directly at the signal space level (cf. with JDF followed by NC). The hierarchical codeword (symbol) decision region mapper directly decodes a function of the symbols (hierarchical network code map $X$) $d_{AB} = X(d_A, d_B)$.

Figure 17: JDF relay strategy (equivalent model)

Figure 18: HDF relay strategy (equivalent model)

(3) CsF relay strategy: The compress and forward strategy (Figure 19) performs a general nonlinear operation on relay to compress the information signal. The nonlinear operation can be typically a soft-demodulation with source compression, or a signal quantisation applied to various versions of the signal (samples, matched filter output, soft measure of symbol/codeword). In CsF strategy, the quality of the link at one phase partially influences the other phase.
c) **Strategy at destination terminal**: The strategy at the destination terminal refers to the *demodulation/decoding technique* used at the final destination. The demodulation/decoding has to respect (i) multiple received signals from various relays or other terminals and (ii) the complementary side-information MAC and BC phase partially independent bottlenecks available about the target data in variety of forms (soft information, perfect knowledge, etc.). A typical example of the strategy is the iterative soft complementary side-information aided decoder.

d) **Comparison of WNC to other PHY multi-user techniques**: A specific comparison of NC vs. WNC has some common features – it operates over *networks*, from source to destination via multiple paths. However, it has some significant differences. NC assumes *discrete* links/channels between pairs of nodes; in WNC signals from different nodes *cannot be separated*. For NC, PHY is still *classical* point-to-point while WNC requires *novel* PHY operating in signal space. Table 2 describes additional details.

<table>
<thead>
<tr>
<th></th>
<th>P2P-PHY</th>
<th>MU-PHY</th>
<th>NC</th>
<th>WNC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Topology: direct neighbours signal interaction</strong></td>
<td>–</td>
<td>+</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td><strong>Topology: full network structure</strong></td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td><strong>Signal structure: at constellation (signal) space level</strong></td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td><strong>Relay Tx signal codeword map: a function of data</strong></td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td><strong>Relay Rx signal codeword map: a function of data</strong></td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
</tbody>
</table>

| Table 2: Summary of multi-source/node PHY techniques |

### 2.3. Network aware coding and decoding

#### 2.3.1. NCM and HDF strategy

The network coded modulation (NCM) with hierarchical decode and forward (HDF) relaying strategy is a particular example of WNC. It builds on multi-source and *network structure aware modulation and coding* (NCM) and hierarchical network code map (HNC map) receiver metric. In simple terms, NCM describes what is sent by the node, and HNC map describes what variable the receiver metric is formed from. The source node strategy means creation of the constellation space multi-source distributed codebooks (NCM schemes) that are used at source nodes. Each node uses the codebook that must be designed in such a way that, when the codeword is received at the relay together (in superposition) with the other source codeword, it would become a valid codeword of some (*hierarchical*) function of the source data. Each relay generally uses a different
HNC map. There are many design problems. The most important one is related to continuous valued parametric channel between sources and the relay. The multisource HNC map codebook (as seen at the relay) must be a valid codebook with regard to given map under all possible channel parameterisations.

The relay node strategies are centralised around finding a sufficient statistic (metric) for a proper HNC map (function of data). The metric may take various (potentially sub-optimal) forms: analogue (linear only processing), decision based (continuous to finite alphabet mapping at various levels: hierarchical symbols, full codewords), or compression based (general nonlinear function of inputs), but in all cases it shares a common principle that it should be a metric (optimally a sufficient statistic) on a given HNC map. Each relay uses some HNC map, and in the case of multiple layers of relays it is a hierarchy of maps (hence the name hierarchical). At the end, the last layer of relays (those that are received by the destinations) must provide a sufficient statistic for given desired target data.

The destination node strategies mainly concern the demodulation and decoding at the destination that properly uses multiple received signals carrying multiple HNC maps and properly uses the hierarchical codeword structure. The final destination node combines all HNC maps received metrics into a sufficient statistic for the target data. The main challenges are the following: the synchronisation and the proper utilisation of mutually extrinsic observations with regard to given desired target data. In the simplistic case of all-linear HNC maps, it means that a composite HNC map matrix must be invertible (over a finite field).

Performance gains can be substantial. Even in the simplest possible case of the butterfly network (Figure 14) the gain in the MAC phase of the NCM scheme using QPSK alphabets is significant [30] (Figure 20). Asymptotically, the 2-WRC MAC phase achieves the performance as in the single user case. The MAC phase is usually a bottleneck due to the constellation space constraints associated with the hierarchical HNC coded symbol. On the other side, the BC phase performance [31] is affected by the quality of the C-SI information as shown in Figure 21.

![Figure 20: Capacity (mean, min/max over all relative phase parameterisations) of MAC and BC phases (assuming reciprocal SNR) for a QPSK alphabet as a function of source-relay and relay-destination SNR](image)
2.3.2. Two-hop X-channel

In recent years a lot of work has been done in the field of structured codes to show their benefits. For example, it is shown in [32] that lattice codes [33] can achieve the capacity of the AWGN point-to-point channel. The authors of [28] developed a strategy based on lattice codes to get a reliable physical layer network coding strategy which can remove the noise at each node in the network by decoding equations of messages. This scheme is called compute-and-forward (CF) and is described more detailed in [25]. In order to efficiently decode the equations that are decoded at a node, the authors of [34] described an inverse compute-and-forward scheme (ICF). This uses the fact that the number of possible equations from one node to the destination is constrained by the other equations received at the destination.

These two schemes can be applied to the two-hop X-channel with multiple antennas at the relays as shown in Figure 22. The two source nodes A and B transmit their common messages $m_1$ and $m_2$ to both receiver nodes E and F via two relay nodes C and D. Transmit and receive nodes have single antennas whereas the relay nodes have multiple antennas. The vector channels $h_{11}, h_{12}, h_{21}, h_{22}$ from the first hop form a SIMO interference channel. The vector channels $g_{11}, g_{12}, g_{21}, g_{22}$ from the second hop form a MISO interference channel. We communicate in two phases. We compare the achievable sum rate of this network under the following two schemes:

1. Using compute-and-forward at the relays and inverse compute-and-forward at the receivers (CF/ICF);

We assume that the network coding coefficients for network coding as well as the equation coefficients for compute-and-forward are all non-zero.

We use compute-and-forward at the relays. The compute-and-forward computation rate is given by [28], Theorem 4. At the receivers we utilise the inverse compute-and-forward strategy [34]. For the NC/DF scheme we get the commonly known MAC regions.

If an equation of the messages is decoded at the relays, it is easy to see that all links in the second hop transport needed information since each destination needs two linear independent equations to decode the original messages. Since the sum rate constraint of the second hop is equal for both schemes, the actual gain comes from the first hop. In Figure 23 we see a significant SNR gain for high SNR for CF/ICF. We can also see that for low SNR CF/ICF performs worse than NC/DF and even goes down to zero rate for SNR lower than 8 dB. This effect can be partly compensated by choosing coefficient vectors with a smaller norm. But since the smallest possible norm is 1, there will always be a zero rate for low SNR.

![Figure 23: Achievable sum rate for CF/ICF compared to NC/DF](image)

2.4. Signal processing for 2-WRC

2.4.1. Bi-directional amplify and forward relaying

In contrast to the uni-directional relaying, bi-directional relaying can compensate the spectral efficiency loss due to the half-duplex constraint of the relay and, therefore, use the radio resources in a more efficient manner [22]. This advantage renders it very attractive for both industry and academia. Figure 24 depicts a scenario where the shared relay with multiple antennas uses a bi-directional AF relaying strategy. The UT of one operator suffer from both the inter-operator interference and the additional self-interference (SI) which is due to the bi-directional relaying protocol. While the SI can be subtracted at the receiver side when CSI is available, the resulting inter-operator interference needs to be managed in an efficient way such that the QoS of all the UT can be guaranteed. Inspired by decoupling of users via block diagonalisation (BD) [19] in
multi-user MIMO (MU-MIMO) systems, we propose a linear MIMO precoding technique which is called the projection based separation of multiple operators (ProBaSeMO) [35] to decouple the multiple operators that share the relay. The ProBaSeMO scheme consists of two steps. First the inter-operator interference is suppressed, e.g. by designing the relay amplification matrix such that the UT of one operator transmit and receive in the null space of the combined channels of all the other UT. Thereby, the system will be decoupled into L parallel independent single-operator 2-WRC sub-systems. Then, in the second step, arbitrary transmission techniques for single-operator 2-WRC systems can be applied separately on each sub-system. Such a design also facilitates the differentiation among multiple operators that share a relay.

Figure 24: Multi-operator two-way relaying system model. The $k$-th terminal belonging to the $\ell$-th operator has $M_k^{(\ell)}$ antennas and the relay station is equipped with $M_R$ antennas.

Figure 25: Sum rate comparison of time-shared approach and ProBaSeMO approach for single-antenna nodes and $L = 2$ operators. $M_R$: number of antennas at the relay.
The system sum rate performance comparison between ProBaSeMO, the optimum solution with respect to the system sum rate and the time-shared approach\(^1\) for the system with single-antenna nodes and multiple-antenna nodes is shown in Figure 25 and Figure 26, respectively. Simulation results illustrate that the ProBaSeMO solution outperforms the time-shared approach for moderate to high SNR. It achieves the same multiplexing gain as the optimal solution. Moreover, it coincides with the optimum curve when the array size at the relay increases but has a much lower computational complexity.

\[\text{Figure 26: Sum rate comparison of different 2-WRC approaches for two-antenna nodes with 8 antennas at the relay and } L = 2 \text{ operators. rOpt: steepest descent method. uWF: multiple-stream transmission. uDET: single stream transmission} \]

\[\text{Figure 27: CDF comparison of relay sharing and non-sharing in an OFDMA system with single-antenna nodes, two operators and two UT per operator. Each operator has one sub-channel. In the non-sharing set-up each operator has its own relay with 4 antennas while in the relay sharing set-up there is only a single relay but with doubled transmit power and 8 antennas. MCA: sum rate maximisation power allocation. MCI: SNR balancing power allocation} \]

\(^1\) The relay is accessed by different operators in a TDMA way.
When operating in an OFDMA based communication system, e.g. LTE, WiMAX, resource allocation algorithms are required to maximise the system performance. In particular, optimal transmit strategies require the joint design of resource allocation schemes on all sub-channels and the precoding matrices at all nodes. Such an optimisation problem is intractable in general and thereby it is more difficult to obtain the optimal solution in this case. However, by simply adopting the ProBaSeMO algorithm per sub-channel but adaptively adjusting the power (using geometric programming) on each sub-channel, it is shown in Figure 27 that relay sharing is still superior to the non-sharing approach especially in the high SNR regime.

### 2.4.2. Relay-assisted wireless network and instantaneous relaying

In modern wireless networks, links are connected through repeaters (or the so called layer 1 relays) in LTE standard to enhance cell coverage or extend coverage to rural area. Layer 1 relays are simple amplifiers and perform no signal processing on the received signal and thus cause negligible delay to the message travelling through relay nodes to destination nodes. If a smart layer 1 relay, capable of gathering channel state information and performing amplify-and-forward, is placed in the system, we obtain a relay-assisted network in which each path from source to destination consumes two time unit. As the simple layer 1 relays perform no signal processing and is transparent to the end nodes, the network is equivalent to an interference relay channel assisted by an instantaneous relay [36], [37]: a memoryless relay-without-delay. The output of the relay depends only on the current input of the relay. The correspondence is shown in Figure 28.

![Figure 28: The wireless relay-assisted network with layer one repeaters and one smart relay is shown in subfigure (a). The dotted lines demonstrate the equivalent links between source the destination taking into account of the presence of the repeaters. All paths from source to destination nodes take two time slots and links from source to relay and relay to destination take one time slot. The equivalent channel is established in subfigure (b) by replacing the relay as an instantaneous relay and information through instantaneous relay arrive at destinations the same time as the direct links.](image)
Interference neutralisation (IN) is a technique of cancelling, zero-forcing or neutralising interference signals by a careful selection of forwarding strategies when the signal travels through relay nodes before reaching the destination. This general idea has been applied to deterministic channels [38], [39] and in two-hop relay channels [22], [40], [41], also known as multi-user zero-forcing and orthogonalise-and-forward. If the application is not delay sensitive and symbol extension is allowed, one can perform aligned interference neutralisation, a combination of aligning and neutralising interference signals [37], [42].

In a $K$-user interference relay channel with an instantaneous relay equipped with $M$ antennas, the received signal at destination $D_i$ is a superposition of the signals from all $K$ sources, the signal from the relay (which is a linear function of all source signals received by the relay) and Gaussian noise, see Figure 28 (b). In order to neutralise all $K-1$ interference signals for all $K$ users, the $K(K-1)$ equations have to be satisfied, each saying that the direct signal from the source $S_j$ and its relay processed signal should cancel each other. If the interference neutralisation is feasible (see analysis in [43]), we can choose a relay linear processing matrix $R$ as a function of all channel states. The result is an improved SINR.

![Figure 29: The achievable rate region of a two-user SISO interference channel is improved significantly by the proposed IN scheme with moderate relay power. The IN scheme attains maximum sum rate point and improves max-min fairness significantly.](image)

In Figure 29, the achievable rate region of IN in a two-user interference relay channel with relay equipped with two antennas is compared to the SISO interference channel (by turning off the relay) and to the upper bound where IN constraint is not enforced. Simulation results show that IN attains the maximum sum rate point and improves the max-min fairness of the system significantly.

### 2.5. System-level performance results

System level simulations are indispensable for evaluating signal processing algorithms in a large communication system. However, compared to the traditional cellular networks, there is little knowledge of efficient relay site planning, relay link budget, best relaying strategies, or efficient resource allocation schemes between macro-cell users and relay users.
In Figure 30 we consider the metropolitan scenario with one-way DF out-of-band relays with multiple antennas (compliant with the Type 1 relay specified in [43]). After assigning UT to the macro-cell BS and relays during the training phase, the protocol works as follows. In the first time slot, the BS communicates with only the relays. In the second time slot, the BS broadcasts to the macro-cell UT while the relays forward the dedicated data to relay UT. To demonstrate the potential sharing gain, we define the following two steps:

- **Non-sharing set-up:** Each operator has its own spectrum and relays.
- **Relay sharing set-up:** The spectrum is fully shared between the two operators. The relays of different operators are assumed to be shared such that they can be treated as a single relay.

![Image of the Manhattan grid with a single cell-layout](image)

**Figure 30:** The Manhattan grid with a single cell-layout

![Simulation results for non-shared and shared relays](image)

**Figure 31:** System level simulation results in the Manhattan grid with non-shared relays  
**Figure 32:** System level simulation results in the Manhattan grid with a shared relay
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency</td>
<td>2 GHz</td>
</tr>
<tr>
<td>Channel model</td>
<td>WINNER II B1 NLOS [45]</td>
</tr>
<tr>
<td>Traffic model</td>
<td>Statistics with full-buffer downlink</td>
</tr>
<tr>
<td>eNB location/height</td>
<td>15 m (above rooftop)</td>
</tr>
<tr>
<td>eNB number of sectors</td>
<td>4</td>
</tr>
<tr>
<td>eNB antennas per sector</td>
<td>2</td>
</tr>
<tr>
<td>eNB maximum Tx power per sector</td>
<td>46 dBm</td>
</tr>
<tr>
<td>eNB elevation + antenna gain</td>
<td>14 dBi</td>
</tr>
<tr>
<td>eNB noise figure</td>
<td>5 dB</td>
</tr>
<tr>
<td>RN location/height</td>
<td>10 m (below rooftop)</td>
</tr>
<tr>
<td>RN antennas</td>
<td>4 (omni-directional)</td>
</tr>
<tr>
<td>RN maximum Tx power</td>
<td>24 dBm</td>
</tr>
<tr>
<td>RN elevation + antenna gain</td>
<td>9 dBi</td>
</tr>
<tr>
<td>RN noise figure</td>
<td>7 dB</td>
</tr>
<tr>
<td>UT location/height</td>
<td>1.5 m (above rooftop)</td>
</tr>
<tr>
<td>UT antennas</td>
<td>1 (omni-directional)</td>
</tr>
<tr>
<td>UT elevation + antenna gain</td>
<td>0 dBi</td>
</tr>
<tr>
<td>UT noise figure</td>
<td>7 dB</td>
</tr>
</tbody>
</table>

Table 3: Key simulation parameters

In both set-ups, we apply spatial division multiple access (SDMA) based signal processing techniques. Numerical results in Figure 31 and Figure 32 are obtained from using the parameters in Table 3. It can be observed from the colour map that the sharing gain is almost two-fold.

2.6. Practical aspects regarding implementation

2.6.1. Hardware enablers

Generally, to enable flexible spectrum sharing in relay networks, three key enablers should be applied: (i) SDR technology; (ii) DCA; (iii) frequency agile and/or broadband RF and BB components, including digital-to-analogue converters, low-pass filters, modulators, power amplifiers and antennas. With these enablers, efficient transmission frequency switching and simultaneous multi-band operation are allowed. Furthermore, they allow integrated implementations with low cost and low power consumption, especially for MIMO operation.

Usually, the base stations (BS, could be source or destination nodes) are supposed to operate in the own bands and shared bands simultaneously. Thus, they require comparably large transmission bandwidth of each RF chain to accommodate neighboured bands. When the different bands are far away from each other, e.g. one on the
2.6 GHz band and one on the 800 MHz band for LTE, separate RF chains are needed to cover these bands.

In contrast, the relay and the UT would probably only operate in one band at a time but require flexible switching. Thus, the bandwidth of them can be smaller. The flexible switching of the operation frequency band is enabled by SDR combined with DCA and frequency agile analogue components.

2.6.2. Time and frequency synchronisation

The proposed relay and spectrum sharing approaches require global time and frequency synchronisation of all involved transceivers in the relay network. Otherwise, the system will suffer from model mismatch and performance degradation. For the proposed approaches, the most critical issue is to synchronise the source nodes in the MAC phase, since accurate alignment of the data symbols on the shared spectrum is required. By using OFDM as the transmission scheme, certain range of time synchronisation error can be tolerated due to the use of cyclic prefix (CP). However, frequency synchronisation error is critical. If the source nodes have different common frequency offsets (CFO)\(^2\), it is difficult for the relay to correct them via post processing.

To achieve synchronisation of the source nodes, the following two cases have to be considered:

1) The source nodes are BS: In this case, all BS of the involved operators should be synchronised accurately using time and frequency reference signals from GPS or the backbone network \([46]\);

2) The source nodes are UT: In this case, all involved UT should first estimate their CFO and pre-compensate it\(^3\) before transmission. The estimation of these CFO can be done based on a broadcasted training sequence (during connection establishment) by the relay\(^4\). The time synchronisation can be coordinated by the relay in a similar way as the BS (via standard procedures).

Note that since the relay is supposed to have low-cost implementation, it probably has neither GPS receiver nor access to the backbone network. Thus, the synchronisation method for the BS (described in case 1 above) does not apply to the relay. Instead, the relay should synchronise itself to the BS in a similar way as the UT (via standard procedures). Furthermore, the frequency synchronisation of the destination nodes in the BC phase can be done via standard post-processing (if necessary).

2.6.3. Channel state information (CSI), channel reciprocity and noise power information

The proposed DF approaches with WNC only require CSI at the receivers, no CSI feedback is necessary. Furthermore, the channel estimation is straightforward. In the MAC phase, MIMO channel estimation schemes, e.g. \([47]\), can be extended by viewing all the source nodes as a virtual transmitter with multiple Tx antennas, where however the synchronisation described in Section 2.6.2 is a prerequisite. In the BC phase, standard channel estimation schemes in cellular downlink can be used.

In contrast, the proposed AF approaches with precoding require CSI both at the transmitter (of the relay) and the receivers (of both the relay and the BS/UT). Moreover,

\(^2\) With regard to an assumed standard carrier frequency.

\(^3\) Simply by digital phase rotation of the Tx signal in time domain.

\(^4\) If the UT have direct connection to a BS, e.g. the complementary side information link, the CFO can also be estimated using the training sequence sent by the BS.
some algorithms also need information about the Rx noise power at the relay for the computation of the precoding matrix. Thus, certain mechanism is needed to make such information available, e.g. via CSI feedback. Here we focus on the 2-WRC-topology with channel reciprocity (using TDD half-duplex relay). In this case, when the channel reciprocity is perfect, the channels in the BC phase are identical to the MAC phase. Thus, after channel estimation in the MAC phase, all CSI are available at the relay for the computation of the AF precoding matrix. In other words, no CSI feedback is necessary.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Relay node (general)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relay antenna height</td>
<td>Outdoor relay: 5 m</td>
</tr>
<tr>
<td></td>
<td>Indoor relay: 2.5 m</td>
</tr>
<tr>
<td>Min. distance between RN and eNB</td>
<td>≥ 35 m</td>
</tr>
<tr>
<td>Min. distance between UT and RN</td>
<td>Outdoor relay: &gt; 10 m</td>
</tr>
<tr>
<td></td>
<td>Indoor relay: ≥ 3 m</td>
</tr>
<tr>
<td>Relays per macro cell</td>
<td>1 to 5</td>
</tr>
<tr>
<td>Penetration loss (relay to UT)</td>
<td>RN with outdoor antenna to UT: 20 dB</td>
</tr>
<tr>
<td></td>
<td>RN with indoor antenna to UT: 0 dB</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Access link</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna configuration (relay–UT)</td>
<td>Omni-directional</td>
</tr>
<tr>
<td></td>
<td>2 Tx, 2 Rx antenna ports</td>
</tr>
<tr>
<td></td>
<td>4 Tx, 4 Rx antenna ports</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Backhaul link</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna configuration (macro–relay)</td>
<td>Directional</td>
</tr>
<tr>
<td></td>
<td>2×2 or 4×4</td>
</tr>
</tbody>
</table>

Table 4: Selected relay model parameters [43]

However, channel reciprocity is not straightforward in practice:

- Even when the radio channel is reciprocal, the RF components at the Tx and Rx of the same transceiver usually have different transfer functions, which are parts of the effective channels. To overcome this problem, either a calibration of the Tx and Rx chains or a proper transceiver design, e.g. [48], is needed. Except for the different transfer functions of the RF components, each equivalent channel can have different gains in the MAC and BC phases, e.g. due to power control. Thus, when reusing the channel estimates of the MAC phase for the BC phase, these channel estimates have to be properly rescaled.

- In both MAC and BC phases, each Rx path receives signals from multiple Tx paths simultaneously. For a common training sequence for time synchronisation, the effective channel is the overlapped version of multiple channels. The overlap of different channels will result in variation of the frame starting point in each Rx path. As a result, each effective BC channel can deviate from the corresponding
MAC channel by a delay (negative/positive) in the impulse response, resulting in corrupted reciprocity. To overcome this problem, the relay should compare the different overlaps of the corresponding channels (based on the channel estimation in the MAC phase) and compute the possible delay values mentioned above. Afterwards, these delay values should be sent to the BS/UT in the BC phase for delay compensation.

Finally, if necessary, each BS/UT should measure their Rx noise power and send it to the relay in the MAC phase. Note that in practice, the Rx noise spectrum is slightly frequency selective. Furthermore, different Rx paths may have different noise power. Therefore, the noise spectrum should be estimated separately for each Rx path.

### 2.7. Business and standardisation feasibility

What has been already proved by the industry partners interest within the 3GPP and its standardisation developments, was the interest in relay nodes and various relaying techniques. So far, two general classes on the relay nodes were considered: stationary relays and mobile relays.

Stationary relays were the first of the relay nodes being standardised by the 3GPP in the E-UTRA Release 10 timeframe, as one of the main LTE/A functionalities. It was seen as a tool to improve cell coverage for high data rates, group mobility, temporary network deployment, the cell-edge throughput and to provide coverage in new areas [43], [49], [50]. The main feature of the relay node with respect to the typical eNB, was the wireless link to the donor cell, where multiple relays might be connected to the same cell. Relays are assumed to be owned by the network operators and deployed in indoor or outdoor scenarios. Additionally, a through-wall scenario was also considered in the frame of the standardisation work.

From the spectrum usage point of view, two options were considered – in both, it shall be possible to operate the eNB-to-relay link on the same carrier frequency as eNB-to-UT links:

- **Inband relay**: eNB-relay link shares the same carrier frequency with relay-UT links;
- **Outband relay**: eNB-relay link does not operate in the same carrier frequency as relay-UT links.

From the UT point of view, relay node might be transparent or not, indicating whether the terminal is aware of being connected to the network via the relay, or not. Moreover, relay may be part of the donor cell (relay without CellID): smart repeaters, decode-and-forward relays, different types of layer 2 relays, and type 2 relays are examples of this type of relaying. Alternatively, relay might control cells of its own (unique CellID is assigned to relay). Not all of the relaying options above mentioned, were considered to be included into the standard.

Creation of the mobile relay specification work was accepted in 2011 timeframe. Mobile relay functionality is different from the stationary relay, as it is supposed to be an access point mounted on vehicle wirelessly connected to the macro cell, where the only deployment scenario foreseen was the high speed train case (up to 350 km/h). Main purpose behind it, was the provision of multiple services of good quality to the group of high speed users, which are experiencing high penetration loss of the radio signal through the carriages shields, as well as significant Doppler frequency shift phenomenon. Furthermore, signalling for the handover purposes can be significantly reduced by the mobile relay feature.
Shared relay, as proposed in this report, might be another class of the relaying techniques adopter by the 3GPP for the global standard creation, for cellular networks purposes. For the high level business feasibility study of the presented shared relay concept and its potential implementation in cellular networks, we attempt to perform a SWOT and a business model canvas analysis [51]. As multiple relaying techniques were presented in this work, we perform general analysis.

2.7.1. **SWOT analysis for shared relay nodes**

SWOT stands for strengths, weaknesses, opportunities and threats. Such an analysis is seen as a valuable tool for the evaluation of new business cases, being able to provide answers to general questions and to show tendencies related to the evaluated case.

**Strengths**

- WNC as solution to overcome orthogonal spectrum sharing scenario drawbacks (performance, interference consideration, relaxed requirements for additional spectrum resources);
- Possibility to share the relay node infrastructure by many network operators, at the same time, location and radio channel;
- Performance gains of various relay sharing techniques;
- Improved spectrum utilisation and efficiency;
- Reduced relay node complexity comparing to typical base station;
- Shared relay nodes and WNC might reuse current network structure;
- Hardware enablers are considered to be already available in the networks (SDR, DAC etc.);
- Potential to use the E-UTRA network as the basis for WNC, e.g. due to OFDM and CP features;
- Possibility to reuse the already standardised relay nodes infrastructure as the basis for the presented concepts, e.g. multi-antenna configurations;
- More flexible resources assignment and scheduling, due to non-orthogonal spectrum sharing usage;
- Possibility to employ proposed schemes in the current frequency plans;
- Operator's own subscribers service shall not be impacted.

**Weaknesses**

- Increased network complexity, e.g. increased signalling, scheduling process;
- Application in the real deployments might be limited due to the network structure and legacy architecture and nodes locations;
- Computational complexity of the node is considered limited comparing to macro BS, but still might be high due to newly proposed L1 techniques;
- In case of half-duplex mode relay, limited applicability of the relaying scenario;
- RAT specific issues might appear, e.g. system architecture and interfaces;
- Terminal complexity increase, e.g. multiple Rx signals to be considered from various relays and other terminals;
- Time and frequency synchronisation might be required in shared relay;
- Shared relay availability will be location dependent.
- RAT specific standardisation requirements estimation:
Resource sharing between operators

- Inter operator interface;
- Channel estimation consideration (pilot structure);
- Channel state information exchange mechanism;
- Network configuration information availability.

Opportunities

- In the long term, it might enable more cooperation between competitors, once initial gains are identified;
- Opportunity to allow new network evolution model, with third party players owning the shared relay architecture;
- Potential extension for multi-operator cooperation scheme (cheaper spectrum acquisition);
- Innovation potential of the novel layer 1 techniques (IPR potential);
- Possibility to obtain new revenue flow (once enabling non orthogonal spectrum usage on owned spectrum bands);
- Potential extension for multi-operator cooperation scheme for more flexible spectrum allocations;
- MNO coalition formation might be seen as attractive tool against an operator not participating in such cooperative spectrum sharing (subject to regulatory monitoring);
- Market competition might motivate network operators to cooperate.

Threats

- RAT specific limitations (depending on the spectrum band regulations);
- Potential reluctance of the operator to employ non-orthogonal spectrum sharing technique (interference avoidance concerns);
- Possible concern for MNO to enter the cooperative action with the competition;
- Scenario might require case specific set-up;
- Potential frequency bands feasibility limitations in the inter-operator scenarios;
- Potential regulatory limitations of such sharing coalition formation due to a monopoly risk;
- Competitive solutions might limit benefits from the presented concepts;
- The expected gains might be limited, depending on the load the other networks;
- Operators might not be interested, as they have sufficiently high amount of spectrum which is underutilised – risk of potential IPR conflicts.

2.7.2. Shared relay business model canvas

Key partners

- Strategic partnership between MNO as business case enabler;
- Cooperation motivated by the additional radio resources availability;
- Telecom equipment vendors for shared relay’s infrastructure: buyer supplier relation;
- Software developers (internal resources or outsourcing) for implementation of the relaying mechanism.
Key activities

- Identification of the potential MNO interested in cooperation;
- Creation of the inter MNO alliance;
- Creation of the business link between MNO sharing relay infrastructure and spectrum for non-orthogonal sharing;
- Formulation of the potential inter operator charging mechanism and pricing;
- Identification of possible network infrastructure and UT issues with regard to planned spectrum sharing;
- Identification of own capabilities to assign certain amount of spectrum for non orthogonal sharing.

Value proposition

- Improved service availability for subscribers (more radio channels available);
- Improved network coverage for subscribers;
- Overall subscriber experience enhancement (applicable for all MNO participating in sharing).

Customer relationship

- Focus on customer retention by their service perception improvements;
- Customer relationships to focus on the automation;
- Cooperating MNO as special case of customers.

Customer segment

- Current customer segmentation to be targeted and current segmentation kept as reference;
- In case of extended spectrum granting to other operators, they also became a separate group of customers.

Key resources

- Running networks;
- Current delivery chains;
- Experienced employees;
- Spectrum resources (own and shared);
- Inter-operator partnership.

Distribution channels

- Mobile service distribution channels to be unchanged;
- In case of extension of the offer, same channels can be utilised;
- In case of non orthogonal spectrum sharing, spectrum grants to be assigned by automated mechanisms, e.g. X2 interface.

Cost structure

- Business case mainly being value driven, with cost awareness;
- Shared relay hardware/software investments for functionality implementation;
- Network operational expenses (OPEX) expected at current level;
- Potentially, inter-operator charges based on the additional spectrum usage (based on the internal agreement between operators) – variable costs.
Revenue streams

- Regular revenue from the subscriptions fees, being customer segment dependant – mostly fixed prices;
- Potential, variable revenues generated by the non orthogonal spectrum sharing from other MNO, as the usage fee.

2.8. Conclusions and further developments

Spectrum sharing between operators in cellular networks can provide a gain in terms of customer satisfaction as well as revenue for operators [52].

In the current report, the potential of sharing a relay (infrastructure) and the same band (spectrum) is studied. In a multi-hop interference network model, intermediate (relay) nodes receive a superposition of codewords from different transmit nodes. In the White Paper it is shown how novel physical layer network coding can improve the achievable individual data rates. The relay nodes act as shared parts of the infrastructure and forward the received codewords by different strategies (decode or amplify or compress and forward). Practical aspects for the hardware, the synchronisation and for obtaining channel information are outlined. As a special case the two-hop multicast interference channel is considered and the achievable performance of compute and forward or network coding in combination with decode and forward is compared. The signal processing for two special scenarios: two-way relaying and instantaneous relaying is described. Link and simplified system level simulations indicate the performance gain on the physical layer. The feasibility of the envisioned approaches in terms of business models and standardisation are described.

In conclusion, spectrum and infrastructure sharing shows a clear benefit in terms of data rates and in terms of feasibility from business and hardware side.
3. Full sharing of resources among wireless operators improves network performance at system-level

3.1. Introduction

Growing mobile traffic demands and their forecasts for the coming years (as estimated e.g. by Cisco in [53] or discussed by Qualcomm in [54]) are indicating, that the traffic increase will not be possible to be secured by currently deployed network architectures. Therefore, new system architectures will be required, taking into account such aspects like spectrum resources availability, deployment and operational costs, as well as power consumption. At the same time wireless network operators would be forced to investigate new forms of efficient usage of their resources, especially avoiding resource wastage and/or underutilisation. Thus, solutions are sought that combine the effort towards an improved transmission efficiency over the wireless medium as well as coordination among the diverse agents involved in the transmission. Those agents are considered primarily as the multiple operators and their transmission equipments. The general principle may be extended to include also the mobile terminals, infrastructure relay nodes, third party nodes also acting as relays (such sharing scenario was studied in Chapter 2), and even centralising RAN architectures. Studies of this kind can also be framed in the context of game theory [55], which is receiving considerable attention from the scientific community for what concerns its application to wireless communications.

In this work, we focus on a conventional RAN comprising a deployment of base stations over the cellular area. This is still the most common kind of infrastructure for a cellular network, even in light of the latest LTE, as well as its evolution in the form of LTE/A standard releases [15]. Thus, we will focus on full resource sharing as a (possibly total) coordination among the BSs. To realise these efficiency improvements, many researchers [56], [57] have proposed techniques based on mutual cooperation among different wireless agents of the same network.

We are interested in investigating cooperation among multiple network operators, especially related to physical and medium access control techniques, and expressed in our context as sharing of physical resources. This approach can achieve efficient usage of the available transmission bandwidth and improve performance by means of spatial and frequency diversity, and we aim at quantifying the benefits brought in terms of throughput and network capacity. In the SAPHYRE project, this has been specifically dubbed as SAPHYRE gain, i.e. a quantification of the comparative network performance gain due to resource sharing [7]. The end goal is to give directions to the operators towards solutions where the adopted sharing paradigms can improve the technical performance of the networks, and therefore lead to improved satisfaction of the users as well as higher revenues.

In more detail, one first resource to be shared is the wireless frequency bands the network operators are licensed to. This leads to the so-called spectrum sharing scenario, where multiple network operators that manage neighboured cells mutually exchange their available frequencies, so as to form a common pool of resources.

The operators can push this sharing concept even further, by extending it to their infrastructures. In this sense, some solutions already appeared in the past aiming at

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Note that other sharing scenarios were also addressed within the SAPHYRE project, for example shared relay nodes scenario, see Chapter 2.
decreasing the OPEX to manage the infrastructure [58]. This approach was originally meant just for sharing the antenna site among multiple operators and saving renting costs. However, the scientific challenge of such an idea would be rather limited and also its applicability would be difficult, due to regulatory constraints imposed by anti-trust agencies.

A completely novel hardware sharing vision for a RAN architecture is presented in [59] where the processing traditionally performed in the base stations is moved into a central unit and connected via high-speed links to spatially distributed transmission points. The benefits of this vision are clear: to use an intelligent network deployment, by dynamically assigning one of more transmission points to some processing resources in the central unit, as a function of the load. Moreover, the site-footprint would be reduced. Such infrastructure sharing leads to significant reductions in total cost of ownership (TCO), in particular in markets where the cost of fibre deployment and then site-rent, represents a big portion of the costs [60].

A technical solution of much greater interest involves the coordinated access to the wireless spectrum performed from multiple points of the network. This leads to an operation mode resembling the so-called CoMP [9], but envisioned in a multi-operator context. Indeed, infrastructure sharing would exploit cooperation in realising a joint resource usage without sharing their material property. Physical layer cooperation would only require exchange of information, i.e. an immaterial good. Especially, we envision infrastructure sharing as a practical way to infer knowledge of the channel condition for any pair of transmitting and receiving antennas, which is required for the beamforming to be effective. CoMP techniques could be implemented natively at the centralisation points.

After reviewing the requirements and the consequences of both spectrum and infrastructure sharing, we will discuss the possibility of merging the two concepts in a full resource sharing paradigm and finally present some evaluations of the resulting scenario. The results seem to imply that a SAPHYRE gain is indeed available. For the best scenario tested, the specific value of the gain is about 15%; however, this value is strongly dependent on the number of users, the scheduling policy adopted, the objective of the resource allocation and the cell topology. For complexity reasons, the system-level evaluations presented here are affected by limitations in the number of cells, users and antennas per transceiver, and therefore the full potential of resource sharing is surely higher in larger scenarios if a joint optimisation of the scheduling and allocation policies is performed, e.g. as foreseen in RAN centralisation. Still, even these preliminary evaluations seem to prove that full resource sharing is worth to be implemented and to be further explored.

3.2. State-of-the-art

Currently, wireless cellular networks use the radio spectrum and the infrastructure so that interference is avoided by exclusive allocation of frequency bands and employment of proprietary base stations. In particular, although effective in interference avoidance, the exclusive allocation of frequencies is inefficient since (i) unused frequencies by one operator cannot be further utilised, leading to resource wastage, and (ii) multi-user diversity is limited to the portion of band an operator has been assigned to. One main idea of the SAPHYRE project is that upon agreement of the operators to share a fraction of their licensed spectra, these drawbacks may be overcome.
Full sharing of resources among wireless operators improves network performance at system-level

It has to be kept in mind, that the sharing initiatives in mobile networks might be subject to verification by the national regulatory bodies, who might be concerned about the competition issues in the mobile services market. With this respect, the European Commission (EC) has formulated a list of objectives for national regulatory authorities to be taken into consideration [61]. This directive within the regulatory framework of electronic communications networks and services covers aspects as competition on the market, efficiency of the spectrum usage and management, customer benefits protection, radio interference limitation, infrastructure investments promotion, etc. Furthermore, the EC has recently declared willingness to create the framework for spectrum sharing among multiple technologies and players, by formulation of objectives towards the harmonisation of the spectrum allocations and rules for mobile broadband [62]. The EC was of the opinion that there should be incentives for spectrum license owners to offer radio resources to other market players, e.g. in sharing the infrastructure investment cost. This action has been triggered following similar recommendation declared by US regulators.

Many solutions are investigated by the scientific community, where wireless communications utilise either spectrum [63] or infrastructure sharing [64], [65]. We briefly review these proposals, with a broader end goal in mind, i.e. to understand whether and for which scenarios spectrum and infrastructure sharing can coexist at the same time, so as to enable full resource sharing.

The idea of spectrum sharing applies when the considered spectrum resources, in the form of radio channels, are shared for multiple purposes, usually to serve multiple subscribers or operators. In the context of this work, we are focusing on the spectrum sharing among network operators, who exchange their available frequencies, so as to form a common resource usage. If all the frequencies dedicated to each operator are in common, we refer to full sharing; otherwise the sharing is partial and some frequencies are reserved to the original users only for their exclusive usage. Spectrum sharing may be further classified into two kinds of scenarios, more precisely, orthogonal (i.e. mutually exclusive) and non-orthogonal spectrum sharing.

In the former scenario, frequency subbands are simply mutually exchanged, so that the usage is still exclusive by one operator. This form of spectrum sharing can consider various granularity of spectrum resources for the sharing mechanisms implementation. LTE/A access technology seems to be suitable for spectrum sharing implementation due to its physical layer design in the form of orthogonal OFDM subcarriers, which are further assembled to form E-UTRA channels. Such design of the physical layer, being complemented with appropriate multi-operator radio resource management, seems to be the best choice for future developments within standardisation bodies, for future networks designs. Orthogonal sharing is relatively simple to implement, but achieves a relevant SAPHYRE gain only in asymmetric scenarios, i.e. whenever some of the operators have a relatively low number of users to serve or some unused frequencies. In fully loaded scenarios, the gain achievable thanks to the increased multi-user diversity is marginal if the number of users is large [66].

Moreover, game theory principles could be exploited for the spectrum pool access modelling. Performance of such mechanisms was studied for HSPA as well as for LTE networks [66], [67]. Furthermore, business modelling aspects of various spectrum sharing scenarios were also studied [63].

In the scenario of non-orthogonal spectrum sharing, every frequency subchannel can be used by multiple operators at the same time. As a consequence, it can aspire to larger
SAPHYRE gains [68], provided that interference is controlled so as to guarantee a good SINR at the intended receivers. In fact, when multiple users are allocated on the same frequency simultaneously, interference arises and must be coordinated through the use of multiple antenna at the BS and proper mitigation techniques, such as beamforming [69]. Depending on the effectiveness of the used beamforming technique, a much higher gain can be achieved; in principle, there could even be a full reuse of the entire spectrum. However, the gain is limited by difficulties in communication among the BSs which should gather knowledge on the channel conditions between every user, including those served by other operators.

In both cases, a 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 [55]. An approach involved in the effort of finding practical ways of sharing the wireless spectrum is cognitive radio [56], [70], where primary users are the license-holders of a spectrum band and secondary users can communicate without interfering the primary users. In particular, the latter (cognitive radios) need to be more sensitive than the former, since they can communicate only if they cannot hear any primary transmission. A suitable mathematical tool dealing with this scenario is game theory since decision-making strategies are defined when a player moves first and another reacts subsequently. Moreover, the fact that spectrum availability problems are due to inefficient usage by licensed users rather than to a real lack of available frequencies, motivates a proper game theoretic analysis where egoistic players are given incentives to cooperate [55].

The most basic form of infrastructure sharing is based on the joint use of the transceiver elements of the network, e.g. masts, antennas. More advanced infrastructure sharing scenarios can consider multi-operator RAN (MORAN), or multi-operator core network (MOCN) [64]. In Figure 33, different scenarios of infrastructure sharing are compared in terms of percentage of sharing, cost and control on the operators.
Full sharing of resources among wireless operators improves network performance at system-level

There have already been few examples of infrastructure sharing enabling on national telecom markets within Europe. For example, Switzerland’s telecom regulator (ComCom) allowed 3G licensees to share their parts of the infrastructure. Due to the fact that radio infrastructure of mobile networks is rapidly developing, and sharing might be subject to competition policy, this form of the sharing was declared to be verified on the case-by-case basis. Further examples of infrastructure and spectrum sharing initiatives across the Europe were reported in [71].

Besides reducing operational costs, the infrastructure sharing approach may help improving channel quality, counteracting channel fades and offering additional spatial diversity to the system. However, strong cooperation among different operators is required. For example, channel information collected individually by the BSs must also be shared to achieve performance improvements [57]. The CoMP approach [9] is an extension of this concept. CoMP can be either intra-site if different sectors referring to the same base station cooperate, or inter-site if cooperation is among base stations. The techniques aim at avoiding interference or exploiting it improving the system throughput.

This triggers the investigation on how multiple operators can coordinate in a way as to exchange mutual full knowledge of the channel conditions between each transmitter-receiver antenna pair. The SAPHYRE project addresses this point within infrastructure sharing, meant as coordinated usage of the available antenna equipment at the BSs of all the involved operators. In the following, we describe how beamforming can be performed in a network-wide scenario as well as which additional requirements are imposed on the BSs.

3.3. Transmit beamforming

Capitalising on the availability of multiple antennas at the base stations, transmit beamforming techniques can be used to mitigate the interference [69]. These techniques are typically used in single-operator cellular networks with aggressive frequency reuse factors; herein, we employ them to manage inter-operator interference in the context of non orthogonal spectrum sharing. The simplest of these techniques is zero-forcing (ZF) which maximizes the link rate under the constraint of generating no interference to the users served by other operators on the same channel. ZF is in general suboptimal because this constraint can be too restrictive.

Performance improvement is expected if one selects another Pareto efficient allocation of rates to the users, where Pareto efficiency means that no user can further improve its rate without at least another user being worse off. In particular, in the following we will choose as a paragon the sum rate (SR) allocation, which aims at selecting the allocation that gets the highest sum rate on the Pareto efficiency boundary.

This kind of allocation requires a joint design of the beamforming vectors by the involved base stations, and therefore requires coordination and information exchange among them, an issue that will be further addressed by implying infrastructure sharing besides spectrum sharing. Moreover, SR also implies to be reflected on the scheduling procedure of the users, also aimed at selecting the users with highest achievable rates [68]. Finally, SR tends to favour the users with the best channel conditions.

Fairer outcomes of the resource conflicts arising due to spectrum sharing can be achieved by alternate allocation techniques, e.g. the Nash bargaining technique, which distributes the rate gains due to cooperation, taking into account the rates that would be obtained without cooperation [72]. The investigation of such techniques is out of the scope of the
Resource sharing between operators

present white paper; the interested reader can find an in-depth analysis in [68]. Here, we simply refer to the SR policy as a reference for the system-level application of beamforming techniques in a full resource sharing context, since it enables a simple evaluation of the SAPHYRE gain with respect to a fixed spectrum assignment, where a certain frequency is only accessible by UT of one single operator.

Without loss of generality, we describe SR beamforming in the case of two operators, A and B, each serving from their BSs one of their users, which achieve rates $R_A$ and $R_B$. For now, we assume that the BSs are adjacently located, so that both users receive the sum of the transmitted signals. The Pareto boundary limits the achievable region of the pair $(R_A, R_B)$, consisting of the operating points for which it is impossible to improve one of the rates, without simultaneously decreasing the other [72]. For the two-user MISO interference channel with perfect channel state information available at the BSs, it has been proven that any point on the Pareto boundary is a linear combination of the beamforming vectors of ZF and those of another technique, the maximum-ratio transmission (MRT) beamforming [73], which is a Nash equilibrium of the system. Thus, the Pareto boundary can be found with the computationally efficient closed-form method in [74]. Using this method, the SR allocation is the point maximising $R_A + R_B$, while the Nash bargaining solution maximises the product $(R_A - R_A^*)(R_B - R_B^*)$, where the $R_j^*$ values are those achieved by MRT.

Above the physical layer abstraction several allocation and scheduling mechanisms may be considered. In particular, we consider that for the basic scenario of fixed spectrum allocation the BSs of both operators independently select one among their users per each of their subcarriers, which are exclusively used. Orthogonal spectrum sharing can be seen as the result of an assignment over the aggregated spectrum comprising both bands of operators A and B performed by a single scheduler [75], which implies a greater scheduling freedom and hence enhances multi-user diversity gains. However, spectrum is still shared orthogonally, therefore any subcarrier is assigned to a single user only. Finally, for non-orthogonal sharing the same allocation can be performed but each subcarrier can be assigned to (at most) two users, exploiting beamforming techniques to coordinate the mutual interference.

For each level of spectrum sharing, different scheduling principles can be applied. To directly evaluate the SAPHYRE gain, we focus on the channel-adaptive maximum sum-rate discipline. Equivalent to the commonly known “maximum SINR” scheduler, this scheme aims at optimising cell throughput by selecting those users with the highest sum of attainable bit rates. This choice is reasonable when applied together with SR beamforming. Other techniques, such as proportional fair scheduling that tries to establish an exponentially smoothed time average of experienced bit rates could be preferable if higher user fairness is desired by the operators.

Finally, we note that a practical implementation of SR beamforming techniques should exploit full knowledge of the channel gains between every transmitter-receiver antenna pair. In this section, we address this information exchange by assuming it for granted through full resource sharing on the infrastructure side. Several PHY studies [76] are actually devoted to investigate partial or imperfect exchange of channel information, and the promising general result is that a considerable fraction of the available gain is still available if the number of users per BS is sufficiently high, a condition which is reasonable in practice, given the premises of this study.
3.4. Base station requirements and constraints for full resource sharing

We now discuss the additional requirements which are necessary for BSs to perform the proposed resources sharing methods. In this paper, we consider the requirements for a full sharing scenario where different operators use the same radio access network and share the same spectrum or several spectrum ranges commonly. In a full sharing scenario, a BS within a shared RAN has to fulfil the following additional requirements.

Due to spectrum sharing, the radio chains of the BS have to operate on an increased frequency bandwidth, as the pooling of the licensed spectrum of two operators results in increased amount of spectrum. A BS can achieve this by either increasing its operating band or aggregating carriers. A generic complexity increase is in order, which is however bearable by the current BS capabilities, see Chapter 1. Also, a further advantage of spectrum increasing is the overhead reduction on the control plane and the avoidance of guard bands. The advantage of aggregating carriers is the backward compatibility and the feasibility of the usage of non continuous spectrum.

The RAN shared by the two operators has to serve the end users of both of them. Assuming a single operator has a given number of end users, the BS could serve a 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. Increasing the number of users, the number of data flows and corresponding connection contexts would increase. The scheduler has to schedule an enlarged number of traffic flows per TTI. Every logical connection has a specific 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. Moreover, according to an enhanced throughput on the wireless interface, for enhanced features like CoMP and for introduction of RAN centralisation, the BS has to provide appropriate backbone capability.

If a BS is used by two or more operators, additional management functionalities are needed. 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 the use of BS virtualisation where a physical BS hosts two or more virtual BSs. This approach requests additional resources for hardware and additional software functionality, i.e. virtual machine monitor and virtualised network components.

The requirements for BSs to achieve the full sharing scenario are mainly fulfilled by a general capacity enhancement for spectrum, power processing and backbone capacity. Additional processing resources are required for handling an increased number of users and enhance operator management. BSs which will be available on the market in the next few years have to be compliant to the 3GPP Release 10 [15] and subsequent releases. Some key requirements of 3GPP Release 10 are spectrum ranges up to 100 MHz and carrier aggregation. A BS which fulfils these requirements may also be enabled for sharing scenarios regarding spectrum ranges and multi-carrier as proposed in SAPHYRE. Furthermore, future trends like Cloud RAN or centralised BS pools will also provide the previous described requirements, adding requirements to the connection of the BS like the availability of dark fibre and regulatory aspects for sharing it [60], [77].
3.5. Performance evaluation

We now describe some evaluations that enable the assessment of the SAPHYRE gain in a full resource sharing scenario, where we adopted non-orthogonal spectrum sharing and co-located base stations that exchange full information about the channel estimations of their end users.

The main system parameters follow the specification imposed by the standard [78] using a propagation model that include shadowing, multipath fading and pathloss [68].

Figure 34 compares the average throughput versus distance of the users from the BS in the case of fixed spectrum assignment with no sharing, orthogonal and non-orthogonal sharing; we consider four antennas for two coordinated single-rank users. For all the cases we consider a maximum sum rate scheduler; the non-orthogonal sharing case includes two kinds of beamforming (ZF and SR). In this specific scenario, ZF and SR perform closely, which is due to the fact that each BS has a relatively large number of transmit antennas and the SNR of the users is in general high, given that the users are close to the BS. Thus, inter-operator interference is the main limiting factor and it is effectively nulled with either the SR or ZF technique. With fewer transmit antennas or lower SNR, larger differences can be expected, especially showing a more favourable performance of SR.

![Figure 34: User throughput vs. distance to serving BS comparison](image)

More in general, the following conclusions can be drawn from the simulation results. The SR technique outperforms ZF in the average user throughput. However, this advantages can be lost in the system-level simulation results. This is mainly due to the fact that the applied packet scheduling compensates such advantages/disadvantages, by selecting the most proper user pair for joint transmission. Also, an overall advantage of non-orthogonal spectrum sharing in the average system throughput can be observed compared to the orthogonal spectrum sharing and fixed spectrum assignment. Moreover, the study can be extended to a wider scenario set-up where multi-user diversity is exploited even further, e.g. by considering a higher number of transmit antennas or multiple data flows per user.
Full sharing of resources among wireless operators improves network performance at system-level

To generalize these results, we consider a scenario with just two antennas at the base station, but with a larger number of users to schedule from. To give a more general quantification of the beamforming gain, we proceed as follows. Whenever a given frequency is not shared among the operator, the result is a single user (SU) allocation, as opposed to the multi-user (MU) allocation within the shared bands. In the non-orthogonal spectrum sharing, the SINR of the users is affected by the interference but is also improved by the specific beamforming scheme used by the base stations. We summarise this SINR degradation with a parameter $\alpha$, that is the ratio between the SINR in the MU case and the SINR in the SU case. Thus, in Figure 35, we evaluate how the parameter $\alpha$ affects the average throughput obtained in downlink by the base station for different percentages of sharing.

As expected the value of throughput increases in the sharing cases with the value of $\alpha$. The sharing gain is obtained when the use of a larger bandwidth balances the degradation of the SINR in the MU scheme. We further explore this investigation by comparing SR and MRT in a sharing scenario with the no-sharing scenario.
Figure 36 shows that using a non-cooperative approach (MRT) among the BS we obtain a loss due to the increase of the interference perceived by the UT. On the other hand, exploiting infrastructure sharing and the cooperation among the BSs through the SR approach, we can achieve a gain that permits to outperform the no-sharing scenario case. We notice that in our scenario we have only one user, so we cannot adopt any scheduling policy that permits to exploit the multi-user diversity and optimises the beamforming algorithms.

These results are then compared with those provided by the first simulation and finally summarised in Figure 37, where we report the SAPHYRE gain. It can be seen how the MRT technique corresponds to a value of $\alpha$ around 0.002, while the SR technique corresponds to a value of $\alpha$ included between 0.02 and 0.05.

![Spectrum sharing gain table](image)

**Figure 37: Spectrum sharing gain table**

### 3.6. Conclusions

This part of the White Paper reports the findings of the SAPHYRE project [7], whose main aim was to demonstrate how sharing paradigms in wireless networks, in particular spectrum and infrastructure sharing, improve spectral efficiency and enhance coverage, ultimately increasing user satisfaction and revenues for operators, thereby decreasing capital and operational expenses. We described and evaluated different scenarios where spectrum and infrastructure sharing were considered in the context of multicell cooperation, namely full resource sharing. More specifically, we investigated the impact of transmit beamforming techniques on non-orthogonal spectrum sharing. Our numerical results show that a properly set full resource sharing may provide a SAPHYRE gain in terms of system-level throughput, with respect to no-sharing and orthogonal spectrum sharing scenarios. The performance of the specific techniques are strongly dependent on several system parameters, such as the number of users, antennas and the specific beamforming techniques used. More importantly, the gains are significant when the number of served users in the cells is large, so that the BSs have enough degrees of freedom to efficiently schedule the users. If the number of users is insufficient, the advantages offered by multi-user diversity cannot be properly exploited.
4. References


Resource sharing between operators


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More information about the SAPHYRE project is available at http://saphyre.eu/