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Abstract

This document describes and analyses different methods for resource allocation and interference management for a set of different sharing scenarios being developed within work package WP4.1

Keywords

Network sharing, RAN sharing, Infrastructure sharing, spectrum sharing, scenarios, reference scenarios, LTE, 3G, 4G, mobile networks, licensed spectrum, TDMA, relay node.

Contents

Abbreviations

3G	3^{rd} Generation
3GPP	3^{rd} Generation Partnership Project
AP	Auctioning Process
API	Abstract Priority Indicator
AU	Auctioning Unit
AUC	AU Carriers
BLER	BLock Error Rate
BS	Base Station(s)
CA	Call Arrival
CAPEX	CAPital EXpenditures
CDF	Cumulative Density Function
CL	Cell Load
CoMP	Co-operative Multi-Point (transmission / reception)
DC-HSDPA	Dual Carrier HSDPA
eNB	enhanced NodeB
HSPA	High Speed Packet Access
HSDPA	High Speed Downlink Packet Access
ITU	International Telecommunication Union
LRM	Lower layer Resource Management
LTE	Long Term Evolution
LTE-A	LTE Advanced
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
MNO	Mobile Network Operator
MRT	Maximum Ratio Transmission
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	OPerating Expenditures
PDCCH	Physical Downlink Control CHannel
PDSCH	Physical Downlink Shared CHannel
PHICH	Physical Hybrid ARQ Indictor CHannel

PRB	Physical Resource Block
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radio Frequency
RMa	Rural Macro cell
RN	Relay Node
RS	Relay Station
RSRP	Reference Signal Received Power
RSSI	Received Signal Strength Indication
SU-MIMO	Single User MIMO
SINR	Signal to Interference and Noise Ratio
TDMA	Time Division Multiple Access
TTI	Transmission Time Interval
UE	User Equipment
UMTS	Universal Mobile Telecommunication System
UMa	Urban Macro cell
URM	Upper layer Resource Management
UT	User Throughput
VCG	Vikrey, Clarke and Groves
WSR	Weighted Sum Rate

1 Executive summary

This document describes resource allocation strategies and interference management techniques being developed within work package WP4.1. Different algorithms and techniques based on different sharing scenarios are defined and analysed. Two basic sharing options like infrastructure sharing and radio resource sharing are considered. Together with the combination of both, it results in three baseline scenarios.

Furthermore partial infrastructure sharing like shared relays is considered. For these different types of scenarios, several resource allocation strategies and interference management techniques are defined suited to the different sharing options. For the radio resource sharing scenario resource allocation techniques are specified and analysed, which operate on different time scales respectively small, medium and large time scales. For the partial infrastructure sharing scenario methods for orthogonal as well as non-orthogonal sharing are analysed. For infrastructure only sharing scenario a mechanism based on multi-operator CoMP is introduced and analysed. Finally for the full sharing scenario, which combines infrastructure and radio resources sharing between operators, novel resource allocation mechanisms are defined and analysed for the orthogonal sharing case and interference management mechanisms for the non-orthogonal case.

2 Introduction

Resource sharing, as an approach to the resource allocation, has become a promising mechanism to allow the evolution of telecommunications beyond 3G technologies [11], [12], [13]. Spectrum sharing permits the network operators to increase/decrease their resources dynamically, based on user's demand. In addition, sharing network elements reduces the cost of acquisition and maintenance of the network per operator (CAPEX and OPEX) [14], [15].

3 Scenario discussion and selection

Resource sharing is feasible in different types of scenarios based on different deployments and combinations. In this document, different sharing scenarios are analysed under the technical aspects of resource allocation and interference management. For this purpose following main scenario categories are specified:

- Spectrum only sharing: which defines a scenario where two or more operators use the licensed radio resources commonly but with different radio access networks, one radio access network per operator. The technical objective in this scenario is mainly resource management. Analysis of several approaches of resource management are performed under different time scale subscenarios.
- Infrastructure sharing: which defines a scenario where two or more operators use different licensed radio resources on a commonly shared radio access network RAN.
- Spectrum and partly infrastructure sharing: also named as relay-assisted resource sharing defines a scenario where every operator use its own radio access network except the relay stations, which are shared between the operators. The radio resources are also shared.
- Full sharing: which defines a scenario where two or more operators use the licensed radio resources as well as the radio access network RAN commonly. The technical objectives in this scenario are mainly the resource management among different operators in case of orthogonal share and interference cancellation in case of non-orthogonal sharing.

4 Spectrum sharing scenarios

4.1 Small time-scale scenario

In this section, we consider the case where the orthogonal spectrum sharing among network operators is performed at short time intervals, in order to exploit the channel fluctuations that arise mainly due to the channel fading. The frequency allocation algorithm is executed with the finest granularity possible thus allowing the maximum flexibility in dynamic spectrum allocation. A coordination among the operators is needed to avoid overlapping in the channel access: in the orthogonal case the access to the common resources is mutually exclusive. The main drawback of this approach is that a lot of overhead might be generated for completing the allocation procedure, whose duration must be kept negligible compared to the allocation interval.

In the following section some possible algorithms for spectrum sharing are presented. Numerical results for a simple network configuration are given as well.

4.1.1 Scenario description

The scenario considered involves two neighbour cells belonging to two different operators sharing adjacent bands in an LTE (Long Term Evolution) system. The time dimension is divided into 10 ms frames consisting of 1 ms sub-frames. The spectrum is split into sub-channels which bundle sub-carriers of total bandwidth 180 kHz. The sub-channels are allocated to the operators in every sub-frame. The Base Station (eNB – enhanced NodeB) managing each cell performs, in the downlink, channel-aware scheduling and resource allocation to its users (UE – User Equipment), in order to exploit the multi-user diversity (intra-cell allocation). Once each BS has built its channel allocation map, all the possible conflicts for the access to the common pool need to be addressed. This is a problem of multiple access to a common set of items, and it should be managed in a proper way so as to avoid resource waste. A classical example of inefficient result is represented by the “tragedy of the commons”, a problem well known in game theory were a set of selfish users ends up in wasting a shared limited resource.

Many algorithms can be proposed to this aim. Two main categories can be identified, centralised and distributed. The former include all those solutions which hypothesise the presence of a central authority (a kind of Oracle or God) who has a complete information about the whole system (nodes’ state, channel state, etc.) and thus is always able to take the best decision. However, this decision might require a high amount of time and/or of computational resources and thus is impractical in real systems, particularly in those where everything is done in real-time. Moreover, the presence of a central node might not be possible/legal in the system analysed. On the other hand, the distributed algorithms are quite closer to an actual network since they consider that each node has only local information and not global and the final state is reached through an interaction/cooperation among the nodes, without any imposition from any external authority. This interaction may consist in an explicit message exchange or in a backward-learning behaviour where each eNB adapts its choices according to the system state that it is able to perceive.

For the case of orthogonal spectrum sharing we have evaluated several algorithms. Hereafter their description.

Monopoly-like upper bound algorithm. We use a centralised approach to evaluate the upper bound on the sharing gain. Despite its inapplicability in a practical scenario, it is useful from a theoretical point of view since can be used for the comparison with other schemes. In particular, the proposed solution aims at maximising the joint sum capacity. The operators behave as if they were a single (monopolist) entity, without any balance consideration. Each sub-channel is always assigned to the UE with the best channel. The resulting capacity is the maximum achievable, a theoretical upper bound.

Safest allocation choice algorithm. This algorithm represents a sort of lower bound on the system performance. If the allocation maps proposed by each eNB do not overlap and thus no contention arises, then there is no problem and the common spectrum can be accessed by both the eNB. Otherwise, in case of at least one contention, the eNBs are forced to switch to the no-sharing case. The good point of this procedure is that it cannot perform worse than the no-sharing case. The drawback, on the other hand, is that in most of the cases it performs exactly as in the non-sharing case and no gain can be obtained. This point is further discussed in the next section, where some figures are be given.

Priority algorithm. The idea behind this choice is to let each operator have a certain control on the sub-channels it decides to share, so that it can get them back when needed. When contention arises on a sub-channel in the common pool, the original owner of that resource wins while the other is forced to quit. As shown in the next section, this algorithm may lead to some resource waste because of the selfishness of the entities involved.

In the following we describe the main results obtained from a simulation campaign. Among the main simulation parameters we have:

- In the following we describe the main results obtained from a simulation campaign. Among the main simulation parameters we have:
- UEs uniformly distributed within the area around their eNB, whose maximum range is of 1500 m;
- transmission frequency of 2110 MHz;
- 20 MHz of total bandwidth in downlink for each eNB;
- average UE speed of 30 km/h, which corresponds approximately to a 60 Hz Doppler shift;
- The radio propagation model includes path loss, 10 dB of wall penetration loss, log-normal shadowing with $\mu = 0$ dB and $\sigma = 8$ dB, multipath fading modelled according to Jakes' model with 6 to 12 scatterers;
- The transmission power in downlink per subchannel is 26.98 dBm;
- The network is supposed to be in saturation with all the UEs constantly backlogged;

4.1.2 Results and business benefits

The simulation tool ns-3 has been extended with the support to multi-cell LTE scenarios and spectrum sharing [10] to make it a suitable validation means.

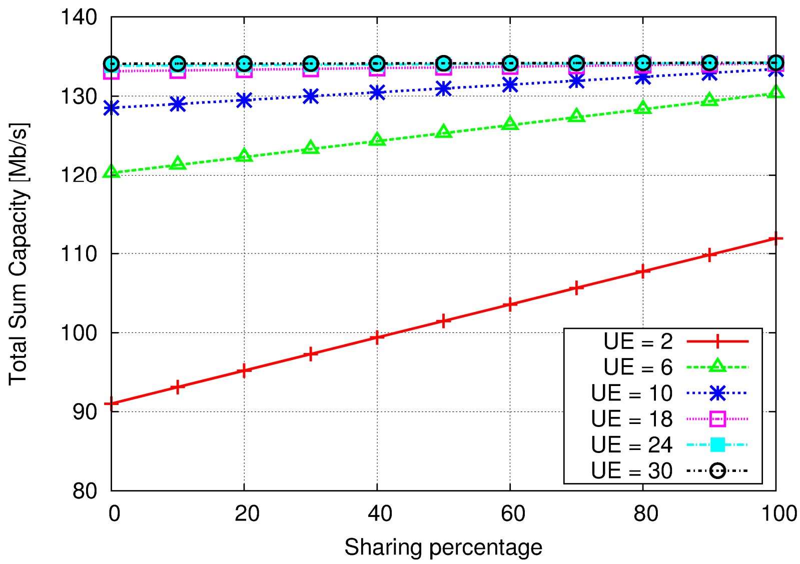

Figure 4-1: Upper bound on the joint cell sum capacity for the short time-scale allocation

Figure 4-1 refers to the upper bound algorithm and shows the joint cell sum capacity that can be achieved for a different number of UEs per cell when the spectrum sharing percentage increases. First of all, a clear increase in the capacity with the number of users can be noted, which is a direct consequence of the multi-user diversity. The larger the number of UEs, the higher the probability that for each sub-channel there is at least one UE with good channel quality. However, for a denser cell the improvement is quite low because for almost all the sub-channels there is with a high probability at least one user in a good situation.

The second important observation that can be done is that there is a neat sharing gain. The sum capacity increases with the sharing percentage, thus there is an incentive for the network operators to share part of their frequencies. For a small number of UEs a 20% gain can be reached over the non-sharing case. The decrease of the marginal gain with the number of UEs is still a consequence of the reduced multi-user diversity.

However, it is important to remind that these values were obtained for a scenario under saturation. In the case of low load, an eNB might have only few active flows and the other eNB could opportunistically exploit most of the unused resources. Therefore, we can consider the results presented in Figure 4-1 as the worst-case upper bound. Moreover, an important role is played by the frequency diversity of the channel: the greater it is, the greater is the gain achievable by the network operators if a larger range of frequencies can be exploited.

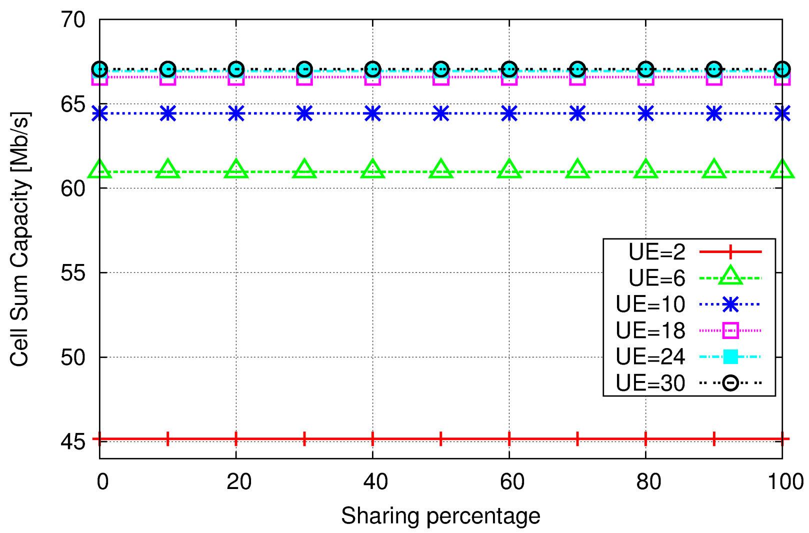

Figure 4-2: Cell capacity for the safest allocation choice algorithm

In Figure 4-2 the sum capacity in each of the two cells is shown for the safest allocation choice algorithm. In this case we can still note the effect of the multi-user diversity, which leads to an increment in the capacity with the number of UEs per cell. On the other hand, it is clear that there is almost no sharing gain at all when the sharing percentage increases: the capacity is almost the same of the non-sharing case (i.e. sharing 0% on the *x*-axis). This is due to the fact that a collision is very likely to happen, in particular when the number of UEs or sharing percentage increases and thus the algorithm resorts very frequently of the non-sharing solution. This is the reason for which such an access arbitration mechanism can be considered as a sort of lower bound on the system performance: on one hand there is no resource waste, but on the other hand there is almost no gain as well.

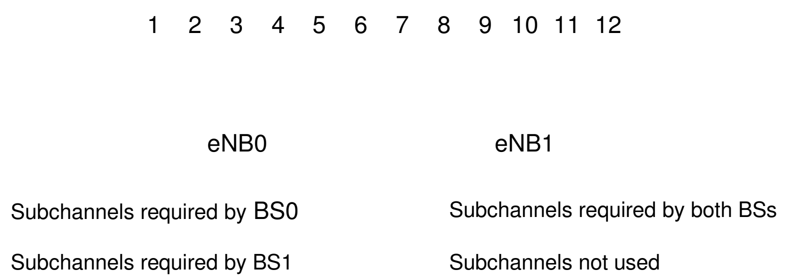

Figure 4-3: Example of resource waste for the priority algorithm

Regarding the priority algorithm, in Figure 4-3 an instance of allocation is depicted. The drawback of this mechanism is that, given the same cell load, an eNB may get more resources than the other because of the priority, as shown in Figure 4-3. In that case eNB1 wins the contention on the sub-channels 7 and 8 since it has a higher priority, and it gets also the sub-channels 5 and 6 since there is no contention on them. At the end of the allocation game, the result is that eNB1 gets the whole common pool plus 2 of its private resources, for a total of 6, while eNB0 gets only 4 sub-channels and cannot benefit from any of the common frequencies. It cannot access the private spectrum of eNB1, which is in part unused in the current time-slot. Therefore, there is a double negative effect: an eNB is getting more than the other (even though the cell load is the same) and a part of the spectrum is wasted. So, this algorithm can perform worse than the non-sharing case unless a correction mechanism is introduced.

4.2 Medium time scale scenario

Within this section, we describe a medium time scale scenario for spectrum sharing, by the introduction of auction-based inter-operator resource sharing mechanism in Multi Carrier HSDPA network.

In the context of auction-based resource sharing, different resource sharing solutions, utilising auctioning concepts have been proposed in the literature. In [16] two auction mechanisms for allocating the received power were proposed. The first is an auction in which users were charged for the received SINR, which, when combined with logarithmic utilities, lead to a weighted max-min fair SINR allocation. The second is an auction in which users were charged for power, which maximised the total utility when the bandwidth is large enough and the receivers were co-located. Both cases were motivated by the scenario in which users wish to purchase a local, relatively short-term data service. In our approach we provide a solution, which requires much less information exchange between auction players, than the concepts mentioned above.

We propose to use a VCG (Vikrey, Clarke and Groves) auctioning mechanism (generalised from the second price auction concept) for equal value, multiunit auctions in the context of radio resource allocation for cellular networks. VCG mechanism is a standard concept in Algorithmic Game Theory and its main advantage is the combination of two properties: maximisation of social value and incentive compatibility, a feature that motivates the involved parties to report their true valuations for the goods being distributed. Our auction-based mechanism can be seen as a compromise between two extreme approaches:

- To jointly schedule the total traffic from all service providers involved in auctions (maximising total radio resources utilisation), or
- To have orthogonal radio resources dedicated to each operator for his exclusive usage (allowing full autonomy of scheduling), which is the case for current market situation.

For that, we introduce a third party virtual Auctioning Unit, responsible for regulating the usage/pricing of the radio resources based on valuations of those resources given by each operator.

4.2.1 VCG mechanism

Vikrey, Clarke and Groves, proposed in a series of papers ([17], [18], [19]) a class of mechanisms (called VCG mechanisms) for distributing goods to users. The common feature of these mechanisms is that they produce socially optimal distributions, at the same time remaining incentive compatible.

Intuitively, the way to obtain incentive compatibility is to charge each user *i* the amount by which the other users suffer from *i* being in the system. In this construction, the payment of *i* does not directly depend on his submitted valuation (for the goods to be distributed), but rather on the valuations of the other users and the distribution itself.

Consider a game played by *m* players interested in *n* identical goods. Each single player *i* has his utility from obtaining a certain amount of these goods. Let $[n]$ be a shorthand for $\{1,2,...,n\}$. Each player submits a function $V_i : [n] \to R$, called valuation to the auctioneer, and based on the submitted valuations the auctioneer assigns goods to players and computes payments. We will assume the utilities and therefore also the submitted functions are submodular, that is the profit from having one more good decreases with the number of goods already obtained.

The main objective of the auctioneer is to maximise the utilisation of the goods (social value maximisation) and therefore he attempts to assign goods so that the total utility is maximised. The following simple VCG mechanism is known for having exactly this property.

For each player $p_i \in P$ define $P^{-p_i} = P \setminus \{p_i\}$to be the set of all players except p_i.

For any subset of players $S \subset P$, we define an assignment *n* goods to *S* to be a function $f : S -> [n]$ such that $\sum_{p \in S} f(p) \leq n$, i.e. such that the total number of assigned goods is at most the number of available goods *n*. Given an assignment *f* we define its *social value* to be the total value the players get from the goods assigned to them in the assignment *f*. More formally, the social value of an assignment *f* is denoted by $Val(f, S) = \sum_{o_i \in S} U_i(f(o_i))$, i.e. the total utility of players given assignment *f*.

Observe, that given the utilities of the players it is trivial to calculate $Val(f, S)$, moreover given the utility functions one may find the social value optimising allocation by running a simple greedy algorithm. This algorithm looks at the marginal profits of obtaining one more good, and, considering goods one by one, allocates the next good to the player whose marginal utility is the highest. The crux of the VCG method lies in revealing the utilities to the auctioneer. One argues that if the prices charged to the players are carefully chosen, players will have no incentive in submitting valuations different then their utilities. Intuitively the users have to pay for the damage they make to the others. We will now specify the payments in more details.

Consider the total profit a group of players $S \subset P$ may make from using *n* goods. We call this maximal total profit the *n*-goods value of the set *S*, and we denote it by $Val_n(S) = \max_{n-goodsassignment\ f} Val(f, S)$.

The mechanism is defined as follows:

- Distribute goods according to an assignment f^* of *n* goods that maximises $Val(f, P)$.

- Charge each player p_i the amount of money equal $Val_n\left(P^{-p_i}\right)-Val_{n-f^*(p_i)}\left(P^{-p_i}\right)$, i.e. the amount by which the total value for the other players gets worse because of p_i using his $f^*(p_i)$ goods.

Observe that the charge may simply be computed by repeatedly applying the greedy algorithm to the setting with one player removed. Such computation would require *2m* runs of the greedy procedure and would then require roughly quadratic time. Note, however, that one may compute the valuations all together by considering a sorted sequence of merged marginal valuations of the different players.

Assuming the submitted valuations are indeed equal the utilities of the players, the computed assignment of channels is by definition the one that maximises the total profit of the players. It remains to argue that no player has any incentive to submit a valuation different then his true utility.

4.2.1.1 Incentive compatibility

Since it is crucial for any mechanism distributing goods based on information submitted by interested parties to enforce truthful reporting of these information to the mechanism,

despite the fact that incentive compatibility is known to hold for any VCG mechanism, we now give a simple formal argument that the proposed mechanism has the desired property.

Theorem 2.1: The above described mechanism is incentive compatible, i.e. no player has an incentive to misreport his utility.

Proof: First observe, that a player cannot influence his output without changing the number of goods assigned to him. It is because the charge attributed to player p_i does not depend on his valuations directly, but only on the number of goods allocated to p_i and the valuations of the other players.

Suppose now that p_i benefits from submitting $V_i \neq U_i$ and getting more goods than he would get by reporting his true utility U_i. Recall that we assumed that utilities and valuations are concave, and therefore valuations can also be expressed by a non-increasing sequences of increments $v_i(j)=V_i(j)-V_i(j-1), v_i(j)\geq v_i(j+1)$ for j=1, ..., n-1. Suppose, that by submitting true valuation U_i player p_i would get $l<n$ goods and consider the $v_i(l+1)$ value, namely the profit p_i would have from receiving one more good. Recall that the auction allocates goods to maximise the total valuation, therefore since p_i did not receive his $(l+1)$ -st good, there had to be another $p_{i'}$ player whose reported profit from getting the good is $v'\geq v_i(l+1)$. For player p_i to get the $(l+1)$-st good, he would have to bid more, and effectively he would pay v' for that the value of the remaining goods to the remaining players would drop by v'. So the net gain in the outcome to the player p_i from getting one more good would be $v_i(l+1)-v'\leq 0$.

It is easy to observe that to get even more goods, player p_i has to pay at least v' per good, which by the concavity of v_i is not in his interest.

Symmetrically one may argue that underreporting a valuation leads to saving that is less than the difference in the utility, and it also does not increase the profit of the player.

A natural question that arises is:

Can perhaps a completely different mechanism, with a different payment structure, be used to obtain socially optimal distribution of goods? There is a result that suggest a rather negative answer. It is known in general for VCG mechanisms that they are essentially the unique mechanisms that are at the same time incentive compatible and distribute goods in socially optimal manner (see e.g. [20]).

4.2.1.2 Mechanism applicability

Application of a VCG mechanism is only possible if the underlying (social value) optimisation problem is computationally easy. We may obtain this by assuming that the distributed goods are of the same value and that the players utility functions are submodular (i.e. the marginal utility of obtaining one more resource unit drops with the number of already obtained goods). Not only it is an acceptable restriction from the application perspective, it is also vital for the construction of the mechanism.

By allowing valuations that are not submodular the optimisation problem becomes NP-hard, which may be shown by a reduction from the Knapsack problem. For auctions with heterogeneous goods, still assuming submodular valuations, the joint utility optimisation can only be approximated with $\left(1+\frac{1}{e}\right)$ factor [21] without the incentive compatibility property, and with a logarithmic factor by an incentive compatible mechanism [22]. In case of heterogeneous goods and non-submodular valuations the problem becomes $\sqrt{n}$ hard to approximate [23] even without incentive compatibility.

4.2.2 Valuation of resources

The main requirement for the players to participate in the described mechanism is to estimate their demand for radio resources and to quantify this demand in terms of money they are willing to pay for each granted resource unit. As we believe only the operator himself can estimate the utility of resources, his utility is not directly known to the mechanism. The only information the mechanism has is the valuation reported by the operator. Having proved that the constructed mechanism is incentive compatible, we are in the position to assume that the reported valuations are indeed the true utilities of the players.

The calculation of these utility functions may take into account different factors and it is completely subjected to the players' judgement. Depending on their politics for traffic and user prioritisation, guarantee of QoS and, possibly, environmental conditions, the players have to decide how important it is to succeed in transferring a certain portion of data.

An example realisation of the valuation functions for two operators was presented on Figure 4-4. It explains the consequence of using the mechanism in case of 2 players, where operator A is getting resources from left to right, and operator B from right to left. The split is on the intersection of the valuation curves, i.e. there is a threshold prize and the number of channels operator X gets is the number of channels for which he is willing to pay above the threshold prize. Note that the payment is lower than the value of the obtained resources, it is the utility of the other operator for getting these resources in addition to what he gets in the computed solution.

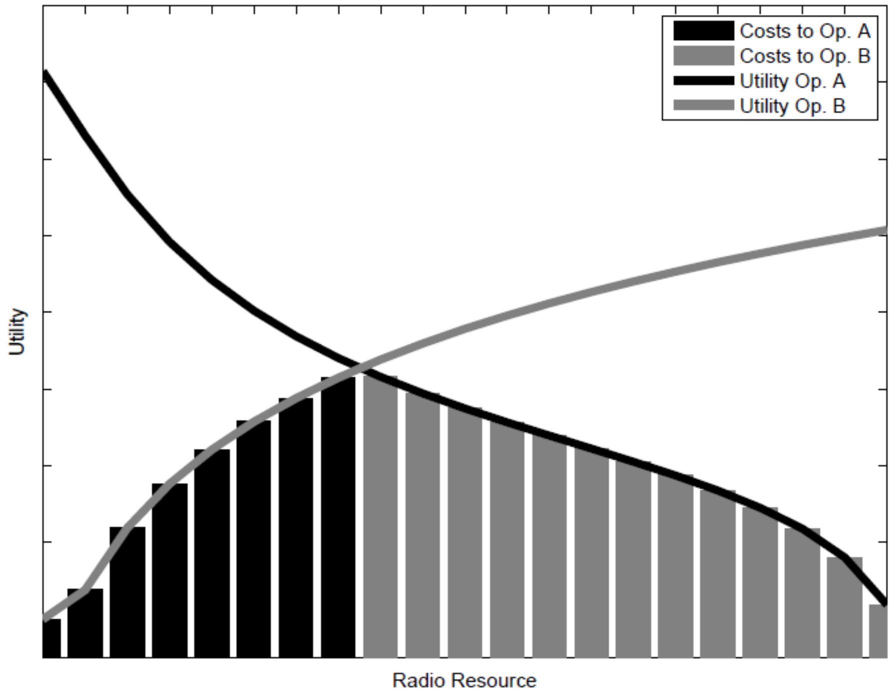

Figure 4-4: Example realisation of resource distribution based on the valuation functions for 2 operators

We believe that a fairly accurate estimation can be computed for short time horizons (within range of seconds) where the number of active connections is not expected to vary too much and the traffic profiles can be recognised.

One of the determining factors in the calculation of the utility function is the amount of data to be transmitted in the next period. Therefore, an easy way of determining the valuation would be a ratio between the amount of buffered data and the number of resources. Assuming Q_k to be the pending data to be transmitted by the cell of Operator *k,* its valuation for getting *x* resources could be given by:

$$U_k(x) = \alpha \sum_{i=1}^{x} \frac{Q_k}{i} = \alpha Q_k \cdot H_x \approx \alpha Q_k \cdot \ln(x)$$

where α represents a scaling constant to convert the values into realistic price, and H_i is the ith harmonic number. Note that this function is closely related to proportional fairness scheduling rules.

Observe that if all players calculate their valuations this way, the goods will be distributed proportionally to the current Q_k values. Moreover, each operator o_k has the guaranty that the total paid fee will be at most αQ_k, even if the other players decide to use different valuation methodologies.

4.2.3 Analytical model

Consider two network operators are interested in providing services, using a particular Radio Access Technology (RAT), over the same geographical area which is typical in case of highly populated networks. We assume these operators have collocated Base Stations (BS), i.e. passive sharing, which is a reasonable assumption since this approach is already widely applied in the market for the network CAPEX/OPEX reduction [24]. Even though described spectrum auctions do not introduce any limitations to the players set, from the practical consideration as well as for the simplification purposes, two co-siting operators are considered as sufficient for the performance analysis.

NOTE: Above mentioned limitation of two MNO operators, which are using same RAT might be slightly misleading: proposed auction-based spectrum sharing can be seen as a RAT solution, as far as national regulations, as well as RAT specification allows (due to RF aspects) certain frequency resources to be used by different RATs. For the purpose of this analysis, RAT selection was required in order to obtain meaningful performance impact values. Therefore, proposed algorithm's performance is verified from only one RAT's perspective and inter-RAT scenarios are out of scope of this paper. Based on the above RAT's selection, it was assumed that auctioning algorithm will run with the HSPA carrier granularity in the frequency domain. Time domain granularity will be limited by the auction periodicity (parameter in this analysis). The spectrum available for the auctioning game will be merged into a single pool of orthogonal channels, which will be available at each cell, and can potentially be used by any operator in TDMA mode, depending on the auction outcomes in each cell. In case of non-shared carriers, frequency reuse 1 was considered.

Resources allocation grants for the pooled radio carriers will be repeated in periodic time intervals, whose length is a parameter of the auctioning algorithm, reflected in the simulation results. For the quantitative verification of this scheme, see Section 4.2.6. The decision of which resources are to be used by each operator for particular time period Δ is taken by the Auctioning Unit (AU). Each AU's decision will be valid for a time period of duration Δ, after which the Auctioning Process (AP) must be repeated and new resources allocation scheme shall be provided.

The duration of the period can vary from system to system depending on the variability of the operators' traffic profiles. In our performance evaluations in Section 4.2.6 the AP frequency was variable.

The AU's decisions will be made based on valuations that operators make on their need for resources in the time period to come. A valuation is a function that encodes the amount of profit a particular operator expects from using a certain number of resources in the next time period.

At each interval, operators calculate their utility for resources in the next interval. How to calculate such utility is not obvious, and may differ from operator to operator. However, we believe operators are able to estimate their demand on radio resources and, therefore, evaluate the value these resources have for them. For more discussion on the possible utility functions see Section 4.2.2.

Together with the decision of who will be able to use particular resources (in this case, HSPA channel) from the auctioning pool, the AU will also calculate the fees to be paid by each operator due to this usage. We expect the created money-flow may affect the business model of the involved parties significantly, which we briefly discuss in Section 4.1.1, where the question to whom and by which means to pay was also attempted.

In summary, the following algorithm will be used for the Auctioning Process:

- First, the players submit their valuations to the cell specific Auctioning Unit (AU),
- Then, AU computes the distribution of frequency resources to the players and the fees to be paid, based on the submitted valuations using a VCG mechanism,
- Finally, AU communicates to the players its decision, and the players are free to schedule their traffic on the resources allocated to them,
- After a time period Δ this procedure is repeated.

It is important to say that once the resources are granted, the operator is free to use its preferable scheduling policy in order to utilise them optimally, independently of the others.

4.2.4 System model

Presented simulation results and analysis was based on the system level model generated in topology of 19 homogeneous cells with 3 sectors per cell, in wrap around configuration. We assume, that two MNO operators who are willing to participate in the auction based spectrum sharing, are co-sited, i.e. passive sharing is employed. These operators provide coverage over the same geographical area and serve their own subscribers only (i.e. no national roaming enabled). UE locations were generated randomly, with equal population of UEs per each sector for each operator. Two different approaches were used for the inter-operator traffic balance modelling, as described in Section 4.2.5.

Co-located BS' enforcement might be seen as a limitation from the network planning perspective, but on the other hand, it opens the possibility to re-use the RF components from the other auction player's infrastructure, which might be a serious advantage in many cases. Moreover, there will be need to exchange certain amount of auctioning related control information. BS co-location might ease practical realisation of such information flow. Detailed solution, as well as standardisation related analysis, is out of scope of this paper. In the following table, more details on the system level model were provided.

Table 1: Selected system level parameters

Parameter	Value and comment
Network layout	Hexagonal grid, 19 sites/57 sectors, wrap around
Network operators	Two operators, co-sited
Spectrum auctions setup	Auctions running in all cells
Inter site distance	500 m
Neighbour cell modelling	Users modelled in whole network; random locations
Cell Isolation	0 dB
UE assignment	Variable #UE per sector, per operator; default: 10/cell/op. →1140UE in total in network
Wrap around	Yes
Carrier frequency	2 GHz
RAT	HSDPA
Number of bands	1
BS antenna configuration	3 sector
Antenna beamwidth	70 deg
Antenna Front To Back ratio	20 dB
NodeB antenna gain	14 dBi
NodeB TX power	43 dBm
Power overhead for Pilot, common, shared & dedicated channels	30% of Node B power for Primary carrier 20% of Node B power for Secondary carrier
Minimum UE to BS distance	35m
Propagation model	$128.1 + 37.6\log_{10}(R)$; R [km]
Shadow fading	8 dB
Shadowing correlation	1 between sectors, 0.5 between sites
Penetration loss	0 dB – indoor scenario not considered
Thermal noise level	-102.9dBm
Channel model	PedA 3km/h, VehA 3km/h
Fading across carriers	Uncorrelated
Spectrum sharing	Variable; default: 50%
Simulation duration	Variable; default: 10sec.
Traffic	Bursty traffic, variable burst size per operator

The Figure 4-5 presents homogeneous, cellular grid of 57 sectorised cells, which was used to run system level simulations. In the following table, more details on the system level model were provided.

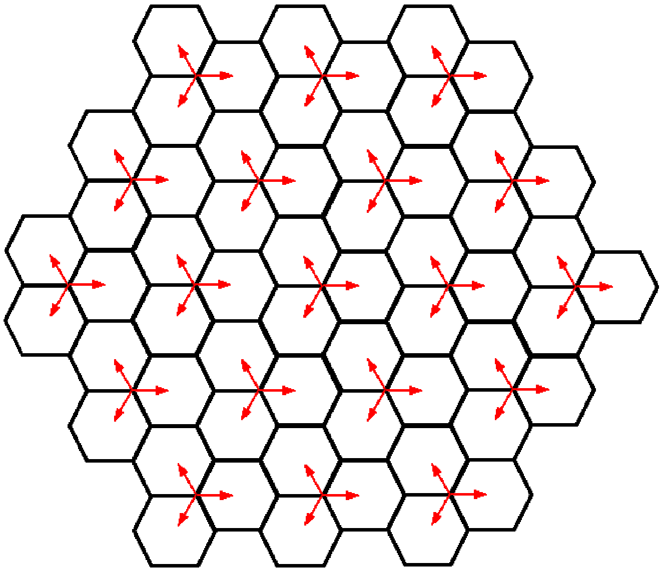

Figure 4-5: Homogeneous cellular network topology grid

4.2.4.1 Spectrum resources consideration

Spectrum resources allowed to be used by the AU in auctions (i.e. AU Carriers – AUC), were proposed to be pooled in one set, as it was described in Section 4.2.3. The most straight forward use-case, would be to have (at least) two collocated operators, who are willing to allow certain percentage of their spectrum (expressed in the number of HSPA carriers in this case) for auctioning purposes. It shall be kept in mind, that AUC carriers can be accessed by any of the auction played, under the TDMA sharing principles. This kind of the spectrum sharing scheme is also called orthogonal spectrum sharing. Furthermore, we assume that licensed bands are considered for described scenarios and all auction players have equal (or, proportional to the amount of shared radio resources) priorities in accessing AUC carriers.

For sake of simplicity, we have assumed that each of the operators have deployed Multi Carrier HSDPA network and each of them agreed to assign number of owned HSPA carrier for the auctioning pool. In the first step, we consider scenario, where both operators participating in the auctions, are allocating one of their carriers to the auctioning pool (Scenario 1), further extending the configuration to Scenario 2 and Scenario 3.

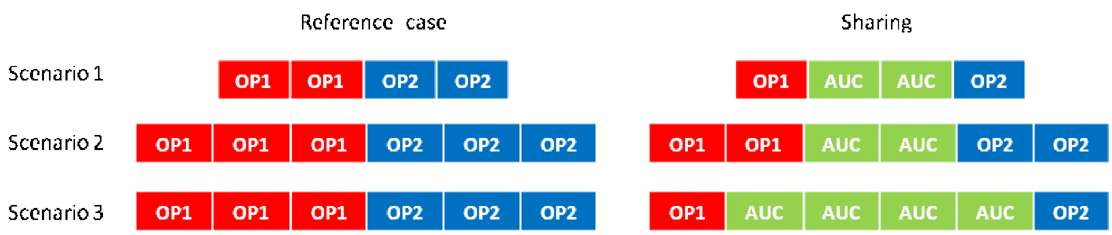

Figure 4-6: Carriers allocation scheme (OP1: Operator1 only, OP2: Operator2 only, AUC: Auctioning carrier – Operator1 or Operator2)

As we assume the available channels are of identical value the decision to be made is the number of channels to be allocated to each of the operators. The decision on the number of channels allocated to each operator is based on their valuation (declared utility) for the resources.

NOTE: Please note, that the radio resources to be pooled for the auctioning purposes might be also provided by third party player, e.g. broadband wireless provider.

4.2.5 Traffic model

It is important to note that the resources sharing scenario is meaningful only in case of highly loaded networks, or in other words, in case of capacity limited networks. From practical point of view: no one is expected to ask for additional spectrum resources, in case when currently owned resources are sufficient for smooth network operation. Traffic model is seen as extremely crucial aspect in the presented analysis, due to the fact, that the used valuation function was simply modelled as the cell specific buffer size for each of operators (i.e. the valuation function for the auctioning purposes was modelled by the variable cell load). Due to the following assumption, it was expected, that the operator with more loaded network is going to use shared carriers from the pool more frequent. Orthogonally modelled traffic arrival model within time domain was proposed in [25] while we evaluate performance of the system by considering a more realistic, partially correlated and varying load balance among two operators, introducing tolerance on top of the reference offered cell load.

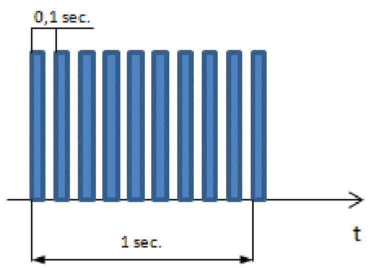

Figure 4-7: Bursty traffic arrival, fixed packet size

Traffic model was based on the operator's specific demands, being defined as the packet burst size. Number of the active users subscribers using high data rate service was fixed and constant for both operators and for each in all sectors. This case was created to evaluate performance impact of the data demand imbalance between auction players. Unbalanced valuations were forced by the unbalanced packet bursts sizes for each of the operators.

Table 2: Scenario specific traffic model parameters

Number of packets per burst	10
Packet arrival rate	0.1 sec.
Packet size	Variable
Packet size within burst	Fixed
UEs per cell	Fixed: 10

4.2.6 Simulation results

In this section we present and analyse simulation results based on the system model as described in Section 4.2.4. In the first step, we present Cumulative Density Function (CDF) of the cell goodput for each of the operators, as a function of the cell load imbalance (Figure 4-9) in Scenario 1. What can be observed, is that in case of equal traffic models, difference between operator's specific goodput is very limited (operator1 gets roughly 100kb/s higher mean goodput) and caused by random distribution of the users. In case of 1:2 load balance between operators, it is clearly visible that the operator network with higher load offer, is able to serve higher rates, while the less loaded network of the second operator is not able to serve as high rates as previously. This behaviour can be easily explained, considering that the assumed valuation function for the auction was based on the linear abstraction of the operators specific cell buffer size. Going to even more extreme scenario of 1:4 load imbalance, the same phenomenon is visible with increased impact in the served load imbalance.

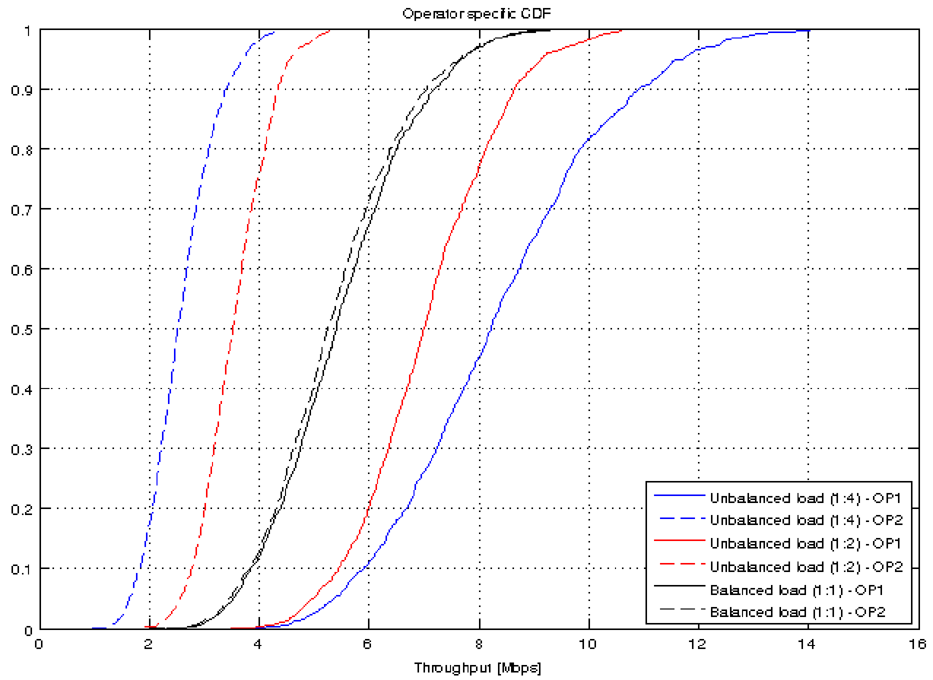

Figure 4-8: Operator specific goodput CDF for sharing scenario; inter-operator load balance as parameter

Based on this initial analysis on example realisation of the VCG based spectrum auctioning, we present more systematic analysis of the sharing impact on the cell goodput, relative to the reference scenario (i.e. no sharing).

Figure 4-10 presents average cell goodput for Scenario1 in both networks (i.e. OP1 and OP2), as function of cell loading, where the load imbalance between operators was ±10%. In contrary to the initially described served load shifting towards the stronger (in terms of auction's valuation function) operator, in this case, we can observe that both players are gaining, where the 50-percetile throughput increase is in range of 6%.

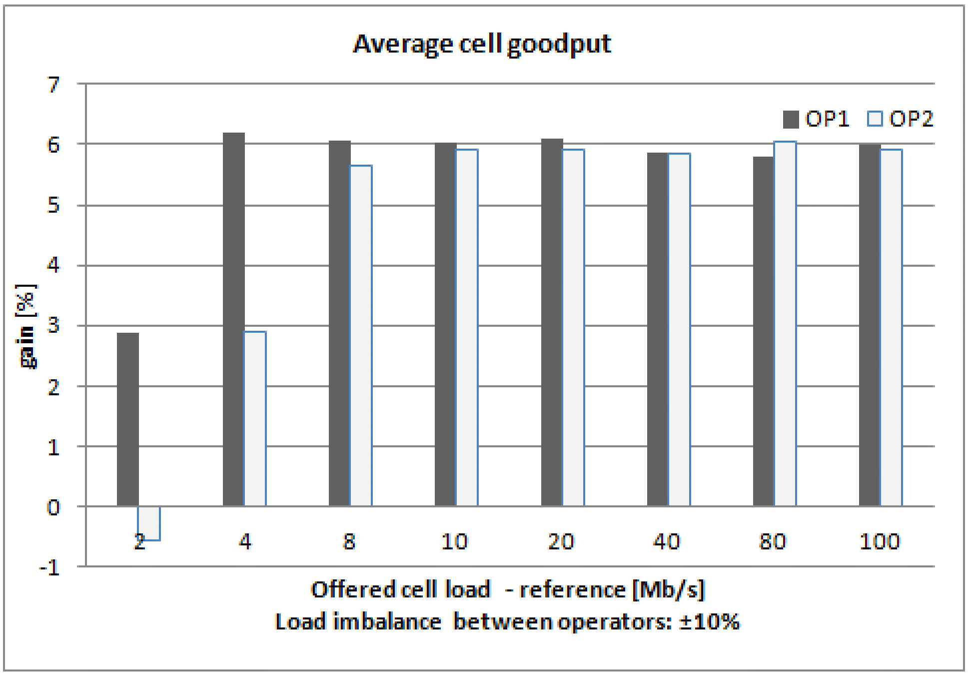

Figure 4-9: Average cell goodput gain as function of the cell load.
Operator specific cell load as reference load +10%/-10% (OP1/OP2)

Below, similar analysis was performed for the scenario, where the offered load imbalance was increase to ±50%.

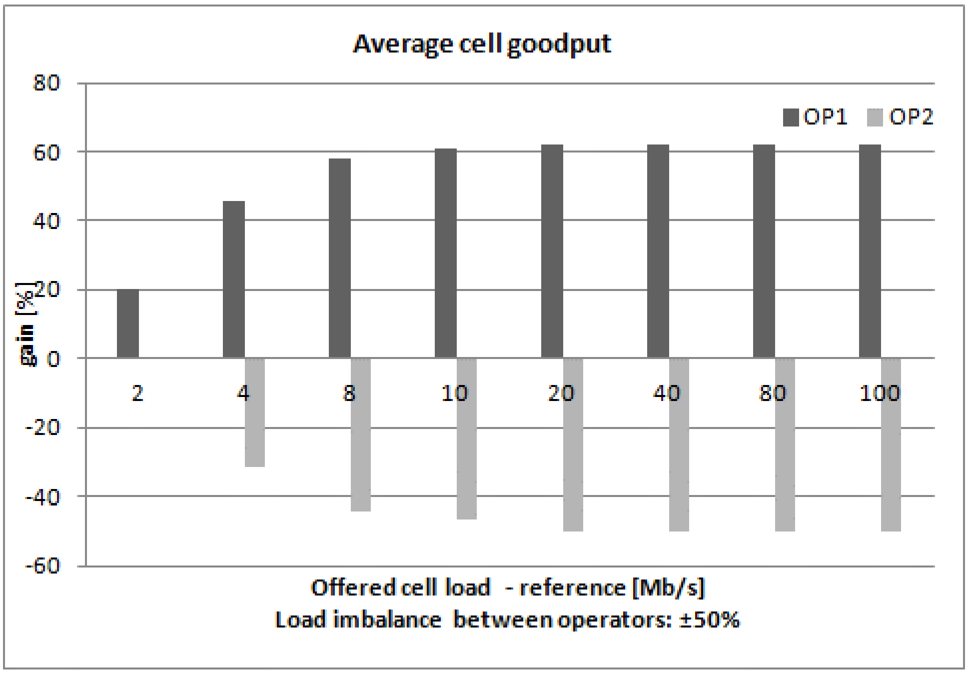

Figure 4-10: Average cell goodput gain as function of the cell load.
Operator specific cell load as reference load +50%/-50% (OP1/OP2)

As depicted on Figure 4-11, increased load imbalance cause very extreme and opposite impacts to each other's networks. The operator, which valuation was higher, received sharing gains in range of 20% – 60%, for the analysed load levels. On the other hand, the less loaded network was forced to decrease served load up to 50%. At this point, further analysis of this algorithm might be seen as useless, due to dramatic pains observed in one of the networks. But this does not have to be the case, as was described in the following analysis, where we have compared the spectrum utilisation figures. Comparing the sum of the served traffic in the reference scenario, with the sum of served traffic in sharing scenario, it was surprisingly observed, that in all evaluated cases, the spectrum utilisation was always increased, as presented on Figure 4-12 and on Figure 4-13.

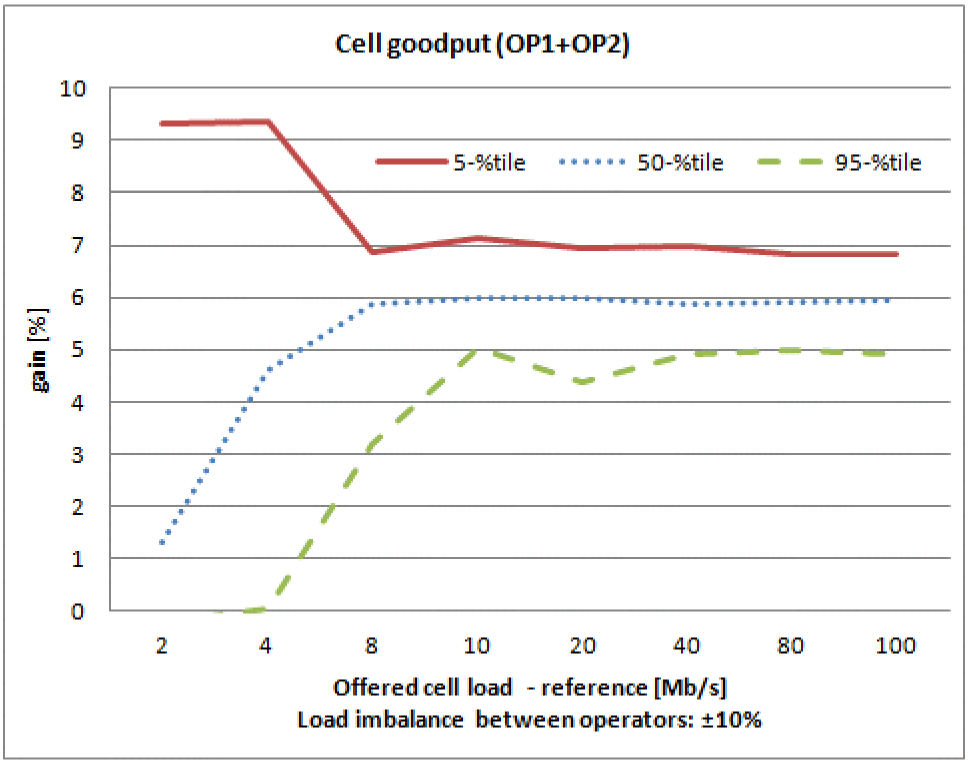

Figure 4-11: Total (OP1 + OP2) cell goodput gains

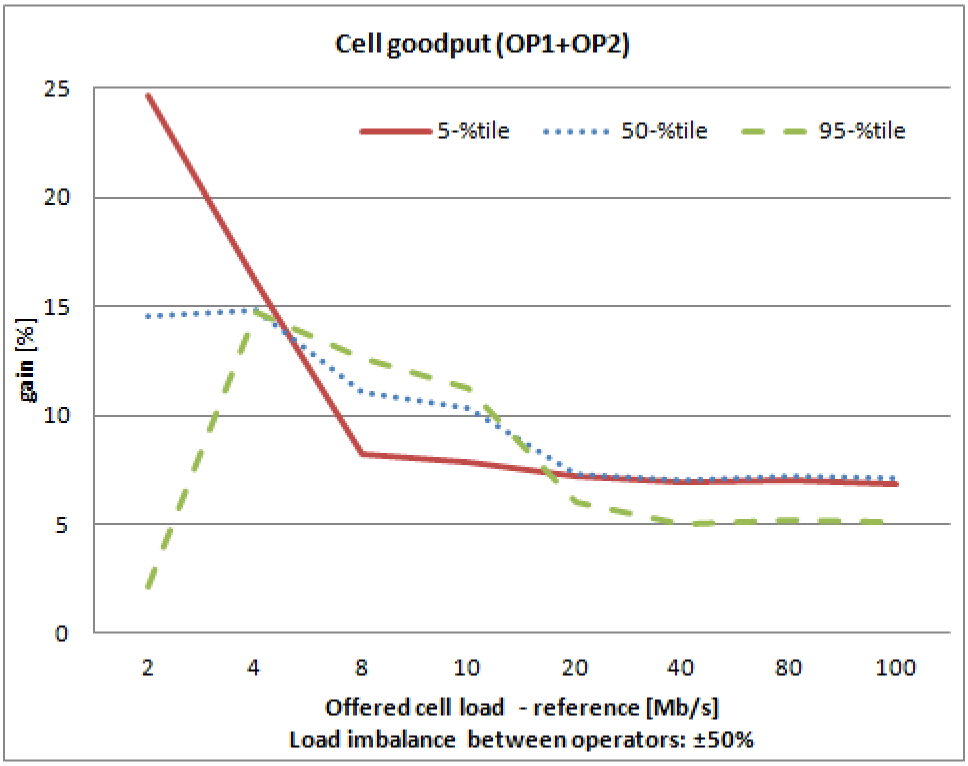

Figure 4-12: Total (OP1 + OP2) cell goodput gains

Based on the presented spectrum utilisation gains, it was concluded, that described spectrum sharing algorithm extended with appropriate business model for the operators coalition formation, might bring visible money revenue gains to the network operators. This conclusion will be further evaluated and extended by the business model consideration from WP5 analyses.

In the next step, we have extended the analysis with the more advanced carrier configurations (i.e. Scenario 2 and Scenario 3, as depicted on Figure 4-6). Based on the collected results, we have compared the spectrum sharing percentage (33% for Scenario 2 and 66% for Scenario 3) on the achieved average cell goodput.

Based on the results presented on Figure 4-13 and Figure 4-14 it is clearly visible, that increasing the spectrum sharing percentage, the total network throughput gains are also increasing.

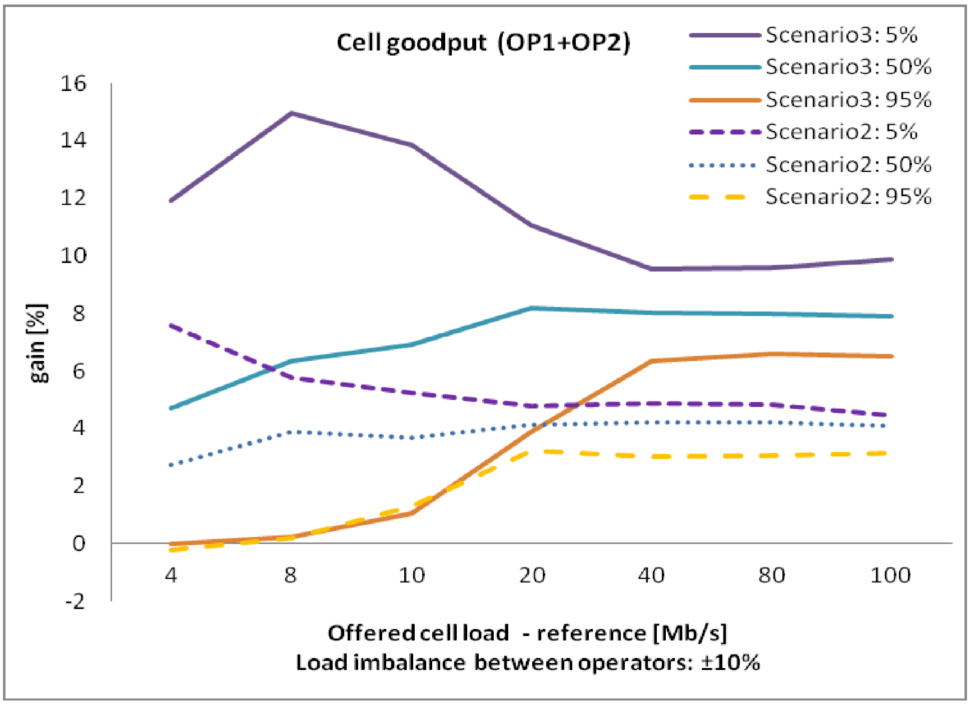

Figure 4-13: Total (OP1 + OP2) cell goodput gains: comparison of the percentiles for various spectrum sharing percentage (Scenario 2 vs. Scenario 3)

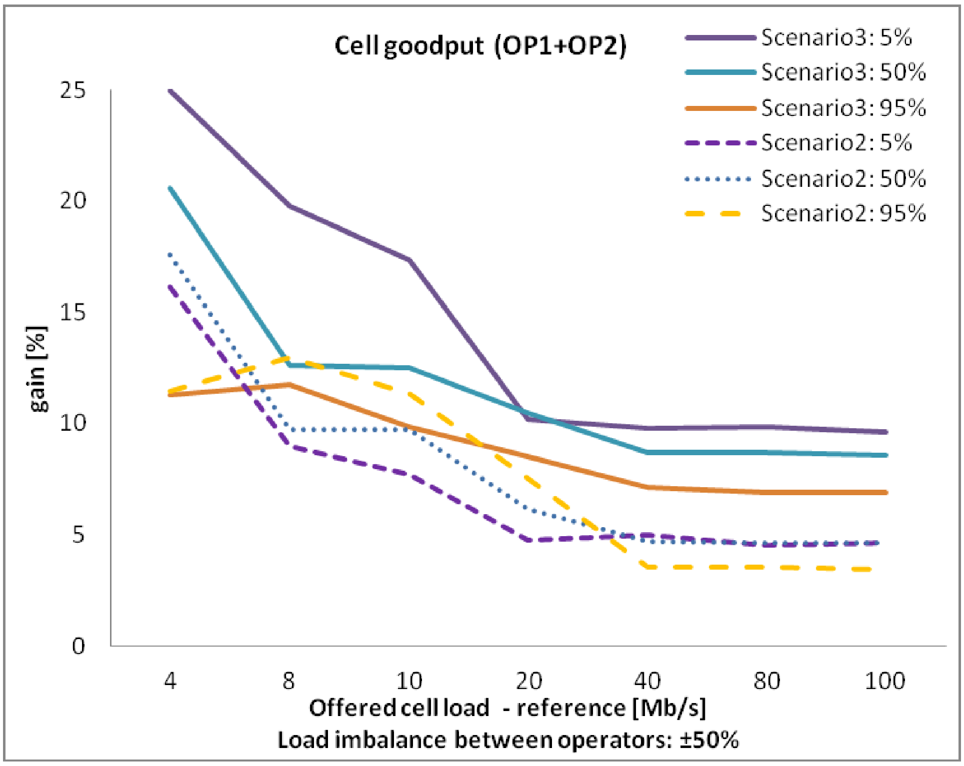

Figure 4-14 Total (OP1 + OP2): cell goodput gains: comparison of thp percentiles for various spectrum sharing percentage (Scenario 2 vs. Scenario 3)

4.2.7 Concluding remarks

We have observed that medium time scale spectrum auctioning algorithm is well suited for cooperation scenarios, where partially correlated and varying traffic patterns are present. Presented discussion and analysis was based on few silent assumptions. First and most limiting in these days, seems to be the availability of sufficiently wide power amplifiers for the RF frontends. The auction based distribution system we proposed, besides technically improving spectrum utilisation as was demonstrated in this paper, can also be seen as means to monetise the spectrum as a scarce resource. Looking at the example of Google AdWords market (i.e. pay-per-usage, with predefined fees) one can see that such monetisation of goods stimulates participation and may be considered as indication of possible developments in the wireless market by creation of new mobile services.

4.3 Large time scale scenario

This section addresses orthogonal spectrum sharing, where users of different operators are scheduled to not simultaneously use the same frequency at relatively large timescale (e.g. seconds or minutes). Both homogeneous and heterogeneous deployments are considered in the analysis. Some numerical results will be presented based on certain approaches of system modelling (mainly network layout, propagation models and traffic models) and resource management algorithms (e.g. the mechanisms of spectrum sharing, and intra-operator/network scheduling).

4.3.1 Scenario description

Orthogonal spectrum sharing is beneficial in the senses that: (1) it is more acceptable for mobile operators, considering robustness and controllability of their own networks; (2) it has less standardisation impact, since no extra physical-layer processing is required, which implies that might be more easily applicable to legacy networks (e.g. UMTS/HSPA, LTE) with some modest adjustment, e.g. using an advanced inter-operator scheduler.

Two scenarios, with different network deployments, are considered in the study:

- Homogeneous deployments, where each of the sharing operators (Operator A and Operator B) has only macro-cells in its respective network. The traffic profiles of the involved networks, even with the same coverage area, might differ significantly due to e.g. the number and types of subscriptions, the types of terminals (high-end or low-end), the types and occurrence times of traffic (video streaming or file download, at day time or night), etc. This results in a difference in the resource utilisation and its temporal variation among the networks, if spectrum were assigned separately and statically to individual operators. In an extreme case, one network might be congested due to lack of available spectrum while the spectrum of the other is slightly used. By spectrum sharing, the spectrum owned by the sharing operators will be dynamically assigned to the sharing networks according to certain criteria, serving their respective users exclusively.
- Heterogeneous deployments, where one operator (Operator A) has only macro-cells while the other (Operator B) has only hotspot cells (pico- or micro-cells) in

the same area. It is assumed that Operator A owns all the subscriptions, although all the terminals have also right to access the hotspot cells and their spectrum based on an agreement between the two operators. A user close to a hotspot cell may have a stronger received signal from the hotspot cell than from any of the macro cells, and thus it might be better served by the hotspot cell as long as the latter has sufficient capacity available. Thus it may be appropriate to assign more spectrum to hot-spot cells when the traffic is highly concentrated around these hotspots cells. This is especially applicable to the case that the traffic distribution is location-dependent with a relatively large percentage of traffic occurring nearby the hotspot cells. By spectrum sharing, the spectrum owned by the two operators will be dynamically assigned to the two networks according to certain criteria. Both networks will serve the users of Operator A. Note that, in this scenario the hotpot cells of Operator B are used to serve the users of Operator A, in this sense it includes also infrastructure sharing.

In both scenarios, each network uses the part of spectrum it is assigned exclusively before the next (re-)assignment, and thus avoiding any inter-network interference. Note that, intra-network inter-cell interference may still exist depending on the used radio technology (e.g. UMTS/HSPA or LTE) and chosen frequency reuse factor.

4.3.2 System model

For the homogeneous scenario, the system model and simulation approaches are as follows:

- Network layout – Operator A and Operator B have a co-located LTE network comprising twelve three-sectored sites (12 x 3) arranged in a hexagonal layout with an inter-site distance of 0.5 km. Each operator owns 10 MHz in the 2100 MHz band.
- Propagation model – Macro-cells have a directional antenna pattern given by [5] with an effective antenna gain of 11.5 dBi and a maximum transmit power of 46 dBm, while each hot-spot cell has omni-directional antenna with a maximum transmit power of 30 dBm. The distance-dependent path loss is given by $138.5 + 32.255\times\log(d)$ (d is distance in km), accompanied by shadowing fading with standard deviation of 8 dB and an indoor penetration loss of 17 dB. Fast fading is not considered.
- Traffic model – Traffic flows are modelled as the download of file with a lognormally distributed size with mean 1.0 Mbit and a standard deviation of 1.5 Mbit. Flows are generated according to a Poisson process with average arrival rate λ sampled uniformly over the entire coverage area.
- Simulation steps – For each initiated flow, the serving cell is selected based on the received pilot strength. The spectrum is assigned to networks with a certain granularity at a certain time scale, according to the time-averaged input metrics (with a certain averaging window) from Operator A and Operator B. The used input for the resource sharing algorithm is presented in detail in Section 4.3.3. At any time, the available radio resources in each cell are evenly shared by the served flows.

For the heterogeneous scenario, the following system modelling and simulation approaches are taken:

- Network layout – Operator A has an LTE network comprising 12 sectorised (12 x 3) sites arranged in a hexagonal layout with an inter-site distance of 1 km, overlaid with Operator B's LTE network consisting of n (n = 1, 3, 6, or 12) hotspot cells (evenly located) per coverage area of each macro-cell (see Figure 4-15). Each operator owns 10 MHz in the 2100 MHz band.
- Propagation model – Macro-cells have a directional antenna pattern given by [5] with an effective antenna gain of 11.5 dBi and a maximum transmit power of 46 dBm, while each hot-spot cell has omni-directional antenna with a maximum transmit power of 30 dBm. The distance-dependent path loss is given by $138.5 + 32.255\times\log(d)$ (for macro-cells) and $127 + 30\times\log(d)$ (for hotspot cells), respectively, accompanied by shadowing fading with standard deviation of 8 dB and an indoor penetration loss of 17 dB. Fast fading is not considered.
- Traffic model – Traffic flows are modelled as the download of file with a lognormally distributed size with mean 1.0 Mbit and a standard deviation of 1.5 Mbit. Flows are generated according to a Poisson process with average arrival rate λ. With probability K, the location of a generated flow is sampled in the service area of the hotspots, while with probability 1-K sampled uniformly over the entire coverage area.
- Simulation steps – For each initiated flow, the serving cell is selected based on the received pilot strength. The spectrum is assigned to networks with a certain granularity at a certain time scale, according to the time-averaged traffic loads (with a certain averaging window) served by macro- and hotspot cells. The used input for the resource sharing algorithm is presented in detail in Section 4.3.3. At any time, the available radio resources in each cell are evenly shared by the served flows.

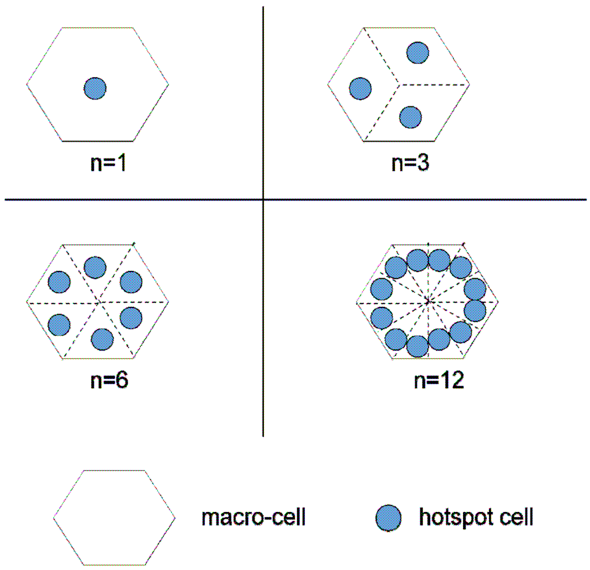

Figure 4-15: Number of picocells per macrocell and their relative location

4.3.3 Resource management

In this section the different spectrum/resource sharing algorithms are presented. The most important parameters that are used in these algorithms are as follows:

- **Time scale** – it is the time interval in which dynamic spectrum sharing algorithm is applied i.e. how often the spectrum can be redistributed between the two operators. The default setting for the time scale is 60 seconds.
- **Average Win**dow – it is the time interval in which the input metric from Operator A and B is measured in order to use it as the input to the spectrum sharing algorithm. The default setting for the average window is 60 seconds.
- **Granularity** – the smallest amount of spectrum that has to be added (or subtracted) to (from) a spectrum pool of Operator A or Operator B. The amount of spectrum redistributed between the two operators has to be a multiple of the granularity parameter. The default setting for the granularity is 6 physical resource blocks (PRBs) of 180 kHz.
- **Minimum reserved spectrum** – is the minimum amount of spectrum that is reserved per spectrum pool i.e. the minimum amount of spectrum that cannot be shared at both operators. The default setting is 6 PRBs.

4.3.3.1 Homogeneous scenario

This sub-section presents two algorithms that are used for dynamic spectrum sharing that are based on different input metrics (from Operator A and Operator B), for the homogeneous scenario. The first algorithm is denoted as 'cell-load (CL) based' algorithm and the second algorithm is labelled as 'call-arrival (CA) based' algorithm.

The CL-based algorithm is using as input the number of served/ongoing users within the measurement/average window as presented below. In order to calculate the number of served users within the measurement window the total amount of 'transfer time' is calculated following (eq.1 below) for all users that are served during that average window, as presented in Figure 4-16.

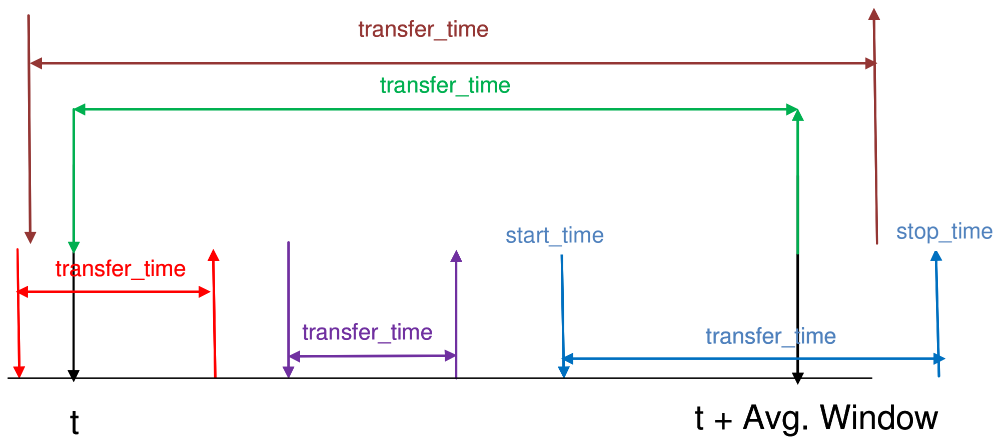

Figure 4-16: Different call start and end times during the average window

There are five different types of calls, depicted with different colours in Figure 4-16, depending of their start and stop time:

1. The calls starting and ending within the measurement window i.e. transfer_time = stop_time – start_time;
2. The calls starting before the measurement window and ending within the measurement window i.e. transfer_time = stop_time – t;
3. The calls starting within the measurement window and ending after the measurement window i.e. transfer_time = (t+AverageWindow) – start_time;
4. The calls active during the whole measurement window i.e. transfer_time = AverageWindow;
5. The calls active during the whole measurement window, but with duration time longer than average window i.e. transfer_time = AverageWindow;

The 'Total Transfer Time' is then a summation of all individual active user transfer times within the measurement window:

$$TotalTransferTime = \sum_i transfer\_time \quad \text{(eq. 1)}$$

Here, *i* denotes all calls that are active at least during a part of the measurement window.

Consequently, the 'total transfer time' is divided by the measurement 'average' window to derive the (effective) number of served users. This 'number of served users' value is taken as an input metric for the spectrum sharing algorithm.

The 'number of served users' metric is calculated per operator in order to evaluate their respective cell load. Note here that this metric takes not only the offered traffic in account but also how effectively the active users are served by the wireless system. For example, for a same level of offered load the 'number of served users' within a predefined measurement interval will be lower for an operator that has higher capacity and/or higher spectral efficiency due to the shorter 'transfer times' per active users.

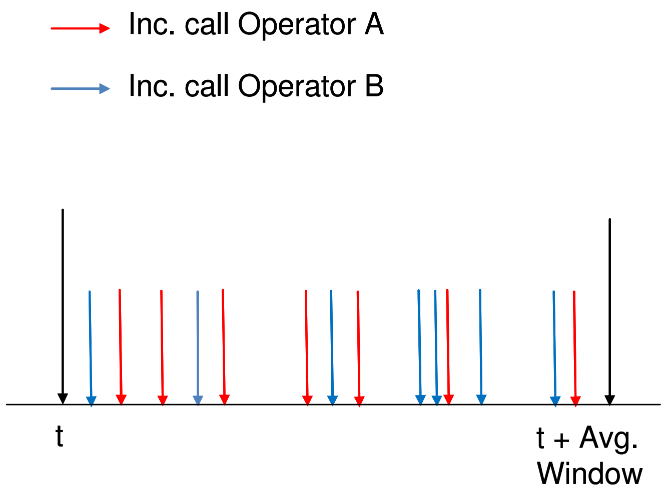

Figure 4-17: Number of call arrivals within the measurement window

On the other hand, the used input for the CA-based algorithm is the number of call arrivals within the measurement/average window. The determination of the number of call arrivals within the measurement window for usage as input in the spectrum sharing algorithms is rather straightforward and defined as follows. Within the average window the total number of call arrivals is counted, per operator, as presented in Figure 4-17. Note that the different colours in Figure 4-17 denote the users of different operators.

Note here that this metric only considers the amount of offered traffic (per operator) and does not take into account how quickly the active users are served.

The amount of shared spectrum depending on:

- The measured input in the previous measurement period.
- The sharing factor and eventually the granularity of sharing
- The total bandwidth assigned to the operators
- The minimum reserved (non-shared) bandwidth per operator.

As a first step the needed spectrum is calculated depending on the input metrics within the previous measurement window (e.g. either ‘number of served users’ or ‘number of call arrivals’) and the total spectrum that is allocated for both operators (eq. 2).

$$needspectrum = \mathrm{abs}(\frac{MetricA}{MetricA + MetricB} * (A.spectrum + B.spectrum) - A.spectrum))$$

$$needspectrum = abs\left(\frac{MetricA}{MetricA + MetricB} * (A.spectrum + B.spectrum) - A.spectrum\right);$$

(eq. 2)

Where $MetricA$ ($MetricB$) is the input metrics for Operator A (Operator B), $A.spectrum$ ($B.spectrum$) is the amount of spectrum Operator A (Operator B) brings in for sharing.

Note here that the calculation of the needed shared spectrum is done proportionally to the input metrics measured in the previous measurement window. After that it must be checked whether the minimum reserved spectrum is not violated with the calculation of the shared spectrum amount (eq.3).

$$deelspectrum = \min(needspectrum, B.spectrum - B.\min) \quad \text{(eq. 3)}$$

At the end, after sharing factor is calculated (eq.4) in order to ensure that the shared spectrum is a multiple of the spectrum granularity the final shared spectrum is calculated in (eq.5).

$$sharingfactor = rounddown(\frac{dealspectrum}{SharingGranularity}) \quad \text{(eq. 4)}$$

$$sharedspectrum = sharingfactor * SharingGranularity \quad \text{(eq. 5)}$$

The spectrum sharing algorithm is triggered for execution periodically with a pre-defined time scale (e.g. default 60 seconds). At each triggering instant the input metric (i.e. either ‘number of served users’ or ‘number of call arrivals’) for the sharing algorithm is calculated per operator. If these input metrics are different then spectrum re-allocation is needed and the amount of shared spectrum that has to be redistributed among the operators as presented below:

If (MetricA<>MetricB) then
{
A.spectrum = A.spectrum μ sharedspectrum
B.spectrum = B.spectrum μ sharedspectrum
};

In situation with two operators e.g. Operator A and Operator B if Metric A is greater than Metric B it means that operator A needs more spectrum than operator B. Consequently, the re-allocation of spectrum is done in such a way that the algorithm shifts the needed spectrum form operator B to operator A. On the other hand, if Metric B is greater than Metric A it means that operator B needs more spectrum and the algorithm shifts the needed spectrum from operator A to operator B.

4.3.3.2 Heterogeneous scenario

The dynamic orthogonal sharing of spectrum between macro- and hotspot- cells heavily relies on traffic distribution in the spatial domain. When a relatively large percentage of traffic occurs nearby the hotspot cells, more spectrum is assigned to the hotspot cells. On the other hand, if traffic is uniformly distributed in the whole area, more spectrum is assigned to the macro-cells. This is reflected in Figure 4-18.

In this study, the portion of spectrum assigned to macro-cells and hotspot cells is proportional to the ration of traffic choosing macro-cells and hotspot cells as best server, respectively.

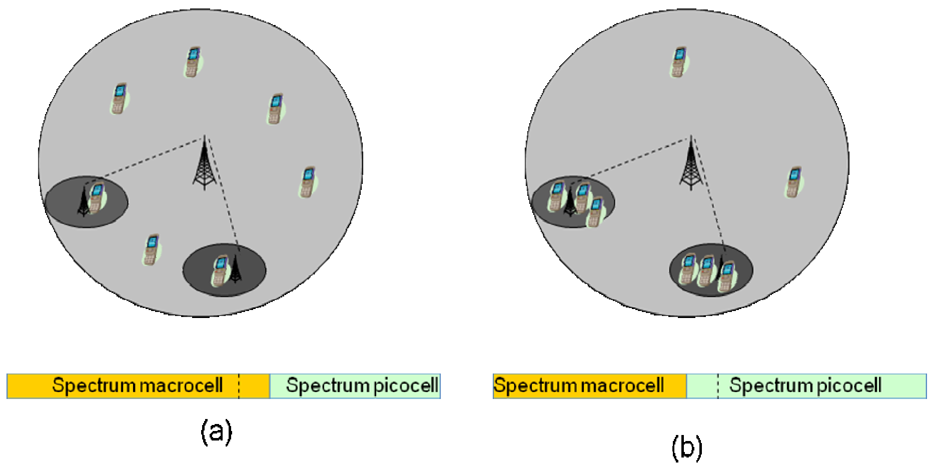

Figure 4-18 :Traffic distribution and spectrum sharing (a) uniformly distributed traffic and (b) most of traffic occurring nearby hotspot cells

4.3.4 Numerical results

4.3.4.1 Homogeneous scenario

In the homogeneous scenario three approaches are used to utilise the spectrum.

- The first approach is without spectrum sharing i.e. fixed spectrum assignment. In this case it is assumed that both operators have 50 PRBs and they cannot share the spectrum. This is the reference case.
- The second approach is dynamic spectrum shared using the input metric “Number of call arrivals within the measurement window”, labelled as call-arrival (CA) based algorithm. The operators have 50 PRBs but they can share the spectrum using call arrival-based algorithm as explained in Section 4.3.3.
- The third approach is dynamic spectrum sharing using the input metric “Number of Served Users within the measurement window”, labelled as cell-load (CL) based algorithm. The operators have 50 PRBs but they can share the spectrum using cell-load based algorithm as explained in Section 4.3.3.

First, as observed from Figure 4-19 CA-based algorithm shares the spectrum almost in a fixed manner and is not depending on the call arrival rate as it follows the proportion of users of Operator A and Operator B. This is not a desired property for a dynamic spectrum sharing. On the other hand the CL-based algorithm is more dynamic as it takes into account the call arrival rate when it shares the spectrum, see Figure 4-19. Without spectrum sharing, as expected, the assigned spectrum is same for both Operators A and B, resulting in two overlapping curves on 50 PRBs in Figure 4-19. Note that at rather high system load (e.g. 500 calls/s) the assigned spectrum for the two operators according to the CA and CL based spectrum sharing algorithm converge towards the 25% versus 75% users share ratio.

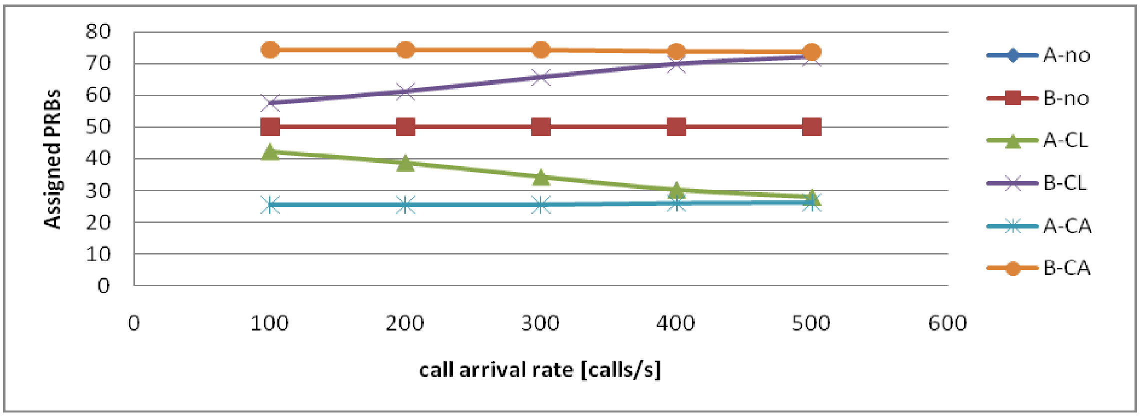

Figure 4-19: Assigned PRBs for Operator A (25%) and B (75%) for the three spectrum sharing approaches

The cell-load (CL) based algorithm results to more comparable 10th percentile user throughput between the two operators as presented in Figure 4-20. This is not the case for call-arrival (CA) based spectrum sharing algorithm, especially for small call arrival rates up to e.g. 200 calls/s. Actually, the difference in 10% throughput with CA-based spectrum sharing is even more pronounced when compared to the case with no spectrum sharing. This is because the CA-based algorithm takes only the number of call arrivals as input metric for the spectrum redistribution while the CL-based algorithm takes the ‘cell load’ into account as well. One drawback of the CL based algorithm is that for low load situations (e.g. up to 200 calls/s) the Operator A that borrows spectrum to Operator B has at the same time somewhat lower 10th percentile user throughput performance. This should be mitigated by adjusting the calculation of the redistributed amount of spectrum with additional limitation that the throughput performance from the system that gives portion of its spectrum does not have lower throughput performance than the system accepting a portion of the spectrum.

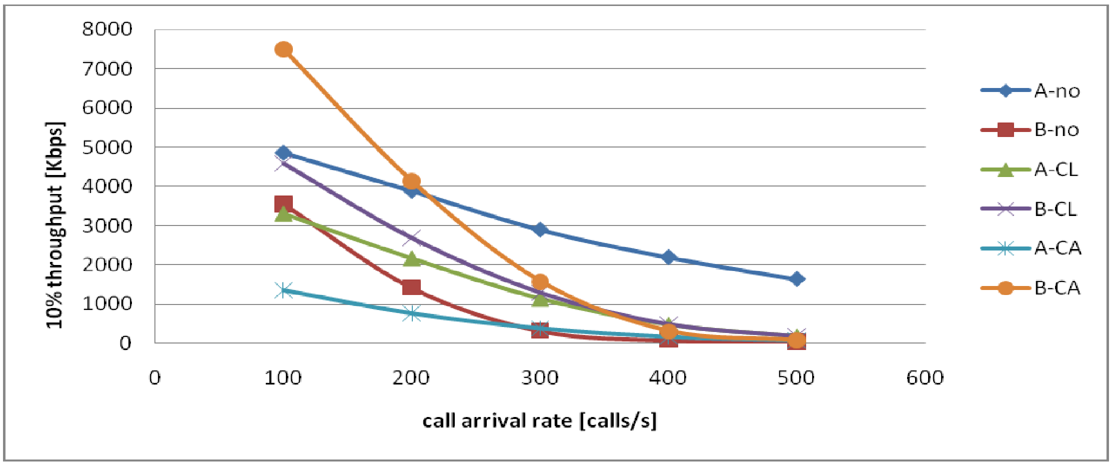

Figure 4-20: 10th percentile user throughput for Operator A (25%) and Operator B (75%) for the three proposed approaches

Figure 4-21 presents the 10th percentile user throughput for the whole system i.e. for all calls no matter to which operator they belong to. As it can be observed the 10th percentile throughput is highest for the CL-based spectrum sharing algorithm. For low load conditions (e.g. up to 200 calls/s) the CA-based spectrum sharing has the worst 10th percentile user throughput performance while for medium and high load conditions (e.g. higher than 200 calls/s) the no sharing reference case results in worst 10th percentile user throughput performance. If we take 1 Mbit/s as acceptable 10th percentile user throughput threshold than the maximum allowable system throughput for the no spectrum sharing case is around 240 calls/s. Consequently, the maximum allowable load for the CA-based and CL-based spectrum sharing is 280 calls/s (17% improvement) and 330 calls/s (37% improvement).

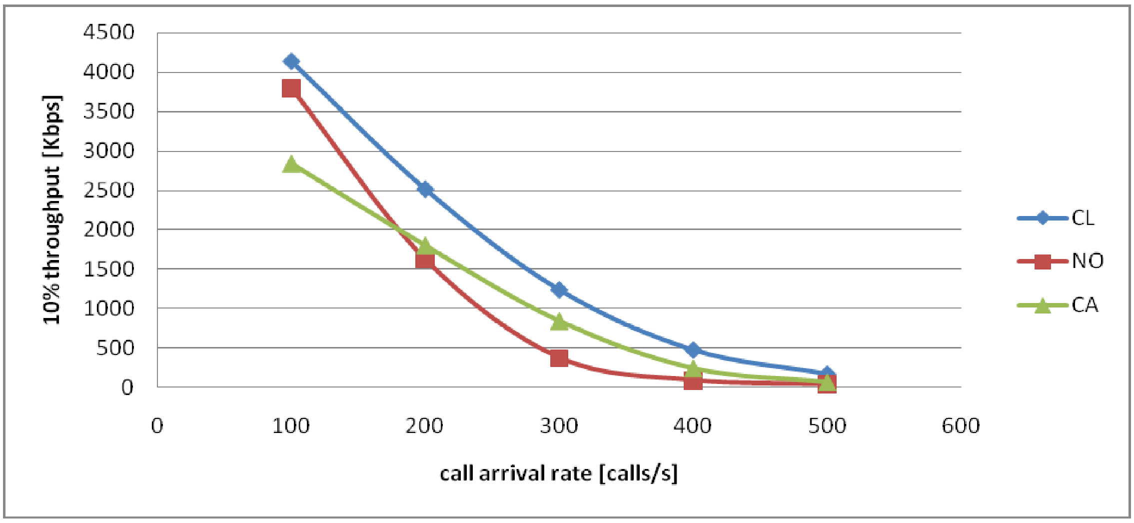

Figure 4-21: 10th percentile user throughput for the whole system and 25% vs. 75% users share

From the simulation results in Figure 4-19 to Figure 4-21 it can be concluded that the CL-based algorithm shares the spectrum dynamically and gives the best performance for the overall system. The most important pros of the CL-based algorithm are presented below.

- If there is a lower acceptable limit for 10th percentile user throughput for both operators (for example 1 Mbit/s) than with cell load based algorithms there is almost 37% gain in terms of system capacity when compared to the no spectrum sharing case.
- Spectrum is dynamically shared i.e. the amount of assigned spectrum resources are variable for different system load.
- 10th percentile user throughput is comparable for both operators

The most important disadvantage for the CL-based algorithm is as follows:

- For small call arrival rate, operator which needs more spectrum (i.e. it borrows from the other operator) has better 10th percentile user throughput performance than the operator that gives the spectrum. Therefore, borrowing the spectrum towards the cooperating operator results in even worse user throughput performance than the cooperating party, which in turn gives low incentive for sharing the spectrum. The reason for this effect is that the decision to share spectrum is cell-load based, and not user throughput based. Consequently, if calls are coming rarely due to the low load level the spectrum assignment for Operator B is larger than Operator A and in fact far more that it is actually needed resulting in very quick serving of the active calls and improved 10th percentile user throughput for Operator B. At the same time the 10th percentile user throughput for Operator A is worsened. This negative effect can be mitigated by applying additional limitation of the amount of shared spectrum that prevents the significant drop of the 10th percentile user throughput of Operator A below the 10th percentile user throughput of Operator B.

The results for Operator A and Operator B user subscription share of 50%/50% are presented in Figure 4-22 and Figure 4-24.

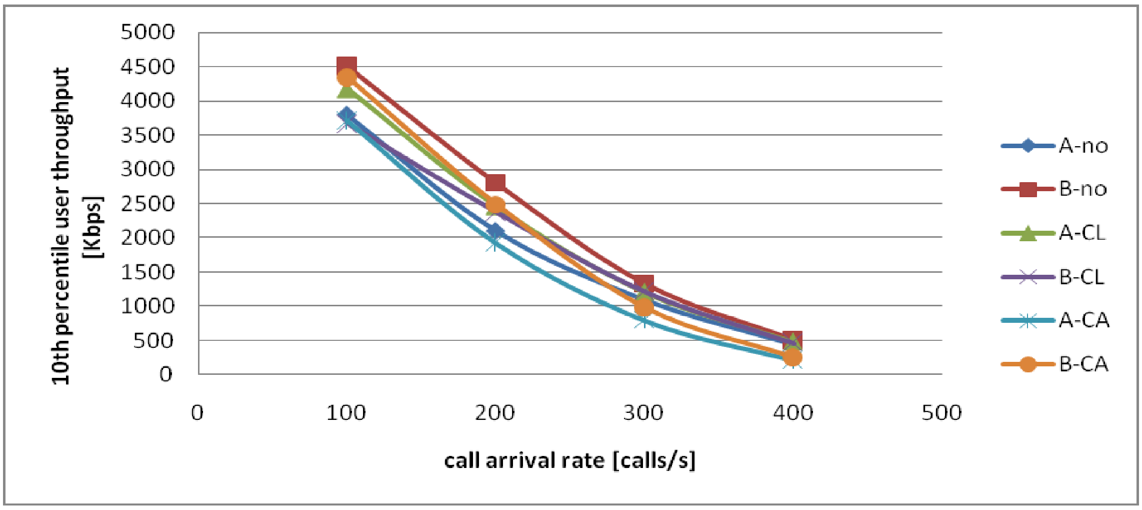

Figure 4-22: 10th percentile user throughput for Operator A (50%) and Operator B (50%) for the three proposed approaches

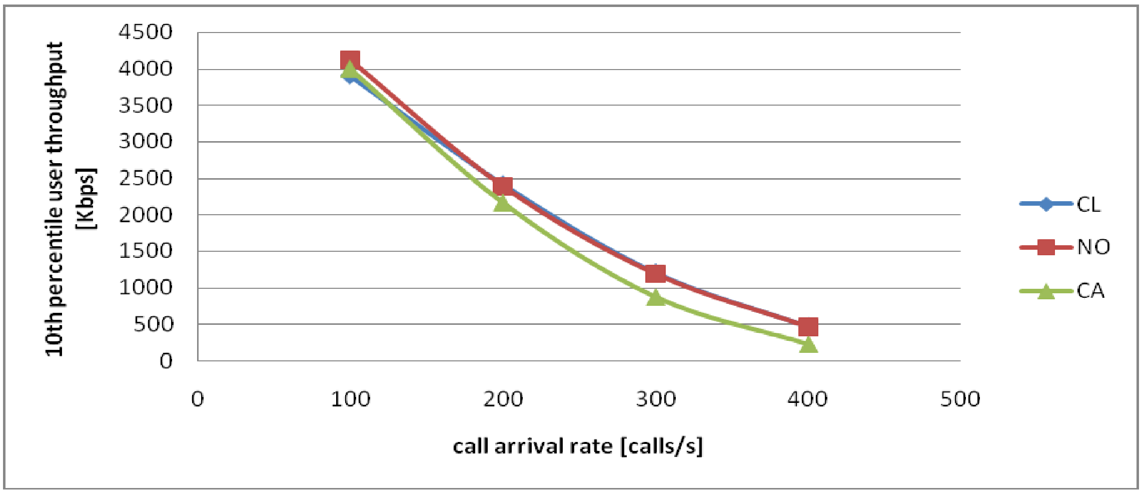

Figure 4-23: 10th percentile user throughput for the whole system and 50% / 50% users share

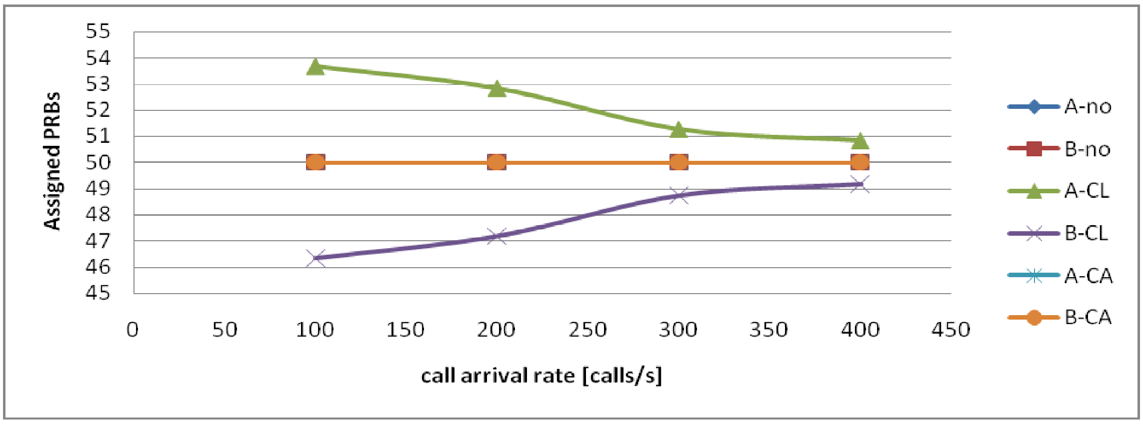

Figure 4-24: Assigned PRBs for the three proposed approaches and 50% / 50% users share

As observed from Figure 4-22 to Figure 4-24 in the case of even load among the two operators the dynamic spectrum sharing (either CA or CL based) does not bring additional gains with respect to the reference case without spectrum sharing.

4.3.4.2 Heterogeneous scenario

For performance comparison, three different spectrum arrangements have been considered for the heterogeneous scenario:

- Non-orthogonal sharing without coordination – In this arrangement, macro-cells and hotspot cells use all the available spectrum without any inter-operator coordination, i.e. the two networks operate in a co-channel frequency reuse manner.
- Separate spectrum assignment – In this arrangement, the two networks have their own statically-assigned spectrum exclusively. Even if some spectrum is not used in one network, it will not be shared to the other network.

- Dynamic orthogonal sharing – In this approach, the proportion of spectrum available to macrocells and hotspot cells is periodically determined, proportional to the amount of traffic selecting macro cells or hotspot cells as best serving cell.

The first two arrangements are reference cases for performance comparison with the dynamic orthogonal sharing.

Some simulations have been performed for the daily profile of K as shown in Figure 4-25with n=3, λ=122 flows/s and the maximum value of K, K_{max}, varying between 0 and 1.

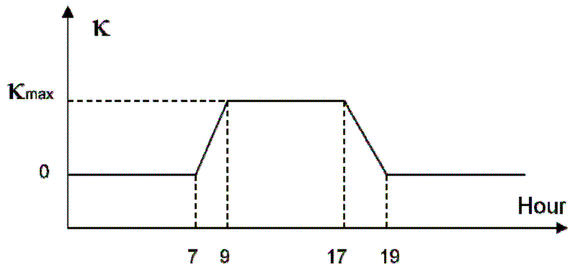

Figure 4-25: Daily profile of location-dependent traffic distributions

In Figure 4-26 and Figure 4-27, the average user throughput and the 10th user throughput percentile are shown, respectively, as a function of κmax for the three spectrum arrangements. The results show that

- The higher $K_{max,}$ the more gain of orthogonal spectrum sharing over separate spectrum assignment in average flow throughput and 10th user throughput percentile. For example, for $\kappa_{max} = 1$, the gain is approximately about 30% for average user throughput and 10% for 10^{th} percentile average user throughput, while for $\kappa_{max} = 0$ almost no gain is observed for both average throughput and 10^{th} user throughput percentile. This indicates that orthogonal spectrum sharing in the heterogeneous scenario is only beneficial if a relatively large percentage of traffic occurring around hotspot cells.
- The spectrum arrangement of “Non-orthogonal sharing without coordination” outperforms significantly the other two spectrum arrangement. This implies that, with “Non-orthogonal sharing without coordination”, although more inter-cell interference (thus lower SINR) is introduced, but since there is more spectrum available per cell (higher bandwidth) this still results in high throughput. Note that, during our simulations no extra inter-cell interference coordination mechanism is applied.

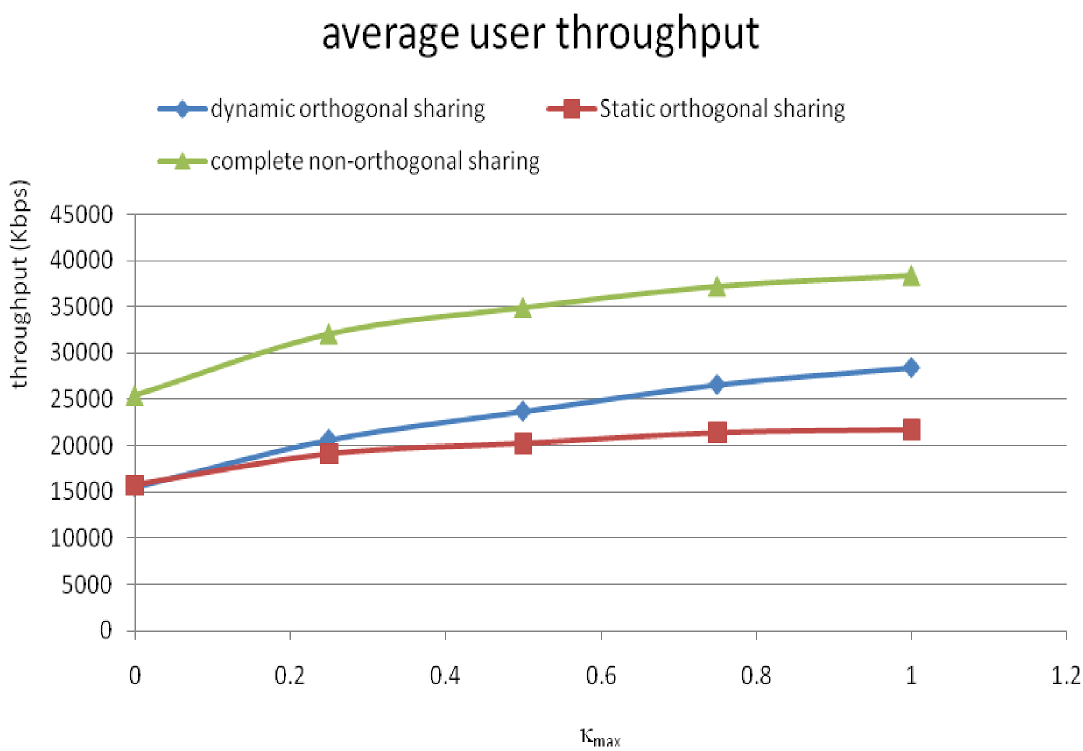

Figure 4-26: The impact of K_{max} on the average user throughput for different spectrum arrangements

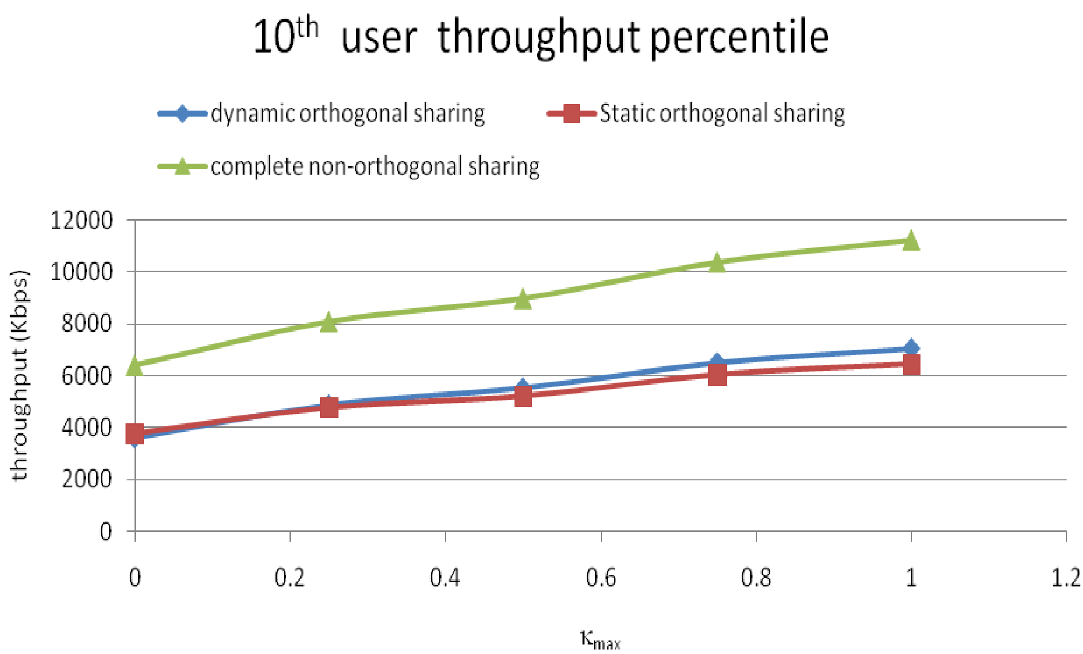

Figure 4-27: The impact of K_{max} on the 10^{th} user throughput percentile for different spectrum arrangements

5 Relay-assisted resource sharing scenario

A major challenge for future mobile communication systems beyond LTE-Advanced is to provide a wide coverage area of high data rate services as well as to increase the system capacity. An approach to achieve wider coverage area is to increase the user throughput (UT) especially at the cell boundary by introducing intermediate nodes that act as relays (RSs). Relays assist the radio transmission between a base station and mobile station in an efficient manner in various types of locations such as places where fixed-line backhaul links are difficult to deploy. Thus, they are indispensable elements of future wireless backhaul networks. In this section, we start with a wireless backhaul scenario with relays. Then we study the potential gain of sharing the wireless backhaul (relays) as well as the spectrum between two operators using MIMO beamforming techniques.

5.1 Scenario description

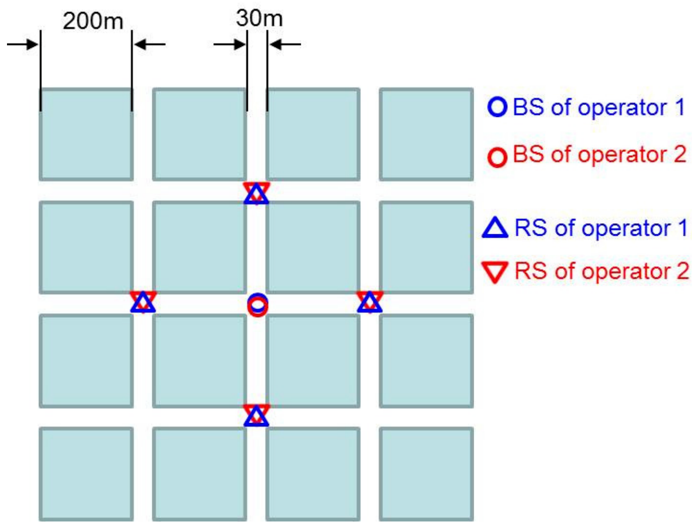

Figure 5-1: The metropolitan scenario under investigation

The metropolitan area scenario under investigation is shown in Figure 5-1. Due to strong shadowing effects in the network, dense networks are required to guarantee the quality of service (QoS) at the user terminals. To this end, each cell in the Manhattan grid comprises of one BS and four relays such that the coverage holes are avoided and the QoS' of the UTs are improved. The two operators who operate in the same area have the overlapped layout. More precisely, both the BSs and relays of the two operators are close to each other.

We define two types of users in this network. Direct users are directly served by the BS while the Relay users are served by the relay. Whether a user is a direct UT or a Relay UT in our initial set-up is simply decided by the measured received signal strength indicator (RSSI) from BS and RS. The relays employed here are one-way decode and forward (DF) MIMO relays. As shown in Figure 5-2, in the first time slot, the data of the relay users is sent via the wireless backhaul link between the BS and the relay. There is no direct link between the BSs and the RS UTs due to the pure channel quality. Then the relay demodulates and decodes the data and then encodes and modulates it again before transmitting to the users. In the second time slot, the BS transmits to its direct users while the relay transmits to the RS UTs. It is assumed that in the second time slot the communication from the BS to direct users and that from the relay to RS users use orthogonal resources, e.g. different subcarriers. Thus, there is no interference created between the direct UTs and the RS UTs. Furthermore, we assume the transmission between the BS and the RS is error-free. Note that the functionality of the relay here is similar to the Layer 3 relay which is defined in LTE Rel. 10, i.e. the relay acts as a Pico BS and it is recognised as a BS from the viewpoint of the UTs [8].

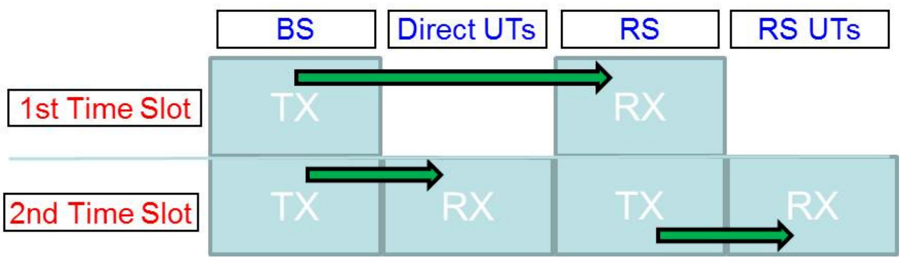

Figure 5-2 Timing in the two-hop networks. Direct UTs are users directly served by the BS while RS UTs are served by the RSs

To demonstrate the potential sharing gain, we consider the following two scenarios:

- Non-sharing scenario: Each operator has its own spectrum and relays.
- Non-orthogonal resource sharing: under the sharing circumstances it is assumed that the spectrum is fully shared between the two operators. The neighbouring relays fully cooperate with each other, i.e. the data streams of different operators are combined such that joint processing of the data of two operators is possible at the relay. In other words, the relays of different operators are treated as a single relay. In the second time slot, the BSs transmission and the relay transmission use different subcarriers. Clearly, in such a scenario inter-operator interference is created and thus advanced signal processing techniques are required to handle these types of interference.

5.2 Resource allocation using beamforming techniques

5.2.1 Non-sharing scenario

Since in the non-sharing scenario different users of the same operator are separated using OFDM techniques, there is no co-channel interference between users. To maximise the received SNR at each user, the maximal-ratio combining transmit (MRT) strategy is used per sub-carrier, i.e. the SNR of each user is given by

$$SNR = P_{\mathrm{R}} \frac{\|\boldsymbol{h}\|_2^2}{P_{\mathrm{N}}}$$

where P_R is the received signal power which takes into accounts the large-scale fading effects such as path-loss and shadowing. The instantaneous fast-fading channel from the BS or RS to the user is denoted as $\boldsymbol{h}$ while P_N stands for the power of thermal noise. For calculating the spectral efficiency, we use the link-to-system mapping curves from the WINNER project [9].

5.2.2 Non-orthogonal sharing scenario

When both the relay and the spectrum are shared, the inter-operator interference is introduced into the system. Again considering the second time slot, the BSs and direct users of different operators have constructed an interference channel which is Topology A in Figure 5-3 while the relay and RS users have created a broadcasting channel which is Topology B in Figure 5-3. Both channels are interference limited especially in the high SNR regime. Therefore, we apply the interference nulling techniques. For simplicity, we use only linear beamforming techniques, i.e. zero forcing along with maximum ratio transmission MRT [6], [7].

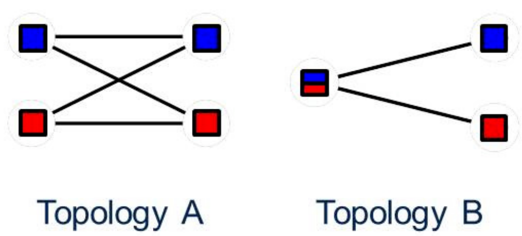

Figure 5-3: Physical layer topologies which are defined in the work package 3 of the SAPHYRE project

5.3 Numerical results

In this section, the preliminary results of this type of resource sharing are given. The system level simulator used here is quasi-static. That is, the user position is fixed during each transmission even though he/she experiences a fast fading corresponding to a given velocity. The major system parameters which are used for obtaining the simulation results are in Table 5-1.

Table 5-1: Key simulation parameters.

Parameters	Value	
Carrier frequency	2	GHz
Channel model	WINNER II B1 NLOS	
Traffic model	Full buffer – Downlink	
eNB parameters		
eNB location/height	15.0	m (above rooftop)
eNB number of sectors	4	
eNB antennas per sector	2	
eNB max tx power per sector	46	dBm
eNB elevation +antenna gain	14	dBi
eNB noise figure	5	dB
RS parameters		
RS location/height	10	m (below rooftop)
RS antennas per RS	4	(omini)
RS max tx power	24	dBm
RS elevation + antenna gain	9	dBi
RS noise figure	7	dB
Penetration loss	17.0	dB
UE parameters		
UE location/height	1.5	m
UE antennas	1	(omini)
UE elevation + antenna gain	0	dBi
UE noise figure	7	dB
Number of UEs	Single user per operator	

Figure 5-4 and Figure 5-5 demonstrates the performance of the non-sharing case and the non-orthogonal resource sharing case. The sharing gain is almost two-fold. However, since the simulation results are obtained under a static scenario which is an extreme case, the sharing gain will decrease if the system dynamics is added, e.g. a statistical traffic model or realistic traffic model. These issues will be addressed in the next deliverable.

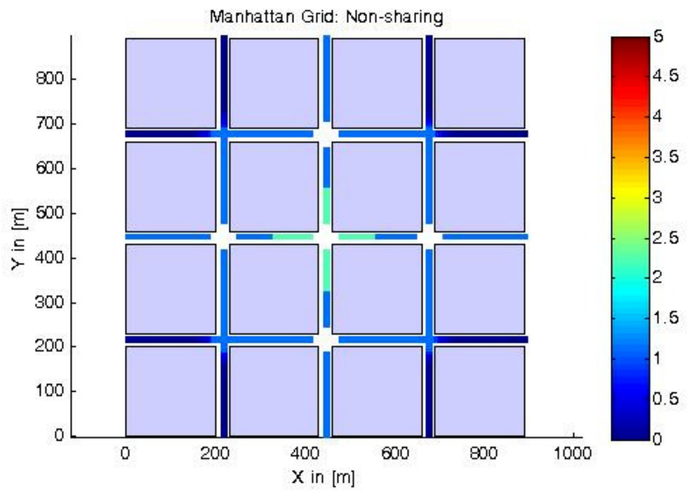

Figure 5-4: The spectral efficiency of the non-sharing case

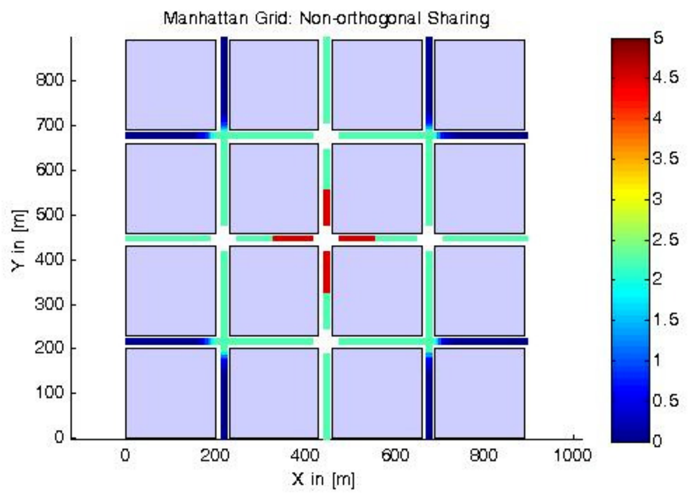

Figure 5-5: The spectral efficiency of the non-orthogonal sharing case

6 Infrastructure sharing scenario

6.1 Multi-operator COMP

In recent years improving cell edge performance via so-called Cooperative Multi-Point (CoMP) transmission and reception is receiving significant attention. Another key trend is the reduction of network costs via infrastructure sharing. In this section, we address the performance benefits of CoMP transmission combined with multi-operator infrastructure sharing, labelled as multi-operator CoMP.

6.1.1 Scenario description

Coordinated multi-point (CoMP) transmission and reception has been identified by 3GPP as a technique to improve average and especially cell-edge user throughput [1]. The basic idea is that, by coordinating the transmission and reception of neighbouring cells, inter-cell interference is mitigated and the performance of especially cell-edge users is improved. There are different types of CoMP, depending on the means of coordination [2]. In this study, we concentrate on downlink CoMP and focus on the so-called 'non-coherent joint transmission CoMP' [3]. In this mode, the same data transport blocks are transmitted by multiple cells in the same PRBs (Physical Resource Blocks) to a given terminal. From the terminal's perspective, the signals from different cells are only different in their respective times of arrival, which is to some extent equivalent to the case where the signals are transmitted by a single cell and experience multipath fading.

Traditionally, e.g. in the 3GPP definition so far, CoMP is only configured within one operator's network. However, in the context of infrastructure sharing, it may be advantageous to extend the concept of CoMP to the multi-operator case, in which case sites/sectors of different operators are involved in the CoMP configuration. As exemplified in Figure 6-1, in some cases a base station of Operator B may be able to contribute better to enhancing a given terminal's connection, than an additional base station of Operator A, in the sense that it may provider a stronger radio link to the terminal. Such inter-operator cooperation requires that the same data can be transmitted using the same PRBs that are assigned to the terminal by the serving home operator base station. To support this, the base stations/sectors of Operator B must be able to utilise the spectrum of Operator A. In the presented study, we assume that the spectrum of Operator A is only used to serve customers of Operator A, potentially in cooperation with one or more base stations of Operator B. Such inter-operator CoMP configuration can be seen as a way of infrastructure (but not spectrum) sharing, since terminals of one operator make use of the infrastructure (base stations) of another operator while solely using their home operator's spectrum.

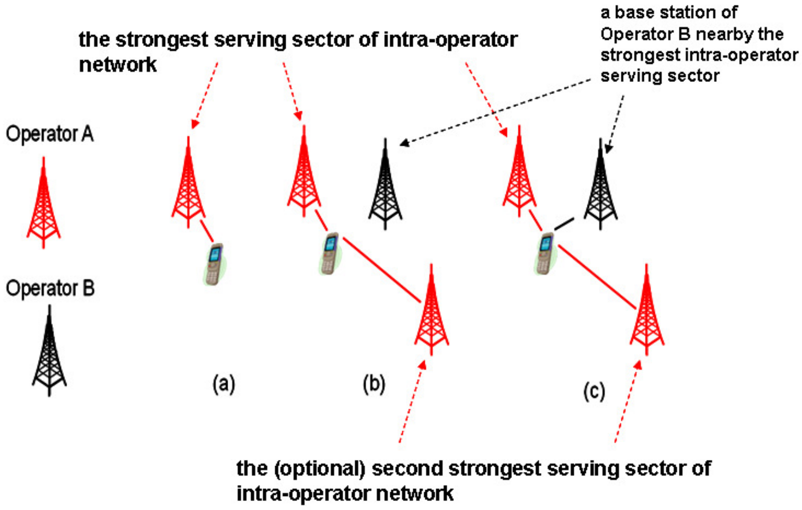

Figure 6-1: Illustration of different transmission and reception schemes: *(a)* single cell transmission; *(b)* intra-operator CoMP; *(c)* inter-operator CoMP

6.1.2 System model

In this sub-section we describe the key modelling aspects regarding network layout, propagation environment and traffic characteristics. Key simulation parameters are given in Table 6-1.

We consider two network operators each running an LTE-Advanced network comprising twelve sectorised (12 ×3) sites that are organised in a hexagonal layout, as depicted in Figure 6-2. A wraparound technique is applied to mimic infinite networks and avoid boundary effects. The degrees of co-siting and 'co-azimuthing' are denoted Δ_{CS} and Δ_{CA}, respectively, and are defined in the figure. Note $\Delta_{CS} = \Delta_{CA} = 0$ corresponds with a scenario of fully co-sited and -azimuthed networks. The antenna diagram is taken from [4].

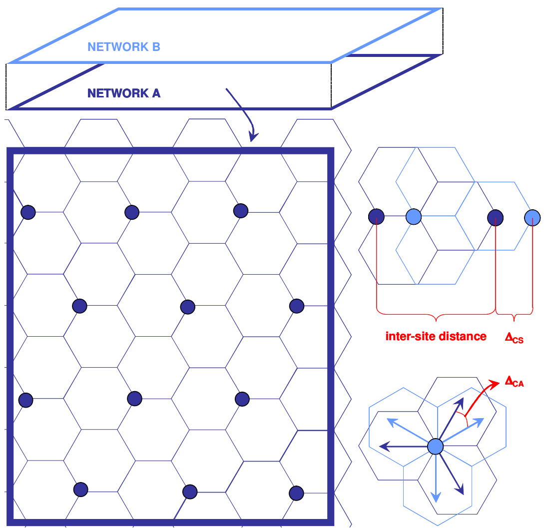

Figure 6-2: Network layout

The propagation environment is characterised by distance-based path loss, shadowing and indoor penetration loss. The key propagation parameters are summarised in Table 6-1. The considered LTE-A networks serve data flows only, which are modelled as the download of file with a lognormally distributed size with mean 1.0 Mbit and a standard deviation of 1.5 Mbit. Flows that associated with customers of network operator A are generated according to a spatially uniform Poisson process with average arrival rate λ. Once a download is completed, the corresponding flow disappears from the system. It is noted that no flow arrival process is modelled for network B, since in the considered scenario of pure infrastructure sharing this does not affect the performance experienced by flow in network A. As will be explained below, the infrastructure of network B is utilised to better serve network A's flows by means of multi-operator CoMP, using network A's frequency spectrum.

Table 6-1: Key simulation parameters

Inter-site distance	1.0	km
Main lobe antenna gain after cable/slant loss	11.5	dBi
Maximum transmit power	46.0	dBm
Noise power density (per PRB)	-121.5	dBm
Noise figure	8.0	dB
Carrier frequency	2100	MHz
Path loss	$138.5 + 32.23 \log_{10}(d_{km})$	dB
Shadowing standard deviation	8.0	dB
Intra-site shadowing correlation	1.0	
Inter-site shadowing correlation	0.5	
Penetration loss	17.0	dB
Average flow size	1.0	Mb
Standard deviation of flow size	1.5	Mb

6.1.3 Resource management

In this section a number of relevant resource management mechanisms are described, including the formation of cell clusters for CoMP application, the construction of active sets and the allocation of radio resources and user bit rates.

6.1.3.1 Intra-/inter-operator CoMP cluster formation

The application of CoMP requires that disjoint clusters are formed comprising multiple cells that may cooperate to jointly serve selected users. Such clustering is needed to allow localised (at the cluster level) and conflict-free resource allocation. Associated impact on control overhead and backhaul requirements, impose a limitation as to the number of cells that can be grouped in such a cluster [3]. In our approach we make use of static intra- and inter-operator cell clusters which are formed as follows. *Intra-operator clusters* comprise three sectors that either belong to neighbouring sites ('different-site intra-operator cluster') or to the same site ('same-site intra-operator cluster'), as illustrated in Figure 6-3.

Similarly there is a need for the formation of *inter-operator clusters*, in order to avoid resource allocation conflicts when resource allocations determined at the intra-operator cluster level, are ‘copied’ to any supporting cells in the other network (see below). The construction of inter-operator cluster is somewhat more challenging since the clustered sectors belong to two distinct networks with potentially very different network layouts in terms of site locations and antenna orientations. To overcome this challenge we developed a specific inter-operator clustering algorithm, which aims at forming clusters that provide the largest performance enhancement potential and essentially works as follows. Consider the construction of inter-operator clusters from the perspective of network A, which determines for each intra-operator cluster in network A an associated set of cells in network B that are candidates for co-serving flows in network A in a multi-operator CoMP fashion. To form these clusters, a large number of user positions are sampled. For each such a position, the best serving cell in both networks A and B are determined. Such a sample indicates an ‘association’ between the intra-operator cluster containing the best serving cell in network A, and the best serving cell in network B. This association holds in the sense that a terminal at the sampled location is likely to benefit from a configuration where the selected best serving cells in both networks would be able to cooperate in a CoMP fashion. Such an identified association is then a trigger to configure the inter-operator clusters to support such cooperation. After evaluating and processing all sampled user positions, the degree of association between each intra-operator cluster in network A and each individual cell in network B is expressed by the number of observed ‘associations’. From the perspective of a given intra-operator cluster in network A, the associated inter-operator cluster in network B then comprises all cells (in network B) whose degree of association is strongest with the given intra-network cluster.

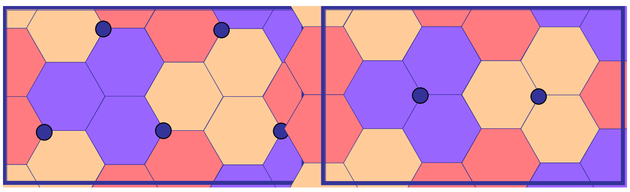

Figure 6-3: Different-site (left) versus same-site (right) intra-operator clustering

6.1.3.2 Active set construction

Given a flow’s uniformly sampled location and the corresponding path gains it experiences towards all sectors, the flow’s *active set*, defined as the set of concurrently serving sectors in both its home (A) and host network (B) is constructed as follows. First, the strongest serving cell in the home network A is selected based in the observed RSRPs (Reference Signal Received Power). In scenarios with an activated CoMP feature, subsequently, the active set may be expanded by adding other candidate cells that belong to the intra- or inter-operator cluster corresponding with the selected strongest serving cell. More specifically, the strongest $AS_{max} - 1$ cells are included in the active set, provided that the measured RSRP is at most $\Delta_{\mathrm{AS,intra}}$ or $\Delta_{\mathrm{AS,inter}}$ worse than that of the strongest serving cell, considering candidate cells of the home and host network, respectively. By setting $\Delta_{\mathrm{AS,inter}}$ lower than $\Delta_{\mathrm{AS,intra}}$ some preference is effectuated towards including home over host network cells in a flow’s active set. Cells of the host network are then only involved if the achieved performance enhancement is expected to be sufficiently large. Note that setting $\Delta_{AS,intra}$ = 0 dB ($\Delta_{AS,inter}$ = 0 dB) does not necessarily switch off intra-operator (inter-operator) CoMP, considering the equal link qualities that a given user may have towards co-sited/azimuthed (intra/inter-operator) sectors.

6.1.3.3 Packet scheduling and rate assignments

The proposed resource fairness-oriented packet scheduling scheme is in charge of assigning PRBs to active flows, and operates at flow arrival and departure instants. As the CoMP feature allows given flows to be simultaneously served by multiple cells, *coordinated* packet scheduling is needed across the intra-network cluster to ensure that a given UE is assigned the same set of PRBs in all its serving cells. The proposed scheduling scheme applies an iterative procedure as follows.

Initialize for each cell in the (intra-network) cluster the number of unassigned PRBs to n_{PRBs} = 50 (assuming a spectrum availability of 10 MHz). For each flow that is served by one or more cells in the cluster, mark which are its serving cells, which initializes for each cell the number of unscheduled flows n_{flows}. The iteration step is then to select the most resource-limited cell, i.e. the one with the smallest ratio of n_{PRBs} / n_{flows}. For this cell the scheme then assigns n_{PRBs} / n_{flows} PRBs to each served flow[1]. For flows in CoMP mode (active set size > 1) this PRB assignment is copied to any other serving cells in the cluster. Subsequently, the served flows are marked as ‘scheduled’, the values of n_{PRBs} and n_{flows} are updated accordingly in each cell and the iteration step is repeated until all flows are scheduled. Note that due to the CoMP restrictions, this does not necessarily imply that all PRBs are assigned.

As an illustration of the scheme, consider the scenario with five flows served by a three-cell cluster in network A given in Table 6-2. Note that flows 2 and 5 are in CoMP mode. According to the scheduling scheme, in the first iteration, CELL A_I has the smallest n_{PRBs} / n_{flows} ratio (50/3 < 50/2 = 50/2) and hence 50/3 PRBs are assigned to its three served flows. In the second iteration, CELL A_{II} is addressed (50/2 < (50–50/3)/1) and hence 50/2 PRBs are assigned to flows 4 and 5. Since all flows are scheduled, the scheme terminates. Note that in CELL A_{III} some PRBs remain unassigned, a drawback which is due to the CoMP-imposed restrictions.

Table 6-2: Scheduling example

	CELL A_I	**CELL A_{II}**	**CELL A_{III}**
FLOW 1	**V**		
FLOW 2	**V**		**V**
FLOW 3	**V**		
FLOW 4		**V**	
FLOW 5		**V**	**V**

[1] This potentially fractional character of the assignment is reasonably assumed to be dealt with at the finer timescale.

The obtained (intra-operator) PRB assignments are 'copied' to the involved cells in the host network. Suppose in the example that the active set of FLOW 4 comprises, besides CELL A_{II}, also CELL B_{III} in network B. Then FLOW 4 is simultaneously served by both cells on the same 25 PRBs that have been assigned in the above procedure. Given the construction of inter-operator cell clusters, this does not lead to any conflicts. Note further that the frequency band in which network B supports network A via multi-operator CoMP is different from that in which network B serves its own flows (potentially sup-ported by network A) and hence supporting another network in inter-operator CoMP mode imposes no resource limitations.

Given the PRB assignments determined by the packet scheduler, the flow-specific bit rates are derived as follows. Firstly, the radio link quality of active flow i served by active set AS_i is given by its *experienced SINR* (signal-to-interference-plus-noise ratio), which for PRB j is calculated as follows:

$$SINR_{ij} = \frac{\sum_{b \in AS_i} P_{bj} G_{bi}}{\sum_{b' \notin AS_i} P_{b'j} G_{b'i} + N},$$

where P_{bj} denotes sector b's current transmit power in PRB j and G_{bi} denotes the total path gain between sector b and user (flow) i. The correspondingly *attainable bit rate* (in Mbit/s) is then given by [5]

$$R_{ij} = 0.18 \cdot \min\{4.4, 0.6 \cdot \log_2(1 + SINR_{ij})\},$$

while the flow's total rate is summed over the assigned PRBs.

6.1.4 Numerical results

In this section, simulation results are presented based on the system model and resource management mechanisms described in Section 6.1.2 and Section 0, respectively. Two key performance indicators are used: average flow throughput and cell edge average flow throughput. The cell edge is defined by a path loss threshold, chosen such that 10% of the flows are considered cell edge flows. A flow for which the sum of distance-based path loss, shadowing, indoor penetration loss and antenna gain towards its strongest serving cell exceeds the path loss threshold is labeled as a cell edge flow.

6.1.4.1 Performance gains from inter-operator CoMP

In this subsection we analyze the gains of inter-operator CoMP with regard to both single-cell transmission and intra-operator CoMP. The following parameter configurations are assumed: $AS_{max} = 3$, $\Delta_{AS,intra} = \Delta_{AS,inter} = 3$ dB and $\Delta_{CS} = 0$ (co-sited). Since $\Delta_{AS,inter} = \Delta_{AS,intra}$, cells of the host network have the same priority as those of the home network in being involved in any flow's active set. Two degrees of co-azimuthing are considered for the two networks, viz. $\Delta_{CA} = 0^o$ (co-azimuthed) and $\Delta_{CA} = 60^o$ ('anti-azimuthed'). The comparison between different degrees of co-azimuthing is of particular interest, considering that in current practices of co-siting among operators, sectors of different operators may typically have different azimuths. Both different-site and same-site intra-operator clustering configurations are considered.

Figure 6-4 and Figure 6-5 show the comparison between single-cell transmission, intra-operator CoMP and inter-operator CoMP in average flow throughput and cell edge average flow throughput, respectively, at different cell loads and for the different-site intra-operator clustering configuration. The following observations can be made from the figures:

- Intra-operator CoMP has little or even no gain in average flow throughput over single-cell transmission, while the cell edge average flow throughput is significantly improved. This is in line with the design objective that intra-operator CoMP mainly benefits cell edge flows, for which the probability of having more than two cells in their active sets is higher than that of cell center flows.
- Inter-operator CoMP with co-azimuthed configuration has significant gain in both average flow throughput and cell edge average flow throughput over both single-cell transmission and intra-operator CoMP. For example, at the cell load of 11 Mbit/s, it has 22% (21%) higher average flow throughput and 39% (24%) higher cell edge average flow throughput over single-cell transmission (intra-operator CoMP). This is largely due to the fact that, with co-sited and co-azimuthed configuration, the host network cell which is co-sited and co-azimuthed with the strongest home network serving cell of each flow (no matter where in the cell) will have the same measured RSRP as the strongest home network serving cell, and thus will be included in the active set of the flow and significantly improve the performance. So all the flows are in inter-operator CoMP mode.
- Inter-operator CoMP with 'anti-azimuthed' configuration has even lower average flow throughput than those of single-cell transmission and intra-operator CoMP. For cell edge average flow throughput, it outperforms single-cell transmission and slightly over intra-operator CoMP. It is outperformed by inter-operator CoMP with co-sited and co-azimuthed configuration on both performance metrics. This is largely due to the fact that, with co-sited and 'anti-azimuthed' configuration, and applying different-site intra-operator clustering, for some flows the host network cell for which the measured RSRP is the strongest might not be in the same cluster where the flow is served. Consider for instance a user located 'in between' a home network site's cells A and B. Assume he is served by cell A and hence, considering the applied intra-operator clustering, not also by cell B. Co-sited host network cell C with an azimuth 'in between' cells A and B is likely to be in the same cluster with either cell A or B. In case of the latter, the given user cannot include it in its active set yet may experience a rather significant degree of interference from cell C, which may support cell B in a multi-operator CoMP fashion. The impact of this source of interference is likely to be larger for cell center than for cell edge flows.

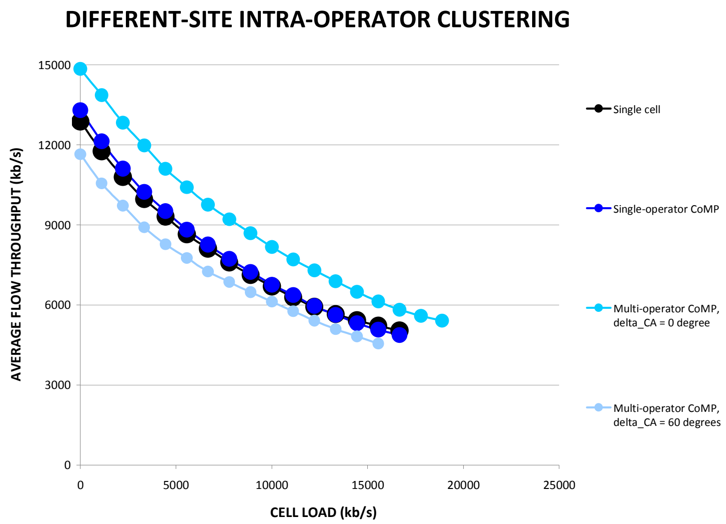

Figure 6-4: Average flow throughput vs. traffic load: single-cell transmission, intra- and inter-operator CoMP (different-site intra-operator clustering)

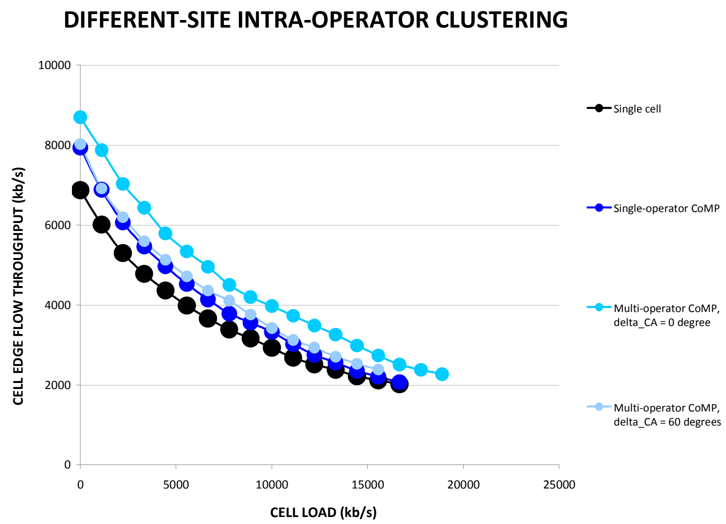

Figure 6-5: Cell edge average flow throughput vs. traffic load: single-cell transmission, intra- and inter-operator CoMP (different-site intra-operator clustering)

Since CoMP mainly aims at improving the performance at cell edge, in the following discussions we will focus more on the impact of intra-/inter-operator CoMP, with different configurations, to the cell edge average flow throughput. Figure 6-6 shows a performance comparison of the single-cell transmission and intra/inter-operator CoMP modes for the same-site intra-operator clustering configuration. The following observations can be made:

- Intra-operator CoMP offers only a little gain in cell edge average flow throughput over single-cell transmission, much lower than that for the different-site intra-operator clustering configuration. The reason is that, for most cell edge flows, the neighbor cells which may help best in improving their performance are not in the same cluster and hence no CoMP candidates. Instead of serving the cell edge flows, they may in fact be strong interferers if they serve flows in other clusters using the same spectrum.

- Inter-operator CoMP outperforms both single-cell transmission and intra-operator CoMP, for both degrees of co-azimuthing. For example, at a cell load of 11 Mbit/s, inter-operator CoMP yields about 33% (39%) higher cell edge average flow throughput compared to the case of intra-operator CoMP, for the co-azimuthed ('anti azimuthed') configuration. The degree of co-azimuthing does not significantly impact the cell edge average flow throughput. For the same-site intra-operator clustering, the change of co-azimuthing degree in fact does not change the inter-operator clustering, and for the majority of flows the active sets are the same. The minor difference in performance is due to the directional antenna pattern, because of which the radio condition for some flows changes slightly with the co-azimuthing degree.

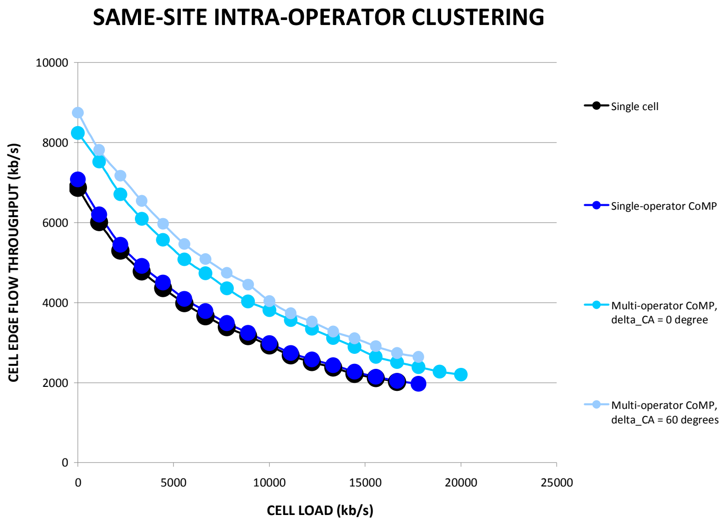

Figure 6-6: Cell edge average flow throughput vs. traffic load (same-site intra-operator clustering)

6.1.4.2 Sensitivity analysis of the CoMP performance gains

We now analyse the sensitivity of the inter-operator CoMP performance with regard to AS_{max}, $\Delta_{AS,inter}$, $\Delta_{AS,intra}$ and Δ_{CS}. The impact of each parameter was investigated in a ceteris paribus setting, assuming a common baseline configuration, given by a different-site intra-operator clustering, AS_{max} = 3, $\Delta_{AS,inter}$ = $\Delta_{AS,intra}$ = 3 dB and Δ_{CA} = 0^o (co-azimuthed).

Figure 6-7 shows the impact of AS_{max} on the cell edge average flow throughput. The general trend is that a higher AS_{max} yields a better performance up to an AS_{max} of about 4, beyond which further gains are negligible (the maximum value of AS_{max} is limited by the total cluster size, which is 6 in our case). One reason is that even with higher AS_{max}, the actual active set size of flows might not be higher due to the limitation of $\Delta_{AS,inter}$ and $\Delta_{AS,intra}$. Another reason is that, even the actual active set size of some flows becomes higher with higher AS_{max}, the extra cells involved in the active set contribute little to the overall SINR due to their relatively lower link qualities.

Figure 6-8 shows the performance impact of $\Delta_{AS,intra}$. The general trend is that better performance is achieved for higher $\Delta_{AS,intra}$. However, the performance for $\Delta_{AS,intra}$= 3 dB is almost identical to that for $\Delta_{AS,intra}$= 2 dB, which indicates that further increase of $\Delta_{AS,intra}$ will not benefit the performance further. Note that inter-operator CoMP with $\Delta_{AS,intra}$ = 0 dB yields a significant performance gain over single-cell transmission. The reason is that in a co-sited and co-azimuthed network configuration, the host network cell which is co-sited and co-azimuthed with the strongest home network serving cell of each flow (regardless of its precise location) will be included in the active set of the flow (even when $\Delta_{AS,intra}$ = 0 dB) and hence significantly improves the performance.

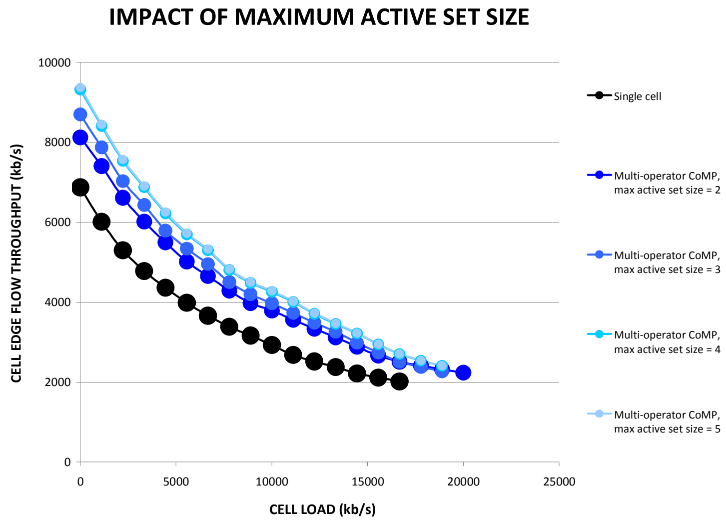

Figure 6-7: Performance impact of AS_{max}

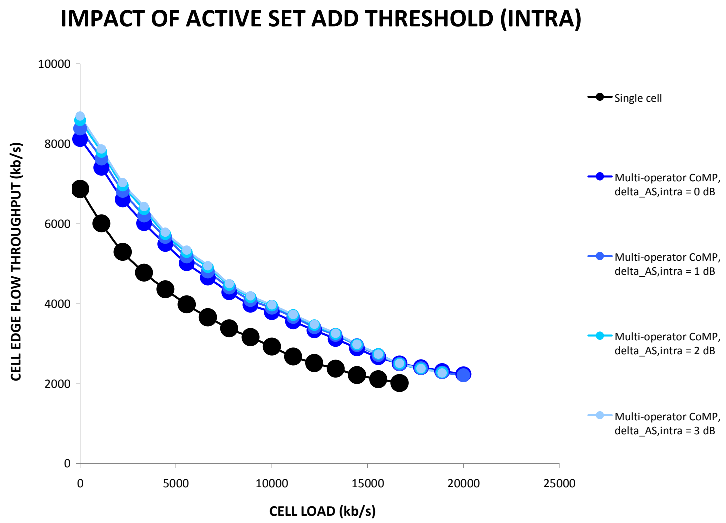

Figure 6-8: Performance impact of $\Delta_{AS,intra}$

Figure 6-9 shows the performance impact of $\Delta_{AS,inter}$. The general trend is that worse performance is experienced with a lower $\Delta_{AS,inter}$. However, when $\Delta_{AS,inter}$ is decreased from 3 dB to 0 dB, the performance is only affected marginally. The reason is that, with a co-sited and co-azimuthed configuration, the host network cell which is co-sited and co-azimuthed with the strongest home network serving cell of each flow (regardless of its precise location) will be included in the active set of the flow for this range of $\Delta_{AS,inter}$.

Figure 6-10 shows the impact of ΔCS, which to some extent influences the performance of inter-operator CoMP. The most interesting observation is that inter-operator CoMP always outperforms single-cell transmission (and also intra-operator CoMP according to Figure 6-5), for all the investigated values of ΔCS. Hence even in a situation of non co-sitting, infrastructure sharing via inter-operator CoMP is still beneficial.

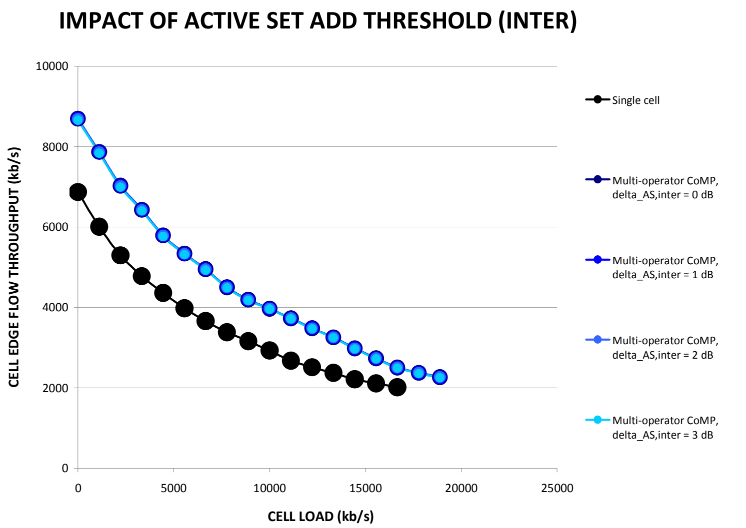

Figure 6-9: Performance impact of $\Delta_{AS,inter}$.

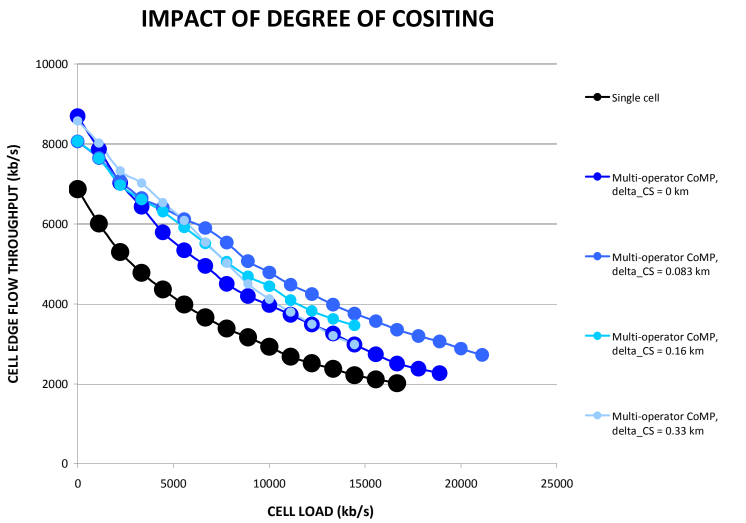

Figure 6-10: Performance impact of Δ_{CS}.

6.1.5 Concluding remarks

We investigated the benefits from inter-operator CoMP downlink transmissions as an extension to the ‘traditional’ intra-operator CoMP feature in LTE-Advanced networks. In order to assess the potential performance gains, we have proposed and assessed procedures for defining inter-operator cell clusters, an intra- and inter-operator cell selection mechanism for inclusion in CoMP transmissions and coordinated inter-operator scheduling. The assessment study focused on different deployment scenarios with regards to the site locations (e.g. co-sited versus non co-sited) and antenna orientations (e.g. co-azimuth versus non co-azimuth orientation).

The results show that inter-operator CoMP can achieve average flow throughput and cell edge flow throughput gains of 21% and 24%, respectively, over intra-operator CoMP for the case of co-azimuth antenna orientation and under a moderate cell load. The average flow throughput performance for the inter-operator CoMP degrades only in the case of non co-azimuth antenna orientation (it is even worse than intra-operator single cell transmission without CoMP) due to the interference from inter-operator cells that is caused by the exclusion of such cells from the inter-operator cluster which is due to the different antenna orientation. Further, it is shown that the active set size up to four intra- or inter-operator cells is sufficient to extract the most of the inter-operator CoMP gains. The inter-operator CoMP performance is rather insensitive to the active set thresholds for inclusion of intra- or inter-operator cells of up to 3 dB. Finally, inter-operator CoMP is outperforming intra-operator CoMP in terms of average and cell edge flow throughput also for the case of non co-siting.

The observed potential gain of inter-operator CoMP emphasises the necessity of further investigating this scenario by taking into account practical limitations posed by infrastructure sharing, e.g. the capacity and latency of exchanging necessary information among different operators’ base stations.

7 Full sharing scenarios

7.1 Non-orthogonal full sharing

Conventional wireless system design is based on the concept of interference-free communication links. Then the system becomes a collection of quasi-independent communication links. In the past, this practical approach has greatly simplified the analysis and optimisation of such systems.

However, assigning each user a separate resource is not always an efficient way of organising the system. If the number of users is high, then each user only gets a small fraction of the overall resource. Shortages are likely to occur when users have high capacity requirements. This will become even more problematic for future wireless networks, which are expected to provide high-rate services for densely populated user environments. The system then might be better utilised by allowing users to share resources, as investigated in SAPHYRE [39].

This development drives the demand for new sharing principles based on the dynamic reuse of the system resources frequency, power, and space (i.e. the distribution and usage of transmitting and receiving antennas over the service area). The classical design paradigm of independent point-to-point communication links is gradually being replaced by a new network-centric point of view, where users avoid or mitigate interference in a flexible way by dynamically adjusting the resources allocated to each user. In this context, interference emerges as the key performance-limiting factor [33]. Interference affects all layers of the communication system, thus new cross-layer approaches are needed for the optimisation and system level evaluation.

Non-orthogonal sharing is inherently cross-layer oriented, since it requires a joint optimisation of all the network functionalities that depend on interference. This mainly involves the physical layer and the medium access control, but also higher layers. Therefore, non-orthogonal sharing makes optimal use of the available degrees of freedom. The concept of non-orthogonal sharing is illustrated in

Figure 7-1 and Figure 7-2.

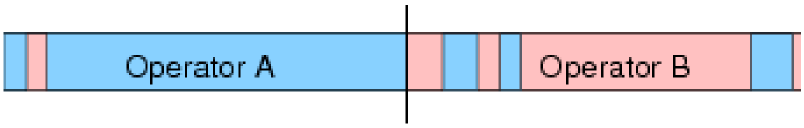

Figure 7-1: Orthogonal Sharing: Users can benefit from empty resources

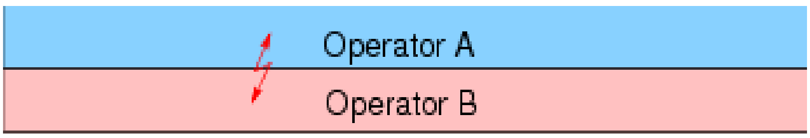

Figure 7-2: Non-orthogonal sharing:

Users gain from allowing all users to access all resources. This causes potential interference, which can be controlled and mitigated by signal processing techniques. We consider a system of K non-orthogonal communication links that can belong to different operators. Independent signals are assumed. Interference among communication links is modelled by interference functions $J_1(p),\ldots,J_K(p)$ as developed in WP2.3. The function $J_k(p)$ yields the interference power of link k, which depends on the vector p, which contains the transmit powers of all K users in the system. In the context of WP4, we focus on the particular case of standard interference functions [45]. The performance of each link is measured by the signal-to-interference + plus noise ratio

$$\mathrm{SINR}_k(p) = \frac{p_k}{J_k(p)} \tag{7.1}$$

The Quality-of-Service (QoS) of link is typically a monotonic function of the signal-to-noise-plus-interference ratio (SINR). Examples include BER, capacity, etc. The theoretical limits can be described in terms of the QoS region, i.e. the set of all jointly achievable QoS, as illustrated in Figure 7-3. In order to fully exploit the available resources, it is desirable to achieve an operating point on the boundary of the region. Common optimisation goals are to maximise the sum efficiency (e.g. sum throughput), to achieve max-min fairness, or some compromise between fairness and efficiency.

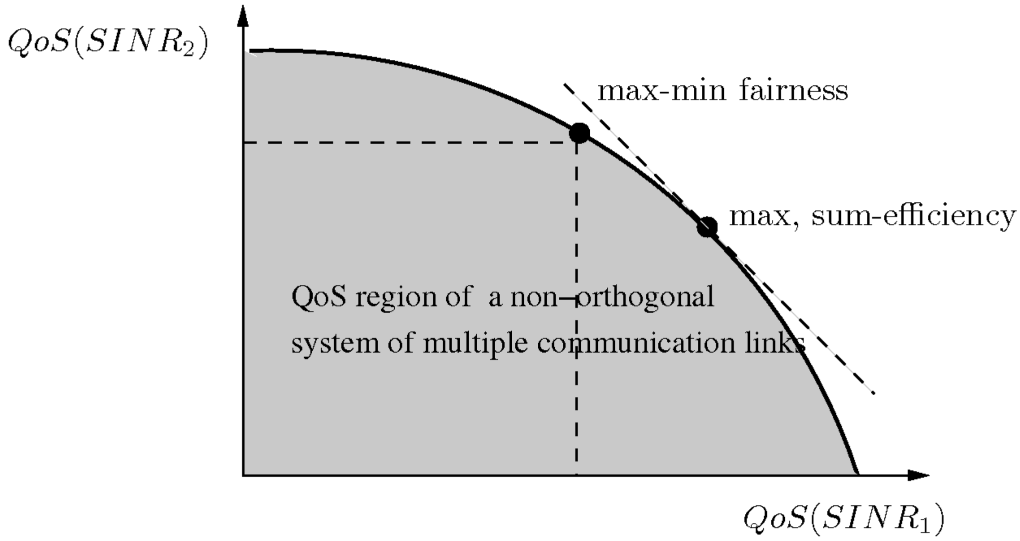

Figure 7-3: Theoretical limits of a shared system

There is a trade-off between the performances of the individual communication links. Increasing the performance of one link generally comes at the cost of another links. The goal of the system optimisation is to find an operating point on the boundary of the region.

The QoS depends on the following system components:

- Power Control/Assignment. By reducing the transmission power, less interference is caused to other links. This enables more efficient sharing strategies and the reuse of resources.

- Signal processing. By optimising the signal processing (e.g. MIMO), interference is avoided and multiple communication links (operators) can utilise the same resource.
- Resource allocation. By dynamically allocating links to frequency carriers, more bandwidth is available for each operator.

The joint optimisation of all three components involves different layers of the communication model, hence a cross-layer approach is required.

In the following we describe non-orthogonal optimisation strategies that were developed in SAPHYRE.

7.1.1 Non-orthogonal throughput maximisation

In the following we describe the approach that was developed within SAPHYRE and published in [40]. The theoretical foundations of the algorithms were developed in WP2 (Deliverable D2.3a/b "Interference Modelling"). WP4 builds on these result.

The system is assumed to consist of K users, which can belong to different operators. The index set is denoted by $K = \{1,2,\ldots,K\}$. The users can transmit over N "resources" $N = \{1,2,\ldots,N\}$. Here, "resources" are used as an abstract term referring to any signalling dimension (e.g. frequency carriers, time slots, sectorisation patterns). For the non-sharing reference case, the users can only access a part of the resources. This will be compared with non-orthogonal sharing of resources, where each user can possibly access all resources.

The user-resource pairs define $L = K \times N$ transmission links. The link set is denoted as $\mathrm{K} = \{1,2,\ldots,L\}$. We will assume that the resources can be accessed freely. In other words, each user can use multiple resources simultaneously, and each resource can be shared by multiple users. It should be emphasised that signals transmitted over different resources can interfere with each other. In practise, this corresponds to inter-carrier interference or interference caused by imperfect sectorisation, for example.

In order to control the interference between the users, we want to assign the resources dynamically, depending on the current interference situation. The users should be able to make use of the available resources and Tx/Rx strategies to fully exploit the potential of the system. The design goal is to find an optimal allocation pattern that determines how the K users are mapped to the N resources. Each user-resource pair (transmission link) is characterised by its transmission power, which can be positive in case of an active link, or zero in case of an inactive link. It is also possible that there is no active link on some resource, which means that this resource is left idle.

The goal is to maximise the weighted sum rate

$$\max \sum_{l=1}^{L} w_l \log(1 + \mathrm{SINR}_l) \tag{7.2}$$

$w_l \geq 0$ are arbitrary weighting factors, which allows for the integration of possible user priorities.

For some special cases, the problem has a convex representation, e.g. for the multiple access MIMO channel with successive interference cancellation and the corresponding broadcast channel. However, the problem is still open for most other types of channels, e.g. the interference channel. Even under the simple assumption of linear interference the problem is NP-hard [34].

Let $P_{m,n} \geq 0$ be the transmission power used by user m on resource n. The special case of $P_{m,n} = 0$ corresponds to an unused (inactive) resource. By denoting the user-resource pair (m,n) with the link index l, all powers $P_{m,n}$ can be stacked into a power vector: $\mathrm{p} = [P_{1,1},\ldots P_{K,1},\ldots,P_{1,N},\ldots,P_{K,N}]^T = [p_1,\ldots,p_L]^T$, where $l = 1,\ldots,m+(n-1)K,\ldots,L$. We further assume that p is constrained to a convex polytope P, which means that the available power is finite.

The SINR of the l th communication link is defined as in (7.1), where $J_l(p)$ represents the (relative) interference experienced by link l. (Here, "relative" means that the interference is scaled by the channel gain of link l.) Thus, we can rewrite (7.2) as

$$R = \max_{p \in P} \sum_{l=1}^{L} w_l \log_2\left(1 + \frac{p_l}{J_l(p)}\right). \tag{7.3}$$

Note, that the maximiser p can contain powers that equal zero. A communication link with zero power is inactive. This happens, e.g. if the channel of the link is bad, or if this link would cause too much interference to other links.

For many practical cases of interest, like the beamforming scenario, the function $J_l(p)$ is a standard interference function characterised by positivity, scalability, and monotonicity. With beamforming, the interference is even a concave standard interference function. Thus, $J_l(p)$ is concave. Concave interference functions have a rich analytical structure [31]. In particular, it was shown in [32] that every concave standard interference function $J_l(p)$ has a representation of the form

$$J_l(p) = \min_{z_l \in Z_l} \left(p^T \psi_l(z_l) + \sigma_n^2(z_l)\right), \forall l \tag{7.4}$$

The vectors $\psi_l(z_l)$ model the cross-power coupling between the links. The coupling coefficients depend on the parameters $z = (z_1,\ldots,z_L)$, which are chosen from compact sets $Z_1,\ldots,Z_L$, respectively. Among all possible parameters, we choose the parameter that minimises the interference and noise $\sigma_n^2(z_l)$, thus z_l has an interpretation as a receive strategy. A special case is where z_k stands for the beamforming vector. Any beamformer that maximises the SINR subject to possible constraints is included in this framework. If zeroforcing beamforming is chosen, then the SINR is reduced to the SNR. In this case, the optimisation simplifies to an optimisation of the transmission powers.

Note, that the proposed framework also includes the case of precoder optimisation for the downlink channel. By exploiting the uplink/downlink duality [41], the precoding problem can be transferred to an equivalent problem involving "virtual" receive beamformers, for which the representation (4) holds. Suboptimal algorithms for this problem were proposed in [43], [42], [44].

When formulating the problem (7.3), we assume that the interference is treated as noise. Thus, generally, the optimal R is not the sum capacity, but an achievable sum rate. Treating interference as additive noise is optimal for the interference channel, only if the interference is very weak. For the multiple-input, single-output (MISO) broadcast (downlink) or the SIMO multiple access (uplink) channel, (7.3) corresponds to the actual information-theoretical capacity under the assumption of dirty-paper coding or perfect successive interference cancellation. For other channels, the approach (7.3) is a common way of optimising the overall system resources and transmit/receive strategies, that usually leads to good results in practise. For example, the effect of finite-alphabet modulation schemes can be included via the signal-to-noise ratio (SNR) gap approximation [30], without changing the structure of the problem.

7.1.2 Optimisation via DC programming

Problem (7.3) has an equivalent reformulation

$$\min_{p\in P} \sum_{l=1}^{L} -w_l \log_2\big(p_l + J_l(p)\big) + w_l \log_2 J_l(p). \tag{7.5}$$

The interference functions J_l are concave by assumption. The logarithm of a concave function is concave, and concavity is preserved under non-negative weighted sums. Thus, (7.5) can be rewritten as the minimisation of a difference of two convex functions (D.C.).

$$\min_{p\in P} f(p) - g(p)$$

$$\text{where} \quad f(p) = -\sum_{l=1}^{L} w_l \log_2(p_l + J_l(p)), \quad \textit{and} \quad g(p) = -\sum_{l=1}^{L} w_l \log_2(J_l(p)). \tag{7.6}$$

Problem (7.6) is known as a D.C. problem. D.C. decompositions exist for a very large class of (non-convex) functions [36], [42], [35]. However, there is no general practical procedure for constructing such a decomposition, and the calculation often requires a significant effort. For the problem at hand, the D.C. decomposition is obtained directly as a consequence of the particular structure of the given sum rate problem and the properties of the assumed interference model.

In SAPHYRE, different algorithms were developed for the throughput maximisation problem [40]. Firstly, prismatic branch & bound strategies with different bounding procedures are proposed for finding a global optimum. These techniques are computationally efficient compared with monotonic optimisation techniques [38]. However, their complexity still grows exponentially with the degrees of freedom. Thus, a sub-optimal, but computationally efficient algorithm based on convex majorant approximations was proposed as well [40]. The algorithms are used for assessing the gain from non-orthogonal sharing.

7.1.3 Achievable gain from non-orthogonal sharing

Orthogonal sharing is conceptually simpler than non-orthogonal sharing. By keeping the users orthogonal, interference is avoided. This is illustrated in Figure 7-1. Orthogonal sharing performs good whenever the system is not fully loaded, i.e. if one operator has idle resources which can be used by other operators.

Non-orthogonal sharing allows every operator to access the entire pool of resources (see Figure 7-2. User share the same resource block, which means that they are subject to possible interference. This technique provides sharing gains even if the system is fully loaded, provided that the interference can be kept within limits. From a theoretical perspective, non-orthogonal sharing is provides optimal results, since it does not put constraints on the resources that are allowed to be used. On the other hand, it is conceptually more difficult. Because of the possible presence of interference non-orthogonal sharing needs to be developed along with the interference at the lower layers (e.g. beamforming). Therefore, non-orthogonal sharing is inherently cross-layer. It requires a joint optimisation of transmit powers, signal processing, resource management, but also higher layer functionalities like load balancing and handover control.

In order to assess the sharing gain, the sum rate of a multi-cellular system was computed with the following parameters.

- **pico cells**
- 3 users per cell
- 3 orthogonal frequency bands, A, B, and C
- SCME-like multipath channel model
- exponential path loss
- 300 randomly chosen user distributions, uniform distr.

Table 7.1: Average non-orthogonal sharing gain

	Power control	Resource allocation	Gain
1)	equal (22dBm)	orthogonal allocation of users	100% (reference)
2)	jointly optimal (max. sum rate)		260%

The simulation shows an average gain of 260% compared to the reference scenario where the users were allocated in an orthogonal manner to different frequency bands A,B, and C. This gain is a result of frequency sharing, i.e. multiple users can share the same resource block. The simulation demonstrates that significant gains can be achieved by non-orthogonal sharing. The actual gain, of course, depends on many factors, including the system load and the cell radius. This will be investigated in the third year of the SAPHYRE project.

7.2 Orthogonal full sharing

7.2.1 Introduction

Full sharing is defined as a scenario where two or more operators share one radio access network as well as their licensed spectrums. The radio access network RAN may comprise of base stations, gateways and network equipment like switches routers and wired or wireless network links.

7.2.2 Advantages of full sharing

The extension of available radio resources by a common usage of different spectrum ranges may lead to several performance improvements. Expected performance improvements may be achieved by statistical multiplex gain, frequency selective scheduling gain and overhead reduction. Two methods of combining available spectrums are applicable. One is carrier aggregation as defined in 3GPP [28] the other is carrier merging. Carrier aggregation is a technique where two or more carriers are commonly used by the base stations and the terminals. This requires modification in the control channels. The advantage of carrier aggregation is a better backward compatibility because base stations can still serve terminals which do not provides carrier aggregation. Furthermore carrier aggregation supports the common use of spectrum ranges which are not adjacent. An advantage of carrier merging is overhead reduction on the physical layer like the avoidance of guard bands between adjacent spectrum and overhead reduction on the MAC layer due to the reduction of control channels.

7.2.2.1 Frequency selective scheduling gain

Frequency selective scheduling is defined as a method where the scheduler allocates the radio resources respectively the physical resource blocks according to the conditions of a particular radio channel. The channel conditions depend among others on the used frequency bands in case of OFDMA on particular subcarriers. The scheduler tries to allocate the physical resource blocks for a particular connection on subcarriers with the best channels condition within the spectrum range. With an extension of the spectrum range the probability of allocation of PRBs with good channel conditions increases, while the scheduling conflicts decrease. Two different scenarios plus one reference scenario where considered:

- A legacy scenario based on a single RAN with a given spectrum range used by one operator was utilised as a reference scenario.
- Full sharing, Greenfield: New Greenfield deployment where two operators install newly a shared RAN and pool their spectrum ranges.
- Full sharing, merged RAN: Two operators build a shared RAN by combining their already deployed RANs and pool there spectrums; this leads to an increased number of sites, reduced cell size and an increased number of users.

7.2.2.2 Simulation results

Simulation campaigns where run for urban scenario and for rural scenarios with following simulation parameters:

- Antenna configurations:
  - Cell/Sector: Uniformed linear antenna array, 4 transmit antennas (0.5λ)
  - Terminal: Uniformed linear antenna array, 2 receive antennas (0.5λ)
- Transmission scheme: SU-MIMO, using release 8 rank 1 and rank 2 codebook
- Channel: ITU Channel Scenario[29], UMa and RMa
- Channel estimation error: no
- Pilot Feedback: Explicit
  - Delay measured from end of reception of TTI until usage: 5 TTI
  - Report periodicity: 5 TTI
  - Explicit channel feedback resolution: 1 channel matrix per 6 PRB
- Monte Carlo experiments: 5, Duration: 1s
- Number of cells/sectors: 57
- Maximum transmit power limited per: sector
- Number of UEs: 570
- Scheduler: Weighted Sum Rate (WSR)
- Proportional fair parameter: Alpha: 1, Beta: 0.9966
- Maximum number of UEs per cell, which can be scheduled at the same time: unlimited
- HARQ: disabled
- Link Adaption: Ideal, after receiving the code block
- Modulation and coding scheme selection: Closest to 30% BLER
- Simulation Model with Wrap Around (
- Figure 7-4)

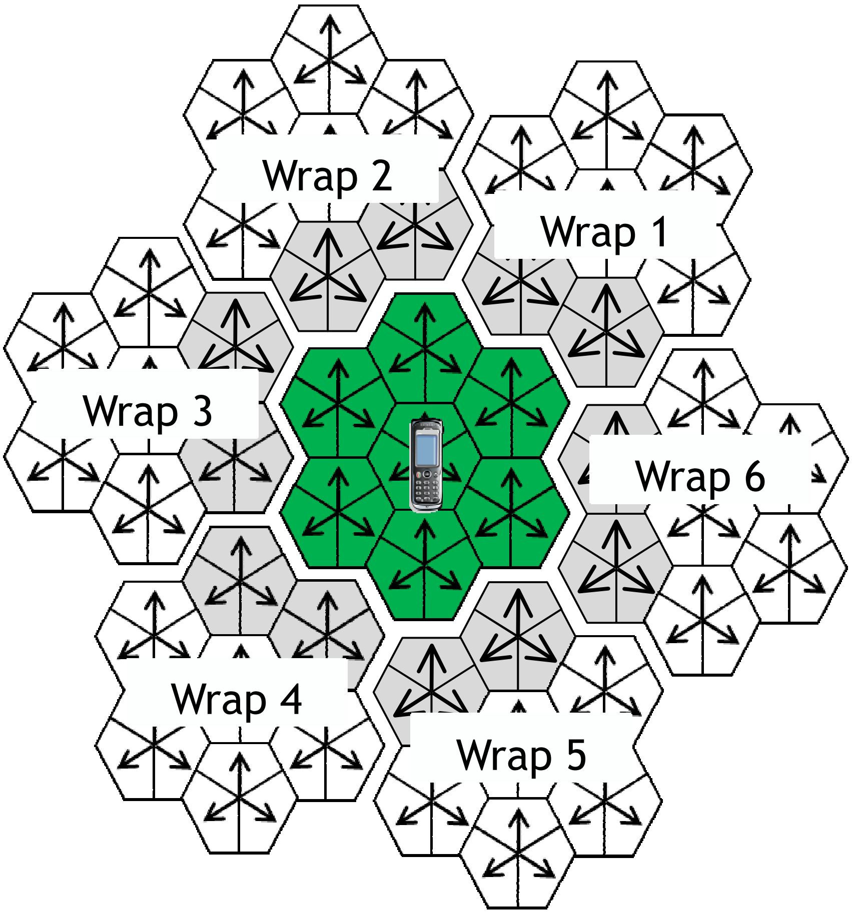

Figure 7-4: Simulation Model with Wrap Around (figure for only 21 cells)

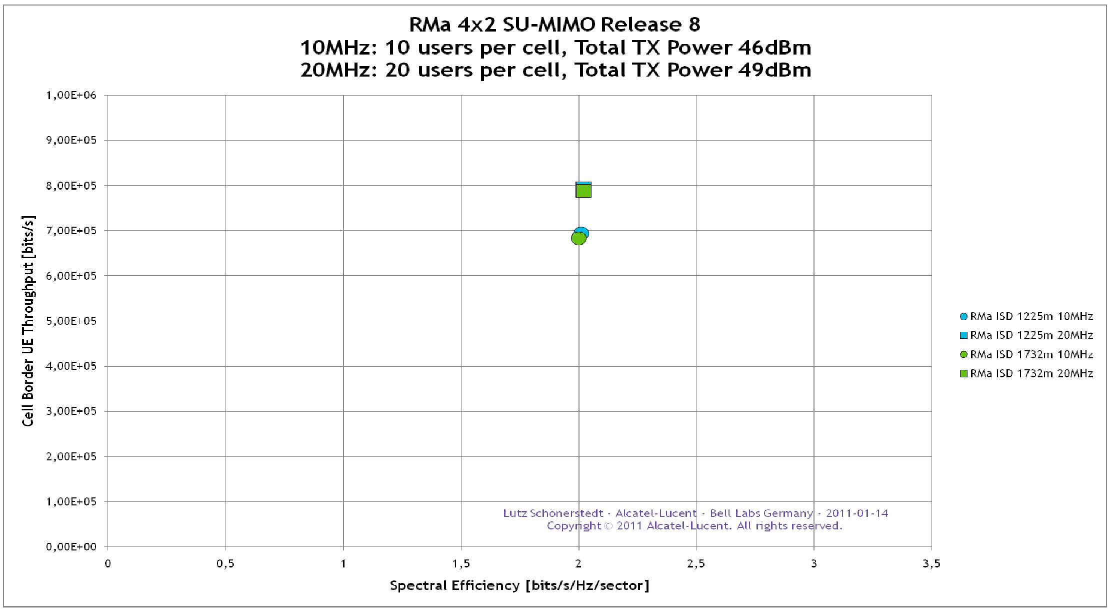

Figure 7-5: Spectral Efficiency and Cell Border User Throughput RMa

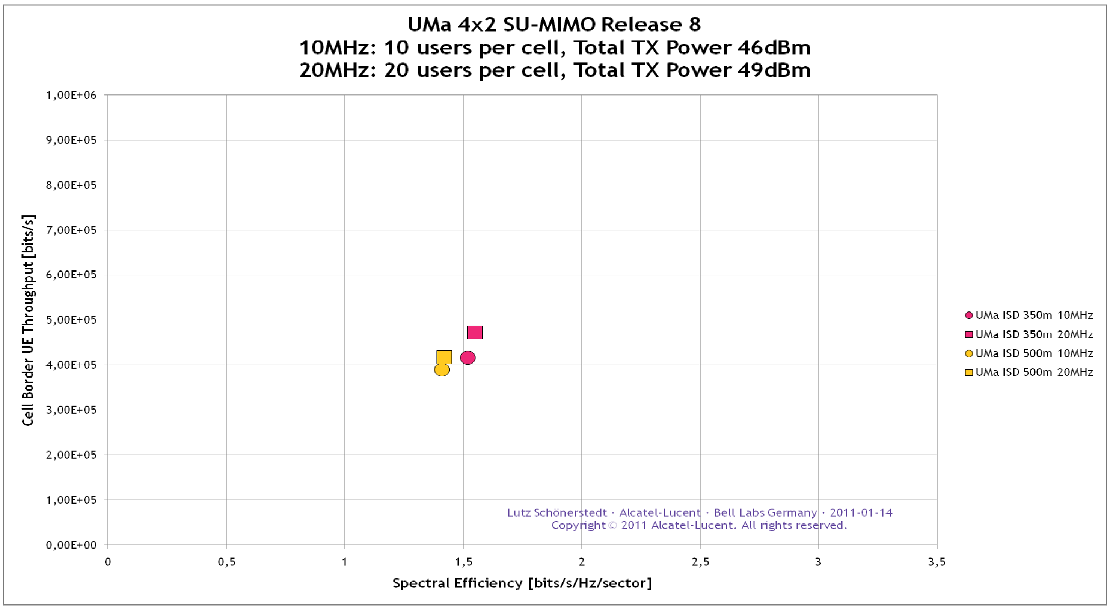

Figure 7-6: Spectral Efficiency and Cell Border User Throughput UMa

Table 7-1: Spectral Efficiency and Cell Border User Throughput UMa

Scenarios	**No sharing legacy**	**Full sharing greenfield**	**Full sharing, RAN combining**
Operators	1	2	2
Spectrum / MHz	10	20	20
Sites per area	n	n	2*n
Cell Size	c	c	c / 2
Users	u	2*u	2*u
Results			
Spectral efficiency gain	**0%**	**< 2%**	**urban 8% rural 0%**
Cell border throughput gain	**0%**	**urban 10% rural 15%**	**urban 10% rural 15%**

Interpreting the simulation results (Figure 7-5, Figure 7-6 and Table 7-1):

- Greenfield RAN scenario: The results show that the spectral efficiency gain based on an increased spectrum is low. If a typical spectrum size of 10 MHz is extended to 20 MHz, the gain of the spectral efficiency is below 2%. Interpreting this result indicates that a spectrum of 10 MHz gives sufficient range for a scheduler to allocate resources according to the channel conditions. Increasing the spectrum has only a low effect on efficiency of resource assignment. This effect continues on further enlargement of the spectrum to broader ranges like 40 MHz or more.

- Merged RAN scenario: The combined use of RAN increase the spectral efficiency, mainly because the number of sites within a given area is increased and the cell size is reduced. Reduced cell sizes lead to on average better channel conditions.

The differences between rural and urban scenarios:

- Urban scenario: Improvements are detectable for the combination of existing RANs in terms of spectral efficiency and cell border throughput.
- Rural scenario: The improvements on spectral efficiency for spectrum enhancement are neglectable as well as for cell size reduction. The gain of cell border throughput relies on spectrum enhancement.

7.2.2.3 Overhead reduction on merged spectrum

To analyse a performance gain on merged spectrum, a comparison was performed between a 10 MHz spectrum and a 20 MHz spectrum. For that purpose an application was used which computes the PDSCH throughput for LTE [27]. Two computations were performed for 10 MHz and 20 MHz with following parameters: Modulation QAM64, coding rate 1, single antenna, cell identity 0, PHICH duration normal, PHICH group scaling 1 and PDCCH Quadruplets 5. The computed PDSCH throughput for 10 MHz is 4,46616 bps/Hz and 4,48308 bps/Hz for 20 MHz, which results in a gain of 0,39%.

7.2.2.4 Conclusion

For urban scenarios it is beneficial if two or more operators combine their deployed RANs to one merged RAN to decrease the cells sizes and increase the number of sites which leads to a gain in spectral efficiency and cell border throughput. For an urban scenario, a greenfield deployment where two or more operators install one RAN and pool their spectrum, offers a gain in cell border throughput, which is caused by the increased spectrum. According to the small gain impacted by the spectrum merging, it is more beneficial to use carrier aggregation to keep the advantage of backward compatibility.

7.2.3 Resource allocation strategies

7.2.3.1 Problem description and motivation

From a technical point of view the full sharing scenario is quite similar to a legacy scenario (one RAN one operator), the main difference is, that two or more operators share the same infrastructure and radio resources. The shared usage of pooled spectrum leads to several performance improvements as describe before. Despite to these advantages the shared usage of radio resources may lead to unfair resource assignment among the different business partners e.g. operators and end users. We define here a fair resources assignment as a mechanism where a business partner get the resources he has paid for. Here we have to distinguish between the mobile network operators and the end users. An end user pay primarily for the amount of traffic e.g. bandwidth and the corresponding quality of service classes e.g. timing constrains. Radio network operators pay mainly for the radio resources itself e.g. the licensed spectrum. According to the physical channel conditions of the air interface the relations between achieved throughput and used radio resources differs. The usage of a legacy scheduling mechanisms, which assign radio resources only based on the quality of service constrains of the end user data flows may lead to unfair radio resources assignments from the operator perspective. E.g. two operators share one base station, one common spectrum pool; every operator serves the same number of end users with the same amount of bandwidth and identical service class. If most of the end users of operator A are locates at positions with poor channel conditions and the end users of operator B are mostly located at positions with good channel conditions, the traffic flows of operator A would consume most of the radio resources due to the poor channel conditions. This radio resource mechanism does not take into account that the radio resources have also be assigned according to the spectrum ownership of the operators. A novel resource allocation mechanism is required, which supports operator as well as end users business constrains. The motivation for the definition of a multi-operator resource management is, that a legacy resource management does not incorporate the business constrains of the mobile network operators. The lack of operator resource management could be a potential obstacle for infrastructure and radio resource sharing.

7.2.3.2 Two layer resource management

The overcome the resource allocation problem as describe before, the here defined radio resource management strategy bases on a two layer resource management. This two layer scheduling consists of one or more instances of an upper layer resource management (one per operator) and one lower layer resource management (Figure 7-7).

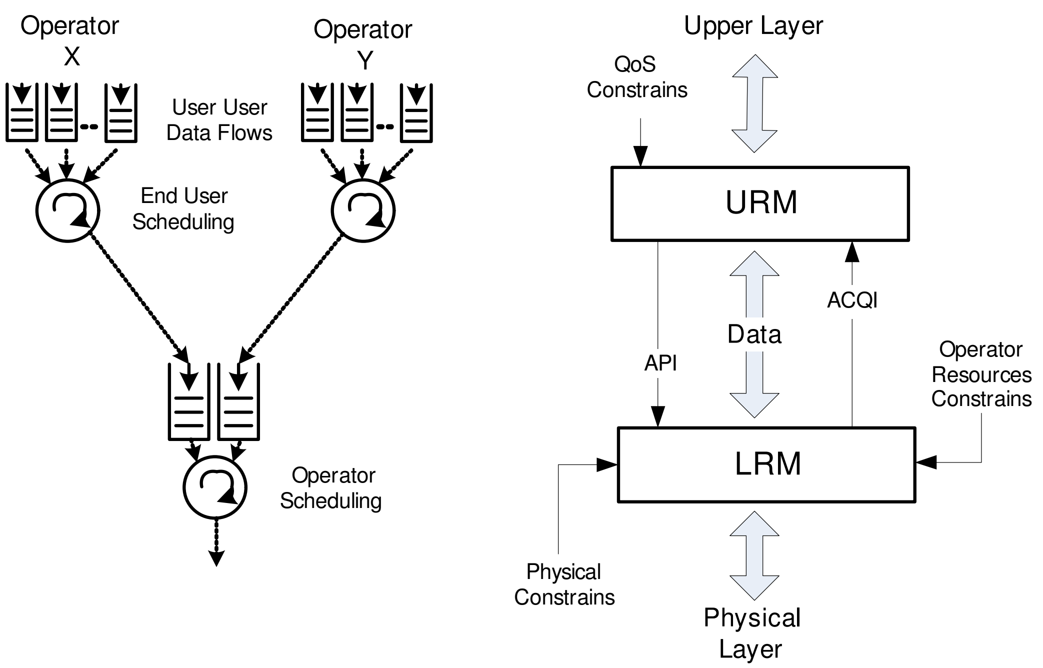

Figure 7-7: Two layered resource management

The upper layer resource management is responsible for the resource allocation among all end users of one operator. The resource allocations strategies of can be round robin, maximised throughput, proportional fair or other. As in a classical approach, the resource management allocates the radio resources according to the quality of service constrain of the traffic flow and the available bandwidth. As an output the resource management delivers data portions tagged with priority indicators in downlink direction. For uplink direction the resource management sends uplink grants also tagged with priority indicators to the lower layer resource management. This priority indicator is a function of the QoS constrains, the buffer levels and transfer conditions. The mechanism of an upper layer resource management can be individually configured or designed per operator. The concept of one upper layer resource management per operator, gives operators a maximum degree of freedom to realise operator individual scheduling mechanisms for an optimal support of operator specific services. After the completion of the scheduling decision the data is transferred together with the priority indicator to the lower layer resource management for further processing. The priority indicator is the primary index for the lower layer resource management for scheduling.

The lower layer resource management schedules the downlink data and uplink grants coming from different upper layer resource management. So the lower layer resource management merges the data flows from different operators. The resource management is performed according to the priority identifiers and the physical channel conditions as in a legacy resource management. Additionally the lower layer resource management uses also resource assignment rules which reflect the business relationships and resource regulations of the different operators. The priority indicators give the lower layer resource management the primary input for scheduling. Despite to the upper layer resource management, the lower layer resource management uses also the parameters of the radio channels conditions for assigning the physical radio resources and constructing the physical channels and frame structure. The physical resource management generates also a physical channel indicator from the physical channel condition and sends this information back to the higher layer resource management. The physical channel indicator gives the higher layer resource management a quantitative feedback of a particular channel condition so the upper layer resource management is able the perform resource assignment depending on the physical channel conditions. The resource management for uplink data transfer performs in a similar manner, instead of data packet which are tagged with abstract priority indicators APIs, the resource management entities generated uplink grants tagged with APIs.

The resource assignment rules define how the assign the radio resources (spectrum) among the operators who share the RAN among the common resource pool. As a basis for resource assignment these rules use the smallest radio resource unit; in case of an OFDMA based radio technologies like LTE, the resource management uses the physical resource block PRB.

To benefit from an increased spectrum pool, the radio resource allocations of a particular operator are not restricted to static spectrum assignments. The allocation bases on percent range of PRSs. For example if two operators use their pooled spectrums corporately and every operator has licensed the same amount of spectrum, every operator has PRB credit of 50% of the total pooled spectrum.

For the achievement of maximum flexibility and support wide set of different scenarios as defined in D5.1, three different classes of PRB credits are defined. The percent rate applies to the total amount of spectrum and the percent rate is specified based on the smallest entity of radio resources in the given radio technology, e.g. for LTE the primary resource block PRB:

- Exclusive PRB credit:
  This credit defines the amount of PRBs in % which is exclusively reserved for one particular operator. Remaining resources (PRBs) of this credit could only be used by other operators, if no data from the particular operator for a given timeslot is available.

- Equal shared PRB credit:
  This credit defines the amount of PRBs in % which may be used be several operators. The resource of this credits are scheduled in an equal manner among the operators. The prioritisation is done be the priority identifier information.

- Priority shared PRB credit:
  This credit defines the amount of PRBs in % which may be used be several operators. The resource of this credits are scheduled in a prioritised manner among the operators. The data of the operator with the highest priority is scheduled first. Within one operator the data is scheduled according to the priority identifier information.

The data is placed in one scheduling slot (subcarrier in LTE) up to the maximum given exclusive PRB credits of the operator or no more data is available is available for the current time slot. Then the scheduler performs a same process for the other operators. If priority shared PRB credits are configured, the scheduler schedules first PRBs of the operator with the highest priority and following with lower priorities up to the credit maximum or no more data is available for the current time slot. If equal shared PRB credits are configured, the scheduler schedules the PRBs from several operators equally according to their priority identifier information elements up to the credit maximum or no more data is available for the current time slot. If there are still unused resources (PRBs) available in the time slot, the scheduler fills these remaining PBRs with data according to their priority identifier information elements. Following Figure 7-8 shows three examples of radio resource partitioning between two operators A and B who share one common spectrum pool and both operators have licensed 50% of the total pooled spectrum range.

- Example 1:
  shows a configuration where every operator use 50% of the total spectrum exclusively.

- Example 2:
  shows a configuration where every operator use 30% of the total spectrum exclusively and the remaining 40% are used commonly with equal priority

- Example 3:
  shows a configuration where every operator use 25% of the total spectrum exclusively and 50% are used commonly with operator priority

Note: The PRB credits are independent from frequency ranges. If regulations determine fixed spectrum portions per operator, the PRB credits can be bind to fixed spectrum assignments.

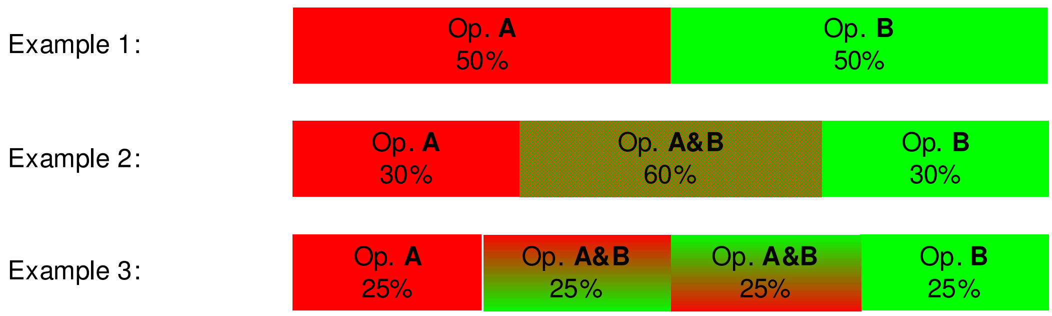

Figure 7-8: Examples: spectrum partitioning

7.2.4 Conclusion

The two layered resource management provides a better decoupling of the end user resource management and operator resource management. Despite to a legacy resource management it supports also the resource spectrum ownership of different operators, independently from the end user service classes and physical channel characteristics. It gives operators full control over their resources, while operators still benefit from common used radio and infrastructure resources. Furthermore the existence of one dedicated higher layer resource management per operator, gives operators the opportunity to implement their individual resource management algorithms for a better support of the specific service classes offered to their end users. This enables a better service differentiation between competing operators and improves the acceptance of full sharing.

Bibliography

[1] 3GPP TS 36.814, 'Further advancements for E-UTRA physical layer aspects', v9.0.0, 2010.

[2] J. Zhu et al, 'A practical design of downlink coordinated multi-point transmission for LTE-Advanced', *VTC'2010*, Taipei, Taiwan, 2010.

[3] S. Brueck et al, 'Centralized scheduling for joint transmission Coordinated Multi-Point in LTE-Advanced', *WSA '10*, Bremen, Germany, 2010.

[4] 3GPP TR 36.912, 'Feasibility study for Further Advancements for E-UTRA (LTE-Advanced), v2.0.0, 2009.

[5] 3GPP TR 36.942, 'Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Frequency (RF) system scenarios', v8.1.0, 2008.

[6] Jian Luo, Andreas Kortke, Wilhelm Keusgen, Jianhui Li, Martin Haardt, Rami Mochaourab, Eduard Jorswieck, Johannes Lindblom, Eleftherios Karipidis, and Erik G. Larsson, "Advanced Beam-Forming Techniques for Inter-Operator Spectrum Sharing: From Theory to Practice", submitted to Proc. Future Network and Mobile Summit 2012, (Berlin,Germany), July 2012

[7] Q. H. Spencer, A. L. Swindlehurst, and M. Haardt, "Zero-forcing methods for downlink spatial multiplexing in multi-user MIMO channels", IEEE Transactions on Signal Processing, vol. 52, pp. 461-471, Feb. 2004.

[8] S. Parkvall et al., 'LTE-Advanced – Evolving LTE towards IMT-Advanced', in IEEE 68th Vehicular Technology Conference, 2008. VTC 2008-Fall, September 2008, pp. 1–5.

[9] F. Roemer, M. Fuchs, and M. Haardt, "Distributed MIMO systems with spatial reuse for high-speed-indoor mobile radio access", in Proc. of the 20th meeting of the Wireless World Research Forum (WWRF), April 2008.

[10] L.Anchora, M Mezzavilla, L. Badia, and M. Zorzi, "Simulation Models for the Performance Evaluation of Spectum Sharing Techniques in OFDMA Networks", in Proc. of the 14th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM), 2011

[11] Kumar, S. Costa, G. Kant, S. Frederiksen, F.B. Marchetti, N. Mogensen, P., Spectrum sharing for next generation wireless communication networks, Cognitive Radio and Advanced Spectrum Management, 2008.

[12] V. Heinonen, P. Pirinen, and J. Iinatti, Capacity gains through interoperator resource sharing in a cellular network, in Proc. IEEE WPMC, 2008.

[13] Xinsheng Zhao Zhiyi Guo Qiang Guo, A cognitive based spectrum sharing scheme for LTE advanced systems, ICUMT, 2010.

[14] Network Sharing in LTE – Opportunity & Solutions, Resource Center, White Papers, Alcatel-Lucent, (2010)

[15] Frisanco, T., P. Tafertshofer, P. Lurin, and R. Ang, Infrastructure sharing and shared operations for mobile network operators: From a deployment and operations view, IEEE International Conference on Communications, pp. 2193-2200, 2008.

[16] Jianwei Huang, Randall A. Berry, Michael L. Honig Auction-based Spectrum Sharing WiOpt04 2004

[17] Vickrey, W. (1961) Counterspeculation, auctions, and competitive sealed tenders. Journal of Finance, 16, 8-37.

[18] Clarke, E. (1971) Multipart pricing of public goods. Public Choice, 11, 1733.

[19] Groves, T. (1973) Incentives in teams. Econometrica, 41, 617631.

[20] N. Nisan, T. Roughgarden, E. Tardos, V.V. Vazirani. Algorithmic Game Theory, Cambridge University Press, 2008.

[21] S. Khot, R.J. Lipton, E. Markakis, and A. Mehta. Inapproximability results for combinatorial auctions with submodular utility functions. In WINE 2005 (LNCS 3828), pages 92-101.

[22] Shahar Dobzinski, Noam Nisan, and Michael Schapira. Truthful randomized mechanisms for combinatorial auctions. In STOC06.

[23] Daniel Lehmann, Liadan Ita OCallaghan, and Yoav Shoham. Truth revelation in approximately efficient combinatorial auctions. In JACM 49(5), pages 577602, Sept. 2002.

[24] Mobile Infrastructure Sharing, GSMA, retrieved on March 7th, 2011 from http://www.gsmworld.com/documents/gsma.pdf

[25] Litjens R., Zhang H. Analytical assessment of the performance impact of spectrum sharing in cellular networks considering different time scales EUSIPCO 2011, 176-180

[26] Berkers, F. Hendrix, G. Chatzicharistou, I. de Haas, T. Hamera, D. To Share Or Not To Share? Business aspects of network sharing for Mobile Network Operators, Intelligence in Next Generation Networks (ICIN), 2010.

[27] Chris Johnson, LTE Visualisation Tool version 1.1, www.lte-bullets.com

[28] 3GPP TR 36.808 Evolved Universal Terrestrial Radio Access (E-UTRA); Carrier Aggregation; Base Station (BS) radio transmission and reception

[29] ITU-R M.2135 – Guidelines for evaluation of radio interface technologies for IMT-Advanced.

[30] J. R. Barry, E. A. Lee, and D. G. Messerschmitt. *Digital Communications*. 3rd ed. Norwell, MA: Kluwer, 2004

[31] H. Boche and M. Schubert. Concave and convex interference functions – General characterisations and applications. *IEEE Trans. Signal Process.*, 56(10):4951–4965, October 2008

[32] H. Boche and M. Schubert. A unifying approach to interference modeling for wireless networks. *IEEE Trans. Signal Process.*, 58(6):3282–3297, June 2010

[33] David Gesbert, Marios Kountouris, Robert W. Heath Jr., Chan-Byoung Chae, and Thomas Slzer. Shifting the MIMO paradigm. *IEEE Signal Processing Magazine*, pages 36–46, September 2007

[34] S. Hayashi and Z.-Q. Luo. Spectrum management for interference-limited multi-user communication systems. *IEEE Trans. Inf. Theory*, 55(3):1153–1175, March 2009

[35] R. Horst and P. M. Pardalos. *Handbook of Global Optimisation*. Kluwer Academic Publishers, Dordrecht, The Netherlands, 1995

[36] R. Horst, P. M. Pardalos, and Ng. V. Thoai. *Introduction to Global Optimisation*. Kluwer Academic Publishers, Dordrecht, The Netherlands, 2000

[37] R. Horst, T. Q. Phong, Ng. V. Thoai, and J. de Vries. On solving a d.c. programming problem by a sequence of linear programs. *Journal of Global Optimisation*, 1:183–203, 1991

[38] Eduard A. Jorswieck and Erik G. Larsson. Monotonic optimisation framework for the MISO IFC. In *Proceedings of the 2009 IEEE International Conference on Acoustics, Speech and Signal Processing*, ICASSP '09, pages 3633–3636, Washington, DC, USA, 2009. IEEE Computer Society

[39] FP7 SAPHYRE Sharing Physical Resources – Mechanisms and Implementations for Wireless Networks. project (FP7-ICT-248001), 2011

[40] Martin Schubert and Holger Boche. Interference Calculus – A General Framework for Interference Management and Network Utility Optimisation. Springer – to appear in Jan. 2012

[41] M. Schubert and H. Boche. Solution of the multi-user downlink beamforming problem with individual SINR constraints. *IEEE Trans. Veh. Technol.*, 53:18–28, January 2004

[42] S. Shi, M. Schubert, and H. Boche. Rate optimisation for multi-user MIMO systems with linear processing. *IEEE Trans. Signal Process.*, 56(8):4020–4030, August 2008

[43] M. Stojnic, H. Vikalo, and B. Hassibi. Rate maximisation in multi-antenna broadcast channels with linear preprocessing. *IEEE Trans. Wireless Commun.*, 5(9):2338–2342, September 2006

[44] C. W. Tan, M. Chiang, and R. Srikant. Maximising sum rate and minimizing MSE on multi-user downlink: Optimality, fast algorithms and equivalence via max-min SIR. In *IEEE International Symposium on Information Theory (ISIT)*, pages 2669–2673, June 2009

[45] R. D. Yates. A framework for uplink power control in cellular radio systems. IEEE J. Sel. Areas Commun., 13(7):1341–1347, September 1995