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Abstract

The paper describes the potential network efficiency gain for network operators by infrastructure and network sharing, which considers both infrastructure and spectrum sharing between wireless cellular network operators. The results and conclusions encourage to consider the inter-operator resources sharing scenarios and techniques as potential solutions for future networks.

Keywords

Infrastructure sharing, network sharing, inter-operator, business model, relay nodes, performance evaluation.

Contents

Abbreviations

2-SRN	2-Source Relay Network
2-WRC	2-Way Relay Channel
3G	3rd Generation
3GPP	3rd Generation Partnership Project
AF	Amplify and Forward
BC	Broadcast Channel
BS	Base Station
CF	Compute and Forward
CFO	Common Frequency Offset
CoMP	Cooperative MultiPoint
CsF	Compress and Forward
C-SI	Complementary Side-Information
CSI	Channel State Information
DCA	Direct Conversion Architecture
DF	Decode and Forward
eNB	eNodeB
E-UTRA	Evolved UTRA
GPS	Global Positioning System
GWCN	GateWay Core Network
H-BC	Hierarchical Broadcast
H-MAC	Hierarchical Multiple Access Channel
HCF	Hierarchical Compress and Forward
HDF	Hierarchical Decode and Forward
HNC	Hierarchical Network Code
HSPA	High Speed Packet Access
HXA	Hierarchical eXclusive Alphabet
HXC	Hierarchical eXclusive Code
ICF	Inverse Compute and Forward
ID	Identification
IN	Interference Neutralisation

JDF	Joint Decode and Forward
LTE(-A)	Long Term Evolution (-Advanced)
MAC	Multiple Access Channel
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MOCN	Multi-Operator Core Network
MORAN	Multi-Operator RAN
MRT	Maximum Ratio Transmission
MU	Multi-User
NC	Network Coding
NCM	Network Coded Modulation
NLOS	Non Line Of Sight
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	OPerational EXpenses
P2P	Point to Point
PHY	PHYsical layer
ProBaSeMO	Projection Based Separation of Multiple Operators
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RF	Radio Frequency
Rx	Receive
SDMA	Spatial Division Multiple Access
SDR	Software Defined Radio
SIMO	Single Input Multiple Output
SINR	Signal to Interference and Noise Ratio
SISO	Single Input Single Output
SNR	Signal to Noise Ratio
SR	Sum Rate
SU	Single-User
SWOT	Strengths, Weaknesses, Opportunities, Threats

TDD	Time Division Duplex
TDMA	Time Division Multiple Access
Tx	Transmit
UE	User Equipment
UT	User Terminal
UTRA	Universal Terrestrial Radio Access
WNC	Wireless Network Coding
WiMAX	Worldwide Interoperability for Microwave Access
ZF	Zero Forcing

1 Executive summary

Within this deliverable, two specific resource sharing scenarios are studied, which are infrastructure and networks sharing (which considered both infrastructure and spectrum sharing) between wireless cellular network operators. The report describes the potential network efficiency gain coming from those sharing schemes for participating network operators. The results and conclusions encourage considering the inter-operator resources sharing scenarios and techniques as potential solutions for the future networks.

Under the infrastructure sharing evaluation, authors present an overview of physical layer coding and processing techniques that utilise relay nodes 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 (WNC). It comprises a number of variants, some of them based on Network Coded Modulation (NCM) 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.

Second of the proposed sharing scenarios, the network sharing is considering not only the infrastructure sharing but also spectrum resource sharing. Authors investigate 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, we explore 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 equipment. This rationale leads to the proposed concept of full resource sharing, which we envision as a viable approach to future wireless networks.

This deliverable is constructed as follows: after a brief introduction of basic ideas of the topic, technical aspects of the two proposed sharing schemes are presented in Chapter 3 and in Chapter 4, respectively. System level performance evaluation on the discussed schemes are presented in Chapter 5. Requirements and hardware enablers are discussed in Chapter 6. Finally, some business and standardisation aspects of the sharing are described in Chapter 7.

2 Introduction

Growing mobile traffic demands and their forecasts for the coming years, e.g. estimated by Cisco in [1] or discussed by Qualcomm in [2], are indicating, that the traffic increase will not be possible to be secured by the 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 underutilisation. Thus, solutions are sought that combine the effort towards 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 equipment. 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 [3], and even centralising Radio Access Network (RAN) architecture. Studies of this kind can also be framed in the context of game theory [4], which is receiving considerable attention from the scientific community for what concerns its application to wireless communications.

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 operators. A major distinguishing point is however form and granularity of that sharing. An *orthogonal* slicing of the spectrum, e.g. into 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 paper focuses on more elaborate form the 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” using 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 this concept 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 extend, 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. 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, set of conceptual works. A representative set covering various angles of view includes [5], [6], [7], [8], [9]. Due to the space limitations, we skip a detailed analysis of these works, but we encourage the reader to refer to these works and references therein to get a more detailed picture.

2.2 Basic idea of network sharing

In this work, we focus on a conventional RAN comprising a deployment of Base Stations (BSs) over the cellular area. This is still the most common kind of infrastructure for a cellular network, even in light of the latest Long Term Evolution (LTE), as well as its evolution in the form of LTE-Advanced (LTE-A) standard releases [10]. Thus, we will focus on full resource sharing as coordination among the BSs. To realise these efficiency improvements, many researchers [11], [12] 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. Within the SAPHYRE project, this has been specifically dubbed as the SAPHYRE gain, i.e. a quantification of the comparative network performance gain due to resource sharing [13]. 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 neighbouring 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 decreasing the OPerational EXpenses (OPEX) to manage the infrastructure [14]. 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 [15] 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 the total cost of ownership, in particular in markets where the cost of fibre deployment, and then site-rent, represents a big portion of the costs [16].

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 Coordinated Multi-Point (CoMP) [17], 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 implementing and exploring further.

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.

It has to be kept in mind, that the sharing initiatives in mobile networks might be subject to verification by the national regulatory bodies, which might be concerned about the competition issues in the mobile services market. With this respect, the European Commission has formulated a list of objectives for national regulatory authorities to be taken into consideration [18]. This directive is within the regulatory framework of electronic communications networks and services, and covers such 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 European Commission has recently declared willingness to create the framework for spectrum sharing among multiple technologies and players, by formulation of objectives towards harmonisation of the spectrum allocations and rules for mobile broadband [19]. Moreover, 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 regulators in the U.S.A.

The scientific community investigates many solutions where wireless communications utilise either spectrum [20] or infrastructure sharing [21], [22]. 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 sub-bands are simply mutually exchanged, so that the usage is still exclusive by one operator. This form of spectrum sharing can consider various granularity of the spectrum resources for the sharing mechanisms implementation. LTE-A radio 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 Evolved Universal Terrestrial Radio Access (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 only achieves a relevant SAPHYRE gain 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 [23].

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 [23], [24]. Furthermore, business modelling aspects of various spectrum sharing scenarios were also studied [20]. In the scenario of non-orthogonal spectrum sharing, multiple operators can use every frequency sub channel at the same time. As a consequence, it can aspire to larger SAPHYRE gains [25], provided that interference is controlled so as to guarantee a good Signal to Interference plus Noise Ratio (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 antennas at the BS and proper mitigation techniques, such as beamforming [26]. Depending on the effectiveness of the used beamforming technique, a much higher gain can be achieved; in principle, there could even be a full re-use 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 [4].

An approach involved in the effort of finding practical ways of sharing the wireless spectrum is cognitive radio [11], [27], 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 problem 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 [4].

The most basic form of infrastructure sharing is based on the joint use of the transceiver elements of the network, e.g. masts and antennas. More advanced infrastructure sharing scenarios can consider Multi-Operator RAN (MORAN) or Multi-Operator Core Network (MOCN) [21]. In Figure 1, different scenarios of infrastructure sharing are compared in terms of percentage of sharing, cost and control on the operators.

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 [28].

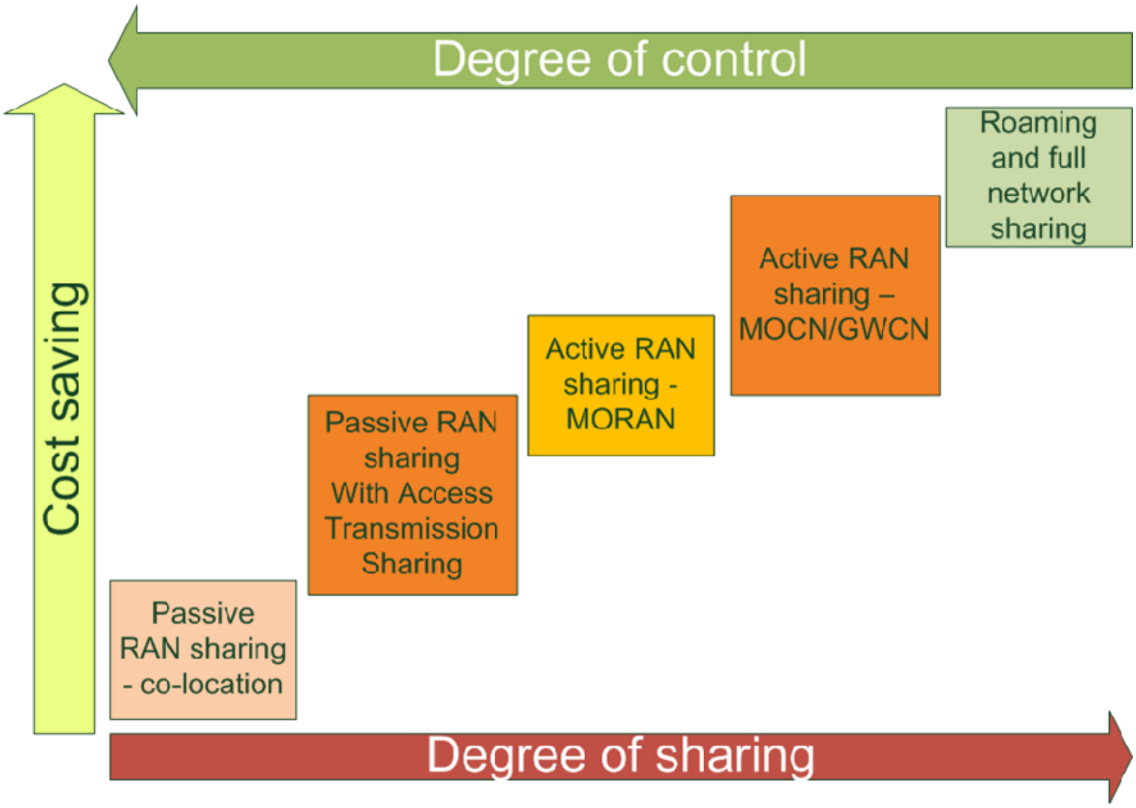

Figure 1: Comparison of infrastructure sharing cases

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 [12]. The CoMP approach [17] 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 so 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 Infrastructure sharing

3.1 System 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 the 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 physical layer (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 management*, e.g. game-theory. 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 2. The network elements are nodes. The data source and destination nodes are called terminals. Apart of the source and destination nodes, there are also the relay nodes, which are neither source nor destinations.

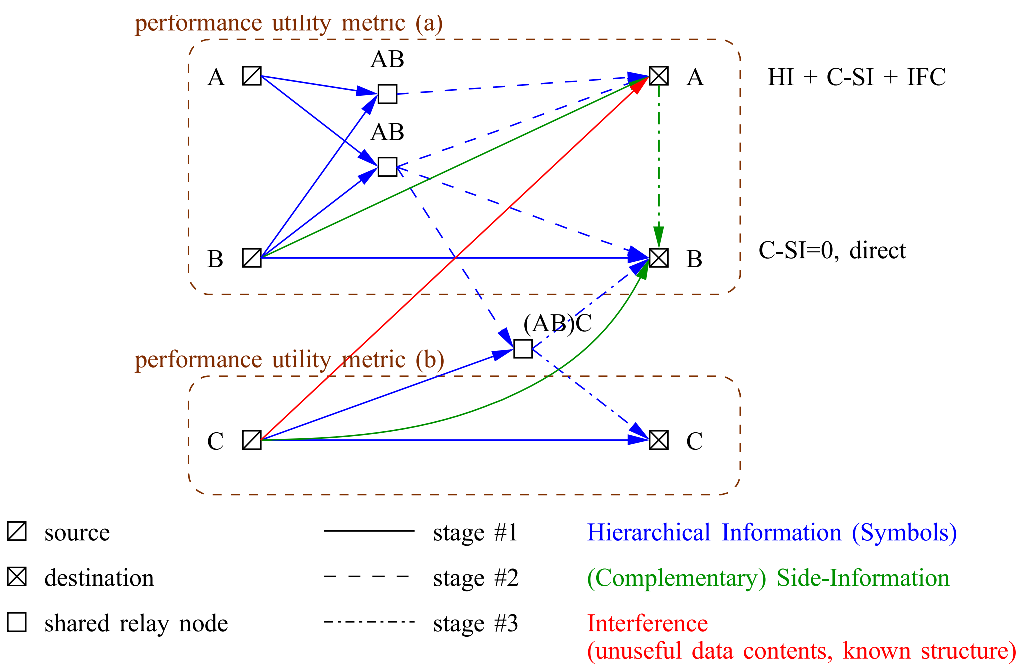

Figure 2: Ultimate scenario with wireless signal space links

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 *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 *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 signal does not carry the information about the desired data, but it carries the information about other parameters or data that helps the receiver decoding 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.

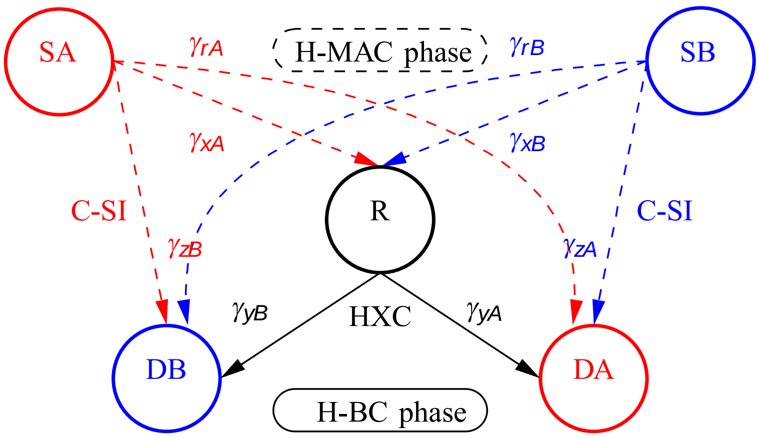

Figure 3: Butterfly network — 2-source relay network with partial C-SI

The *Butterfly network* — 2-Source Relay Network (2-SRN) as presented on Figure 3, can be seen as simplified scenario, which captures the phenomena of multiple sources, a shared common node, partial (imperfect) Complementary Side-Information (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 the Hierarchical Decode/Compress and Forward (HDF/HCF) strategy which uses Hierarchical eXclusive Code or Hierarchical eXclusive Alphabet. It uses two stages (phases): Hierarchical Multiple Access Channel (H-MAC) and Hierarchical Broadcast Channel (H-BC). The HDF strategy requires C-SI at the destination. It can be both, the perfect C-SI or partial (soft) C-SI.

3.2 Classification of the WNC technique

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

1. 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.
2. 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: (i) Amplify and Forward (AF), (ii) Decode and Forward (DF) (Joint/Hierarchical), (iii) Compress and Forward (CsF).
   a) AF relay strategy: The AF relay strategy (Figure 4) 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 the relay–destination channel is due to the added noise on that channel.

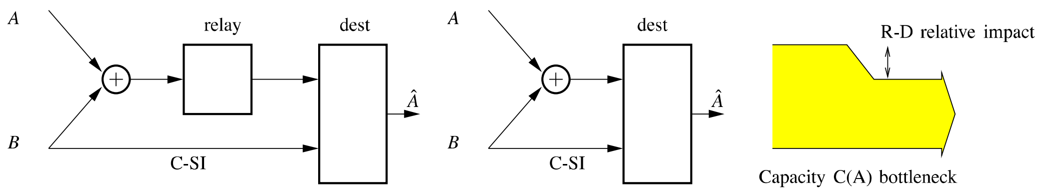

Figure 4: AF relay strategy — equivalent model: 2-WRC scenario from the A-data perspective

   b) DF relay strategy: Any decode and forward strategy (Figure 5), of arbitrary variant, makes *full decisions* at the relay. The decisions can be made on a symbol, a bit, or a codeword, etc. 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.
      i. Joint DF — the *joint simultaneous separate* decoders (symbol demappers) decode symbols from A and B separately.
      ii. Hierarchical DF — the *hierarchical codeword (symbol)* is decoded by a specific decision region mapper.

All xDF strategies have independent Multiple Access Channel (MAC) and Broadcast Channel (BC) phase bottlenecks. The particular MAC and BC throughputs depend on the strategy variant.

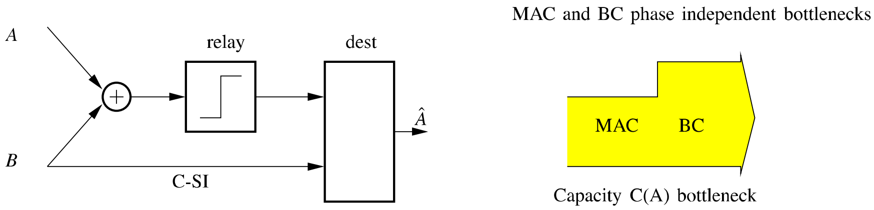

Figure 5: DF relay strategy — equivalent model: 2-WRC scenario from the A-data perspective

c) 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 6). Then the individual decision can be used for example to form the discrete NC (Network Coding) coded BC phase symbol. The JDF exists in two sub-variants depending on how the individual decisions were made. They can be done either by decoders with *separate marginalised metric* or by *composite hypothesis* decoders but regardless of this, in both cases, providing separate estimates $[\hat{d}_A, \hat{d}_B]$.

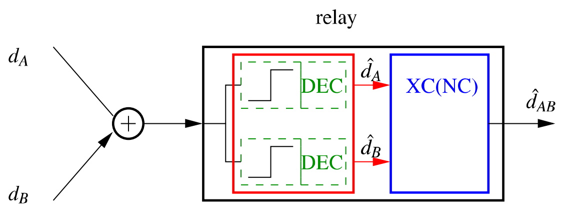

Figure 6: JDF relay strategy — equivalent model

d) 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. 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 functions of the symbols (Hierarchical Network Code map) $d_{AB} = \chi(d_A, d_B)$.

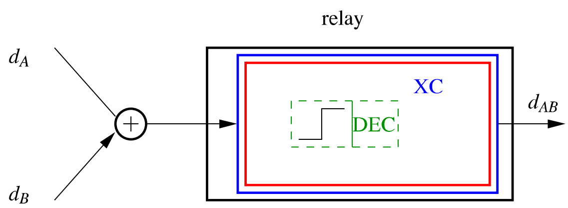

Figure 7: HDF relay strategy — equivalent model

e) CsF relay strategy: The Compress and Forward strategy (CsF; Figure 8) 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.

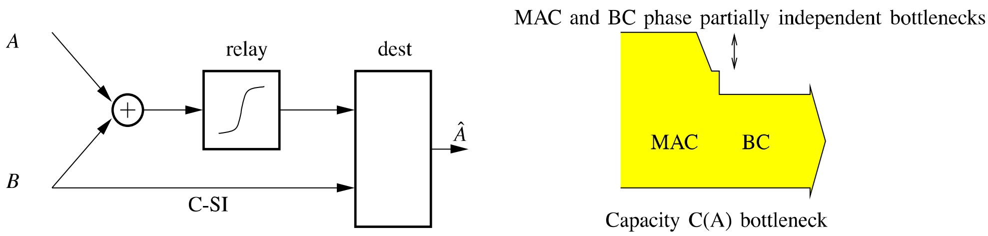

Figure 8: CsF relay strategy — equivalent model: 2-WRC scenario from the A-data perspective

3. Strategy at destination terminal: The strategy at the destination terminal refers to the demodulation/decoding technique used at the final destination. The demodulation/decoding must respect (i) multiple received signals from various relays or other terminals, and (ii) the complementary side-information 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.
4. 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 is 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 1 describes additional details.

Table 1: Summary of multi-source/node PHY techniques

	P2P-PHY	**MU-PHY**	**NC**	**WNC**
Topology: direct neighbours signal interaction (MACL)	–	+	–	+
Topology: full network structure (NET)	–	–	+	+
Signal structure: at constellation (signal) space level	+	+	–	+
Relay Tx signal codeword map: a function of data	–	–	+	+
Relay Rx signal codeword map: a function of data	–	–	–	+

3.3 Network aware coding and decoding

3.3.1 NCM and HDF strategy

The Network Coded Modulation (NCM) with Hierarchical Decode and Forward (HDF) relaying strategy is a particular example of Wireless Network Coding (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 the node sends, 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 multi-source 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 3) the gain in the MAC phase of the NCM scheme using QPSK alphabets is significant [29] (Figure 9). Asymptotically, the 2-WRC MAC phase achieves the same performance as 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 [30] is affected by the quality of the C-SI information as is shown in Figure 10.

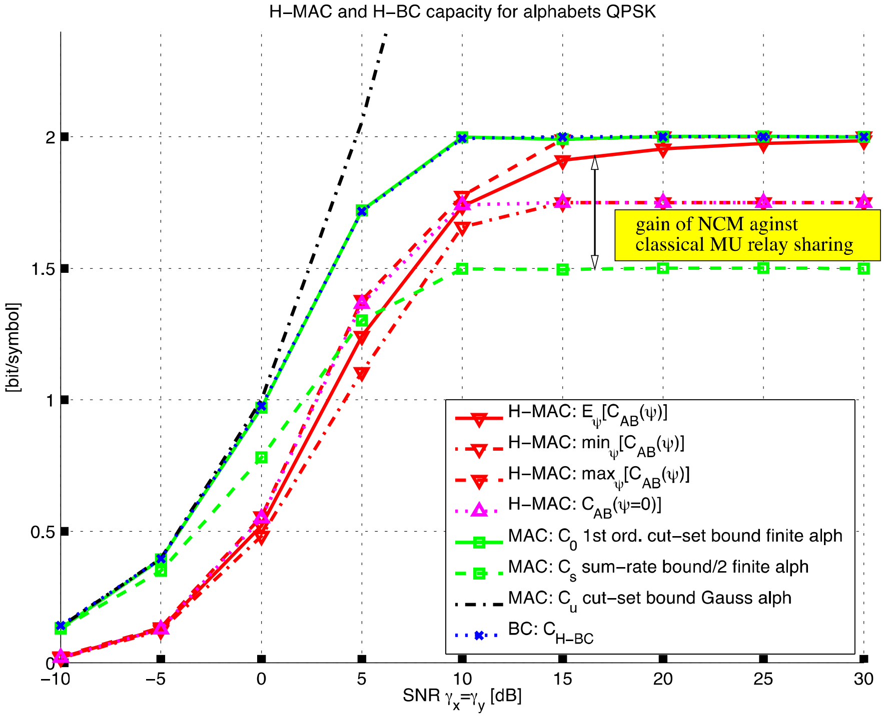

Figure 9: Capacity (mean, min./max. over all relative phase parameterisations) of MAC and BC phase (assuming reciprocal SNR) for QPSK alphabet as a function of source-relay and relay-destination SNR

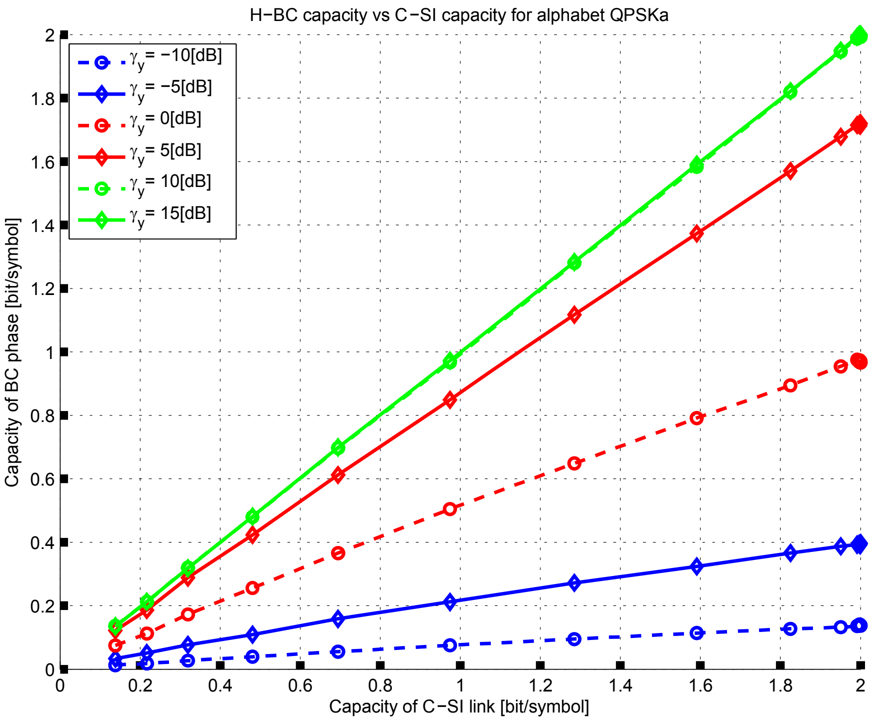

Figure 10: Capacity of BC phase of NCM using QPSK alphabet as a function of the quality of C-SI

3.3.2 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 [31] that lattice codes [32] can achieve the capacity of the AWGN point-to-point channel. The authors of [8] 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 in detail in [5]. To efficiently decode the equations that are decoded at a node, the authors of [33] 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 11. 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.

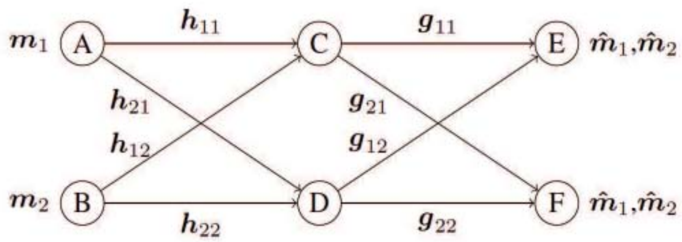

Figure 11: Two-hop X-channel with multiple antennas at the relays

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 Single Input Multiple Output (SIMO) interference channel. The vector channels g_{11}, g_{12}, g_{21}, g_{22} from the second hop form a Multiple Input Single Output (MISO) interference channel. We communicate in two phases. We compare the achievable sum-rate of this network under the following two schemes:

- Using CF at the relays and ICF at the receivers;
- Using NC with JDF.

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

We use CF at the relays. The CF computation rate is given by [8]. At the receivers we utilise the inverse CF strategy [33]. 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 12 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 $\vec{a}_i$ with a smaller norm. But since the smallest possible norm is 1, there will always be a zero rate for low SNR.

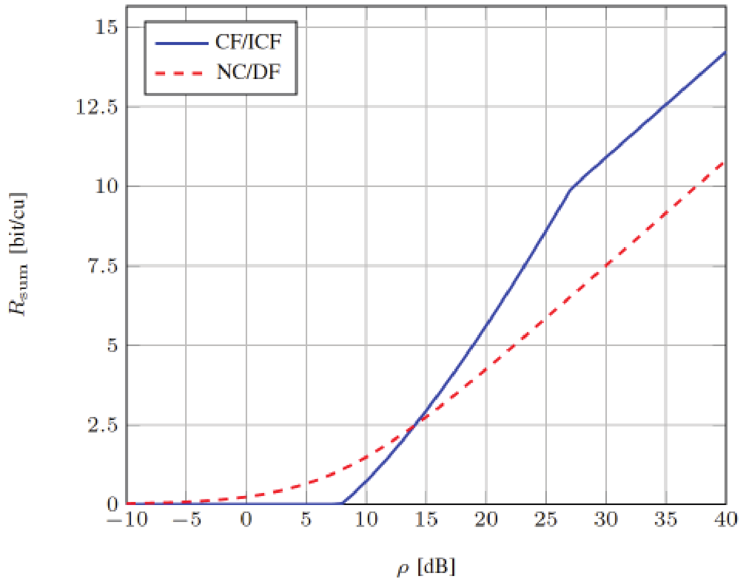

Figure 12: Achievable sum-rate for CF/ICF compared to NC/DF

3.4 Signal processing for 2-WRC

3.4.1 Bi-directional amplify and forward relaying

In contrast to the unidirectional 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 [34]. This advantage renders it very attractive for both industry and academia. Figure 13 depicts a scenario where the shared relay with multiple antennas uses a bi-directional AF relaying strategy. User Terminals (UTs) of one operator suffer from both the inter-operator interference and the additional self-interference, which is due to the bi-directional relaying protocol. While the self-interference can be subtracted at the receiver side when Channel State Information (CSI) is available, the resulting inter-operator interference needs to be managed in an efficient way such that the QoS of all UTs can be guaranteed. Inspired by decoupling of users via block diagonalisation [35] in multi-user MIMO systems, we propose a linear MIMO precoding technique, which is called the Projection Based Separation of Multiple Operators (ProBaSeMO) [36] in order 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 UTs of one operator transmit and receive in the null space of the combined channels of all the other UTs. 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 system can be applied separately on each sub-system. Such a design also facilitates the differentiation among multiple operators that share a relay.

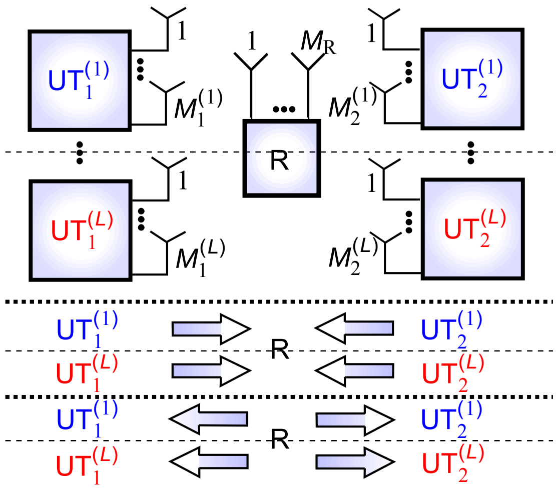

Figure 13: Multi-operator two-way relaying system model: The k^{th} terminal belonging to the l^{th} operator has $M_k^{(l)}$ antennas and the relay station is equipped with M_R antennas.

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 14 and Figure 15, 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.

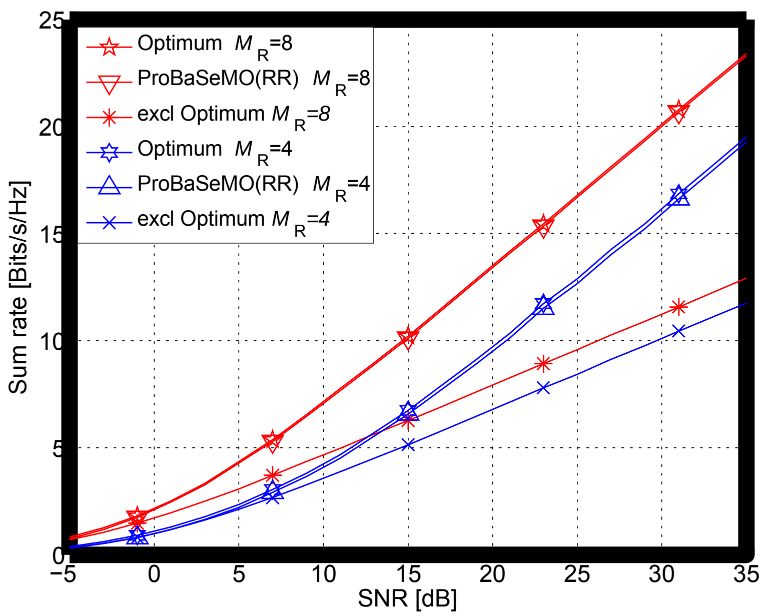

Figure 14: Sum-rate comparison of time-shared approach and ProBaSeMO approach for single-antenna nodes and L=2 (two operators); M_R: number of antennas at the relay

[1] The relay is accessed by different operators in a TDMA way.

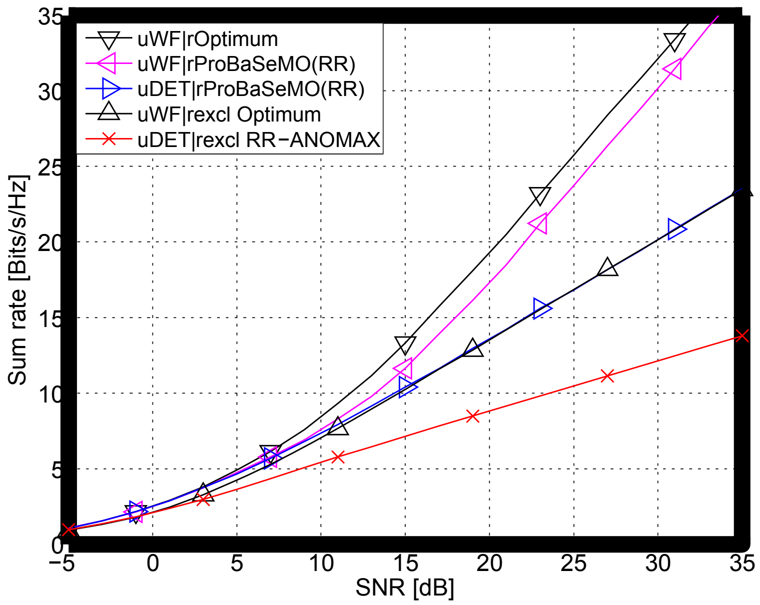

Figure 15: Sum-rate comparison of difference 2-WRC approaches for two-antenna nodes with 8 antennas at the relay and L=2 (two operators); uWF: multiple-stream transmission; uDET: single stream transmission; rOptimum: steepest descent method

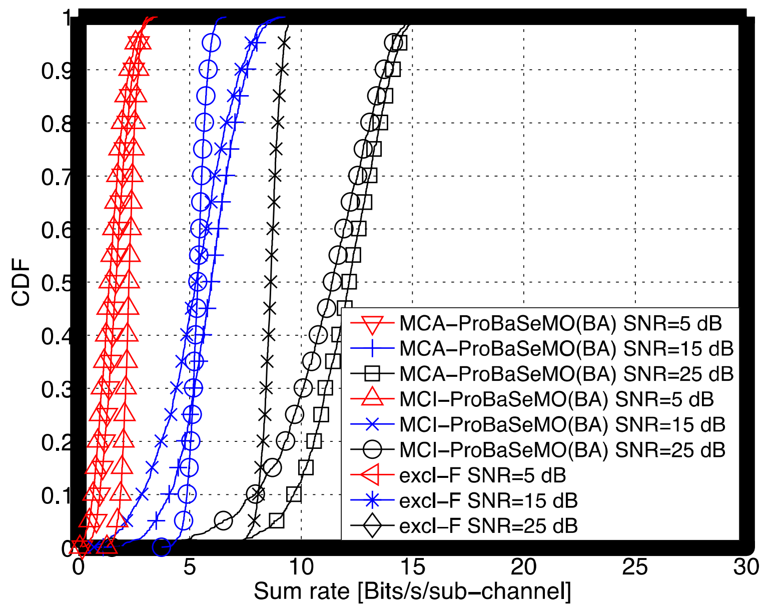

Figure 16: CDF comparison of relay sharing and non-sharing in an OFDMA system with single-antenna nodes, two operators and two UE per operator: Each operator has one sub-channel. In the non-sharing set-up each operator has its own relay with 4 antennas while in the relay sharing set-up there is only a single relay but with doubled transmit power and 8 antennas. MCI: SNR balancing power allocation; MCA: sum rate maximisation power allocation

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 16 that relay sharing is still superior to the non-sharing approach especially in the high SNR regime.

3.4.2 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. The 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 to destination nodes. If a smart Layer 1 relay, capable of gathering channel state information and performing AF, 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 [37], [38]: 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 17.

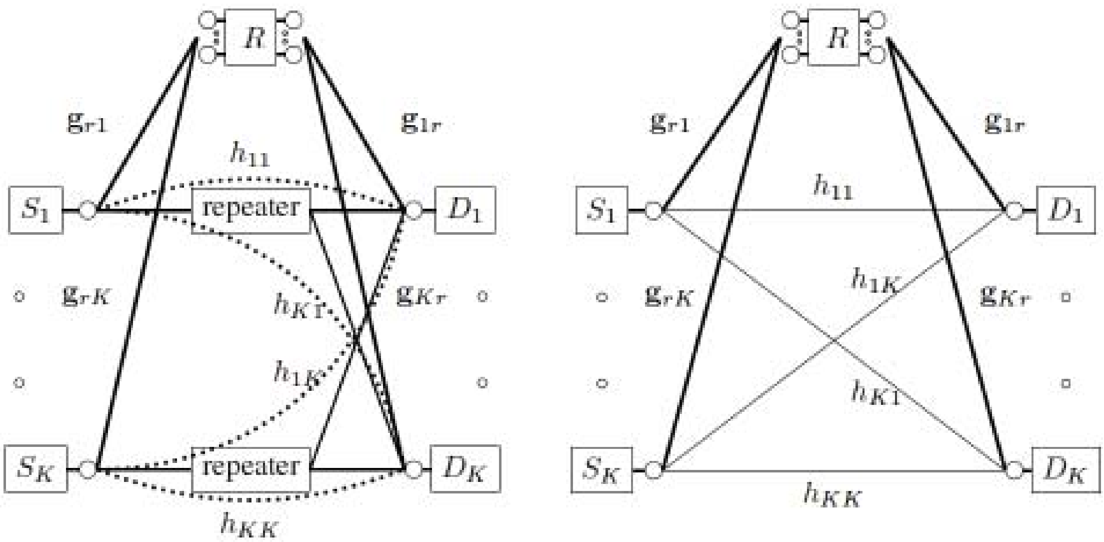

Figure 17: The wireless relay-assisted network with layer one repeaters and one smart relay is shown in subfigure (a). The dotted lines demonstrate the equivalent links between source the destination taking into account of the presence of the repeaters. All paths from source to destination nodes take 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.

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 [39], [40], and in two-hop relay channels [34], [41], [42], 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 [38], [43].

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 17 (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 [44]), we can choose a relay linear processing matrix $\boldsymbol{R}$ as a function of all channel states. The result is an improved SINR.

In Figure 18, the achievable rate region of IN in a two-user interference relay channel with relay equipped with two antennas is compared to the Single Input Single Output (SISO) interference channel (by turning off 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.

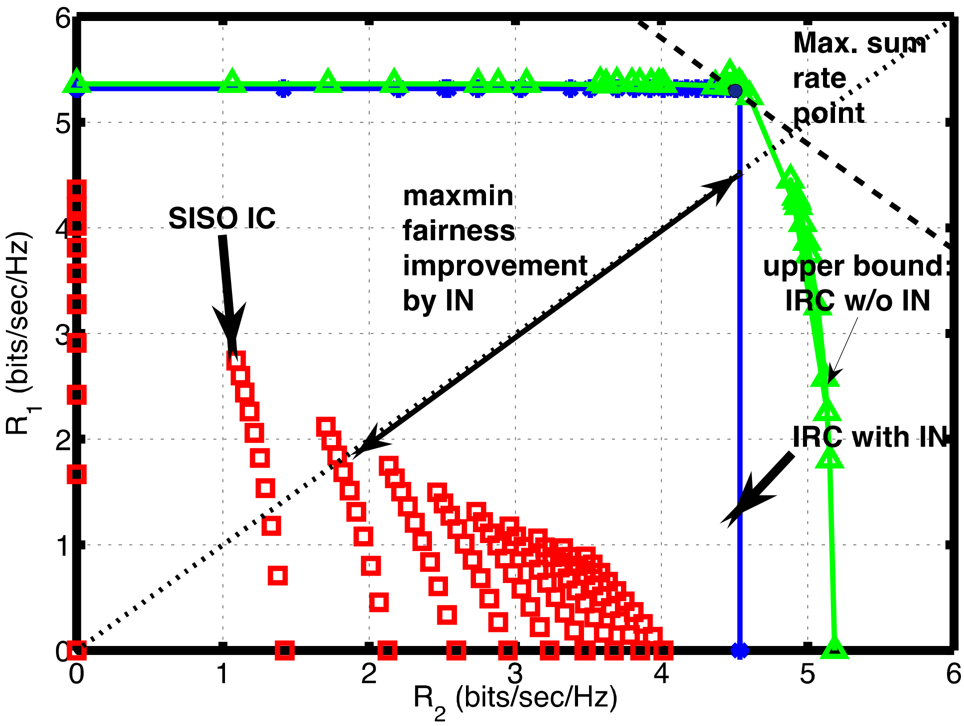

Figure 18: The achievable rate region of a two-user SISO interference channel is improved significantly by the proposed IN scheme with moderate relay power. The IN scheme attains maximum sum rate point and improves max-min fairness significantly.

4 Network sharing

Capitalising on the availability of multiple antennas at the base stations, transmit beamforming techniques can be used to mitigate the interference [26]. 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 maximises 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 involving 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, the SR also implies to be reflected on the scheduling procedure of the users, also aimed at selecting the users with highest achievable rates [25]. Finally, the 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 [45]. The investigation of such techniques is out of the scope of this work; the interested reader can find an in-depth analysis in [25]. 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 User Equipment (UE) 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 [45]. 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 [46], which is a Nash equilibrium of the system. Thus, the Pareto boundary can be found with the computationally efficient closed-form method in [47]. 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 [48], 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 the operators desire higher user fairness.

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 deliverable, we address this information exchange by assuming it for granted through full resource sharing on the infrastructure side. Several physical layer studies [49] 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.

5 System-level performance evaluation results

In this chapter we are looking at the system level performance evaluation of both presented sharing scenarios, being discussed in Chapter 3 and Chapter 4.

5.1 Performance of the infrastructure sharing

System level simulations are indispensable for evaluating the signal processing algorithms in a large communication system. However, compared to 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.

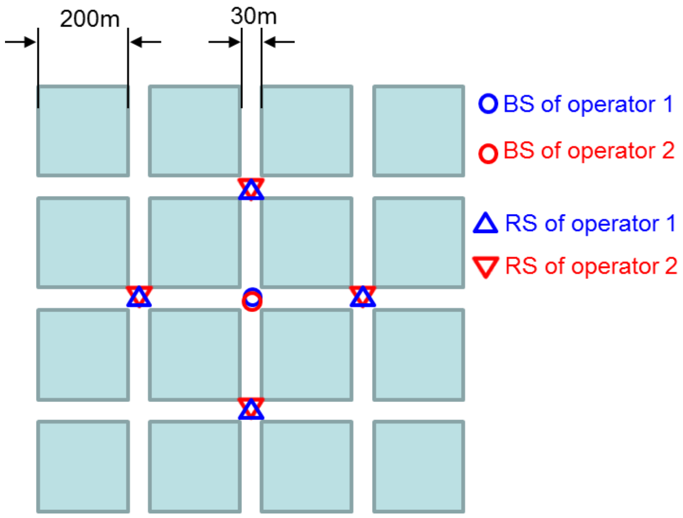

Figure 19: The Manhattan grid with a single cell-layout

In Figure 19 we consider the metropolitan scenario with one-way DF out-of-band relays with multiple antennas (compliant with the Type 1 relay specified in [50]. After assigning UE 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 UE while the relays forward the dedicated data to relay UE. 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.

In both set-ups, we apply SDMA based signal processing techniques. Numerical results presented in Figure 20 and Figure 21 were obtained using the parameters in Table 2. It can be observed from the colour map that the sharing gain is almost twofold.

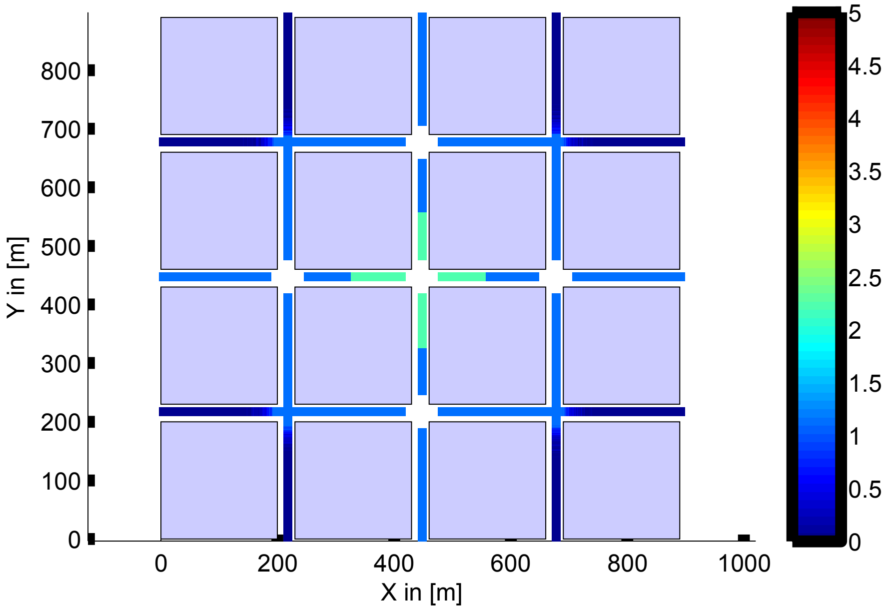

Figure 20: System level simulation results in the Manhattan grid with non-shared relay

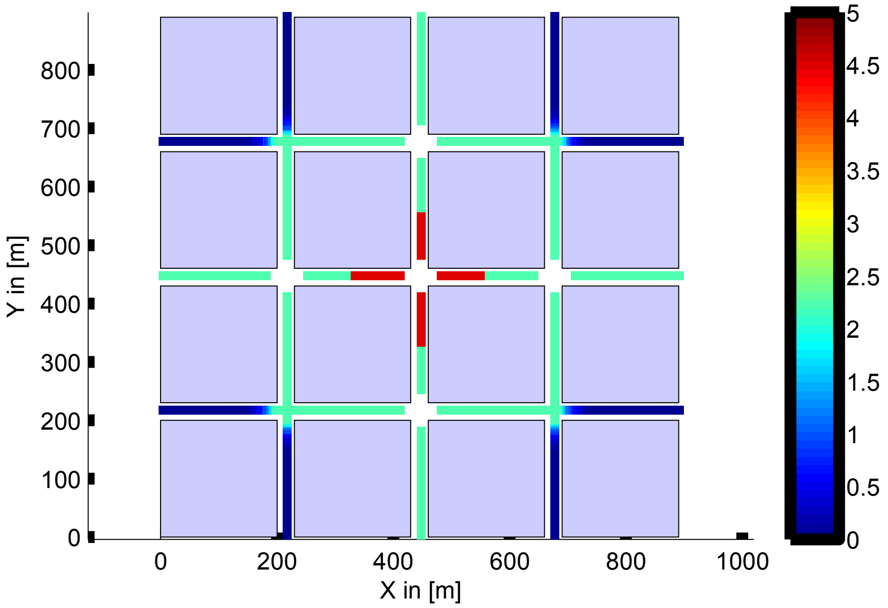

Figure 21: System level simulation results in the Manhattan grid with shared relay

Table 2: Key simulation parameters

Parameter	Value
Carrier frequency	2 GHz
Channel model	WINNER II, B1 NLOS [51]
Traffic model	Statistics with full-buffer downlink
eNB location/height	15 m (above rooftop)
eNB number of sectors	4
eNB antennas per sector	2
eNB maximum Tx power per sector	46 dBm
eNB antenna gain	14 dBi
eNB noise figure	5 dB
RN location/height	10 m (below rooftop)
RN antennas	4 (omnidirectional)
RN maximum Tx power	24 dBm
RN antenna gain	9 dBi
RN noise figure	7 dB
UE location/height	1.5 m (above rooftop)
UE antennas	1 (omnidirectional)
UE antenna gain	0 dBi
UE noise figure	7 dB

5.2 Performance of the network sharing

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 [52] using propagation models that include shadowing, multipath fading and pathloss [25].

Figure 22 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 Signal-to-Noise-Ratio (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 and lower SNR larger differences can be expected, especially showing a more favourable performance of the SR.

More in general, the following conclusions can be drawn from the simulation results. The SR technique outperforms ZF in the average user throughput; however, these 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.

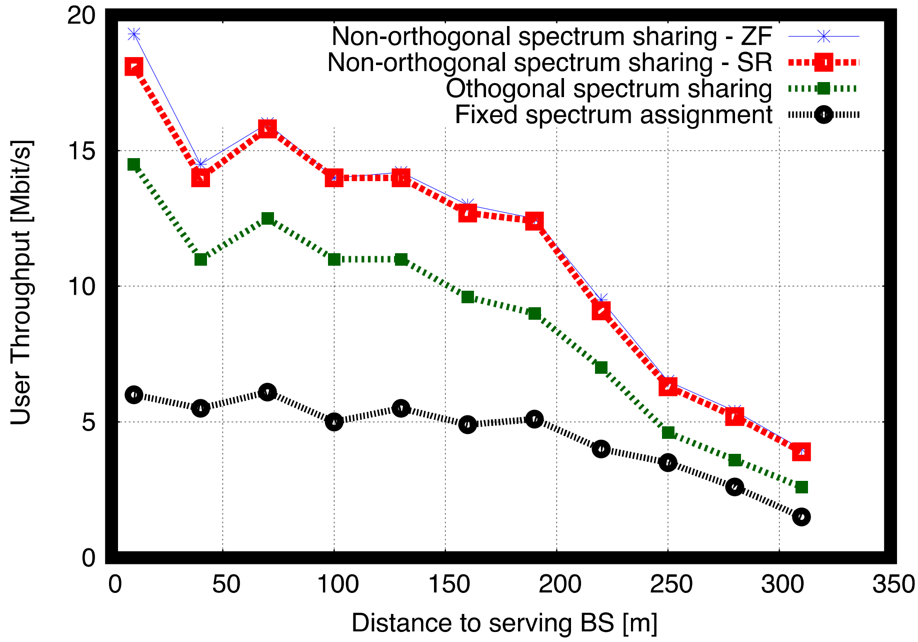

Figure 22: User throughput vs. distance to serving BS comparison

To generalise 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 α, which is the ratio between the SINR in the MU case and the SINR in the SU case. Thus, in Figure 23, we evaluate how the parameter α 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 α. 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.

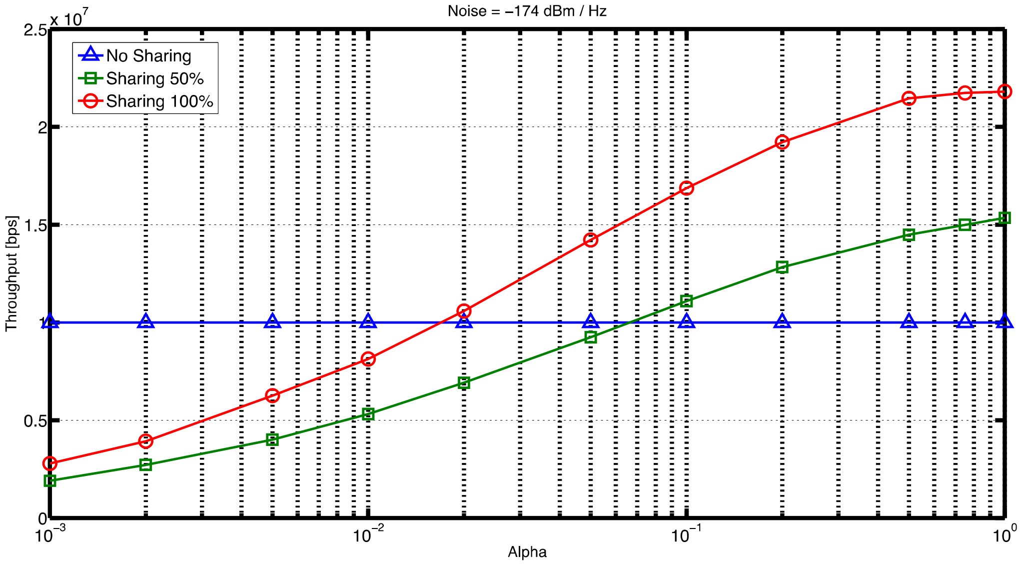

Figure 23: Throughput vs. alpha for different percentages of sharing

Figure 24 shows that using a non-cooperative approach (MRT) among the BSs we obtain a loss due to the increase of the interference perceived by the UE. 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.

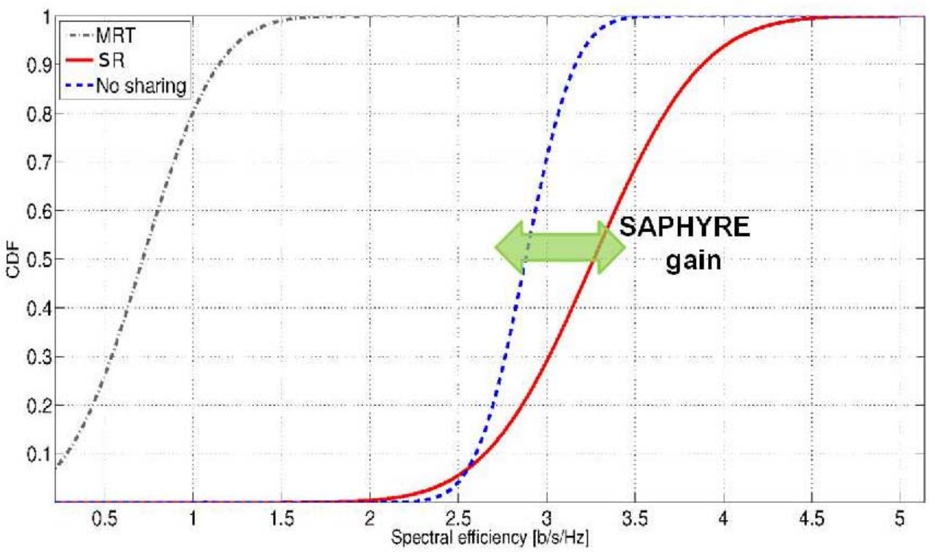

Figure 24: Spectrum sharing gain for different beamforming techniques

These results are then compared with those provided by the first simulation, and finally summarised in Figure 25 where we report the SAPHYRE gain. It can be seen how the MRT technique corresponds to a value of α around 0.002, while the SR technique corresponds to a value of α included between 0.02 and 0.05.

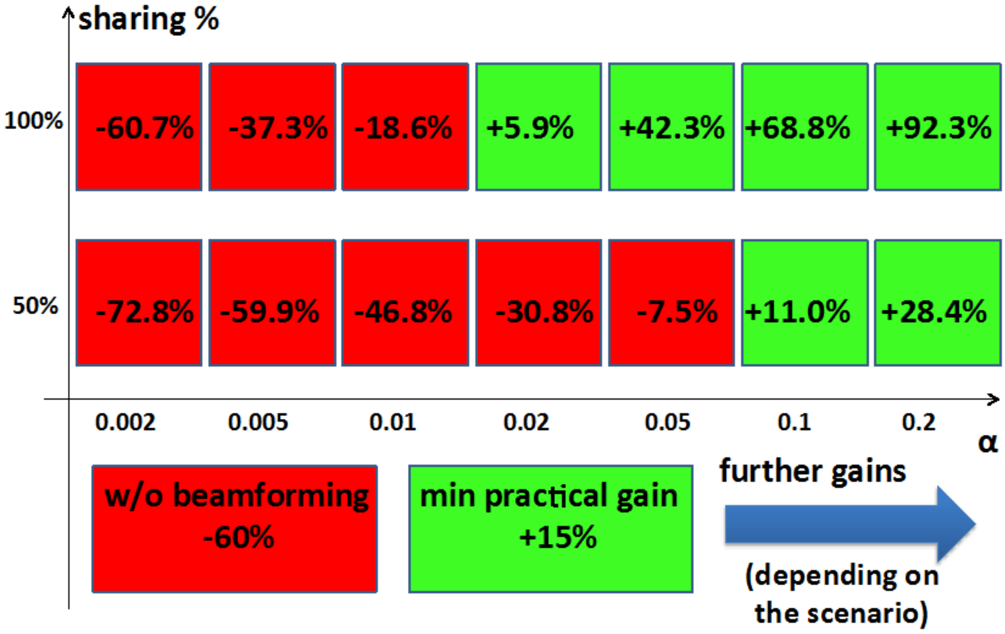

Figure 25: Spectrum sharing gain table

6 Practical aspects regarding implementation

In this chapter we are discussion aspects related to the sharing scenario implementation, including the hardware aspects and imperfections, which might impact the overall performance of the system.

6.1 Hardware enablers

Generally, to enable flexible spectrum sharing in relay networks, three key enablers should be applied:

1. Software Defined Radio (SDR) technology;
2. Direct Conversion Architecture (DCA);
3. Frequency agile, broadband radio frequency (RF) and baseband components including digital-to-analog converters, low-pass filters, modulators, power amplifiers and antennas. With these enablers, efficient transmission frequency switching and simultaneous multiband operation are allowed. Furthermore, they allow integrated implementations with low cost and low power consumption, especially for MIMO operation.

Usually, the BS (which 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 neighbouring 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 User Terminals 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 analog components.

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. 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:

[2] With regard to the assumed standard carrier frequency.

1. The source nodes are BSs: In this case, all BSs of the involved operators should be synchronised accurately using time and frequency reference signals from GPS or the backbone network [53];
2. The source nodes are UTs: In this case, all involved UTs should first estimate their CFO and pre-compensate it before transmission. The estimation of these CFOs can be done based on a broadcasted training sequence (during connection establishment) by the relay . The time synchronisation can be coordinated by the relay in a similar way as the BSs (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 BSs (described in case 1 above) does not apply to the relay. Instead, the relay should synchronise itself to the BSs in a similar way as the UTs (via standard procedures). Furthermore, the frequency synchronisation of the destination nodes in the BC phase can be done via standard post-processing (if necessary).

6.3 Channel state information, channel reciprocity and noise power information

The proposed DF approaches with WNC require only the CSI at the receiver side and no CSI feedback is necessary. Furthermore, the channel estimation is straightforward. In MAC phase, MIMO channel estimation schemes, e.g. [54], can be extended by viewing all the source nodes as a virtual transmitter with multiple Tx antennas, where the synchronisation described in Section 6.2 is the 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 BSs/UTs). Moreover, 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. However, channel reciprocity is not straightforward in practice:

1. 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. [55], 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;
2. 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 BSs/UTs 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.

6.4 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 [56]. 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 transmission time interval. 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 two or more operators use a BS, additional management functionalities are needed. This can be done by a legacy approach like a mobile virtual network operator, 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 [10] and subsequent releases. Some key requirements of the 3GPP Release 10 are spectrum ranges up to 100 MHz and carrier aggregation. A BS that fulfils these requirements may also be enabled for sharing scenarios regarding spectrum ranges and multicarrier 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 [16], [57].

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. Until now, two general classes on the relay nodes were considered: stationary relays and mobile relays.

Stationary relay was 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 [50], [58], [59]. 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, through-wall scenario was considered during 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-UE links:

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

From the UE 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 Cell_ID): smart repeaters, DF 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 Cell_ID 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 functionality.

Shared relay, as proposed in this paper, 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 creation of the SWOT as well as business model canvas analysis [60]. As multiple relaying techniques were presented in this work, we perform general analysis.

Table 3: SWOT analysis for shared relay nodes

STRENGTHS • WNC as solution to overcome the 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 re-use current network structure; • Hardware enablers are considered to be already available in the networks, e.g. SDR; • Potential to use the E-UTRAN network as the basis for WNC, e.g. due to OFDM and cyclic prefix features; • Possibility to re-use 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 Layer 1 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 dependant; • RAT specific standardisation requirements estimation: – Inter-operator interface; – Channel estimation consideration (pilot structure); – Channel state information exchange mechanism; – Network configuration information availability.
OPPORTUNITIES • In long-term, might enable more cooperation between competitors, once initial gains being identified; • Opportunity to allow new network evolution model, with 3rd 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 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-ups; • Potential frequency bands feasibility limitations in the inter-operator scenarios; • Potential regulatory limitations of such sharing coalition formation due to 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 under-utilised; • Risk of potential IPR conflicts.

Table 4: Shared relay business model canvas

<table>
<tr>
<td rowspan="2">KEY PARTNERS
• Strategic partnership between MNOs as business case enabler;
• Cooperation motivated by the additional radio resources availability;
• Telecom equipment vendors for shared relay’s infrastructure: buyer–supplier relation;
• SW developers (internal resources or outsourcing) for implementation of the relaying mechanism.</td>
<td>KEY ACTIVITIES
• Identification of the potential MNOs interested in cooperation;
• Creation of the inter-MNO alliance;
• Creation of the business link between MNOs 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 UE issues with regard to planned spectrum sharing;
• Identification of own capabilities to assign certain amount of spectrum for non-orthogonal sharing.</td>
<td rowspan="2">VALUE PROPOSITION
• Improved service availability for subscribers (more radio channels available);
• Improved network coverage for subscribers;
• Overall subscriber experience enhancement (applicable for all MNOs participating in sharing).</td>
<td>CUSTOMER RELATIONSHIP
• Focus on customer retention by their service perception improvements;
• Customer relationships to focus on the automation;
• Cooperating MNOs as special case of customers.</td>
<td rowspan="2">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.</td>
</tr>
<tr>
<td>KEY RESOURCES
• Running networks;
• Current delivery chains;
• Experienced employees;
• Spectrum resources (own + shared);
• Inter-operator partnership.</td>
<td>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.</td>
</tr>
<tr>
<td colspan="3">COST STRUCTURE
• Business case mainly being value-driven, with cost awareness;
• Shared relay HW/SW investments for functionality implementation;
• Network OPEX costs expected at current level;
• Potentially, inter-operator charges based on the additional spectrum usage (based on the internal agreement between operators) – variable cost.</td>
<td colspan="2">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 MNOs, as the usage fee.</td>
</tr>
</table>

8 Conclusions

This deliverable report the findings of two white papers which were generated by the SAPHYRE project, 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 infrastructure as well as network sharing (more specifically, the impact of transmit beamforming techniques on non-orthogonal spectrum sharing) was considered. Our numerical results show that a properly set full resource sharing may provide a SAPHYRE gain in terms of system-level throughput, with regard to non-sharing scenarios. The performances of the specific techniques are strongly dependent on several system parameters, such as the number of users, antennas, and the specific beamforming techniques used.

In a multi-hop interference network model, intermediate (relay) nodes receive a superposition of codewords from different transmit nodes. In the work, 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, synchronisation, and 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.

For the network sharing, 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.

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. In general, sharing between operators in cellular networks can provide a gain in terms of customer satisfaction as well as revenue for operators.

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