Multi-cell Coordination Techniques for DL OFDMA Multi-hop Cellular Networks

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A Paco, Mari, Ester, Mariarita: los cuatro pilares que me "soportan"

"Of all the things I've done,
the most vital is coordinating those who work
with me and aiming their efforts
at a certain goal."

W. Disney

"Mathematics is like love;
a simple idea,
but it can get complicated."

R. Drabek

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ABBREVIATIONS AND ACRONYMS

AES: Advanced Encryption Standard
ASN: Access Service Network
BPSK: Binary Phase Shift Keying
BS: Base Station
DES: Data Encryption Standard
DL: Downlink
F: Frame (in the basic frame for 802.16m)
FDD: Frequency Division Duplex
FDM: Frequency-Division Multiplexing
FFR: Fractional Frequency Reuse
FFT: Fast Fourier Transform
FtB: Front to Back ratio
H-FDD: Half Frequency Division Duplex
IEEE: Institute of Electrical and Electronics Engineers
IFFT: Inverse Fast Fourier Transform
IMT-Advanced: International Mobile Telecommunications- Advanced
ISI: Inter-Symbol Interference
LOS: Line Of Sight
MAC: Medium Access Control
MCS: Modulation and Coding Scheme
MS: Mobile Station
MSR: Maximizing the Sum-Rate
N_{cs}: Number of coordinated sectors (sectors within the coordinated area)
NLOS: Non Line Of Sight
N_{ncs}: Number of non-coordinated sectors (sectors outside the coordinated area)
RS: Relay Station
N_s: Number of sectors per cell
OFDM: Orthogonal Frequency-Division Multiplexing
OFDMA: Orthogonal Frequency-Division Multiplexing Access
PF: Proportional Fair
QAM: Quadrature Amplitude Modulation
QoS: Quality of Service
QPSK: Quadrature Phase Shift Keying
RF: Radio Frequency
ROCKET: Reconfigurable OFDMA-based Cooperative NetworKs Enabled by Agile SpecTrum Use.

RR: Round Robin
RRM: Radio Resource Management
RTG: Reception Transition Gap
S: OFDMA symbols (in the basic frame for 802.16m)
s.t.: Subjected To
SbC: SubChannel
SC: Single Carrier
SF: Subframe (in the basic frame for 802.16m)
SFH: Superframe Header
SFR: Soft Frequency Reuse
SINR: Signal to Interference-plus-Noise Ratio
SNR: Signal to Noise Ratio
SPF: Superframe (in the basic frame for 802.16m)
T_{cp}: OFDM Cyclic Prefix period
TDD: Time Division Duplex
TDMA: Time Division Multiple Access
T_s: OFDM Symbol period
TTG: Transmission Transition Gap
UL: Uplink
UPC: Universitat Politècnica de Catalunya (Technical University of Catalonia)
Wi-Fi: Wireless Fidelity
WiMAX: Worldwide Interoperability for Microwave Access

1. INTRODUCTION

The main objective of this project is to design coordinated spectrum sharing and reuse techniques among cells with the goal of mitigating interference at the cell edge and enhance the overall system capacity. The performance of the developed algorithm will be evaluated in an 802.16m (WiMAX) environment.

In conventional cellular networks, frequency planning is usually considered to keep an acceptable signal-to-interference-plus noise ratio (SINR) level, especially at cell boundaries. Frequency assignations are done under a cell-by-cell basis, without any coordination between them to manage interference. Particularly this approach, however, hampers the system spectral efficiency at low reuse rates. For a specific reuse factor, the system throughput depends highly on the mobile station (MS) distribution and the channel conditions of the users to be served. If users served from different base stations (BS) experience a low level of interference, radio resources may be reused, applying a high reuse factor and thus, increasing the system spectral efficiency. On the other side, if the served users experience large interference, orthogonal transmissions are better and therefore a lower frequency reuse factor should be used. As a consequence, a dynamic reuse factor is preferable over a fixed one.

This work addresses the design of joint multi-cell resource allocation and scheduling with coordination among neighbouring base stations (outer coordination) or sectors belonging to the same one (inner coordination) as a way to achieve flexible reuse factors. We propose a convex optimization framework to address the problem of coordinating bandwidth allocation in BS coordination problems.

The proposed framework allows for different scheduling policies, which have an impact on the suitability of the reuse factor, since they determine which users have to be served. Therefore, it makes sense to consider the reuse factor as a result of the scheduling decision.

To support the proposed techniques the BSs shall be capable of exchanging information with each other (decentralized approach) or with some control element in the back-haul network as an ASN gateway or some self-organization control entity (centralized approach).

Results are obtained considering realistic channel models of different scenarios for various cell radius, frequency planning and scheduling policies and let us to evaluate the improvement of the system capacity as well as the impact of the interference from the BS inside the coordinated area and outside it.

The work is structured as follows: first of all, we present the state of the art and the notation we will use throughout all the document. Then, the strategy that maximizes the sum-rate in the coordinated area is introduced for the TDMA case and for the OFDMA case. After that, relay enhanced transmission are considered. Finally, the simulation methodology and results are presented.

This work has been developed within the framework of the European project ROCKET, carried out by a consortium of 9 partners coordinated by UPC. The objective of ROCKET (*R*econfigurable *O*FDMA *C*ooperative networ*K*s *E*nabled by agile spec*T*rum use) is to provide a ubiquitous wireless solution to reach bit rates higher than 100 Mbps with peak throughputs higher than 1 Gbps, by means of advanced multi-user cooperative transmissions, improved opportunistic spectrum usage and ultra-efficient MAC design.

2. STATE OF THE ART

One of the most relevant techniques of traditional networks to mitigate interference is fixed frequency planning. It consists of assigning frequency sub-bands in the space domain, either at cell or sector level. It can be also called fixed frequency reuse, since sub-bands are “reused” spatially trying to keep as separated as possible the zones which use the same one. These frequency assignations are static, or at least, assigned under long-term criteria.

We can find in literature ([IEEE802.16m-07/020], [Sankaran09]) a widely used notation to refer to different static reuse configurations or frequency patterns[1]. The most used are:

- Fixed reuse 1/3/1: all cells and sectors have assigned the same band. The nomenclature stands for one band allocated to all cells, three sectors per cell and the same band for all sectors.

- Fixed reuse 1/3/3: one band allocated to all cells, the band is split in three and each sub-band is allocated to different sectors.

- Fixed reuse 3/3/1: the band is split in three and allocated to clusters of three neighbour cells, three sectors per cell and all sectors use the same band.

As we commented before, new applications require a smarter and more dynamic control of the interference. That is why new technologies consider new techniques as soft frequency reuse (SFR) and fractional frequency reuse (FFR). In soft frequency reuse, the overall bandwidth is shared by all base stations but for the transmission on each sub-carrier the base stations are restricted to a certain power bound. Fractional frequency reuse splits the given bandwidth in two parts: one for inner (cell-centre) users and the other one for outer (cell-edge) users. The inner part is completely reused by all base stations; the outer part is divided among the base stations [Bohge09].

[1] *We can find a deeper analysis about frequency patterns in subchapter 7.5.*

We can see in figure 1 and 2 a representation of SFR and FFR respectively:

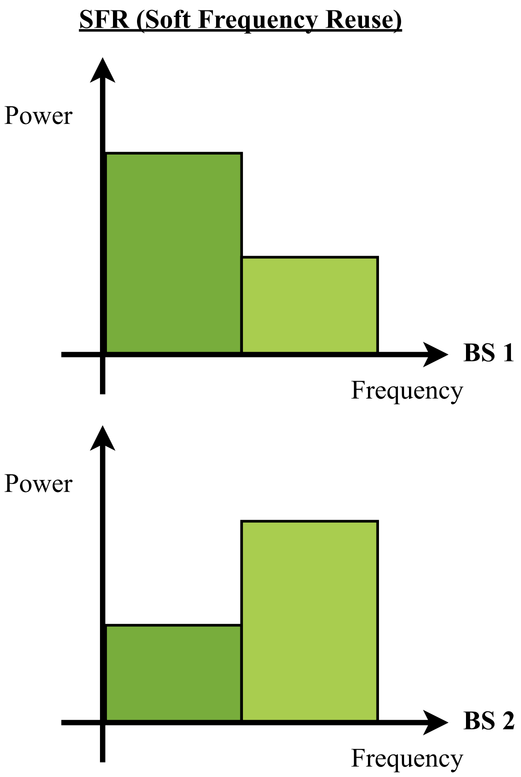

Figure 1. Soft frequency reuse

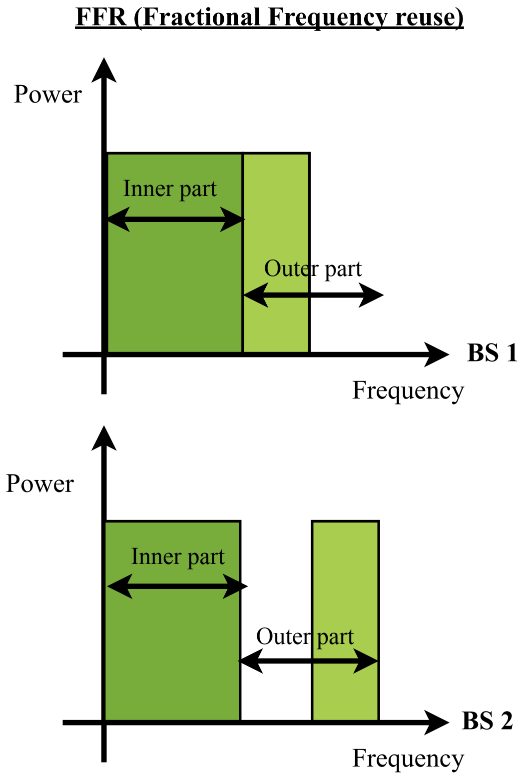

Figure 2. Fractional frequency reuse

SFR is detailed in [Doppler09] (for the Nokia Research Center), where they apply power masks among all the subcarriers, trying to equilibrate the interference pattern. That provides a solution which is more flexible than a fixed frequency reuse and, at the same time sectors can transmit in the whole band, unlike FFR, where the band is reduced. Using power masks, while a sector is transmitting with the maximum power in a sub-band x, the neighbour one will be transmitting with the maximum power in a different sub-band, let's denote it by y, although it still continues transmitting in the x sub-band, but allocating less power, with the aim to reduce the interference that may cause to the neighbour sector. Then, infinite possibilities arise from this idea, thinking on different types of masks, different combinations for one, two or more sectors. Specifically, in the approach presented in [Doppler09], masks are fixed, and the coordination of the sectors is done in groups of three. However, we can also find other articles about the optimum selection of power masks in these kind of systems, as in [Bohge09].

SFR and FFR schemes can be combined. Actually, sometimes in literature, the mix of both, thus, fractional frequency reuse with different power per carrier allocations is referred as

FFR. [Stolyar07] proposes a fractional frequency reuse with non-uniform transmission of power across subcarriers. They establish a "selfish" optimization algorithm which, without a priori frequency planning nor coordination, leads the system into efficient frequency reuse patterns. The optimization variables are power and frequency allocation, assigning different sub-bands or the whole one, trying to find a stable distribution among "edge" and "inner" users of all cells. This idea is extended in [Stolyar08], where two methods are presented: a Sector Autonomous algorithm that adjusts transmit powers in each sub-band by means of an heuristic approach and a coordinated one, that implements a Multi-sector Gradient Method by pursuing maximization of a network utility function.

There also raise interesting approaches as the one presented in [Sankaran09]. It is a kind of FFR but in time domain: they define a combo frame which consists of dividing each downlink subframe in two parts. In the first part, each sector transmits using one third of the bandwidth (each base station has associated three sectors), eliminating the interference from neighbour sectors. This orthogonal mode is good to serve the users with bad SINR, the users in the cell edge. In the second part, all sectors transmit together using a full reuse, thus, using the whole bandwidth. In this case, there is more interference but it is a good option for users with a good SINR, who can transmit using more bandwidth than in the orthogonal part.

Defining these two figures for each user:

***$SE[SINR_{orth}]$*:** spectral efficiency with *SINR* if the user is served in the orthogonal part

***$SE[SINR_{non\text{-}orth}]$*:** spectral efficiency with *SINR* if the user is served in the non-orthogonal part

Users can be allocated in the orthogonal part if $SE[SINR_{orth}] > 3SE[SINR_{non\text{-}orth}]$. Otherwise, he will be allocated in the other part. The factor 3 is necessary because in the orthogonal part each user is transmitting using a third part of the bandwidth.

Then, users who are near to the base station use all sub-bands while users who are near to the cell edge use only one:

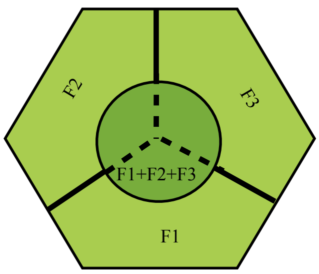

Figure 3. Combo frame and FFR zones

Finally, we have found also a different technique in [Chang09], where the channel assignment problem is faced using the mathematical graph theory. The idea is to assign nodes to each base station or access point in the communication network, and represent with an edge the co-channel interference. Then, the optimization of the problem lies in "colouring" the nodes. It is applied an iterative method to find solutions where the cells and sectors are correctly balanced in terms of traffic and interference.

3. NOTATION

Through the rest of the document we will use the following notation:

P_{BS}: total power emitted by a BS antenna, specifically for one sector

P_{RS}: total power emitted by a RS antenna

ρ : constant related to per-carrier fading statistic[2]

γ : SNR penalty[2]

N_0: noise spectral density

W_T: total bandwidth

$L_m(i,k)$: path-loss between the *k*-th user in the *i*-th sector and the BS in sector *m*

$L_m^{br}(i)$: path-loss between the BS in sector *m* and the RS in the *i*-th sector

$L_m^{ru}(i,k)$: path-loss between the RS in sector *m* and the *k*-th user in the *i*-th sector

N_s: number of sectors per cell (number of sub-bands)

N_{cs}: number of coordinated sectors (sectors within the coordinated area[3])

N_{ncs}: number of non-coordinated sectors (sectors outside the coordinated area)

SNR_u: SNR of the user signal

SNR_{Iint}: SNR of interfering signals[4] coming from sectors within the coordinated area (internal interference)

SNR_{Iext}: SNR of interfering signals coming from sectors outside the coordinated area (external interference)

$w_{BS}(i)$: fraction of the total bandwidth assigned to the *i*-th sector

$w^{(f)}{}_{BS}(i)$: fraction of the total bandwidth assigned to the *i*-th sector in the second hop of non-orthogonal (full reuse) phase with relays

$W^{(o)}(i,k)$: fraction of the total bandwidth allocated to the *k*-th user in the *i*-th sector in the orthogonal phase during the scheduling period

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[2] *See annex 3, section A3.4.*

[3] *See subchapter 7.2.*

[4] *See subchapter 7.9 for a complete description about all interfering sources and signals.*

$W^{(f)}(i,k)$: fraction of the total bandwidth allocated to the k-th user in the i-th sector in the non-orthogonal phase (full reuse) during the scheduling period

$W_1^{(f)}(i,k)$: fraction of the total bandwidth allocated to the k-th user in the i-th sector in the first hop for the non-orthogonal phase with relays during the scheduling period

$W_2^{(f)}(i,k)$: fraction of the total bandwidth allocated to the k-th user in the i-th sector in the second hop for the non-orthogonal phase with relays during the scheduling period

$T^{(o)}(i,k)$: fraction of the total time of the scheduling period allocated to the k-th user in the i-th sector for the orthogonal phase

$T^{(f)}(i,k)$: fraction of the total time of the scheduling period allocated to the k-th user in the i-th sector for the non-orthogonal phase

t: fraction of the total time of the scheduling period dedicated to the orthogonal phase

$t_i^{(1)}$: portion of the total time dedicated to the first hop in orthogonal relay enhanced transmissions in the i-th sector

$t_i^{(2)}$: portion of the total time dedicated to the second hop in orthogonal relay enhanced transmissions in the i-th sector

$t^{(1)}$: portion of the total time dedicated to the first hop in non-orthogonal relay enhanced transmissions

$t^{(2)}$: portion of the total time dedicated to the second hop in non-orthogonal relay enhanced transmissions

Other definitions:

Fixed reuse $1/N_s$: it will be the general denomination for all static reuses in which the system bandwidth is split in N_s equal parts and assigned to different sectors and/or cells. Examples of fixed reuses $1/N_s$, with N_s equal to three, are fixed reuses 1/3/3 and 3/3/1.

Fixed reuse 1: it is another denomination for fixed reuse 1/3/1, where all the cells and sectors use the total bandwidth (full reuse).

4. TRANSMISSION WITH COORDINATION

In order to improve the served rate, considering also quality of service, we propose a coordinated radio resource management (RRM) for downlink transmissions. In our approach, unlike the fixed frequency planning in conventional cellular networks, available resources are put into a common resource pool and dynamically allocated to different sectors based on dynamic parameters that affect radio network performance. These allocations can be done at a short time scale, comparable to the MAC frame time. The following assumptions, which influence the performance and operational amenability of the network, will be taken:

- The existence of a dedicated back-haul connecting the BS's.
- The consideration of MS's with interference measurement capabilities, already supported by 802.16m [Hamiti08].
- The restriction of the channel state information (CSI) to the link path loss. While its slowly varying nature helps keeping the feedback load under control, its sole knowledge precludes the BS processing workload to become unaffordable, as in the case where each per-tone fading state is available [Wong99, Calvo09].

We want to coordinate the resource allocation in an optimal way. So we will focus all the mathematical approaches as a maximization problem on some variables, which will be directly related to the resource assignation.

After describing the three scheduling policies we have considered, we have decided to start by explaining a simple and illustrative case: the optimization for a TDMA access and after that, we will introduce the solution for the OFDMA 802.16m case.

4.1 Scheduling policies

One important part in the radio resource management is the scheduling strategy. It is the process which relates directly the resources to the users, in the sense that it is the responsible to select the users who are going to be served at each moment.

We have considered three different scheduling methods in this work, but there exist others. None of them is better than the others, since each one has a different objective.

It is worthy to mention that the mathematical optimizations we can find in this work are based on maximizing either the sum-rate or a very similar figure of merit of the coordinated area. In the following lines we are going to describe the variants in which each scheduling method introduces in the optimization procedure.

- Maximizing the sum-rate

As the method name says, the objective is to provide the maximum rate in the coordinated area. The mathematical procedure is to maximize directly the sum-rate in the coordinated area, thus, the sum of all user rates that are transmitting during the scheduling period.

We obtain the best results in terms of spectral efficiency and channel capacity. However it is achieved by serving only the best users in the coordinated area.

- Proportional fair

When proportional fair scheduling is considered, we introduce weighting factors in the sum-rate. These factors allow to prioritize those users or services with higher weights. In this way, fairness issues or QoS criteria can be introduced. The weighting factors allow the scheduler to allocate the user with the maximum ratio of achievable instantaneous data rate over the average received data rate.

To that end, the weight for the k-th user in the i-th sector is computed as follows:

$$\mu(i,k) = \frac{1}{Th(i,k,t)} \qquad (4.1)$$

where $Th(i,k,t)$ is the average given throughput to user k in the i-th sector at time t.

It is obtained as follows:

$$Th(i,k,t) = \left(1 - \frac{1}{t_c}\right) \cdot Th(i,k,t-1) + \frac{R(i,k)}{t_c} \qquad (4.2)$$

with *R(i,k)* the instantaneous rate assigned to this user and t_c a memory factor.

If the weighting factors are equal for all users, maximizing the weighted sum-rate is equivalent to maximizing the system spectral efficiency, as in the previous method.

- Round Robin

In this scheduling method, users are cyclically scheduled irrespective of the channel condition and their own served rate. Despite this method is more fair than the previous are, this fairness is achieved at the expense of the total served rate.

4.2 Resource allocation for TDMA access

4.2.1 Transmission strategy

In this subchapter, we are going to present the coordinated RRM applied to a TDMA system. In TDMA, users are orthogonalized in time, thus, they are served in different time slots, but they can use the whole available bandwidth each time they transmit. In order to coordinate the resource allocation for different BSs, we divide the frame into small time parts called scheduling periods (see subchapter 6.2). During this scheduling period, users are served according to the solution of the coordinated RRM problem and the adopted scheduling policy. Furthermore, we will define two different time phases within each scheduling period:

- An orthogonal phase, in which sector allocations are separated in time. Therefore, there is no interference among the set of coordinated sectors.

- A non-orthogonal phase, in which each BS transmit without considering the other coordinated sectors. Therefore, we could expect an increase on the total rate in the coordinated area, because all sectors are transmitting at the same time, but it's at the price of increasing the interference from neighbouring sectors. The benefits of this phase will depend on each situation and scenario, regarding users distribution within the coordinated area.

Once defined these two time phases, our objective is to find the best time allocation that will maximize a measurement of the quality of the system. According to this figure of merit, we need to obtain:

- The portion of the total time for each phase (orthogonal and non-orthogonal).

Let us to denote by t the duration of the orthogonal phase, normalized to one, and $(1-t)$ the duration of the non-orthogonal phase.

- The portion of the total time allocated to each user for both cases.

We define two matrices $\mathbf{T^{(o)}}$ and $\mathbf{T^{(f)}}$ to represent the time allocated to the *k*-th user in the *i*-th sector. $T^{(o)}(i,k)$ values refer to the orthogonal phase and $T^{(f)}(i,k)$ to the non orthogonal one.

In figure 4 we can see an example of time allocation. We can see the difference between the orthogonal phase and the non-orthogonal one.

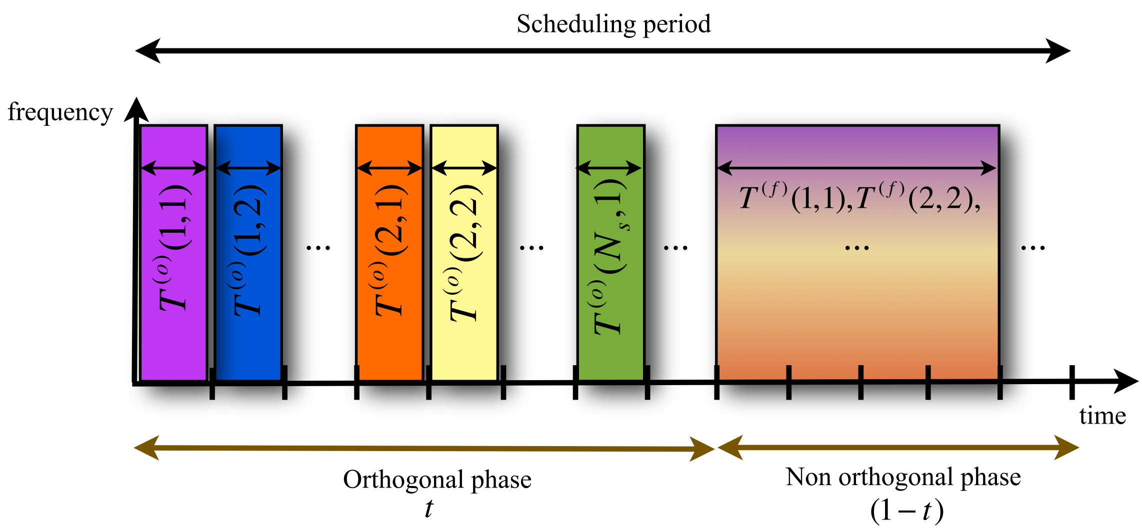

Figure 4. Frequency-time representation for TDMA coordinated RRM

4.2.2 Maximizing the sum-rate

Our optimization objective is to find the values of t, $\mathbf{T^{(o)}}$ and $\mathbf{T^{(f)}}$ that maximize the total sum-rate in the coordinated area. The maximum rate at with transmissions can be done is given by the ergodic capacity. We are considering a multi-carrier system and non detailed knowledge of the attenuation per carrier, so that the optimal per-carrier power allocation is uniform. Codewords are interleaved and allocated across carriers, and hence the channel capacity may well be approximated by the ergodic capacity, provided that the number of carriers is sufficiently large and the channel gains are independent [Muñoz09].

We can use a lower bound for the ergodic capacity[5] , which applied to the k-th user in the i-th sector for the orthogonal phase, thus, without interference from the coordinated sectors, is:

$$C^{(o)}(i,k) = \log(1+\rho\gamma \frac{SNR_u(i,k)}{1+SNR_{Iext}(i,k)}) = \log(1+\rho\gamma \frac{\frac{P_{BS}}{N_0 W_T L_i(i,k)}}{1+\sum_{m=1}^{Ncs} \frac{P_{BS}}{N_0 W_T L_m(i,k)}}) \quad (4.3)$$

[5] *Lower bound for the ergodic capacity for SISO direct link transmissions. See annex 3, section A3.4.*

where ρ is related to per-carrier fading statistics (see annex 3, section A3.4) and γ the SNR penalty [Simoens09, ch. 5], which is 4 dB.

In the non-orthogonal phase, coordinated sectors can transmit at the same time, so the interference from the coordinated sectors needs to be considered, and the lower bound of the ergodic capacity becomes:

$$C^{(f)}(i,k)=\log(1+\rho\gamma\frac{SNR_u(i,k)}{1+SNR_{Iint}(i,k)+SNR_{Iext}(i,k)})=$$

$$=\log(1+\rho\gamma\frac{\frac{P_{BS}}{N_0W_TL_i(i,k)}}{1+\sum_{j=1_{j\neq i}}^{Ncs}\frac{P_{BS}}{N_0W_TL_j(i,k)}+\sum_{m=1}^{Nncs}\frac{P_{BS}}{N_0W_TL_m(i,k)}}) \qquad (4.4)$$

We focus on the sum-rate maximization. Therefore, the optimization problem can be written as follows:

$$\max_{\mathbf{T}^{(o)},\mathbf{T}^{(f)},t}\left(\sum_{i=1}^{Ns}\sum_{k=1}^{K}T^{(o)}(i,k)C^{(o)}(i,k)+\sum_{i=1}^{Ns}\sum_{k=1}^{K}T^{(f)}(i,k)C^{(f)}(i,k)\right) \qquad (4.5)$$

$$s.t. \qquad \mathbf{T}^{(o)}\succeq 0_{NsxK},\mathbf{T}^{(f)}\succeq 0_{NsxK}$$
$$0\leq t\leq 1 \qquad (4.6)$$

$$1_{1xNs}\mathbf{T}^{(o)}\mathbf{1}_{Kx1}-t=0 \qquad (4.7)$$

$$\mathbf{T}^{(f)}\mathbf{1}_{Kx1}-(1-t)\mathbf{1}_{Kx1}=\mathbf{0}_{Nsx1} \qquad (4.8)$$

The problem is convex[6] on $\mathbf{T}^{(o)}$, $\mathbf{T}^{(f)}$, and *t*, because of the linearity on the optimization variables.

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[6] *See annex 5.*

The solution is presented as follows:

- Allocate only one user in the orthogonal phase (the best of the whole coordinated area, in terms of capacity, or SINR, which is equivalent), and allocate N_s users in the non-orthogonal one (the best of each sector). Thus, for the orthogonal phase,

$$\begin{aligned} T^{(o)}(i^*,k^*) &= t \\ T^{(o)}(i,k) &= 0 \end{aligned} \tag{4.9}$$

for (i,k) different from (i^*,k^*), with

$$(i^*,k^*) = \arg\max_{i,k}\left\{C^{(o)}(i,k)\right\} = \arg\max_{i,k}\left\{\frac{SNR_u(i,k)}{1+SNR_{Iext}(i,k)}\right\} \tag{4.10}$$

For the non-orthogonal phase,

$$\begin{aligned} T^{(f)}(i,k_i^*) &= (1-t) \\ T^{(f)}(i,k) &= 0 \end{aligned} \tag{4.11}$$

for k different from k_i^*, with

$$k_i{*} = \arg\max_{k}\left\{C^{(f)}(i,k)\right\} = \arg\max_{k}\left\{\frac{SNR_u(i,k)}{1+SNR_{Iint}(i,k)+SNR_{Iext}(i,k)}\right\}, i=1,\ldots,Ns \tag{4.12}$$

- Choose only one phase for each scheduling period. The transmission will be orthogonal if the best user in the whole coordinated area has a higher capacity (without interference) than the sum of the capacities of the best users at each sector (with interference, and the bandwidth reduced by a factor N_s). It is equivalent to evaluate the SINR instead of the capacities.

Then,

$$t = 1 \rightarrow if \max_{i,k}\left\{C^{(o)}(i,k)\right\} > \sum_{i=1}^{Ns}\max_{k}\left\{C^{(f)}(i,k)\right\} \qquad (4.13)$$

or

$$t = 0 \rightarrow if \max_{i,k}\left\{C^{(o)}(i,k)\right\} \leq \sum_{i=1}^{Ns}\max_{k}\left\{C^{(f)}(i,k)\right\} \qquad (4.14)$$

We are going to prove it in the following lines. Then, taking the expression *(4.5)*, we can find an upper-bound if we consider in the expression only these capacities:

- The capacity of the best user in the coordinated area, according to the definition of capacity in the orthogonal phase.

$$C^{(o)*} \triangleq \max_{i,k}\left\{C^{(o)}(i,k)\right\} \qquad (4.15)$$

- The capacities of the best users in each coordinated sector. Since the transmission is non-orthogonal, we can consider all sectors.

$$C^{(f)}(i) \triangleq \max_{k}\left\{C^{(f)}(i,k)\right\} \qquad (4.16)$$

Then, the upper-bound is:

$$\sum_{i=1}^{Ns}\sum_{k=1}^{K}T^{(o)}(i,k)C^{(o)}(i,k) + \sum_{i=1}^{Ns}\sum_{k=1}^{K}T^{(f)}(i,k)C^{(f)}(i,k) \leq \sum_{i=1}^{Ns}\sum_{k=1}^{K}T^{(o)}(i,k)C^{(o)*} + \sum_{i=1}^{Ns}\sum_{k=1}^{K}T^{(f)}(i,k)C^{(f)}(i) \qquad (4.17)$$

and according to the constraints *(4.7)* and *(4.8)*, this expression becomes equal to:

$$tC^{(o)*} + (1-t)\sum_{i=1}^{Ns}C^{(f)}(i) \qquad (4.18)$$

Now, introducing this new capacity,

$$C^{(f)*} \triangleq \sum_{i=1}^{Ns} C^{(f)}(i) \tag{4.19}$$

We can upper-bound again the expression:

$$tC^{(o)*} + (1-t)\sum_{i=1}^{Ns} C^{(f)}(i) \leq t\max(C^{(o)*}, C^{(f)*}) + (1-t)\max(C^{(o)*}, C^{(f)*}) \tag{4.20}$$

And finally we find the maximum, which is reached for the values of *t*, $\mathbf{T}^{(o)}$ and $\mathbf{T}^{(f)}$, previously indicated:

$$t\max(C^{(o)*}, C^{(f)*}) + (1-t)\max(C^{(o)*}, C^{(f)*}) = \max(C^{(o)*}, C^{(f)*}) \tag{4.21}$$

In the following figure, we illustrate the optimal solution. Let's consider two consecutive scheduling periods and three sectors. One possible assignation could be the following one: the orthogonal solution for the first scheduling period, where only one user transmits, and the non-orthogonal one for the second, where one user by sector (three) transmit at the same time:

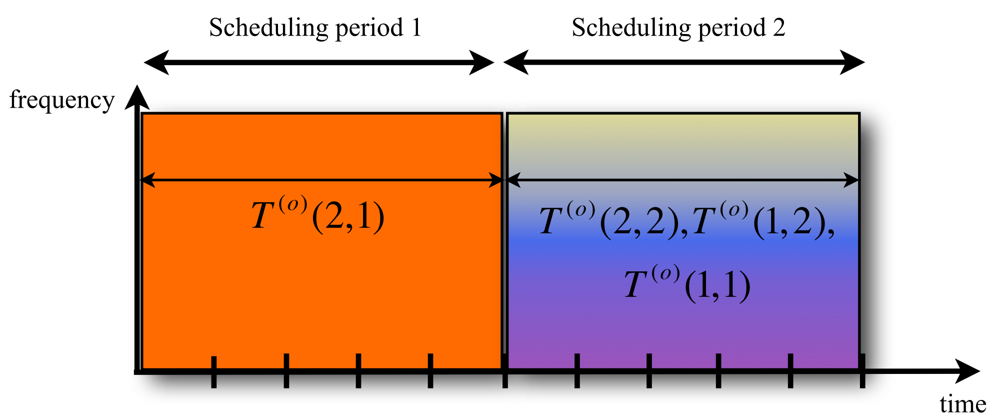

Figure 5. Frequency-time representation of the optimal solution for TDMA coordinated RRM

4.2.3 Proportional fair

Maximizing the weighted sum-rate doesn't increase the difficulty of the optimization procedure at all. We only need to replace *(4.5)* by:

$$\max_{\mathbf{T}^{(o)},\mathbf{T}^{(f)},t}\left(\sum_{i=1}^{Ns}\sum_{k=1}^{K}T^{(o)}(i,k)\mu(i,k)C^{(o)}(i,k)+\sum_{i=1}^{Ns}\sum_{k=1}^{K}T^{(f)}(i,k)\mu(i,k)C^{(f)}(i,k)\right) \quad (4.22)$$

which is still linear on the optimization variables.

4.3 Resource allocation for OFDMA access

4.3.1 Transmission strategy

In this subchapter we are going to describe the coordinated resource allocation scheme for a OFDMA system to be applicable in the 802.16m standard. We commented some coordinated schemes in chapter 2. The technique we propose is similar to the one developed in [Sankaran09] (for Motorola Inc): a fractional frequency reuse where orthogonal and non-orthogonal parts are separated in time. We follow the same idea, but we split optimally the band considering the interference from neighbour sectors, instead of dividing it in three equal parts. Other two differences are that we propose coordination among sectors of the same BS or different BSs, and the time dedicated to the orthogonal or non-orthogonal parts is also optimized, not fixed.

In OFDMA systems, users have assigned 'slots' which consist of a certain allocation of frequency subchannels for a certain number of symbols. The adoption of orthogonal frequency division multiple-access (OFDMA) allows for a fine granularity in resource allocation [Chang07]. However, when considering OFDMA, an infinite number of possibilities in defining and allocating resources arise. Since we target practical solutions to the allocation problem, we shall fix some simplifying structure for the ease of analysis. Therefore, we consider again scheduling periods consisting of two phases: orthogonal phase and non-orthogonal, or full reuse, phase. During each scheduling period, we will optimize resource allocation according to the adopted scheduling method, to obtain:

- The fraction of the total duration of each phase (orthogonal and not orthogonal)

Let us to denote by t the duration of the orthogonal phase, normalized to one, and $(1-t)$ the duration of the non orthogonal phase.

- The portion of the total bandwidth allocated to i-th sector during the orthogonal phase, $w_{BS}(i)$. We define a vector which contains the N_s (number of sectors) components: $\mathbf{w}_{BS}$.

- The portion of the total bandwidth allocated to each user.

We define two matrices $\mathbf{W^{(o)}}$ and $\mathbf{W^{(f)}}$ to represent the portion of bandwidth allocated to the k-th user in the i-th sector. $W^{(o)}(i,k)$ values refer to the orthogonal phase and $W^{(f)}(i,k)$ to the non orthogonal one.

In the physical implementation the percentage of bandwidth is assigned by selecting a concrete number of OFDM subchannels to each user. Depending on the available number of subchannels in the system, the granularity will be different, and with a higher number, more accurate assignations can be performed and better results may be obtained (see table 1 in subchapter 6.1).

In figure 6 we can see an example of bandwidth allocation. We can see the difference between the orthogonal phase and the non-orthogonal one.

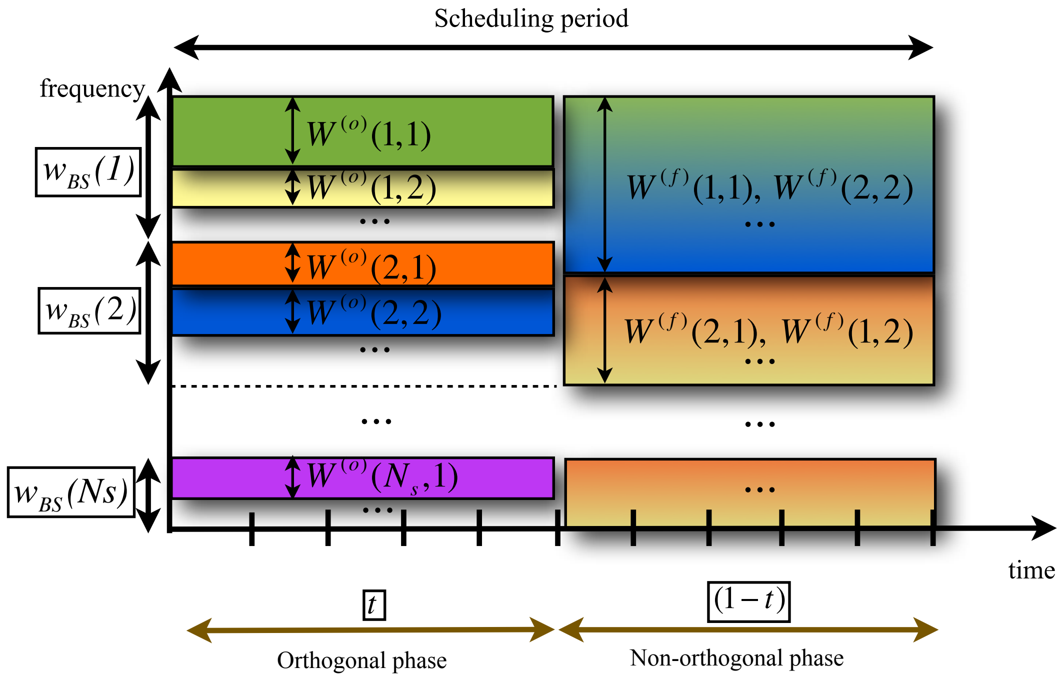

Figure 6. Frequency-time representation for OFDMA coordinated RRM

4.3.2 Maximizing the sum-rate

In this section, we are going to find the optimum resource allocation that maximizes the sum-rate in the coordinated area. Again, the maximum rate for each user will be given by the ergodic capacity.

In the orthogonal phase, each sector has assigned a portion of the whole available bandwidth ($w_{BS}(i)$) and there is only external interference:

$$C^{(o)}(i,k) = \log\left(1+\rho\gamma\frac{\frac{SNR_u(i,k)}{w_{BS}(i)}}{1+SNR_{Iext}(i,k)}\right) = \log\left(1+\rho\gamma\frac{\frac{P_{BS}}{N_0 w_{BS}(i) W_T L_i(i,k)}}{1+\sum_{m=1}^{Nncs}\frac{P_{BS}}{N_0 W_T L_m(i,k)}}\right)$$

(4.23)

In the non-orthogonal phase, each sector uses the whole bandwidth. The interference increases because it comes from the non-coordinated sectors (external interference) as in the orthogonal phase, but also from the coordinated sectors (internal interference):

$$C^{(f)}(i,k) = \log\left(1+\rho\gamma\frac{SNR_u(i,k)}{1+SNR_{Iint}(i,k)+SNR_{Iext}(i,k)}\right) =$$

(4.24)

$$= \log\left(1+\rho\gamma\frac{\frac{P_{BS}}{N_0 W_T L_i(i,k)}}{1+\sum_{j=1_{j\neq i}}^{Ncs}\frac{P_{BS}}{N_0 W_T L_j(i,k)}+\sum_{m=1}^{Nncs}\frac{P_{BS}}{N_0 W_T L_m(i,k)}}\right)$$

We focus on the maximization of the sum-rate normalized by the total bandwidth W_T, and the duration of the scheduling period. Then, the problem is written as follows:

$$\max_{\mathbf{W}^{(o)},\mathbf{W}^{(f)},\mathbf{w}_{\mathbf{BS}},t}\left(\sum_{i=1}^{Ns}\sum_{k=1}^{K} tW^{(o)}(i,k)C^{(o)}(i,k)+\sum_{i=1}^{Ns}\sum_{k=1}^{K}(1-t)W^{(f)}(i,k)C^{(f)}(i,k)\right)$$

(4.25)

$$\begin{aligned} s.t.\qquad & \mathbf{W}^{(o)}\succeq\mathbf{0}_{NsxK},\mathbf{W}^{(f)}\succeq 0_{NsxK},\mathbf{w}_{BS}\succeq\mathbf{0}_{Nsx1} \\ & 0\le t\le 1 \\ & \mathbf{W}^{(o)}\mathbf{1}_{Kx1}-\mathbf{w}_{BS}\le\mathbf{0}_{Nsx1} \\ & \mathbf{1}_{1xNs}\mathbf{w}_{BS}-1\le 0 \\ & \mathbf{W}^{(f)}\mathbf{1}_{Kx1}-\mathbf{1}_{Nsx1}\le\mathbf{0}_{Nsx1} \end{aligned} \qquad (4.26)$$

The solution of the problem is:

- In the orthogonal phase, each sector selects the best user, in terms of capacity, or SINR, and the bandwidth is split among N_s sectors and each user will transmit using only the whole bandwidth assigned to his sector:

$$\begin{aligned} W^{(o)}(i,k_i^*) &= w_{BS}(i) \\ W^{(o)}(i,k) &= 0 \end{aligned} \qquad (4.27)$$

with k different from k_i^*, which is:

$$k_i^* = \arg\max_k C^{(o)}(i,k) = \arg\max_k\left[\log\left(1+\rho\gamma\frac{\frac{SNR_u(i,k)}{w_{BS}(i)}}{1+SNR_{Iext}(i,k)}\right)\right], i=1,...,Ns \qquad (4.28)$$

Also in the non-orthogonal phase, only the best user in each sector is served, but in this case all of them will be able to transmit using the whole bandwidth of the system.

$$W^{(f)}(i,k_i^*) = 1$$
$$W^{(f)}(i,k) = 0 \tag{4.29}$$

with k different from k_i*, which is:

$$k_i^* = \arg\max_k \left[C^{(f)}(i,k) \right] = \arg\max_k \left[\log\left(1 + \rho\gamma \frac{SNR_u(i,k)}{1 + SNR_{Iint}(i,k) + SNR_{Iext}(i,k)} \right) \right], i = 1,...,Ns$$

(4.30)

- Choose only one phase for each scheduling period. That is,

$$t = 1 \quad if \sum_{i=1}^{Ns} \max_k \left\{ C^{(o)}(i,k) \right\} > \sum_{i=1}^{Ns} \max_k \left\{ C^{(f)}(i,k) \right\} \tag{4.31}$$

and

$$t = 0 \quad if \sum_{i=1}^{Ns} \max_k \left\{ C^{(o)}(i,k) \right\} \le \sum_{i=1}^{Ns} \max_k \left\{ C^{(f)}(i,k) \right\} \tag{4.32}$$

The proof is based on applying the primal decomposition[7] method to the variable t, separating the orthogonal phase problem and the non-orthogonal one. Once treated independently, they can be optimized on t:

$$\max_{t} \left[t \max_{\mathbf{x}} f(\mathbf{x}) + (1-t) \max_{\mathbf{y}} g(\mathbf{y}) \right] \tag{4.33}$$
$$s.t. \quad 0 \le t \le 1$$

[7] *See annex 5, section A5.2.1.*

Then, we can rewrite *(4.25)* as follows:

$$\max_{\substack{t \\ s.t.\ 0\le t\le 1}} \left[\max_{\substack{\mathbf{W}^{(o)},\mathbf{w}_{\mathbf{BS}} \\ s.t.\ \mathbf{W}^{(o)} \succeq \mathbf{0}_{NsxK} \\ \mathbf{w}_{BS} \succeq \mathbf{0}_{Nsx1} \\ \mathbf{W}^{(o)}\mathbf{1}_{Kx1}-\mathbf{w}_{BS}\le \mathbf{0}_{Nsx1} \\ \mathbf{1}_{1xNs}\mathbf{w}_{BS}-1\le 0}} \sum_{i=1}^{Ns}\sum_{k=1}^{K} R^{(o)}(i,k) + \max_{\substack{\mathbf{W}^{(f)} \\ s.t.\ \mathbf{W}^{(f)}\succeq \mathbf{0}_{NsxK} \\ \mathbf{W}^{(f)}\mathbf{1}_{Kx1}-\mathbf{1}_{Nsx1}\le \mathbf{0}_{Nsx1}}} \sum_{i=1}^{Ns}\sum_{k=1}^{K} R^{(f)}(i,k) \right]$$

(4.34)

The problem is convex[8] in all variables, as we are going to show when we define all terms. First of all, $R^{(f)}$ is the total throughput in the non-orthogonal phase:

$$R^{(f)} = \sum_{i=1}^{Ns}\sum_{k=1}^{K} R^{(f)}(i,k) = \sum_{i=1}^{Ns}\sum_{k=1}^{K} (1-t)W^{(f)}(i,k)C^{(f)}(i,k) \qquad (4.35)$$

This expression is convex on t and $W^{(f)}$ because of the linearity. Then, as we did in the previous subchapter *(4.16)*, we can express the capacity of the best user in each sector as:

$$C^{(f)}(i) = \max_k \left[C^{(f)}(i,k) \right] = \max_k \left[\log\left(1+\rho\gamma \frac{SNR_u(i,k)}{1+SNR_{Iint}(i,k)+SNR_{Iext}(i,k)} \right) \right]$$

(4.36)

The total throughput in the non orthogonal phase can be upper-bounded by the following expression:

$$\sum_{i=1}^{Ns}\sum_{k=1}^{K} R^{(f)}(i,k) \le (1-t)\sum_{i=1}^{Ns}\sum_{k=1}^{K} W^{(f)}(i,k)C^{(f)}(i) =$$

(4.37)

$$= (1-t)\sum_{i=1}^{Ns}\left(\sum_{k=1}^{K} W^{(f)}(i,k) \right) C^{(f)}(i) = (1-t)\sum_{i=1}^{Ns} C^{(f)}(i) = (1-t)C^{(f)*}$$

---

[8] *See annex 5.*

This result comes from the constraint *(4.26)* which expresses that the sum of $W^{(f)}$ over all the users in a sector is equal to one.

We can achieve this upper-bound if each sector only assign its available bandwidth only to one user, actually, the best one k_i^* :

$$k_i^* = \arg\max_k \left[C^{(f)}(i,k) \right] = \arg\max_k \left[\log\left(1 + \rho\gamma \frac{SNR_u(i,k)}{1 + SNR_{Iint}(i,k) + SNR_{Iext}(i,k)} \right) \right], i = 1,...,Ns$$

(4.38)

$$\begin{aligned} W^{(f)}(i,k_i^*) &= 1 \\ W^{(f)}(i,k) &= 0 \end{aligned} \qquad (4.39)$$

for k different from k_i^*.

We can proceed in a similar way with the first term of *(4.34)*. Let's denote it by the total throughput in the orthogonal phase.

$$\sum_{i=1}^{Ns}\sum_{k=1}^{K} R^{(o)}(i,k) = t\sum_{i=1}^{Ns}\sum_{k=1}^{K} W^{(o)}(i,k) C^{(o)}(i,k) \qquad (4.40)$$

We can find the best user in each sector:

$$k_i^* = \arg\max_k C^{(o)}(i,k) = \arg\max_k \left[\log\left(1 + \rho\gamma \frac{\dfrac{SNR_u(i,k)}{1 + SNR_{Iext}(i,k)}}{w_{BS}(i)} \right) \right], i = 1,...,Ns \qquad (4.41)$$

which is the same than:

$$k_i^* = \arg\max_k \left[\frac{SNR_u(i,k)}{1 + SNR_{Iext}(i,k)} \right], i = 1,...,Ns \qquad (4.42)$$

Then, let us denote the SNRs of this user as:

$$\begin{aligned} SNR_u(i) &= SNR_u(i,k_i^*) \\ SNR_{Iext}(i) &= SNR_{Iext}(i,k_i^*) \end{aligned} \tag{4.43}$$

The key point is that we can find this maximum very easily because it depends only on the SINR of the users of the sector. The bandwidth assigned to the sector (*$w_{BS}(i)$)* is common for all of them.

The upper-bound in this case is:

$$R^{(o)} = \sum_{i=1}^{Ns}\sum_{k=1}^{K} W^{(o)}(i,k)\log\left(1+\rho\gamma\frac{\dfrac{SNR_u(i,k)}{1+SNR_{Iext}(i,k)}}{w_{BS}(i)}\right) \le \sum_{i=1}^{Ns}\sum_{k=1}^{K} W^{(o)}(i,k)\log\left(1+\rho\gamma\frac{\dfrac{SNR_u(i)}{1+SNR_{Iext}(i)}}{w_{BS}(i)}\right)$$

$$= \sum_{i=1}^{Ns}\left(\sum_{k=1}^{K} W^{(o)}(i,k)\right)\log\left(1+\rho\gamma\frac{\dfrac{SNR_u(i)}{1+SNR_{Iext}(i)}}{w_{BS}(i)}\right) = \sum_{i=1}^{Ns} w_{BS}(i)\log\left(1+\rho\gamma\frac{\dfrac{SNR_u(i)}{1+SNR_{Iext}(i)}}{w_{BS}(i)}\right) \tag{4.44}$$

We can reach this upper-bound with equality if we assign all the available bandwidth of each sector to the best user in the sector, thus, who has the highest SINR. Remember that each sector only has available a portion of the total bandwidth, which has been split among all the coordinated sectors.

$$\begin{aligned} W^{(o)}(i,k_i^*) &= w_{BS}(i) \\ W^{(o)}(i,k) &= 0 \end{aligned} \tag{4.45}$$

for k different from k_i^*.

We have simplified our problem *(4.34)* and now we have to maximize over the rest of the variables:

$$\max_{\substack{t \\ s.t.\ 0\le t\le 1}} \left[t \max_{\substack{\mathbf{w_{BS}} \\ s.t.\ \mathbf{w}_{BS}\succeq \mathbf{0}_{Nsx1} \\ \mathbf{1}_{1xNs}\mathbf{w}_{BS}-1\le 0}} \left[\sum_{i=1}^{Ns} w_{BS}(i)\log\left(1+\rho\gamma\frac{\frac{SNR_u(i)}{1+SNR_{Iext}(i)}}{w_{BS}(i)}\right)\right] + (1-t)C^{(f)*} \right] \qquad (4.46)$$

The fact that function $G(x)=ax\log\left(1+\frac{b}{x}\right)$ is concave in $x\ge 0, \forall a,b\ge 0$, together with the linearity of *t*, makes *(4.46)* a convex problem[9].

The next step is to find the optimum bandwidth allocation among the coordinated sectors that maximizes the capacity of the orthogonal phase.

Actually, we can formulate a maximization problem which is convex on the optimizing variables $w_{BS}(i)$:

$$\max_{\mathbf{w}_{BS}} \left[\sum_{i=1}^{Ns} w_{BS}(i)\log\left(1+\rho\gamma\frac{\frac{SNR_u(i)}{1+SNR_{Iext}(i)}}{w_{BS}(i)}\right)\right] \qquad (4.47)$$

$$\begin{aligned} s.t.\quad & \mathbf{w}_{BS}\succeq \mathbf{0}_{Nsx1} \\ & \mathbf{1}_{1xNs}\mathbf{w}_{BS}-1\le 0 \qquad (4.48) \\ & i=1,\dots,Ns \end{aligned}$$

[9] *If a function f(x) is concave, then -f(x) is convex. See annex 5.*

This problem can be decomposed into N_s independent sub-problems by using the dual decomposition method[10]:

$$\max_{\mathbf{w}_{BS}} \left[w_{BS}(i)\log\left(1+\rho\gamma\frac{\frac{SNR_u(i)}{1+SNR_{Iext}(i)}}{w_{BS}(i)}\right) - \lambda w_{BS}(i)\right] \quad (4.49)$$

$$s.t. \quad \mathbf{w}_{BS} \succeq \mathbf{0}_{Nsx1} \quad i=1,...,Ns \quad (4.50)$$

The variable λ is the Lagrange multiplier associated to the relaxation $\mathbf{1}_{1xNs}\mathbf{w}_{BS} - 1 \leq 0$. It can be interpreted as a price of bandwidth which links the N_s sub-problems.

The optimal value for λ (λ^*) can be iteratively found by using the bisection method [Boyd04]:

Step 1: let λ=1, l = 0, $u > \lambda^*$, and a tolerance $\varepsilon > 0$ (for example, $\varepsilon = 10^{-5}$)

Step 2: update λ by $\lambda = \frac{l+u}{2}$

Step 3: obtain $w_{BS}(i)$ independently by solving the N_s sub-problems of *(4.49)*

Step 4: If $\sum_{i=1}^{Ns} w_{BS}(i) \geq 1$, $l = \lambda$, else $u = \lambda$

Step 5: If $u - l > \varepsilon$, go to step 2

Then, two possible strategies arise for the practical implementation:

- At every iteration, each sector broadcast $w_{BS}(i)$ to the rest of sectors, which update the price of bandwidth independently until convergence.

- Every sector reports the optimum $w_{BS}(i)$ to a central unit which computes the price of bandwidth accordingly and communicates this value to the sectors. The process is repeated until the price of the bandwidth converges.

---

[10] *See annex 5, section A5.2.2.*

The last step to finish the global maximization problem is to maximize over t, thus, selecting the orthogonal phase or the non orthogonal one:

$$\max_t \left[tR^{(o)} + (1-t)R^{(f)} \right] \tag{4.51}$$

$$s.t. \quad 0 \leq t \leq 1 \tag{4.52}$$

In a similar way to the one we saw in the TDMA case:

$$tR^{(o)} + (1-t)R^{(f)} \leq t\max(R^{(o)}, R^{(f)}) + (1-t)\max(R^{(o)}, R^{(f)}) \tag{4.53}$$

and finally,

$$t\max(R^{(o)}, R^{(f)}) + (1-t)\max(R^{(o)}, R^{(f)}) = \max(R^{(o)}, R^{(f)}) \tag{4.54}$$

This maximum is achieved choosing only one phase for each scheduling period.

Figure 7 represents the optimal solution for the orthogonal phase and for the non orthogonal phase when considering three sectors. For each scheduling period, the best of both solutions would be selected.

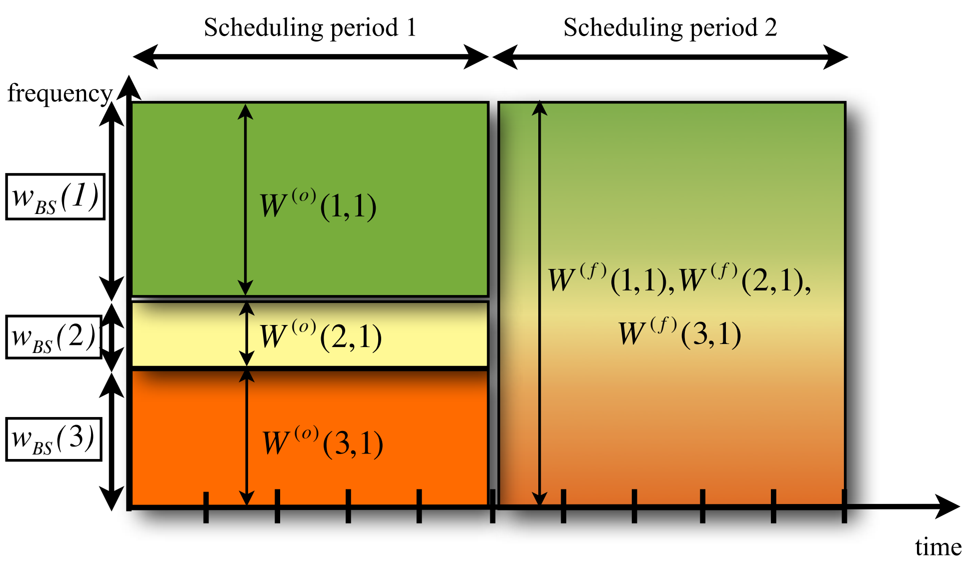

Figure 7. Frequency-time representation of the optimal solution for OFDMA coordinated RRM

4.3.3 Proportional fair

Along the following subchapter, our objective is going to be slightly different. We want to maximize the sum-rate in the coordinated area, but setting a kind of fairness in the system. Of course, the capacities defined for each phase will be the same but the objective function is going to be the weighted sum-rate, in spite of the sum-rate:

$$\max_{\mathbf{W}^{(o)},\mathbf{W}^{(f)},\mathbf{w_{BS}},t}\left(\sum_{i=1}^{Ns}\sum_{k=1}^{K} t\mu(i,k)W^{(o)}(i,k)C^{(o)}(i,k)+\sum_{i=1}^{Ns}\sum_{k=1}^{K}(1-t)\mu(i,k)W^{(f)}(i,k)C^{(f)}(i,k)\right) \tag{4.55}$$

$$\begin{aligned} s.t. \qquad & \mathbf{W}^{(o)}\succeq\mathbf{0}_{NsxK},\mathbf{W}^{(f)}\succeq 0_{NsxK},\mathbf{w}_{BS}\succeq\mathbf{0}_{Nsx1} \\ & 0\le t\le 1 \\ & \mathbf{W}^{(o)}\mathbf{1}_{Kx1}-\mathbf{w}_{BS}\le\mathbf{0}_{Nsx1} \\ & \mathbf{1}_{1xNs}\mathbf{w}_{BS}-1\le 0 \\ & \mathbf{W}^{(f)}\mathbf{1}_{Kx1}-\mathbf{1}_{Nsx1}\le\mathbf{0}_{Nsx1} \end{aligned} \tag{4.56}$$

We can apply again a primal decomposition[11] to the convex problem by optimizing the objective function for any fixed value of *t*, so that we first can find an optimal solution for both transmission phases, treating them as independent optimization sub-problems and finally finish the maximization on *t*.

$$\max_{\substack{t \\ s.t.\ 0\le t\le 1}}\left[\begin{array}{l} t \max\limits_{\mathbf{W}^{(o)},\mathbf{w_{BS}}} \left[\sum_{i=1}^{Ns}\sum_{k=1}^{K}\mu(i,k)W^{(o)}(i,k)C^{(o)}(i,k)\right]+ \\ \quad s.t.\ \ \mathbf{W}^{(o)}\succeq\mathbf{0}_{NsxK},\mathbf{w}_{BS}\succeq\mathbf{0}_{Nsx1} \\ \quad\quad \mathbf{W}^{(o)}\mathbf{1}_{Kx1}-\mathbf{w}_{BS}\le\mathbf{0}_{Nsx1} \\ \quad\quad \mathbf{1}_{1xNs}\mathbf{w}_{BS}-1\le 0 \\ +(1-t) \max\limits_{\mathbf{W}^{(f)}} \left[\sum_{i=1}^{Ns}\sum_{k=1}^{K}\mu(i,k)W^{(f)}(i,k)C^{(f)}(i,k)\right] \\ \quad s.t.\ \ \mathbf{W}^{(f)}\succeq 0_{NsxK} \\ \quad\quad \mathbf{W}^{(f)}\mathbf{1}_{Kx1}-\mathbf{1}_{Nsx1}\le\mathbf{0}_{Nsx1} \end{array}\right] \tag{4.57}$$

[11] *See annex 5, section A5.2.1.*

First of all, let us focus on the sub-problem concerning the non-orthogonal part:

$$\max_{\mathbf{W}^{(f)}} \left[\sum_{i=1}^{Ns} \sum_{k=1}^{K} \mu(i,k) W^{(f)}(i,k) C^{(f)}(i,k) \right]$$
$$s.t. \quad \mathbf{W}^{(f)} \succeq 0_{NsxK} \tag{4.58}$$
$$\mathbf{W}^{(f)} \mathbf{1}_{Kx1} - \mathbf{1}_{Nsx1} \leq \mathbf{0}_{Nsx1}$$

The weighted capacity of the best user in each sector is:

$$\hat{C}^{(f)}(i) = \max_k \left[\mu(i,k) C^{(f)}(i,k) \right] = \max_k \left[\mu(i,k) \log\left(1 + \rho\gamma \frac{SNR_u(i,k)}{1 + SNR_{Iint}(i,k) + SNR_{Iext}(i,k)} \right) \right] \tag{4.59}$$

The weighted sum-rate in the non orthogonal phase can be upper-bounded by the following expression:

$$\sum_{i=1}^{Ns} \sum_{k=1}^{K} \mu(i,k) W^{(f)}(i,k) C^{(f)}(i,k) \leq \sum_{i=1}^{Ns} \sum_{k=1}^{K} W^{(f)}(i,k) \hat{C}^{(f)}(i) =$$
$$= \sum_{i=1}^{Ns} \left(\sum_{k=1}^{K} W^{(f)}(i,k) \right) \hat{C}^{(f)}(i) = \sum_{i=1}^{Ns} \hat{C}^{(f)}(i) = \hat{C}^{(f)*} \tag{4.60}$$

According to the constraint *(4.56)* which expresses that the sum of $W^{(f)}$ over all the users in a sector is equal to one.

The sub-problem of the orthogonal phase is:

$$\max_{\mathbf{W}^{(o)}, \mathbf{w}_{\mathbf{BS}}} \left[\sum_{i=1}^{Ns} \sum_{k=1}^{K} \mu(i,k) W^{(o)}(i,k) C^{(o)}(i,k) \right]$$
$$s.t. \quad \mathbf{W}^{(o)} \succeq \mathbf{0}_{NsxK}, \mathbf{w}_{BS} \succeq \mathbf{0}_{Nsx1} \tag{4.61}$$
$$\mathbf{W}^{(o)} \mathbf{1}_{Kx1} - \mathbf{w}_{BS} \leq \mathbf{0}_{Nsx1}$$
$$\mathbf{1}_{1xNs} \mathbf{w}_{BS} - 1 \leq 0$$

In this case, if we try to proceed in the same way than in the case of maximizing the sum-rate:

$$\sum_{i=1}^{Ns}\sum_{k=1}^{K}W^{(o)}(i,k)\mu(i,k)\log\left(1+\rho\gamma\frac{\frac{SNR_u(i,k)}{w_{BS}(i)}}{1+SNR_{Iext}(i,k)}\right)\leq\sum_{i=1}^{Ns}\sum_{k=1}^{K}W^{(o)}(i,k)\max_k\left[\mu(i,k)\log\left(1+\rho\gamma\frac{\frac{SNR_u(i,k)}{w_{BS}(i)}}{1+SNR_{Iext}(i,k)}\right)\right]$$

(4.62)

We obtain a valid upper-bound, but while in the previous case the argument which maximized the expression matched up with the one which provided the highest SINR *(4.42)*, now it doesn't. This maximum depend on $\mu(i,k)$, $SNR_u(i,k)$, but also on $w_{BS}(i)$, because it affects to $SNR_u(i,k)$ but not to $\mu(i,k)$, and we can have trade-offs with users with a high link but with a low weight or the opposite and all these situations will also depend on the assigned bandwidth $w_{BS}(i)$. Then, we can't maximize it only respect to *k*, because we also have to consider the bandwidth. We can state two conclusions:

- The maximization of the weighted capacity has to be introduced into the global maximization over the bandwidth variables ($W^{(o)}(i,k)$ and $w_{BS}(i)$):

$$\begin{aligned}\max_{\mathbf{W}^{(o)},\mathbf{w}_{\mathbf{BS}}}&\sum_{i=1}^{Ns}\sum_{k=1}^{K}W^{(o)}(i,k)\max_k\left[\mu(i,k)\log\left(1+\rho\gamma\frac{\frac{SNR_u(i,k)}{w_{BS}(i)}}{1+SNR_{Iext}(i,k)}\right)\right]\\ s.t.\quad&\mathbf{W}^{(o)}\succeq\mathbf{0}_{NsxK},\mathbf{w}_{BS}\succeq\mathbf{0}_{Nsx1}\\&\mathbf{W}^{(o)}\mathbf{1}_{Kx1}-\mathbf{w}_{BS}\leq\mathbf{0}_{Nsx1}\\&\mathbf{1}_{1xNs}\mathbf{w}_{BS}-1\leq 0\end{aligned}\qquad(4.63)$$

- Now it's not possible to sum separately $W^{(o)}(i,k)$ over *k*, because the maximum depends on $w_{BS}(i)$:

$$\sum_{k=1}^{K}W^{(o)}(i,k)\qquad(4.64)$$

It means that now we can't assure that the best option is to transmit only to one user by sector. We have to consider all of them when we optimize over the bandwidth variables. So our optimization sub-problem is:

$$\max_{\mathbf{W}^{(o)},\mathbf{w_{BS}}}\left[\sum_{i=1}^{Ns}\sum_{k=1}^{K}\mu(i,k)W^{(o)}(i,k)C^{(o)}(i,k)\right]=$$
$$s.t.\quad \mathbf{W}^{(o)}\succeq\mathbf{0}_{NsxK},\mathbf{w}_{BS}\succeq\mathbf{0}_{Nsx1}$$
$$\mathbf{W}^{(o)}\mathbf{1}_{Kx1}-\mathbf{w}_{BS}\leq\mathbf{0}_{Nsx1}$$
$$\mathbf{1}_{1xNs}\mathbf{w}_{BS}-1\leq 0$$
$$=\max_{\mathbf{W}^{(o)},\mathbf{w_{BS}}}\left[\sum_{i=1}^{Ns}\sum_{k=1}^{K}\mu(i,k)W^{(o)}(i,k)\log\left(1+\rho\gamma\frac{\frac{SNR_u(i,k)}{w_{BS}(i)}}{1+SNR_{Iext}(i,k)}\right)\right] \quad (4.65)$$
$$s.t.\quad \mathbf{W}^{(o)}\succeq\mathbf{0}_{NsxK},\mathbf{w}_{BS}\succeq\mathbf{0}_{Nsx1}$$
$$\mathbf{W}^{(o)}\mathbf{1}_{Kx1}-\mathbf{w}_{BS}\leq\mathbf{0}_{Nsx1}$$
$$\mathbf{1}_{1xNs}\mathbf{w}_{BS}-1\leq 0$$

We can decompose it in N_s sub-problems, as in the case of maximizing the sum-rate, but now the number of variables will be higher, because we have to consider all the users in each sector in the optimization, while in the previous case we only considered the best one. We can apply a dual decomposition respect to some coupling constraint about a bandwidth variable, but first we have to do a change of variable to make the objective function convex on it. So the optimization sub-problem:

$$\max_{\mathbf{W}^{(o)},\mathbf{w_{BS}}}\left[\sum_{i=1}^{Ns}\sum_{k=1}^{K}\mu(i,k)W^{(o)}(i,k)\log\left(1+\rho\gamma\frac{\frac{SNR_u(i,k)}{w_{BS}(i)}}{1+SNR_{Iext}(i,k)}\right)\right]$$
$$s.t.\quad \mathbf{W}^{(o)}\succeq\mathbf{0}_{NsxK},\mathbf{w}_{BS}\succeq\mathbf{0}_{Nsx1} \quad (4.66)$$
$$\mathbf{W}^{(o)}\mathbf{1}_{Kx1}-\mathbf{w}_{BS}\leq\mathbf{0}_{Nsx1}$$
$$\mathbf{1}_{1xNs}\mathbf{w}_{BS}-1\leq 0$$

defining this new variable:

$$P(i,k)=\frac{W^{(o)}(i,k)}{w_{BS}(i)} \tag{4.67}$$

becomes:

$$\begin{aligned}
&\max_{\mathbf{W}^{(o)},\mathbf{w_{BS}},\mathbf{P}}\left[\sum_{i=1}^{Ns}\sum_{k=1}^{K}\mu(i,k)W^{(o)}(i,k)\log\left(1+\rho\gamma\frac{P(i,k)\frac{SNR_u(i,k)}{1+SNR_{Iext}(i,k)}}{W^{(o)}(i,k)}\right)\right]\\
&s.t.\quad \mathbf{W}^{(o)}\succeq\mathbf{0}_{NsxK},\mathbf{w}_{BS}\succeq\mathbf{0}_{Nsx1},\mathbf{P}\succeq\mathbf{0}_{NsxK}\\
&\qquad \mathbf{W}^{(o)}\mathbf{1}_{Kx1}-\mathbf{w}_{BS}\le\mathbf{0}_{Nsx1}\\
&\qquad \mathbf{P1}_{Kx1}-\mathbf{1}_{Nsx1}\le\mathbf{0}_{Nsx1}\\
&\qquad \mathbf{1}_{1xNs}\mathbf{w}_{BS}-1\le 0
\end{aligned} \tag{4.68}$$

Now the problem becomes convex on the allocated variables. It can be shown resorting to the function $G(x,y)=ax\log\left(1+b\frac{y}{x}\right)$ which is concave in $x,y\ge 0, \forall a,b\ge 0$. Considering $\sum_{i=1}^{Ns}w_{BS}(i)\le 1$ as the relaxation associated to the Lagrange multiplier (λ), we can decompose the whole maximization problem into N_s sub-problems, one sub-problem by sector. The new decoupled sub-problem is:

$$\begin{aligned}
&\max_{\mathbf{W}^{(o)},\mathbf{w_{BS}},\mathbf{P}}\left[\sum_{k=1}^{K}\mu(i,k)W^{(o)}(i,k)\log\left(1+\rho\gamma\frac{P(i,k)\frac{SNR_u(i,k)}{1+SNR_{Iext}(i,k)}}{W^{(o)}(i,k)}\right)\right]-\lambda w_{BS}(i)\\
&s.t.\quad \mathbf{W}^{(o)}\succeq\mathbf{0}_{NsxK},\mathbf{w}_{BS}\succeq\mathbf{0}_{Nsx1},\mathbf{P}\succeq\mathbf{0}_{NsxK}\\
&\qquad \mathbf{W}^{(o)}\mathbf{1}_{Kx1}-\mathbf{w}_{BS}\le\mathbf{0}_{Nsx1}\\
&\qquad \mathbf{P1}_{Kx1}-\mathbf{1}_{Nsx1}\le\mathbf{0}_{Nsx1}\\
&\qquad \mathbf{1}_{1xNs}\mathbf{w}_{BS}-1\le 0
\end{aligned} \tag{4.69}$$

This convex problem is feasible to solve with software tools. However, the number of optimizing variables is very high, and even if it is possible to find the solution, it would be interesting to consider a simpler alternative method, which even if it wouldn't give us an optimal solution, it could provide us a good one, but with a lower complexity and faster. We have to consider that this problem has to be solved for any downlink scheduling period. So we have proposed a sub-optimal method which consists of selecting only one user by sector (k_i^*) and transmitting only to him.

In this way, the optimizing variables are only the ones which correspond to the bandwidth assigned to each sector, but not the distribution over the users:

$$\max_{\substack{\mathbf{w_{BS}} \\ s.t.\ \ \mathbf{w}_{BS} \succeq \mathbf{0}_{Nsx1}}} \left[\mu(i,k_i^*) w_{BS}(i) \log\left(1 + \rho\gamma \frac{\dfrac{SNR_u(i,k_i^*)}{1+SNR_{Iext}(i,k_i^*)}}{w_{BS}(i)} \right) \right] - \lambda w_{BS}(i) \qquad (4.70)$$

with λ associated to the relaxation $\sum_{i=1}^{Ns} w_{BS}(i) \leq 1$

We have selected the served users by considering the weighted capacity for a fixed value of the bandwidth assigned to each sector. We have assigned the total bandwidth of the system, W_T , so that $w_{BS}(i) = 1$:

$$k_i^* = \arg\max_k C^{(o)}(i,k) = \arg\max_k \left[\mu(i,k) \log\left(1 + \rho\gamma \frac{SNR_u(i,k)}{1+SNR_{Iext}(i,k)} \right) \right], i = 1,...,Ns \qquad (4.71)$$

4.4 On - off combinations

As we know, in the optimization problem we have considered two different phases: orthogonal and non-orthogonal. Each phase offers different combinations or possibilities regarding to the number of stations transmitting at the same time and the frequency overlapping between them. The aim of this subchapter is to describe and introduce in the global optimization problem some combinations which are not been considered in the mathematical approach. First, let's check what combinations are already defined:

4.4.1 Non-orthogonal phase

In the orthogonal phase there is only one possibility: all coordinated BSs transmit using the whole available bandwidth.

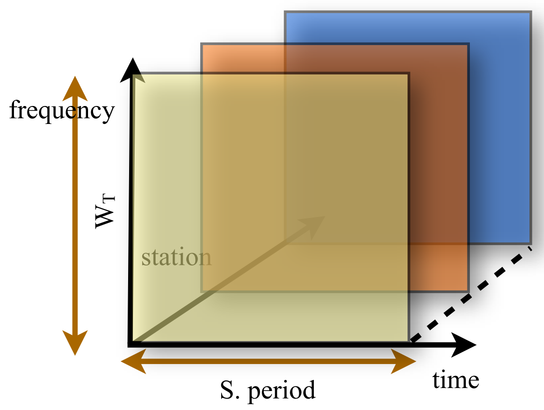

Figure 8. Non-orthogonal combination

4.4.2 Orthogonal phase

In this case, BSs transmit always orthogonally. However, we can have all of them transmitting or not, since the coordinated RRM could assign a zero bandwidth to one or more BSs, as we can see in figures 9 and 10:

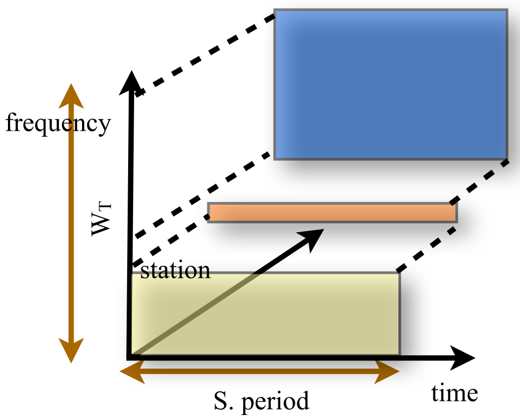

Figure 9. Orthogonal combination, all BSs transmitting

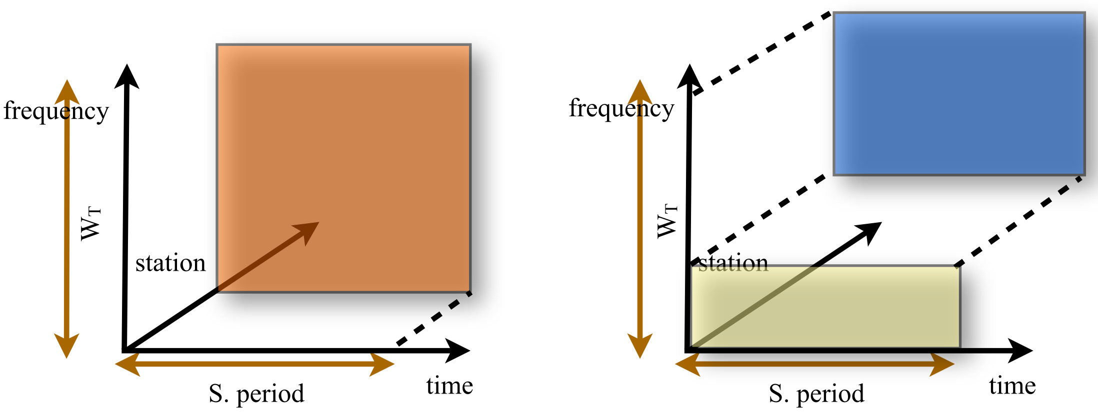

Figure 10. Orthogonal combination, some BSs transmitting.

4.4.2 Mixed combinations

Now let's present the new combinations:

<u>2 orthogonal/1 all bandwidth:</u>

One station transmit with the whole available bandwidth and the other two transmit in orthogonal sub-bands. We can see it in figure 11.

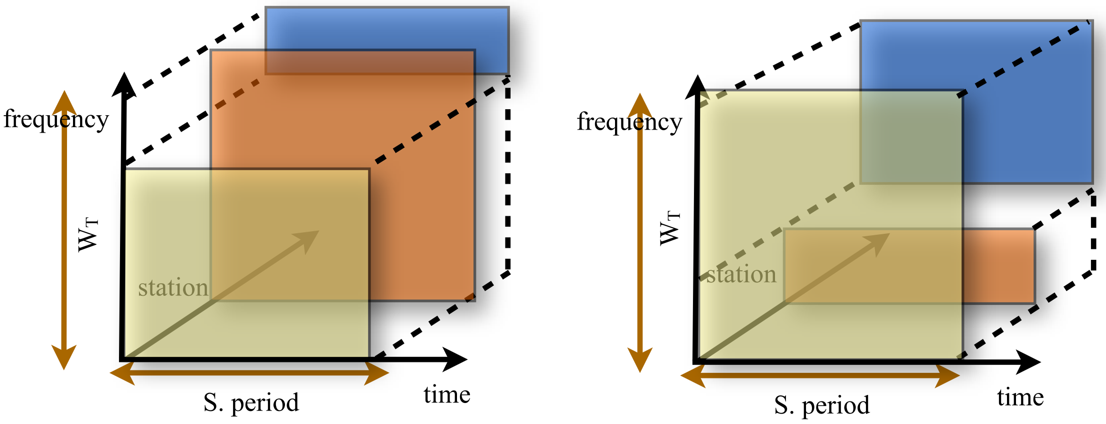

Figure 11. 2 orthogonal / 1 all bandwidth

<u>2 all bandwidth/1 off:</u>

Two stations transmit using the whole bandwidth and the other one is in off, as we can see in figure 12.

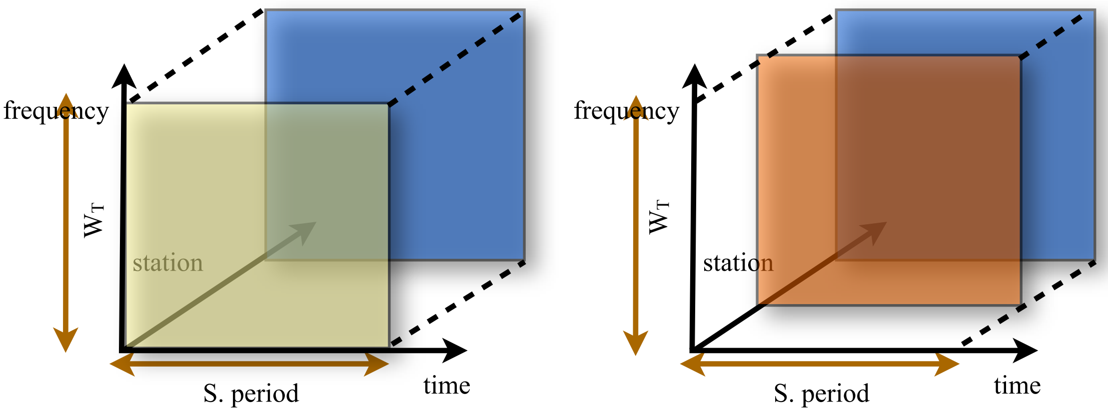

Figure 12. 2 all bandwidth / 1 off

4.5 Compatibility with fixed frequency patterns

The proposed techniques consist on allocating dynamically the resources, in time or frequency. We can combine them with fixed frequency reuses by assigning a static frequency pattern in the area, but then, resource allocation may be performed dynamically, according to the described techniques. In TDMA systems, users may be orthogonalized in time, independently of the frequency pattern. In OFDMA, the sub-band assigned statically to a coordinated area may be split into smaller ones, orthogonalizing in frequency users and sectors. Only one condition has to be fulfilled: coordinated sectors have to share the same frequency band, if not, there is no sense to coordinate them. To do this, fixed reuse 1/3/1 is always possible, since there is a unique frequency band for all sectors and cells. However, when using a fixed reuse 1/3, first of all, we have to find which configurations or frequency patterns[12] are possible to work with, thus, those which have spatial zones where the contiguous sectors have assigned the same sub-band. There are only two: reuse 3/3/1 and 1/3/3(2). When we use the reuse 3/3/1, we will apply an inner coordination (among sectors belonging to the same BS). In the other case, inner coordination is not possible, but we can apply the outer one (among sectors belonging to different BSs). We can see it in figures 13 and 14:

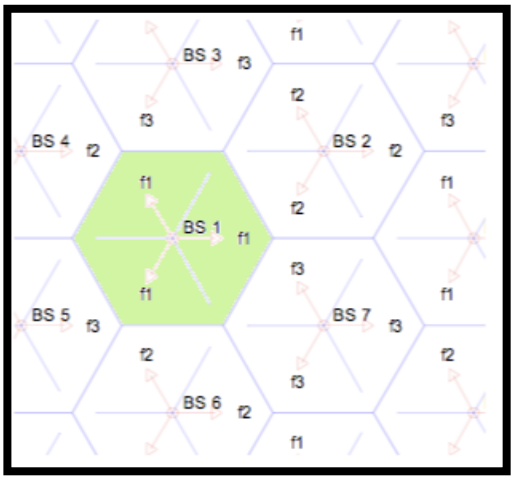

Figure 13. Inner coordination

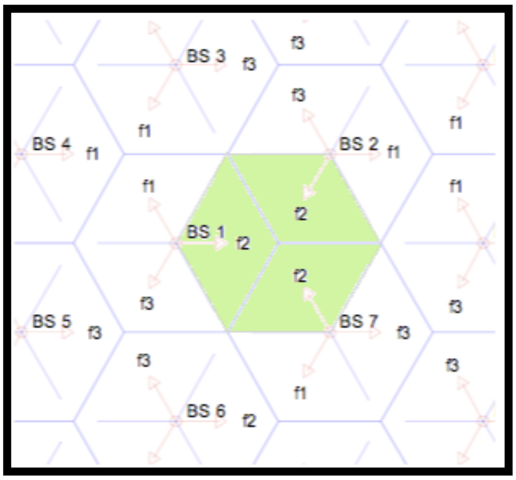

Figure 14. Outer coordination

[12] *See subchapter 7.5.*

In coordinated schemes over reuse 1/3, even if users and sectors are orthogonalized in time or frequency, the maximum transmission bandwidth will be a sub-band of the total one. In our case, since we have three sectors per cell, and we split equally the total bandwidth among them, transmission bandwidth is a third of the total bandwidth of the system.

In relation to the interference in reuses 1/3, it will come only from the sectors which use the same frequency sub-band, thus, what we define as I'_{int} and I'_{ext}[13], and all carriers will be transmitting a power increased by a N_s factor[14] (three in our case).

[13] *See subchapter 7.9.*

[14] *See section 7.8.1.*

5. RELAY ENHANCED TRANSMISSIONS WITH COORDINATION

5.1 Forwarding protocol

In this chapter, relay support is considered to enhance the coordinated radio resource management. We have implemented a “decode and forward” protocol, in which relays receive, decode the signals and then, they retransmit them. They don’t act as repeaters, which would also amplify interfering signals and noise. We will consider two hop transmissions, thus, only one relay between the base station and the mobile one.

For the forwarding protocol, the equivalent capacity for the two hops link is the minimum of C_1 and C_2, thus, the capacities of both hops respectively, considering the portion of time dedicated to each one (t_1 and t_2):

$$\begin{aligned} & C_{eq} = \min\{t_1 C_1, t_2 C_2\} \\ & s.t. \quad t_1, t_2 \in [0,1] \\ & \qquad C_1 \geq 0 \\ & \qquad C_2 \geq 0 \\ & \qquad t_1 + t_2 = 1 \end{aligned} \tag{5.1}$$

For a certain value of t_1 and t_2, this equivalent capacity can be optimized:

$$\begin{aligned} & \max_{t_1, t_2}\{\min\{t_1 C_1, t_2 C_2\}\} \\ & s.t. \quad t_1, t_2 \in [0,1] \\ & \qquad C_1 \geq 0 \\ & \qquad C_2 \geq 0 \\ & \qquad t_1 + t_2 = 1 \end{aligned} \tag{5.2}$$

The maximum is the intersection of these two lines:

$$t_1 C_1 = (1 - t_1) C_2 \tag{5.3}$$

Then, selecting the optimum values for t_1 and t_2, the equivalent capacity of this two hop system is:

$$C_{eq} = \max_{t_1, t_2} \{ \min \{ t_1 C_1, t_2 C_2 \} \} = \frac{C_1 C_2}{(C_1 + C_2)} \tag{5.4}$$

Let's see an example. Considering the following situations:

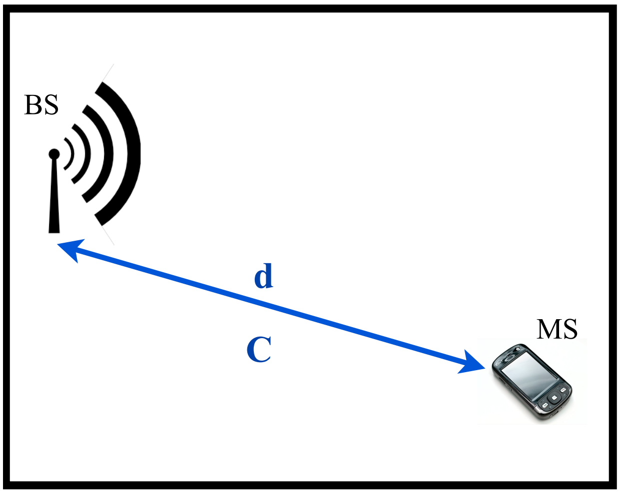

Figure 15. One hop link

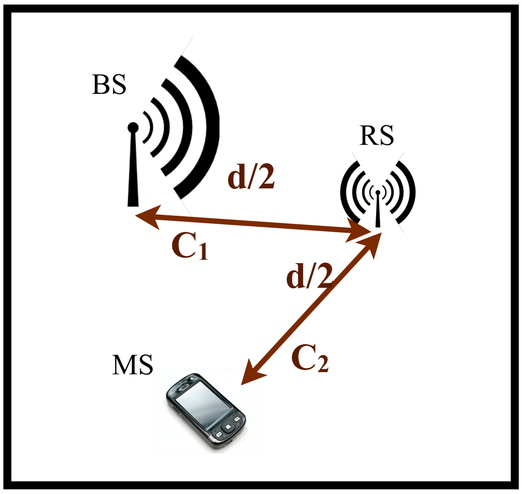

Figure 16. Two hop link

The capacity in figure 15 depends on distance *d*:

$$C = \log(1 + \beta d^{-\alpha}) \tag{5.5}$$

However, the capacities in figure 16 depend on the half of the distance (for simplicity, we have chosen the same constant β for all hops):

$$C_1 = C_2 = \log(1 + \beta \left(\frac{d}{2} \right)^{-\alpha}) \tag{5.6}$$

And the equivalent capacity for the transmission is:

$$C_{eq} = \frac{C_1 C_2}{(C_1 + C_2)} \quad (5.7)$$

Let's compare both capacities, in a graphical representation. Then, for $\beta = 10^3$, and a propagation constant of $\alpha = 2.5$, we have:

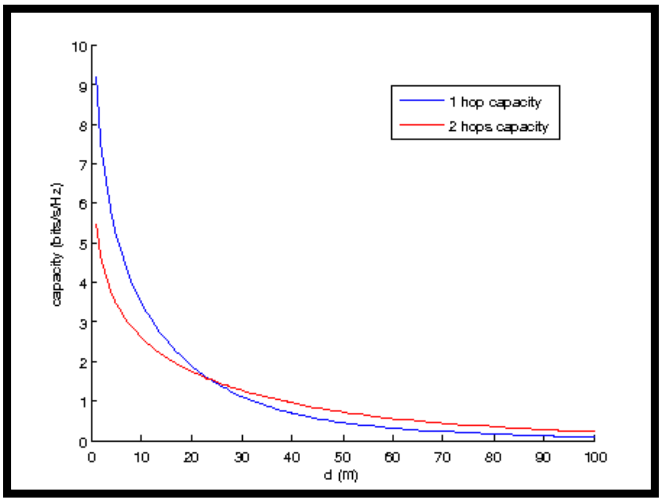

Figure 17. One hop capacity vs two hops capacity.

We see how for small distances, direct transmission is better than the other, but there is one point from which it is worth to transmit using a relay.

In our approach, we deploy two relays per sector to enhance the spatial coverage, but each user will select the relay with the best link in the second hop. Furthermore, only one relay per sector is considered during each scheduling period.

Relays are not shared, thus, they serve uniquely to the sector which they are assigned to. The position of the relays, distance and angle, proposed in [IEEE802.16m-08/004r3] are the 60% of the cell radius and 26 degrees with respect to the boresight of the sector antenna. We will also obtain the results for relay positions of 0 degrees, and we will also perform a sweep of values to find the optimal distance between the base station and them.

We suppose that relays are placed in such positions that the first hop is equal for the coordinated sectors, or have at least a very similar quality connection.

5.2 Resource allocation for OFDMA access in relay enhanced transmissions

5.2.1 Transmission strategy

In the following subchapter we are going to introduce the use of relays in the coordinated OFDMA resource allocation problem. We will follow similar steps and procedures than for TDMA and OFDMA approaches (subchapters 4.2 and 4.3). Once again, we propose to divide the scheduling period into two phases: an orthogonal part and a non-orthogonal one, with the difference that in this case, during each phase, transmissions may be carried out using the relays or without them (direct transmission).

In the orthogonal phase with relays, each sector is allocated a disjoint (not necessarily equal) fraction of the total bandwidth which is denoted as $w_{BS}(i)$. We use the same notation for it than in case of direct transmissions. Also for $W^{(o)}(i,k)$, which expresses the portion of the total bandwidth dedicated to each user. The duration of the first and second hop transmission may be different for each sector, and they are optimum. For the *i*-th sector, they are denoted as $t_i^{(1)}$ and $t_i^{(2)}$.

In the non-orthogonal phase with relays, all sector BSs transmit over the entire bandwidth. However, as the interference pattern is modified compared with direct transmissions, transmissions to/from RSs are allocated orthogonally in frequency in order to control the interference. This imposes some restrictions, as the fact that the duration of the first and second hop must be now equal for all the coordinated sectors. They are now denoted as $t^{(1)}$ and $t^{(2)}$. $W_1^{(f)}(i,k)$ and $W_2^{(f)}(i,k)$ stand for the portion of bandwidth dedicated to each user in the first and second hop, respectively, and $w_{BS}^{(f)}(i)$ is the fraction of the total bandwidth dedicated to each sector in the second hop (orthogonal).

For direct transmissions we maintain the notation for the portion of bandwidth dedicated to each sector ($w_{BS}(i)$) in the orthogonal phase, and to each user in the orthogonal ($W^{(o)}(i,k)$) and non-orthogonal phase ($W^{(f)}(i,k)$).

Figure 18 shows the frequency-time scheme for relay enhanced coordinated transmissions:

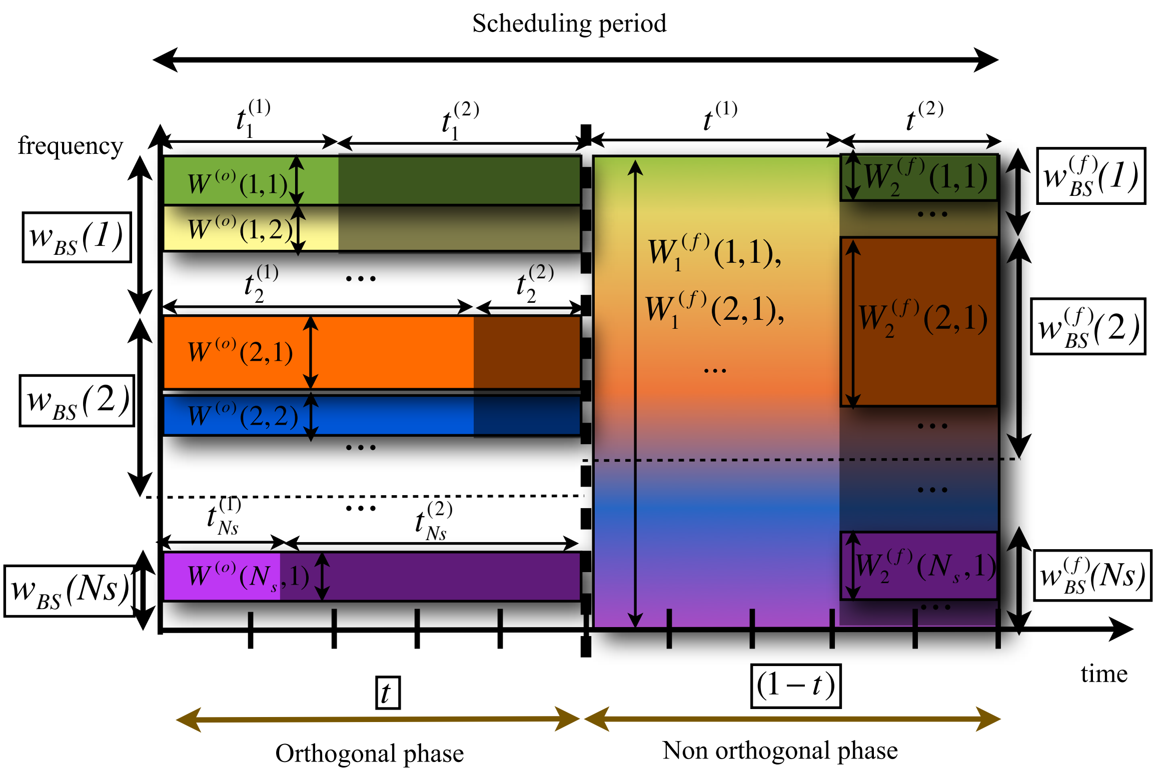

Figure 18. Frequency-time representation for OFDMA coordinated RRM with relays

The following scheme summarizes all the available transmission modes:

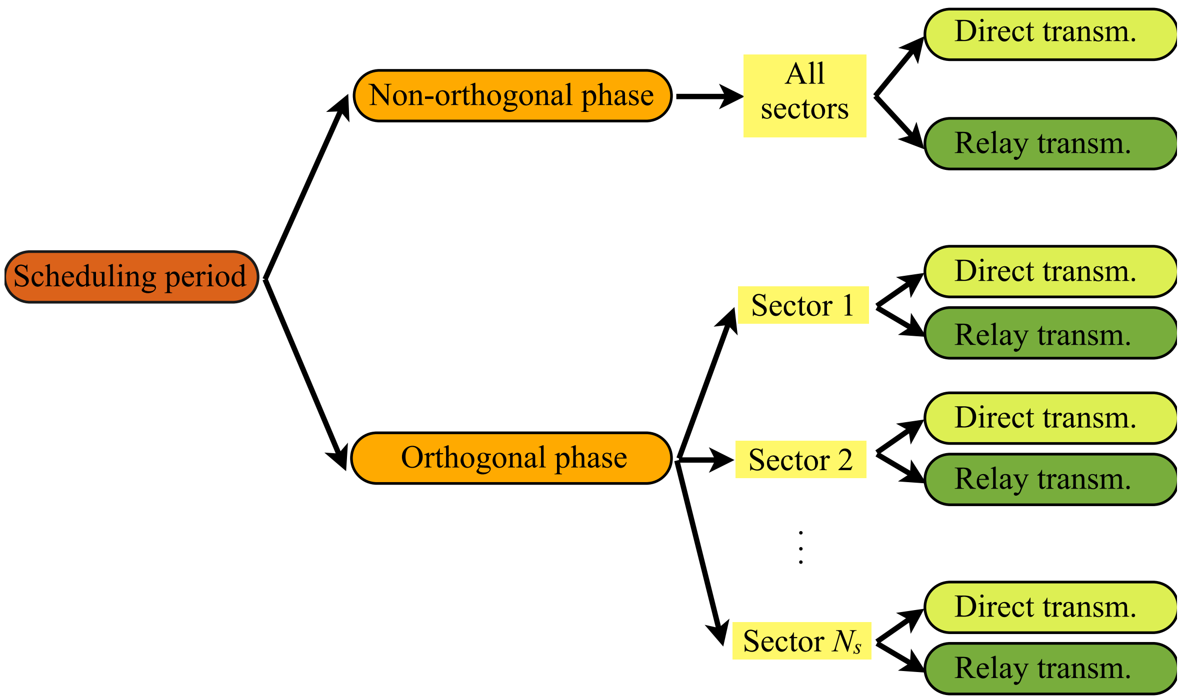

Figure 19. Scheme of available transmission modes

First of all, during each scheduling period we select only one phase: orthogonal or non-orthogonal; we select the one which provides a higher rate. If the non-orthogonal phase is selected, all sectors will transmit with relay or none of them will. We will choose the solution which offers a higher sum-rate in the coordinated area. However, if the orthogonal phase is adopted, each sector selects independently the transmission mode, basing the decision on the value of the capacity without relays and the capacity with them.

Now, let us describe the expressions for the capacity. Firstly, the non-orthogonal phase. The expression of the capacity for the transmission without relays (direct transmission) is:

$$C^{(f)}_{without\_relays}(i,k) = \log(1+\rho\gamma \frac{SNR_u(i,k)}{1+SNR_{Iint}(i,k)+SNR_{Iext}(i,k)}) =$$

$$= \log(1+\rho\gamma \frac{\frac{P_{BS}}{N_0 W_T L_i(i,k)}}{1+\sum_{j=1_{j\neq i}}^{Ncs} \frac{P_{BS}}{N_0 W_T L_j(i,k)} + \sum_{m=1}^{Nncs} \frac{P_{BS}}{N_0 W_T L_m(i,k)}}) \tag{5.8}$$

In the case of the transmission with relays, there are two capacities to consider:

Capacity for the first hop:

$$C^{(f)}_1(i) = \log(1+\rho\gamma \frac{SNR_{base-relay}(i)}{1+SNR_{I_{int\text{-}relay}}(i)+SNR_{I_{ext-relay}}(i)}) =$$

$$= \log(1+\rho\gamma \frac{\frac{P_{BS}}{N_0 W_T L^{br}_i(i)}}{1+\sum_{\substack{j=1\\ j\neq i}}^{Ncs} \frac{P_{BS}}{N_0 W_T L^{br}_j(i)} + \sum_{m=1}^{Nncs} \frac{P_{BS}}{N_0 W_T L^{br}_m(i)}}) \tag{5.9}$$

Capacity for the second hop:

$$C_2^{(f)}(i,k) = \log\left(1+\rho\gamma\frac{SNR_{relay-user}(i,k)}{1+SNR_{I_{ext-user}}(i,k)}\right) =$$

$$= \log\left(1+\rho\gamma\frac{\frac{P_{RS}}{N_0 w_{BS}^{(f)}(i)W_T L_i^{ru}(i,k)}}{1+\sum_{m=1}^{Nncs}\frac{P_{BS}}{N_0 W_T L_m(i,k)}}\right) \tag{5.10}$$

Let us remember the equivalent capacity for the two hop transmissions.

$$C_{with-relays}^{(f)}(i,k) = \min\left\{t^{(1)}C_1^{(f)}(i,k), t^{(2)}C_2^{(f)}(i,k)\right\} \tag{5.11}$$

The capacity for the orthogonal phase and direct transmission is:

$$C_{without\_relays}^{(o)}(i,k) = \log\left(1+\rho\gamma\frac{\frac{SNR_u}{1+SNR_{Iext}}}{w_{BS}(i)}\right) = \log\left(1+\rho\gamma\frac{\frac{P_{BS}}{N_0 w_{BS}(i)W_T L_i(i,k)}}{1+\sum_{m=1}^{Nncs}\frac{P_{BS}}{N_0 W_T L_m(i,k)}}\right) \tag{5.12}$$

The capacities for the orthogonal phase and transmission with relays are:

$$C_1^{(o)}(i) = \log\left(1+\rho\gamma\frac{\frac{SNR_{base-relay}(i)}{w_{BS}(i)}}{1+SNR_{I_{ext-relay}}(i)}\right) =$$

$$= \log\left(1+\rho\gamma\frac{\frac{P_{BS}}{N_0 w_{BS}(i)W_T L_i^{br}(i)}}{1+\sum_{m=1}^{Nncs}\frac{P_{BS}}{N_0 W_T L_m^{br}(i)}}\right) \tag{5.13}$$

$$C_2^{(o)}(i,k) = \log\left(1 + \rho\gamma \frac{\frac{SNR_{relay-user}(i,k)}{w_{BS}(i)}}{1 + SNR_{I_{ext-user}}(i,k)}\right) =$$

$$= \log\left(1 + \rho\gamma \frac{\frac{P_{RS}}{N_0 w_{BS}(i) W_T L_i^{ru}(i,k)}}{1 + \sum_{m=1}^{Nncs} \frac{P_{BS}}{N_0 W_T L_m(i,k)}}\right) \tag{5.14}$$

Finding the optimum values for $t_i^{(1)}$ and $t_i^{(2)}$, the maximum equivalent capacity is:

$$C_{with\_relays}^{(o)} = \frac{C_1^{(o)} C_2^{(o)}}{(C_1^{(o)} + C_2^{(o)})} \tag{5.15}$$

5.2.2 Maximizing the sum-rate

The global problem, considering orthogonal and non-orthogonal phase and transmission with relays and without them is:

$$\max_{\substack{\mathbf{W_1},\mathbf{W_2},\mathbf{w_{BS}},t,\\ t^{(1)},t^{(2)},\\ t_i^{(1)},t_i^{(2)}}} \left(\begin{array}{c} t\sum_{i=1}^{Ns}\sum_{k=1}^{K} W^{(o)}(i,k)\max\left\{C^{(o)}_{with\_relays}(i,k), C^{(o)}_{without\_relays}(i,k)\right\} + \\ (1-t)\max\left\{\sum_{i=1}^{Ns}\sum_{k=1}^{K}\min\left\{t^{(1)}W_1^{(f)}(i,k)C_1^{(f)}(i), t^{(2)}W_2^{(f)}(i,k)C_2^{(f)}(i,k)\right\}, \sum_{i=1}^{Ns}\sum_{k=1}^{K} W^{(f)}(i,k)C^{(f)}_{without\_relays}(i,k)\right\} \end{array} \right) \tag{5.16}$$

$$\begin{array}{ll} s.t. & \mathbf{W}^{(o)} \succeq \mathbf{0}_{NsxK}, \mathbf{W}^{(f)} \succeq 0_{NsxK}, \mathbf{w}_{BS} \succeq \mathbf{0}_{Nsx1}, \mathbf{w}_{BS}^{(f)} \succeq \mathbf{0}_{Nsx1} \\ & \mathbf{W}_1^{(f)} \succeq 0_{NsxK}, \mathbf{W}_2^{(f)} \succeq 0_{NsxK} \\ & 0 \le t \le 1, t_i^{(1)} \ge 0, t_i^{(2)} \ge 0, t^{(1)} \ge 0, t^{(2)} \ge 0 \\ & \mathbf{W}^{(o)}\mathbf{1}_{Kx1} - \mathbf{w}_{BS} \le \mathbf{0}_{Nsx1} \\ & \mathbf{1}_{1xNs}\mathbf{w}_{BS} - 1 \le 0 \\ & \mathbf{1}_{1xNs}\mathbf{w}_{BS}^{(f)} - 1 \le 0 \\ & \mathbf{W}^{(f)}\mathbf{1}_{Kx1} - \mathbf{1}_{Nsx1} \le \mathbf{0}_{Nsx1} \\ & \mathbf{W}_1^{(f)}\mathbf{1}_{Kx1} - \mathbf{1}_{Nsx1} \le \mathbf{0}_{Nsx1} \\ & \mathbf{W}_2^{(f)}\mathbf{1}_{Kx1} - \mathbf{w}_{BS}^{(f)} \le \mathbf{0}_{Nsx1} \\ & t^{(1)} + t^{(2)} + t - 1 = 0 \\ & t_i^{(1)} + t_i^{(2)} + t = 0 \end{array} \tag{5.17}$$

We can differentiate the orthogonal phase and the non-orthogonal one by means of the variable *t*. As we did in chapter 4.3, expression *(4.34)* we can apply the primal decomposition and separate them as two independent problems, maximize each one of them, and finally transmit with the one which offers a higher sum-rate in the coordinated area.

Let us start by the non-orthogonal phase. Since we have imposed the condition that all coordinated sectors have to use the same scheme (with or without relays) the maximization in this zone is relatively easy, by defining the following variable:

$$R^{(f)} = \max\left\{R^{(f)}_{with-relays}, R^{(f)}_{without-relays}\right\} \tag{5.18}$$

The optimization of the direct transmission ($R^{(f)}_{without-relays}$) has been described in chapter 4.3 *(4.35 - 4.39)*. Now, let's detail the one for the transmission with relays, which is quite more complex.

The sum-rate for the non-orthogonal phase with relays is:

$$R^{(f)}_{with-relays} = \sum_{i=1}^{Ns}\sum_{k=1}^{K}\min\left\{t^{(1)}W_1^{(f)}(i,k)C_1^{(f)}(i), t^{(2)}W_2^{(f)}(i,k)C_2^{(f)}(i,k)\right\} \quad (5.19)$$

It is the minimum capacity among first and second hop. Then, the maximization problem becomes:

$$\max_{\mathbf{W}_1^{(f)},\mathbf{W}_2^{(f)},\mathbf{w}_{\mathbf{BS}}^{(f)},t^{(1)},t^{(2)}}\left[\sum_{i=1}^{Ns}\sum_{k=1}^{K}\min\left\{t^{(1)}W_1^{(f)}(i,k)C_1^{(f)}(i), t^{(2)}W_2^{(f)}(i,k)C_2^{(f)}(i,k)\right\}\right] \quad (5.20)$$

$$\begin{aligned} s.t. \quad & \mathbf{W}_1^{(f)} \succeq 0_{NsxK}, \mathbf{W}_2^{(f)} \succeq 0_{NsxK}, \mathbf{w}_{BS}^{(f)} \succeq \mathbf{0}_{Nsx1} \\ & t_a \geq 0, t_b \geq 0, t^{(1)} \geq 0, t^{(2)} \geq 0 \\ & \mathbf{W}_1^{(f)}\mathbf{1}_{Kx1} - \mathbf{1}_{Nsx1} \leq \mathbf{0}_{Nsx1} \\ & \mathbf{W}_2^{(f)}\mathbf{1}_{Kx1} - \mathbf{w}_{BS}^{(f)} \leq \mathbf{0}_{Nsx1} \\ & \mathbf{1}_{1xNs}\mathbf{w}_{BS}^{(f)} - 1 \leq 0 \\ & t^{(1)} + t^{(2)} + t - 1 = 0 \end{aligned} \quad (5.21)$$

We can upper-bound this expression:

$$\begin{aligned} & \sum_{i=1}^{Ns}\sum_{k=1}^{K}\min\left\{t^{(1)}W_1^{(f)}(i,k)C_1^{(f)}(i), t^{(2)}W_2^{(f)}(i,k)C_2^{(f)}(i,k)\right\} \leq \\ & \sum_{i=1}^{Ns}\min\left\{t^{(1)}\sum_{k=1}^{K}W_1^{(f)}(i,k)C_1^{(f)}(i), t^{(2)}\sum_{k=1}^{K}W_2^{(f)}(i,k)C_2^{(f)}(i,k)\right\} \end{aligned} \quad (5.22)$$

And we can apply the bandwidth constraint in the non-orthogonal first hop ($\mathbf{W}_1^{(f)}\mathbf{1}_{\mathbf{Kx1}} - \mathbf{1}_{\mathbf{Kx1}} \leq 0_{Nsx1}$), supposing that the capacity in the first hop, already defined, is the same for all users. It is a feasible supposition, because relays are placed in such a way that capacities between the base station and the relays stations are, at least, similar.

Then:

$$\sum_{i=1}^{Ns}\min\left\{t^{(1)}\sum_{k=1}^{K}W_1^{(f)}(i,k)C_1^{(f)}(i),t^{(2)}\sum_{k=1}^{K}W_2^{(f)}(i,k)C_2^{(f)}(i,k)\right\}\leq\sum_{i=1}^{Ns}\min\left\{t^{(1)}C_1^{(f)}(i),t^{(2)}\sum_{k=1}^{K}W_2^{(f)}(i,k)C_2^{(f)}(i,k)\right\}=$$

$$\sum_{i=1}^{Ns}\min\left\{t^{(1)}C_1^{(f)}(i),t^{(2)}\sum_{k=1}^{K}W_2^{(f)}(i,k)\log\left(1+\rho\gamma\frac{\dfrac{SNR_{relay-user}(i,k)}{1+SNR_{I_{ext-user}}(i,k)}}{w_{BS}^{(f)}(i)}\right)\right\}$$

(5.23)

Now, we can find the best user in each sector:

$$k_i^*=\arg\max_k C_2^{(f)}(i,k)=\arg\max_k\left[\log\left(1+\rho\gamma\frac{\dfrac{SNR_{relay-user}(i,k)}{1+SNR_{Iext-user}(i,k)}}{w_{BS}^{(f)}(i)}\right)\right],i=1,...,Ns \quad (5.24)$$

Which coincides with the user who has the highest SINR:

$$k_i^*=\arg\max_k\left[\frac{SNR_{relay-user}(i,k)}{1+SNR_{Iext-user}(i,k)}\right],i=1,...,Ns \quad (5.25)$$

Now, let us denote the SNRs of this user as:

$$\begin{aligned}SNR_{relay-user}(i)&=SNR_{relay-user}(i,k_i^*)\\SNR_{Iext-user}(i)&=SNR_{Iext-user}(i,k_i^*)\end{aligned} \quad (5.26)$$

We can upper-bound again the expression *(5.23)*:

$$
\begin{aligned}
&\sum_{i=1}^{Ns}\min\left\{t^{(1)}C_1^{(f)}(i),t^{(2)}\sum_{k=1}^{K}W_2^{(f)}(i,k)\mathrm{og}\left(1+\rho\gamma\frac{\frac{SNR_{relay-user}(i,k)}{1+SNR_{I_{ext-user}}(i,k)}}{w_{BS}^{(f)}(i)}\right)\right\}\leq \\
&\sum_{i=1}^{Ns}\min\left\{t^{(1)}C_1^{(f)}(i),t^{(2)}\sum_{k=1}^{K}W_2^{(f)}(i,k)\log\left(1+\rho\gamma\frac{\frac{SNR_{relay-user}(i)}{1+SNR_{I_{ext-user}}(i)}}{w_{BS}^{(f)}(i)}\right)\right\}\overset{(a)}{=} \\
&\sum_{i=1}^{Ns}\min\left\{t^{(1)}C_1^{(f)}(i),t^{(2)}w_{BS}^{(f)}(i)\log\left(1+\rho\gamma\frac{\frac{SNR_{relay-user}(i)}{1+SNR_{I_{ext-user}}(i)}}{w_{BS}^{(f)}(i)}\right)\right\}
\end{aligned}
\qquad (5.27)
$$

The equality *(a)* is reached by applying the constraint $\mathbf{W}_2^{(f)}\mathbf{1}_{Kx1}-\mathbf{w}_{BS}^{(f)}\leq 0$, allocating the whole available bandwidth to the best user in the sector, thus, who has the highest SINR. Remember that each coordinated sector only has available a portion of the total bandwidth, which has been split optimally among them.

$$
\begin{gathered}
W_2^{(f)}(i,k_i^*)=w_{BS}^{(f)}(i) \\
W_2^{(f)}(i,k)=0
\end{gathered}
\qquad (5.28)
$$

for k different from k_i^*.

Now, we only have to solve this convex problem[15]:

$$\max_{\mathbf{w}_{\mathbf{BS}}^{(f)},t^{(1)},t^{(2)}} \left[\sum_{i=1}^{Ns} \min\left\{ t^{(1)}C_1^{(f)}(i), t^{(2)}w_{BS}^{(f)}(i)\log\left(1+\rho\gamma\frac{\frac{SNR_{relay-user}(i)}{1+SNR_{I_{ext-user}}(i)}}{w_{BS}^{(f)}(i)}\right)\right\}\right] \qquad (5.29)$$

$$\begin{aligned} s.t. \quad & \mathbf{w}_{BS}^{(f)} \succeq \mathbf{0}_{Nsx1}, t^{(1)} \geq 0, t^{(2)} \geq 0 \\ & \mathbf{1}_{1xNs}\mathbf{w}_{BS}^{(f)} - 1 \leq 0 \\ & t^{(1)} + t^{(2)} + t - 1 = 0 \end{aligned} \qquad (5.30)$$

The final sum-rate will be:

$$R^{(f)} = \max\left\{R_{with-relays}^{(f)}, R_{without-relays}^{(f)}\right\} \qquad (5.31)$$

where:

$R_{with\_relays}^{(f)}$ is expressed in *(5.29)* with the constraints *(5.30)*, and $R_{without\_relays}^{(f)}$:

$$R_{without\_relays}^{(f)} = \sum_{i=1}^{Ns} C_{without\_relays}^{(f)}(i,k_i^*) \qquad (5.32)$$

with:

$$k_i^* = \arg\max_k \left\{C_{without\_relays}^{(f)}(i,k)\right\}, i = 1,...,Ns \qquad (5.33)$$

[15] *The sum and the minimum of convex functions is also convex.*

Now we can upper-bound the global objective function as:

$$t\sum_{i=1}^{Ns}\sum_{k=1}^{K}W^{(o)}(i,k)\max\left\{C_{with\_relays}^{(o)}(i,k),C_{without\_relays}^{(o)}(i,k)\right\}+$$
$$+(1-t)\max\left\{\sum_{i=1}^{Ns}\sum_{k=1}^{K}\min\left\{t^{(1)}W_1^{(f)}(i,k)C_1^{(f)}(i),t^{(2)}W_2^{(f)}(i,k)C_2^{(f)}(i,k)\right\},\sum_{i=1}^{Ns}\sum_{k=1}^{K}W^{(f)}(i,k)C_{without\_relays}^{(f)}(i,k)\right\}\leq$$
$$\leq\left(t\sum_{i=1}^{Ns}\sum_{k=1}^{K}W^{(o)}(i,k)\max\left\{C_{with\_relays}^{(o)}(i,k),C_{without\_relays}^{(o)}(i,k)\right\}+(1-t)R^{(f)}\right)$$

(5.34)

Going back to the global problem, divided into two sub-problems, now we focus on the orthogonal phase:

$$\max_{\substack{t\\ s.t.\ \ 0\leq t\leq 1}}\left[t\max_{\substack{\mathbf{W}^{(o)},\mathbf{w_{BS}}\\ s.t.\ \ \mathbf{W}^{(o)}\succeq\mathbf{0}_{NsxK}\\ \mathbf{w}_{BS}\succeq\mathbf{0}_{Nsx1}\\ \mathbf{W}^{(o)}\mathbf{1}_{Kx1}-\mathbf{w}_{BS}\leq\mathbf{0}_{Nsx1}\\ \mathbf{1}_{1xNs}\mathbf{w}_{BS}-1\leq 0}}\left[\sum_{i=1}^{Ns}\sum_{k=1}^{K}W^{(o)}(i,k)\max\left\{C_{with\_relays}^{(o)}(i,k),C_{without\_relays}^{(o)}(i,k)\right\}\right]+(1-t)R^{(f)}\right]$$

(5.35)

We propose the following maximization sub-problem:

$$\max_{\mathbf{W}^{(o)},\mathbf{w_{BS}}}\left[\sum_{i=1}^{Ns}\sum_{k=1}^{K}W^{(o)}(i,k)\max\left\{C_{with\_relays}^{(o)}(i,k),C_{without\_relays}^{(o)}(i,k)\right\}\right]$$

$$\begin{aligned}s.t.\quad &\mathbf{W}^{(o)}\succeq\mathbf{0}_{NsxK}\\ &\mathbf{w}_{BS}\succeq\mathbf{0}_{Nsx1}\\ &\mathbf{W}^{(o)}\mathbf{1}_{Kx1}-\mathbf{w}_{BS}\leq\mathbf{0}_{Nsx1}\\ &\mathbf{1}_{1xNs}\mathbf{w}_{BS}-1\leq 0\end{aligned}\qquad (5.36)$$

We can't find the maximum between the capacity with relays and without them directly because they depend on the assigned bandwidth[16], which is actually an optimization variable. We have to deal with the whole maximization problem *(5.36)*.

We could think on applying the dual decomposition method and simplify the problem through the bandwidth relaxation $1_{1xNs}\mathbf{w}_{BS}-1\le 0$. However, in this case, this procedure can't assure us to find an global optimal solution for the problem because the objective function is not convex, since the maximum of two convex functions[17] is not a convex one.

Trying to solve this matter, we have implemented a second option: a simplification of the problem in which we select the transmission scheme a priori. Of course we maintain the independence of the sectors in the choice, so that there can be users inside the coordinate area using different schemes.

The assumption we can consider to do the choice is that for all the possible values of the assigned bandwidth, the capacity with relays is always greater or always lower than the capacity of direct transmission. Thus, it let us choose the transmission scheme with the highest value of capacity computed for a random value of bandwidth. We have found experimentally that it is a good consideration for many cases. Of course we could be not choosing correctly in some cases, but we are talking about a sub-optimal or approximative method.

Once selected the best transmission scheme for each user of the coordinate area, we can define the following capacity:

$$C^{(o)}(i,k)=\max\left\{C^{(o)}_{with\_relays}(i,k),C^{(o)}_{without\_relays}(i,k)\right\} \tag{5.37}$$

where the capacity is evaluated with a random value for the assigned bandwidth. Then, we upper-bound the rate in the coordinated area:

$$\begin{aligned} R^{(o)} &= \sum_{i=1}^{Ns}\sum_{k=1}^{K}W^{(o)}(i,k)C^{(o)}(i,k) \le \sum_{i=1}^{Ns}\sum_{k=1}^{K}W^{(o)}(i,k)C^{(o)}(i) \\ &= \sum_{i=1}^{Ns}\left(\sum_{k=1}^{K}W^{(o)}(i,k)\right)C^{(o)}(i) = \sum_{i=1}^{Ns}w_{BS}(i)C^{(o)}(i) \end{aligned} \tag{5.38}$$

---

[16] *If bandwidth was split fixedly without optimization, the maximum of these capacities could be computed directly for each user. That is the case for orthogonal fixed reuses (considered in the results).*

[17] *The maximum of two convex functions is not a convex one, whereas the minimum is.*

where:

$$C^{(o)}(i) = \max_{k}\left[C^{(o)}(i,k)\right] \tag{5.39}$$

And the equality is reached by serving only the best user in each sector:

$$\begin{aligned} W^{(o)}(i,k_i^*) &= w_{BS}(i) \\ W^{(o)}(i,k) &= 0 \end{aligned} \tag{5.40}$$

for k different from $k_i^* = \arg\max_{k} C^{(o)}(i,k)$

Then the optimization convex[18] sub-problem becomes:

$$\max_{w_{BS}}\left[\sum_{i=1}^{Ns} w_{BS}(i) C^{(o)}(i)\right] \tag{5.41}$$

$$\begin{aligned} s.t. \quad & \mathbf{w}_{BS} \succeq \mathbf{0}_{Nsx1} \\ & \mathbf{1}_{1xNs}\mathbf{w}_{BS} - 1 \leq 0 \\ & i=1,\ldots,Ns \end{aligned} \tag{5.42}$$

However, the experimental results have shown that this is a very conservative method, and we obtain higher rates by directly applying the dual decomposition method to the double maximization problem *(5.36)*, even if we are trying to maximize a non convex function and maybe reaching a local maximum.

---

[18] The problem is convex on the w_{BS} variable because the capacity $C^{(o)}$ is also convex on it. It has be shown that the capacity without relays is convex. The capacity with relays is also convex, since it is the minimum of two convex expressions.

In this case, the optimization problem is:

$$\begin{aligned}
&\max_{\mathbf{W}^{(o)},\mathbf{w}_{\mathbf{BS}}}\left[\sum_{i=1}^{Ns}\sum_{k=1}^{K}W^{(o)}(i,k)\max\left\{C^{(o)}_{with_relays}(i,k),C^{(o)}_{without_relays}(i,k)\right\}\right]\\
&\quad s.t.\quad \mathbf{W}^{(o)}\succeq\mathbf{0}_{NsxK}\\
&\qquad\quad \mathbf{w}_{BS}\succeq\mathbf{0}_{Nsx1}\\
&\qquad\quad \mathbf{W}^{(o)}\mathbf{1}_{Kx1}-\mathbf{w}_{BS}\leq\mathbf{0}_{Nsx1}\\
&\qquad\quad \mathbf{1}_{1xNs}\mathbf{w}_{BS}-1\leq 0
\end{aligned} \tag{5.43}$$

We apply the dual decomposition method to this expression, and divide the global problem into N_s sub-problems, one by each sector. The relaxation associated to the Lagrange multiplier (λ) will be $\sum_{i=1}^{Ns}w_{BS}(i)\leq 1$. The new decoupled sub-problem is:

$$\begin{aligned}
&\max_{\mathbf{W}^{(o)},\mathbf{w}_{\mathbf{BS}}}\left[\sum_{k=1}^{K}W^{(o)}(i,k)\max\left\{C^{(o)}_{with_relays}(i,k),C^{(o)}_{without_relays}(i,k)\right\}\right]-\lambda w_{BS}(i)\\
&\quad s.t.\quad \mathbf{W}^{(o)}\succeq\mathbf{0}_{NsxK}\\
&\qquad\quad \mathbf{w}_{BS}\succeq\mathbf{0}_{Nsx1}\\
&\qquad\quad \mathbf{W}^{(o)}\mathbf{1}_{Kx1}-\mathbf{w}_{BS}\leq\mathbf{0}_{Nsx1}\\
&\qquad\quad \mathbf{1}_{1xNs}\mathbf{w}_{BS}-1\leq 0
\end{aligned} \tag{5.44}$$

We can simplify it by selecting the best user in each sector since:

$$\begin{aligned}
&\sum_{k=1}^{K}W^{(o)}(i,k)\max\left\{C^{(o)}_{with_relays}(i,k),C^{(o)}_{without_relays}(i,k)\right\}\leq\\
&\leq\sum_{k=1}^{K}W^{(o)}(i,k)\max\left\{C^{(o)}_{with_relays}(i,k_i^{1*}),C^{(o)}_{without_relays}(i,k_i^{2*})\right\}
\end{aligned} \tag{5.45}$$

where:

$$k_i^{1*}=\arg\max_k C^{(o)}_{with\_relays}(i,k),\quad i=1,\ldots,Ns \tag{5.46}$$

$$k_i^{2*}=\arg\max_k C^{(o)}_{without\_relays}(i,k),\quad i=1,\ldots,Ns \tag{5.47}$$

We can find the user who maximizes each capacity independently of the bandwidth because it is common for all users in the sector.

The equality in *(5.45)* can be reached by only serving the user k_i^{1*} or k_i^{2*} in each sector. The selection will be done in the global maximization problem:

$$\max_{\mathbf{W}^{(o)},\mathbf{w}_{\mathbf{BS}}} \left[\sum_{k=1}^{K} W^{(o)}(i,k) \max\left\{ C_{with\_relays}^{(o)}(i,k_i^{1*}), C_{without\_relays}^{(o)}(i,k_i^{2*}) \right\} \right] - \lambda w_{BS}(i)$$

$$\begin{aligned} s.t. \quad & \mathbf{W}^{(o)} \succeq \mathbf{0}_{NsxK} \\ & \mathbf{w}_{BS} \succeq \mathbf{0}_{Nsx1} \\ & \mathbf{W}^{(o)} \mathbf{1}_{Kx1} - \mathbf{w}_{BS} \le \mathbf{0}_{Nsx1} \\ & \mathbf{1}_{1xNs} \mathbf{w}_{BS} - 1 \le 0 \end{aligned} \qquad (5.48)$$

Which becomes still simple:

$$\max_{\mathbf{w}_{\mathbf{BS}}} \left[w_{BS}(i) \max\left\{ C_{with\_relays}^{(o)}(i,k_i^{1*}), C_{without\_relays}^{(o)}(i,k_i^{2*}) \right\} \right] - \lambda w_{BS}(i) \qquad (5.49)$$

$$\begin{aligned} s.t. \quad & \mathbf{w}_{BS} \succeq \mathbf{0}_{Nsx1} \\ & \mathbf{1}_{1xNs} \mathbf{w}_{BS} - 1 \le 0 \end{aligned} \qquad (5.50)$$

The last step to finish the global maximization problem is to maximize over *t*, thus, selecting the orthogonal zone or the non orthogonal one:

$$R = \max_t \left[tR^{(o)} + (1-t) R^{(f)} \right] \qquad (5.51)$$

$$s.t. \quad 0 \le t \le 1 \qquad (5.52)$$

As we have seen in subchapters 4.2 and 4.3:

$$tR^{(o)} + (1-t)R^{(f)} \le t \max(R^{(o)}, R^{(f)}) + (1-t)\max(R^{(o)}, R^{(f)}) \qquad (5.53)$$

Finally,

$$R = t\max(R^{(o)}, R^{(f)}) + (1-t)\max(R^{(o)}, R^{(f)}) = \max(R^{(o)}, R^{(f)}) \tag{5.54}$$

This maximum is achieved choosing only one zone for each scheduling period.

5.2.3 Proportional fair

We detailed the solution for the direct transmission in subchapter 4.3, section 4.3.3. Now, let's comment the relay based one. The objective is to maximize the weighted sum-rate. Let us start by the non-orthogonal zone:

$$\max_{\mathbf{W}_1^{(f)}, \mathbf{W}_2^{(f)}, \mathbf{w}_{\mathbf{BS}}^{(f)}, t^{(1)}, t^{(2)}} \left[\sum_{i=1}^{Ns} \sum_{k=1}^{K} \min\left\{ t^{(1)} W_1^{(f)}(i,k) C_1^{(f)}(i), t^{(2)} W_2^{(f)}(i,k) \mu(i,k) C_2^{(f)}(i,k) \right\} \right] \tag{5.55}$$

$$\begin{aligned} s.t. \quad & \mathbf{W}_1^{(f)} \succeq 0_{NsxK}, \mathbf{W}_2^{(f)} \succeq 0_{NsxK}, \mathbf{w}_{BS}^{(f)} \succeq \mathbf{0}_{Nsx1}, t^{(1)} \geq 0, t^{(2)} \geq 0 \\ & \mathbf{W}_1^{(f)} \mathbf{1}_{Kx1} - \mathbf{1}_{Nsx1} \leq \mathbf{0}_{Nsx1} \\ & \mathbf{W}_2^{(f)} \mathbf{1}_{Kx1} - \mathbf{w}_{BS}^{(f)} \leq \mathbf{0}_{Nsx1} \\ & \mathbf{1}_{1xNs} \mathbf{w}_{BS}^{(f)} - 1 \leq 0 \\ & t^{(1)} + t^{(2)} + t - 1 = 0 \end{aligned} \tag{5.56}$$

We can proceed in the same way than for the rate maximization *(5.20 - 5.23)*, and we arrive to this convex problem:

$$\max_{\mathbf{W}_2^{(f)},\mathbf{w}_{\mathbf{BS}}^{(f)},t^{(1)},t^{(2)}}\left[\sum_{i=1}^{Ns}\min\left\{t^{(1)}C_1^{(f)}(i),t^{(2)}\sum_{k=1}^{K}\mu(i,k)W_2^{(f)}(i,k)\log\left(1+\rho\gamma\frac{\frac{SNR_{relay-user}(i,k)}{1+SNR_{I_{ext-user}}(i,k)}}{w_{BS}^{(f)}(i)}\right)\right\}\right] \tag{5.57}$$

$$\begin{aligned} s.t. \quad & \mathbf{W}_2^{(f)}\succeq 0_{NsxK},\ \mathbf{w}_{BS}^{(f)}\succeq\mathbf{0}_{Nsx1},\ t^{(1)}\geq 0, t^{(2)}\geq 0 \\ & \mathbf{W}_2^{(f)}\mathbf{1}_{Kx1}-\mathbf{w}_{BS}^{(f)}\leq\mathbf{0}_{Nsx1} \\ & \mathbf{1}_{1xNs}\mathbf{w}_{BS}^{(f)}-1\leq 0 \\ & t^{(1)}+t^{(2)}+t-1=0 \end{aligned} \tag{5.58}$$

Now we could make a change of variable as in *(4.66 - 4.68)* or apply the same simplification by preselecting one user by sector *(4.70 - 4.71)*.

By applying the change of variable, we have the following problem:

$$\max_{\mathbf{W}_2^{(f)},\mathbf{P},t^{(1)},t^{(2)}}\left[\sum_{i=1}^{Ns}\min\left\{t^{(1)}C_1^{(f)}(i),t^{(2)}\sum_{k=1}^{K}\mu(i,k)W_2^{(f)}(i,k)\log\left(1+\rho\gamma\frac{P(i,k)\frac{SNR_{relay-user}(i,k)}{1+SNR_{I_{ext-user}}(i,k)}}{W_2^{(f)}(i,k)}\right)\right\}\right] \tag{5.59}$$

$$\begin{aligned} s.t. \quad & \mathbf{W}_2^{(f)}\succeq 0_{NsxK},\ \mathbf{w}_{BS}^{(f)}\succeq\mathbf{0}_{Nsx1},\mathbf{P}\succeq 0_{NsxK}\ t^{(1)}\geq 0, t^{(2)}\geq 0 \\ & \mathbf{W}_2^{(f)}\mathbf{1}_{Kx1}-\mathbf{w}_{BS}^{(f)}\leq\mathbf{0}_{Nsx1} \\ & \mathbf{P}\mathbf{1}_{Kx1}-\mathbf{1}_{Nsx1}\leq\mathbf{0}_{Nsx1} \\ & \mathbf{1}_{1xNs}\mathbf{w}_{BS}^{(f)}-1\leq 0 \\ & t^{(1)}+t^{(2)}+t-1=0 \end{aligned} \tag{5.60}$$

Otherwise, as we did in *(4.71)* we consider the preselection of users by means of the weighted capacity for a fixed value of the bandwidth assigned to each sector. We have implemented this one, with the total bandwidth of the system, W_T , so that $w_{BS}^{(f)}(i)=1$:

$$k_i^* = \arg\max_k \left[\mu(i,k) C_2^{(f)}(i,k)\right] = \arg\max_k \left[\mu(i,k)\log\left(1+\rho\gamma \frac{SNR_{relay-user}(i,k)}{1+SNR_{Iext-user}(i,k)}\right)\right], i=1,...,Ns$$

(5.61)

In this way, the optimizing variables are only the corresponding with the bandwidth assigned to each sector, but not the distribution over the users:

$$\max_{\mathbf{w}_{\mathbf{BS}}^{(f)}, t^{(1)}, t^{(2)}} \left[\sum_{i=1}^{Ns} \min\left\{ t^{(1)} C_1^{(f)}(i), t^{(2)} \mu(i,k) w_{BS}^{(f)}(i) \log\left(1+\rho\gamma \frac{\dfrac{SNR_{relay-user}(i,k_i^*)}{1+SNR_{I_{ext-user}}(i,k_i^*)}}{w_{BS}^{(f)}(i)}\right)\right\}\right]$$

(5.62)

$$\begin{aligned} s.t. \qquad & \mathbf{w}_{BS}^{(f)} \succeq \mathbf{0}_{Nsx1}, t^{(1)} \geq 0, t^{(2)} \geq 0 \\ & \mathbf{1}_{1xNs} \mathbf{w}_{BS}^{(f)} - 1 \leq 0 \\ & t^{(1)} + t^{(2)} + t - 1 = 0 \end{aligned} \qquad (5.63)$$

Then, the expression of the sum-rate will be:

$$R^{(f)} = \max\left\{ R_{with-relays}^{(f)}, R_{without-relays}^{(f)} \right\} \qquad (5.64)$$

Where $R_{with-relays}^{(f)}$ is expressed in *(5.62)* with the constraints *(5.63)*, and $R_{without\_relays}^{(f)}$:

$$R_{without\_relays}^{(f)} = \sum_{i=1}^{Ns} C_{without\_relays}^{(f)}(i,k_i^*) \qquad (5.65)$$

where

$$k_i^* = \arg\max_k \left\{ \mu(i,k) C_{without\_relays}^{(f)}(i,k) \right\} \tag{5.66}$$

In the case of the orthogonal phase, we have applied again directly the maximization method to the non convex problem because the results are better. We also simplify the optimization problem preselecting one user by sector and the procedure is almost the same than for the maximization of the rate.

Now we select the best user in each sector for each transmission scheme but considering the weighted capacities:

$$R^{(o)} = \max_{\mathbf{w_{BS}}} \left[w_{BS}(i) \max\left\{ C_{with\_relays}^{(o)}(i,k_i^{1*}), C_{without\_relays}^{(o)}(i,k_i^{2*}) \right\} \right] - \lambda w_{BS}(i) \tag{5.67}$$

$$s.t. \quad \mathbf{w}_{BS} \succeq \mathbf{0}_{Nsx1} \qquad \mathbf{1}_{1xNs}\mathbf{w}_{BS} - 1 \le 0 \tag{5.68}$$

Where:

$$k_i^{1*} = \arg\max_k \left[\mu(i,k) C_{with\_relays}^{(o)}(i,k) \right], \quad i = 1,...,Ns \tag{5.69}$$

$$k_i^{2*} = \arg\max_k \left[\mu(i,k) C_{without\_relays}^{(o)}(i,k) \right], \quad i = 1,...,Ns \tag{5.70}$$

The maximum of the global problem is achieved choosing only one zone (orthogonal or non orthogonal) for each scheduling period.

$$R = t \max(R^{(o)}, R^{(f)}) + (1-t)\max(R^{(o)}, R^{(f)}) = \max(R^{(o)}, R^{(f)}) \tag{5.71}$$

6. SYSTEM FRAMEWORK

We target to provide techniques suitable to be implemented in emerging standards such as 802.16m[19]. The goal of this chapter is to describe those aspects and features of 802.16m directly related to the proposed RRM scheme and allow its implementation.

6.1 OFDM subchannels

802.16m uses Orthogonal Frequency Division Multiplexing (OFDM), distributing the transmitted data into a set of orthogonal subcarriers or tones. There are available three different permutation schemes in OFDM, thus, the distribution of tones or subcarriers along the spectrum. They are detailed in annex 1, as well as a complete description of this modulation. However, we only use the PUSC or FUSC modes in our simulations, where tones are spread over the entire band.

The 802.16m standard uses an advanced version of OFDM known as Scalable OFDM (SOFDM) which is able to work with different FFT sizes and channel bandwidths, from 5 to 20 MHz. The most important OFDM parameter for our proposal is the number of available subchannels, which are created by assigning a certain number of subcarriers to each subchannel. The number of subchannels is directly related to the granularity of the bandwidth assignations. If more subchannels are available, a more accurate frequency distribution is performed and better results may be achieved. The maximum number of subchannels is 60, for FUSC mode and a FFT size of 2048 samples.

Table 1 shows the number of OFDMA downlink subchannels for PUSC and FUSC modes [IEEE 802.16-2004] and [IEEE 802.16-2005].

Parameter	***Value***		
FFT size (samples)	*512*	*1024*	*2048*
Number of subchannels in PUSC mode	*8*	*16*	*32*
Number of subchannels in FUSC mode	*15*	*30*	*60*

Table 1. SOFDM parameters

[19] See Annex 2 to find a description of WiMAX and 802.16 standards, as well as their evolution during recent years.

6.2 Frame structures in 802.16m

In this subchapter, we will present both basic and relay frame structures defined in 802.16m standard. We will provide an overview of their types, duration and subdivisions. Later on, we will discuss about the compatibility and the practical implementation of the explained optimization methods, with and without relay support, within these physical frames.

6.2.1 Basic frame structure

The basic frame structure in 802.16m consists of three distinctions or unit groupings:

- Superframe (SPF): the length is 20 ms and it is divided into four equal frames. It always begins with a superframe header (SFH).

- Frame (F): the length is 5 ms, and it is divided into eight subframes if channel bandwidth is 5, 10 or 20 MHz. Otherwise, if bandwidth is 7 or 8.75 MHz it is divided into 6 or 7 subframes for cyclic prefixes (see annex 1) of 1/16 or 1/8 respectively.

- Subframe (SF): the first distinction between subframes is done according to if they are used in the downlink or in the uplink. After that, four types of subframes are defined:

    - Type-1: it consists of 6 OFDMA symbols
    - Type-2: it consists of 7 OFDMA symbols
    - Type-3: it consists of 5 OFDMA symbols
    - Type-4: it consists of 9 OFDMA symbols

We can see graphically in figure 20 this hierarchy.

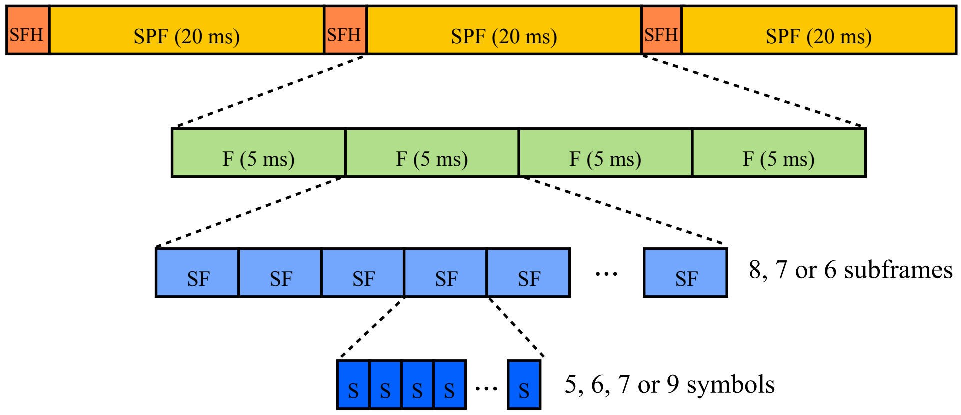

Figure 20. Basic frame structure

This basic frame can be applied to all duplexing modes (TDD, FDD or H-FDD) defined for 802.16m. The frame in TDD has two differentiated parts, one for the DL and other for the UL. They are separated by a transmission or reception transition gap (TTG or RTG), of 105.714 and 60 μs respectively, which are necessary to allow switching the transmission and reception circuitry. H-FDD frame structure is similar to the TDD one, but DL and UL transmit in different frequency bands. However, in FDD the DL and the UL are transmitted simultaneously in different bands.

We focus on TDD frames. However, the applicability to FDD frames would be similar. Channel bandwidth, length of the cyclic prefix, number of subframes and their type are defined. Figure 21 shows an example of a TDD frame, for bandwidths of 5, 10 or 20 MHz (8 subframes) and a cyclic prefix of 1/8. It has seven type-1 subframes and one type-3. We can consider each subframe of the TDD downlink as our scheduling period.

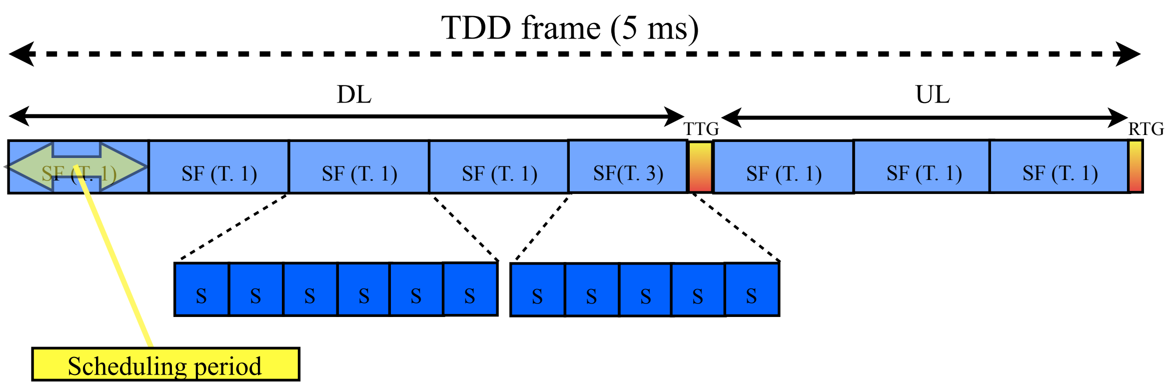

Figure 21. Inclusion of scheduling period in TDD frame structure for cyclic prefix 1/8 and channel bandwidth 5, 10 or 20 MHz

6.2.2 Relay frame structure

As we detail in annex 2, IEEE 802.16m allows for relay support. In this case, instants when relay or direct transmissions and receptions are effectuated are defined in the frame. The following definitions refer to the zones of the relay frame structure proposed in [IEEE 802.16m-09/0034r2]. These zones are constituted by an integer number of subframes.

- DL Access Zone: BSs or RSs transmit to MSs in the downlink. Preambles, headers and unicast transmissions are transmitted in this zone.
- DL Transmit Zone: BSs or RSs transmit to subordinated RSs or to MSs in the downlink.
- DL Receive Zone: RSs receive from superordinated stations (BSs or RSs) in the downlink.
- UL Access Zone: BSs receive from MSs in the uplink.
- UL Transmit Zone: RSs transmit to superordinated stations (BSs or RSs) in the uplink.
- UL Receive Zone: BSs or RSs receive from subordinated RSs or from MSs in the uplink.
- Network Coding Transmit Zone: it is located only in the odd-hop RSs which is directly attached to the BSs. Network coded transmissions are performed to BSs and to the even-hop RSs. It is being studied how to perform transmissions to MSs in this zone.
- Network Coding Receive Zone: BSs or even-hop RSs receive network coded transmissions from the odd-hop RSs attached directly to BSs.

The standard considers transparent and non-transparent relays. When transparent relays are deployed, control information is sent only by base stations. Moreover, when non-transparent relays are used, they are also able to send control information. The frame structure is different in both cases, as we can see in figures 22 and 23.

We can differentiate three different types of frame: BS frame, odd-hop RS frame and even-hop RS frame. BS frames can transmit either to RS or to MS; odd-hop RS frames can transmit to BS, RS or MS and even-hop RS frames only can transmit to RS or to MS. The transmissions of the downlink (green colour) are performed in first place and finally the ones of the uplink (blue colour).

In the transparent ARS frame, the DL Receive Zone is located at the beginning of DL subframes, which is followed by the DL Access Zone, and UL zone configuration is the same as non-transparent ARS case. The DL subframes in the super-ordinate station of a transparent ARS, e.g., ABS or non-transparent ARS, starts with the DL Transmit Zone [IEEE 802.16m-09/0034r2, p. 133].

Figures 22 and 23 also show the scheduling periods for direct transmission and transmission with relays in the frame:

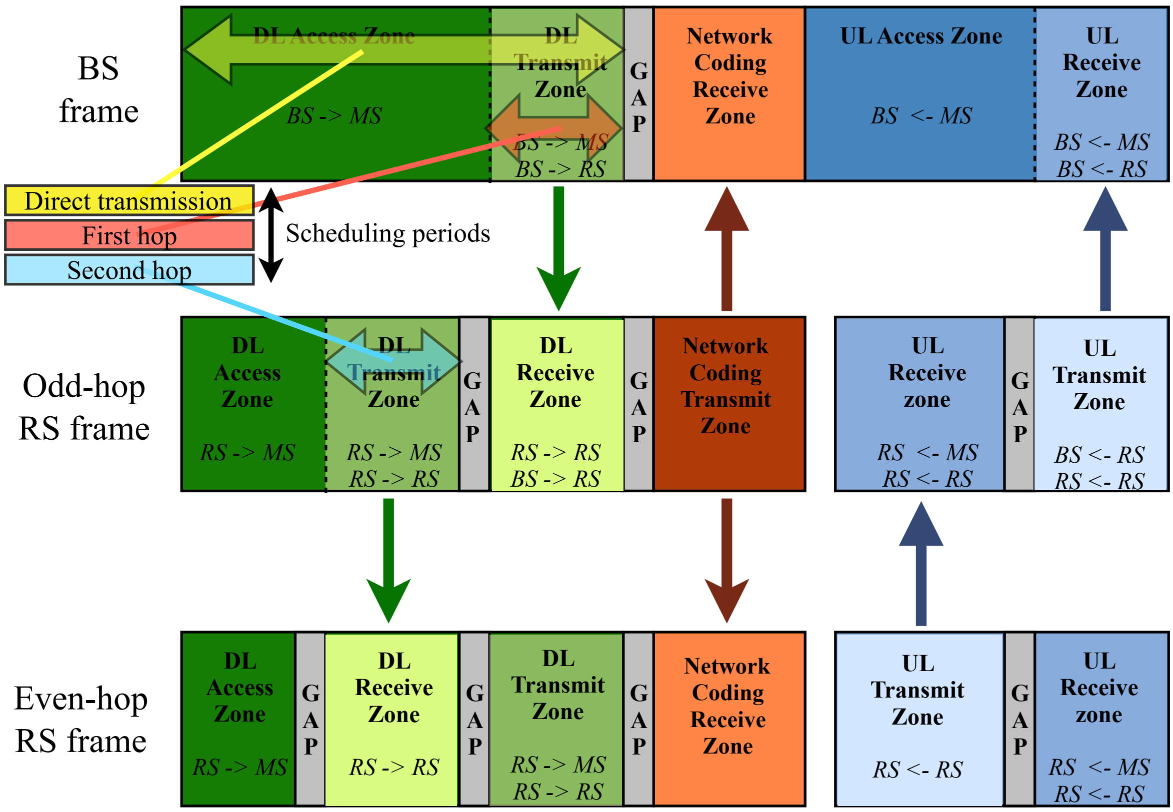

Figure 22. Inclusion of scheduling periods in non-transparent relay frame structures

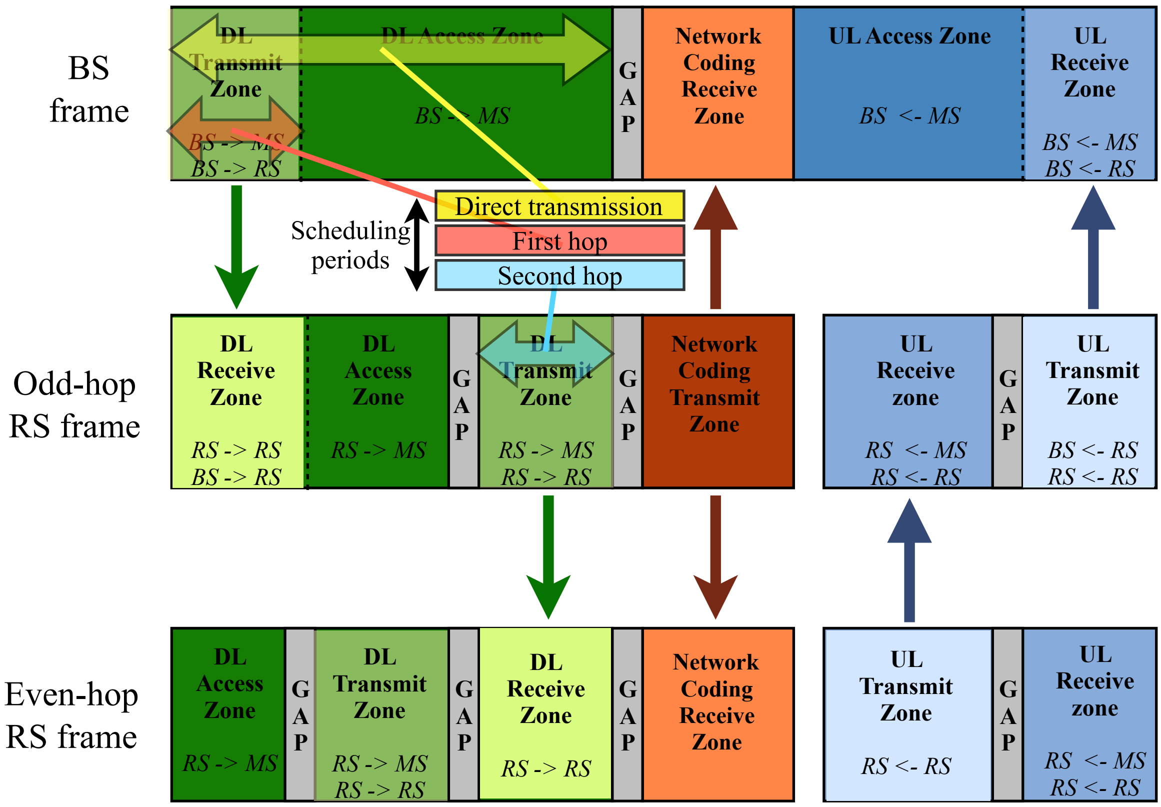

Figure 23. Inclusion of scheduling periods in transparent relay frame structures

In the downlink, the most significant difference between both cases, according to our purposes, is that transparent relays let us to effectuate first and second hop transmissions during the same frame, while non-transparent relays need at least two. Our work is focused only on the downlink and considers direct or two-hop relay transmissions.

Figures 24 and 25 show a single transmission from BS to the MS through non-transparent relays and transparent ones, respectively:

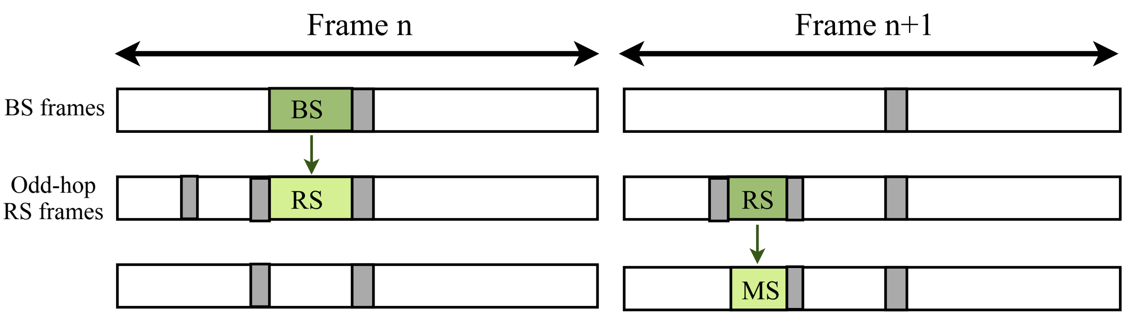

Figure 24. Two hop transmission from BS to MS with non-transparent relays

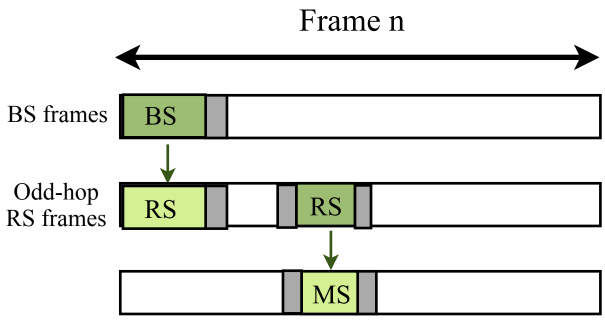

Figure 25. Two hop transmission from BS to MS with transparent relays

Transparent relays are more convenient to our proposal, as we decide jointly the duration of the first and second hop for all the coordinated stations. Applying such decision is unpractical when more than one frame is involved.

7. SIMULATION METHODOLOGY

This section presents all practical considerations and parameters involved in the simulations, as well as the description of the scenarios and models where the coordinated RRM is going to be evaluated.

7.1 Antennas

We have considered omnidirectional antennas for relay and user stations, while those of the base stations are sectorial. We will use two base station antennas in transmission and each station will have three pair of antennas, defining three sectors. Moreover, we will place only one in each relay and mobile station.

The sectorial antennas have the following radiation pattern:

$$A(\theta) = -min\left\{12\left(\frac{\theta}{\theta_{3dB}}\right)^2, FtB\right\} \qquad (7.1)$$

Where θ_{3dB} is the 3 dB beamwidth, in our case, 70º, and FtB is the front to back ratio, 20 or 30 dB. In figure 26, the normalized radiation linear pattern is represented. We can see how the attenuation increases quickly with the angle until reach the maximum value of attenuation, 30 dB, in this case.

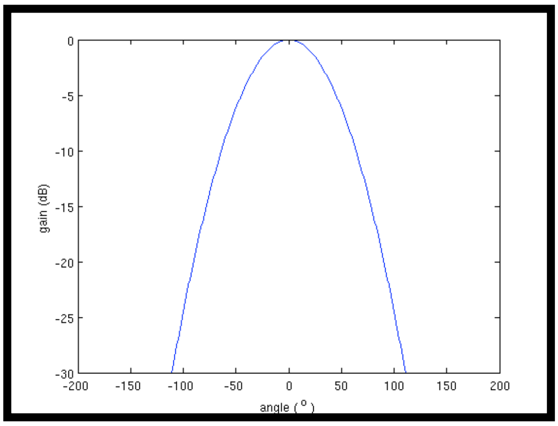

Figure 26. Normalized radiation linear pattern of the antennas

We can also represent the same diagram in polar coordinates. Furthermore, if we represent the diagram of the antennas of one base station, as we can see in figure 27, we can appreciate the implicitly created sectors, and the overlapping of the signals of adjacent sectors, causing a higher interference.

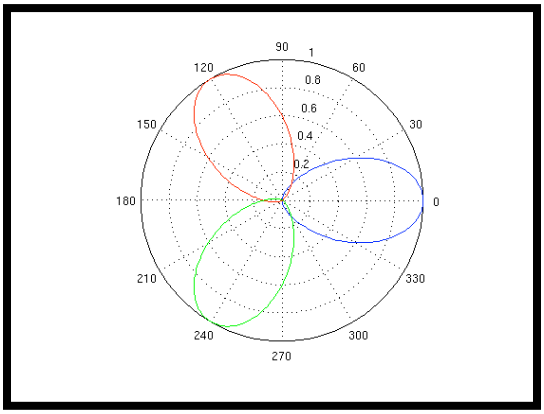

Figure 27. Normalized radiation polar pattern of the antennas

7.2 Simulation area

We have simulated a scenario formed by 19 cells. Following the recommendations of [ROCKET-1D109], we have defined the cells as hexagons, covering all the area. In the centre of each cell we have placed a base station with three sector antennas. This way, there are implicitly defined a total of 57 sectors, three in each cell.

We can define as coordinated area the set of sectors which coordinate the assignation of resources. This is the particular zone of the total simulation area where we place randomly the users that will be served.

Furthermore, in this work we will consider two types of coordinated areas: inner and outer. The difference between them is the following one:

- inner area: comprises sectors of the same cell, assigned to the same base station.
- outer area: comprises sectors of different cells, assigned to different BS.

We could think on many different possibilities and combinations when selecting the coordinated sectors, but, even if the mathematical approach can be applied to N_s sectors placed wherever we want, in this work we will always coordinate a total of 3 sectors, which can belong to the same base station or not, thus, giving rise to one of these two situations:

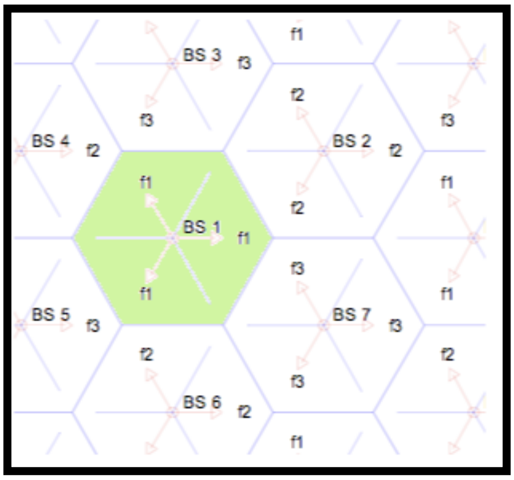

Figure 28. Inner area

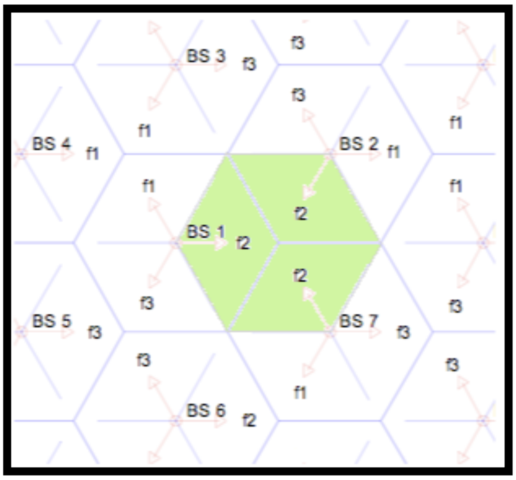

Figure 29. Outer area

These two areas lead to two different types of coordination: inner coordination and outer coordination.

Note that inner coordination is managed by one BS, while outer coordination requires communication among several BSs.

7.3 Antenna orientations

As we have commented before, each base station has three sectorial antennas, and the orientation of their main lobe can be chosen to point either at the vertex of the hexagon or to its edge. The interference pattern would be different in each case. We consider both situations, as converging sectors or offset sectors, respectively:

7.3.1 Converging sectors

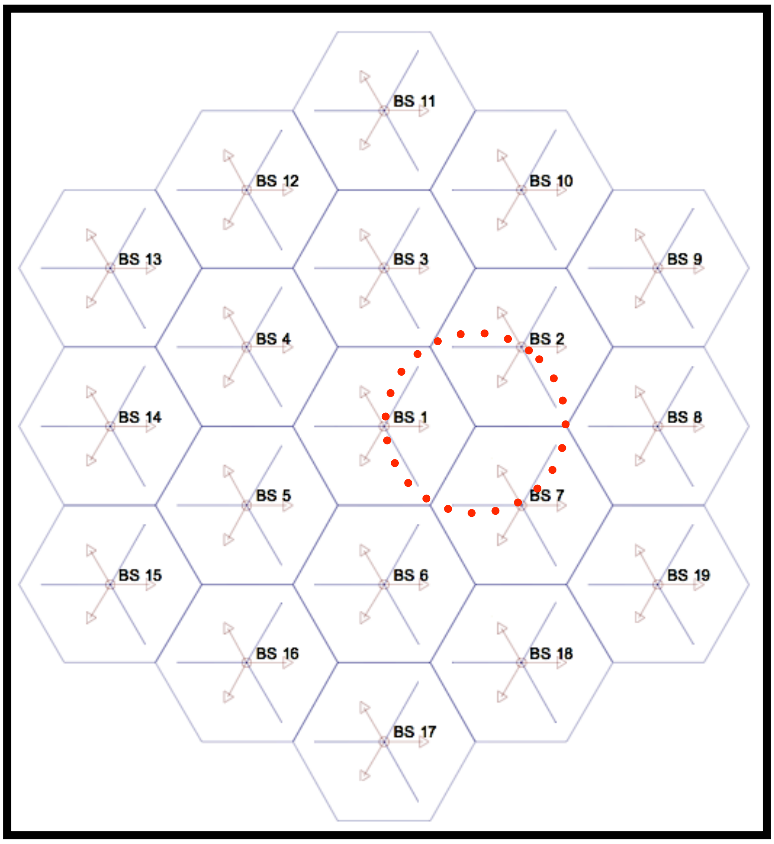

Figure 30. Antenna orientations: converging sectors

In this case, the antenna lobe of each sector points a vertex of the cell hexagon. Even if interference is higher at the cell edge, users situated near to any vertex will experience the maximum interference because the signals which come from the neighbour sectors arrive with the direction of maximum antenna gain. An outer coordination would be a good option to improve the service to users placed there. Considering for instance, the cluster (or sector grouping) marked with the circle in figure 30, and coordination between BS1, 2 and 7, note that as users move away from their corresponding base station, the contribution of the other two BSs gets higher. Moreover, although this interference within the cluster may be controlled by coordinating the resource assignation, it is expected to be significant at the frontiers between neighbour clusters. In this case, since there is not considered coordination at cluster level, the most relevant parameter is the directivity of the antennas, furthermore, their front to back ratio.

7.3.2 Offset sectors

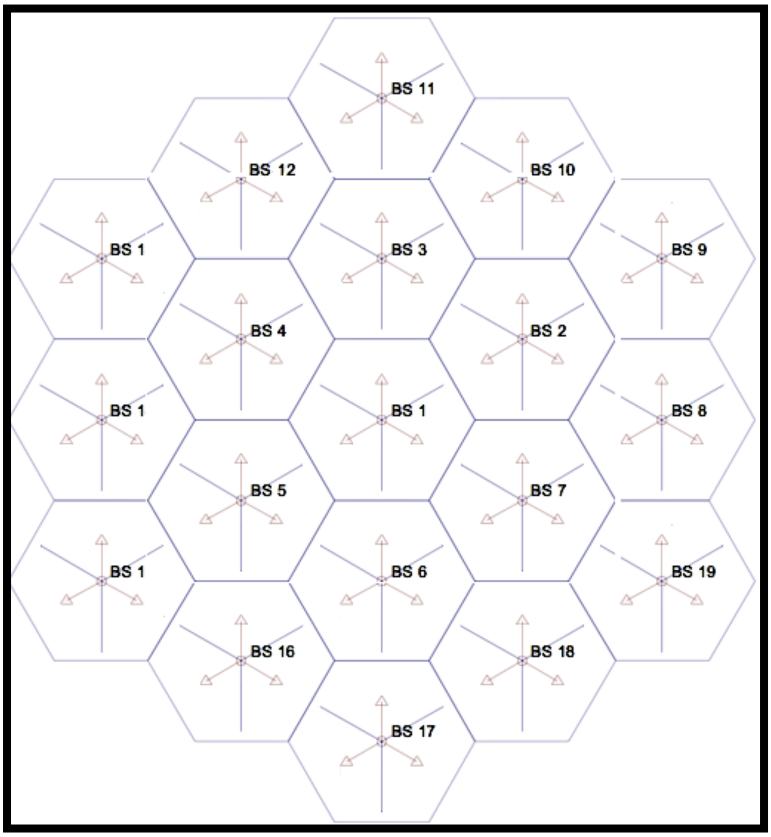

Figure 31. Antenna orientations: offset sectors

Now, the antenna lobes point to the edge of the hexagon separating two cells, and the highest interference is expected on the sides of the hexagons, but not in the vertex as in the previous configuration.

The main advantage of this scheme is that while users move away from its base station in the direction of maximum gain, the signal from the interfering sectors is attenuated by their own radiation pattern, and they have a higher SINR than in the converging configuration. The drawback is that users who move away in others directions are losing its own signal because of the radiation pattern while the interfering signals arrive from directions of a higher gain. In this case, an outer coordination could seem a priori less effective than for the converging orientation, because the interference patterns are highly mixed. However, that is not the case for the inner one.

7.4 Simulation parameters

In tables 2, 3 and 4 we can observe the parameters used in all simulations related to the link, antennas and about WiMAX.

Link budget parameters	
Noise power spectral density	*-174 dBm/Hz*
Noise figure at relay station	*5 dB*
Noise figure at mobile station	*7 dB*
Body losses	*10 dB*
Base station transmit power	*40 dBm*
Relay station transmit power	*30 dBm*
SNR penalty	*4 dB*

Table 2. Link budget parameters.

Antenna parameters	
Base station antenna gain	*17 dB*
Base station height	*32 m*
Relay station antenna gain	*5 dB*
Relay station height	*30 m*
Mobile station antenna gain	*-1 dB*
Number of antennas per BS sector	*2 antennas*
Number of antennas per RS	*1 antenna*
Number of antennas per MS	*1 antenna*
Front to back ratio (FtB)	*20 dB / 30 dB*

Table 3. Antenna parameters.

WiMax parameters for FUSC	
Carrier frequency	*2.5 GHz*
Total bandwidth	*10 MHz*

Table 4. WiMax parameters for FUSC.

7.5 Frequency planning and coordinated sectors

Once cells and sectors are defined by the placement of the base stations and the sectorial antennas, there appears another important factor in the design of the system: the frequency planning, thus, how frequencies are assigned to each cell and sectors. It is a concept directly related to the frequency reuse, which expresses the frequency pattern which is created when frequencies are assigned and reassigned in different sectors. These ideas can be interpreted in terms of assigned frequency carrier or the assigned frequency band, depending on the system technology.

Generally we differentiate two main groups of frequency reuse: reuse 1 and reuse $1/N$. We call reuse 1 a frequency planning in which all cells and sectors share the same frequency carrier or frequency band. On the other hand, a reuse $1/N$ is a frequency planning where the total band is split in N sub-bands, and sectors alternate them following a pattern. Also, the power per carrier increases by a multiplicative factor N in these kind of reuses (see section 7.8.1).

There are many combinations to distribute the sub-bands among all the sectors. We are going to describe the ones we have used in this work:

- 1/3/1: it is the equivalent to what we have called reuse 1. The nomenclature stands for one band allocated to all cells, three sectors per cell and the same band for all sectors.

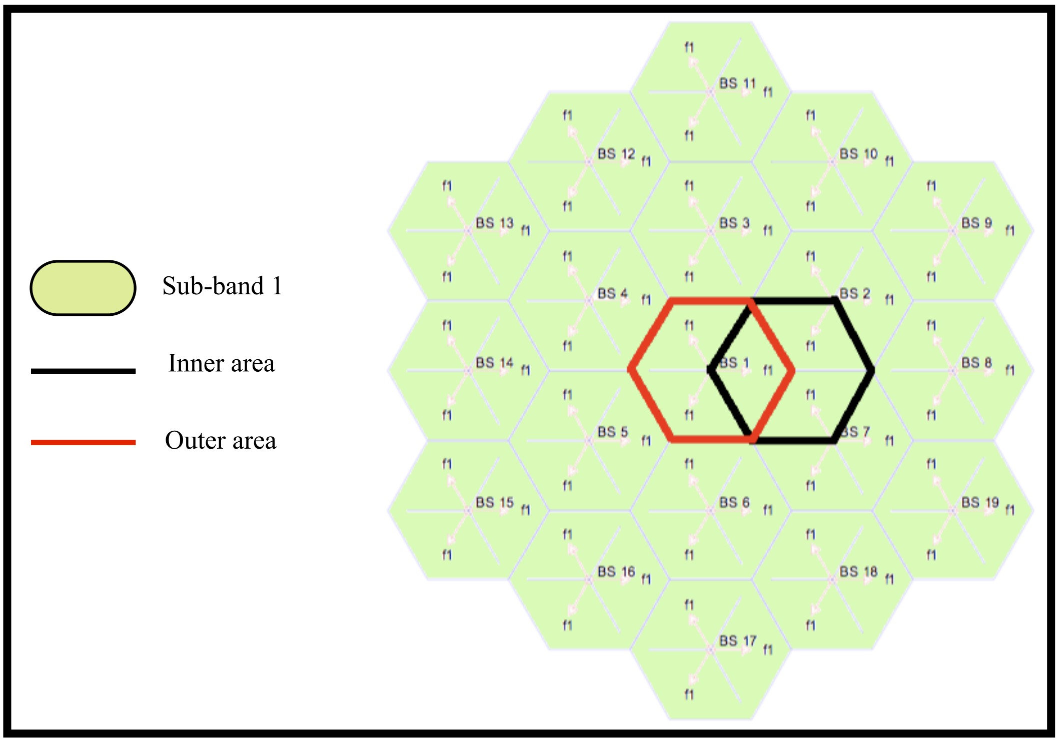

Figure 32. Reuse 1/3/1 (reuse 1)

In this case, all sectors and cells use the same frequency band, even if the interference increases, so inner or outer coordination could be applied to improve the spectral efficiency of the system.

- 1/3/3 (1): this is a particular case of reuse 1/*N*, where *N* is equal to three. The nomenclature stands for one band allocated to all cells, three sectors per cell, the band is split in three and each sub-band is allocated to different sectors.

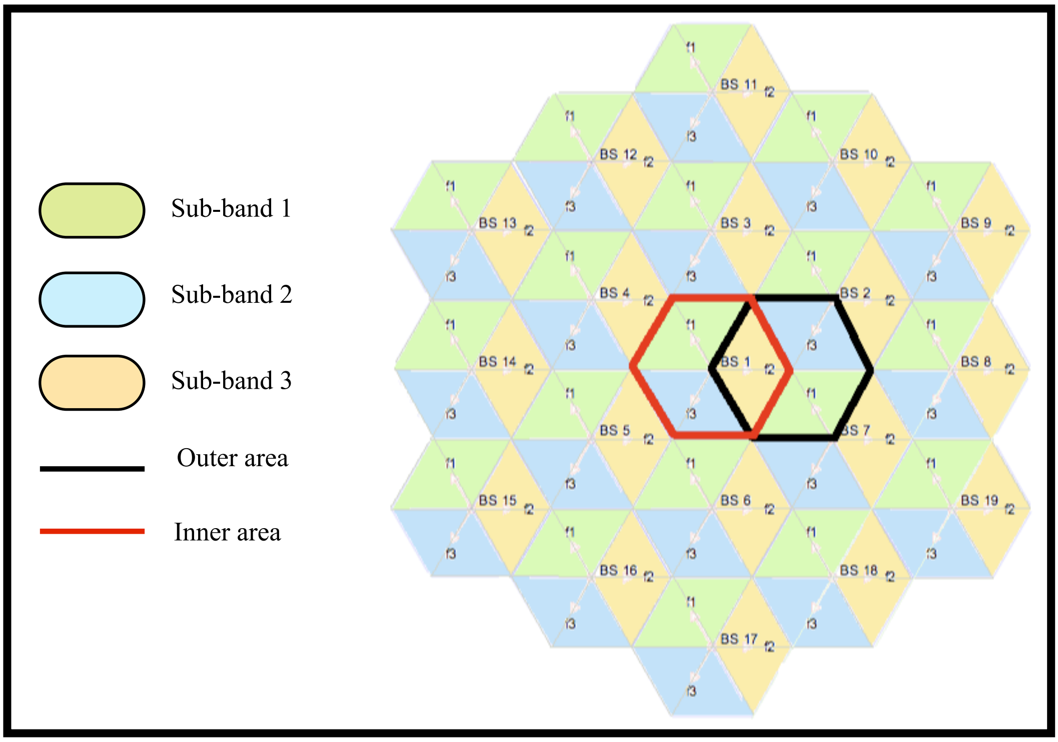

Figure 33. Reuse 1/3/3

It is interesting to see that sectors in the outer area and the inner one are always orthogonalized in frequency. Using this pattern, the interference between all neighbour sectors and cells is minimum, but the possibilities to apply a coordinated management of the resources are reduced since contiguous sectors don't share a common sub-band.

● 3/3/1: this is another case of reuse 1/3. Now the band is split in three and allocated to clusters of three neighbour cells, three sectors per cell and all sectors use the same band.

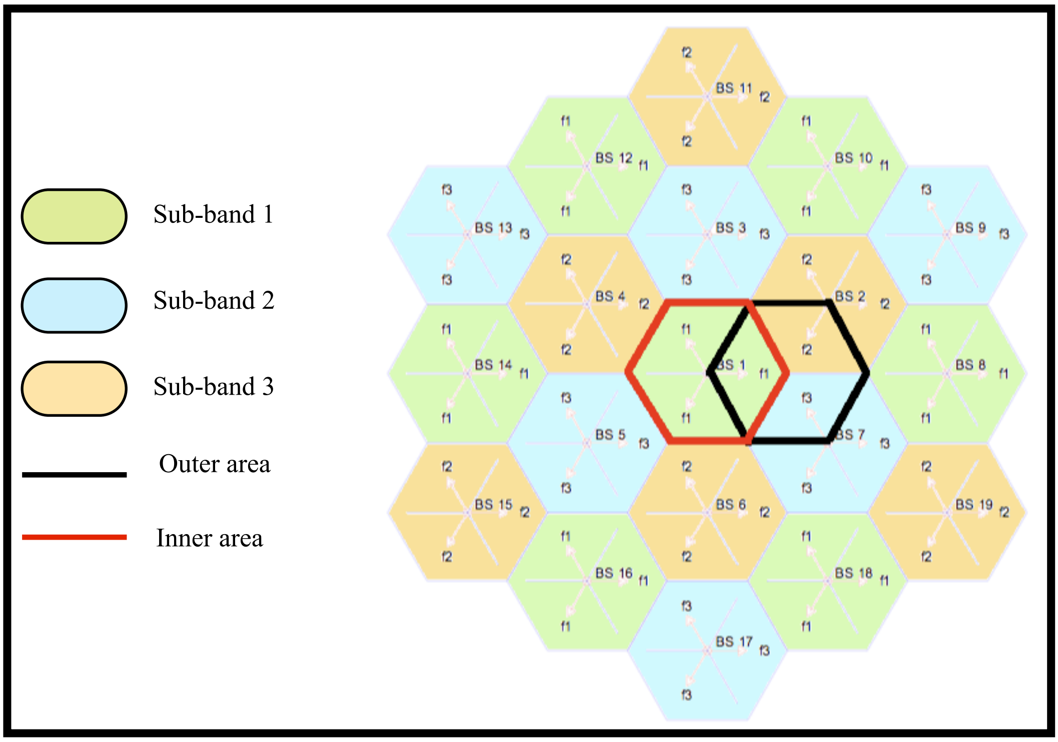

Figure 34. Reuse 3/3/1

In this case sectors in the outer area are orthogonalized in frequency but not the ones in the inner area, which we could considered as a reuse 1 in a small scale. However, it's important to appreciate that the power per carrier is multiplied by 3. Now, the interference from other cells is reduced but not the one between sectors belonging to the same cell, so inner coordination could be applied to minimize it.

Apart from these frequency scenarios, which are proposed in [IEEE 802.16m-08/0034r2], we have also introduced a different one, which is a variant of 1/3/3, allocating one band to all cells, splitting it in three, but allocating the sub-bands in a way that the coordinated sectors use the same one. We will call this scheme 1/3/3 (2) while we will refer to the one proposed in [IEEE 802.16m-08/0034r2] as 1/3/3 (1). We can see it in figure 35.

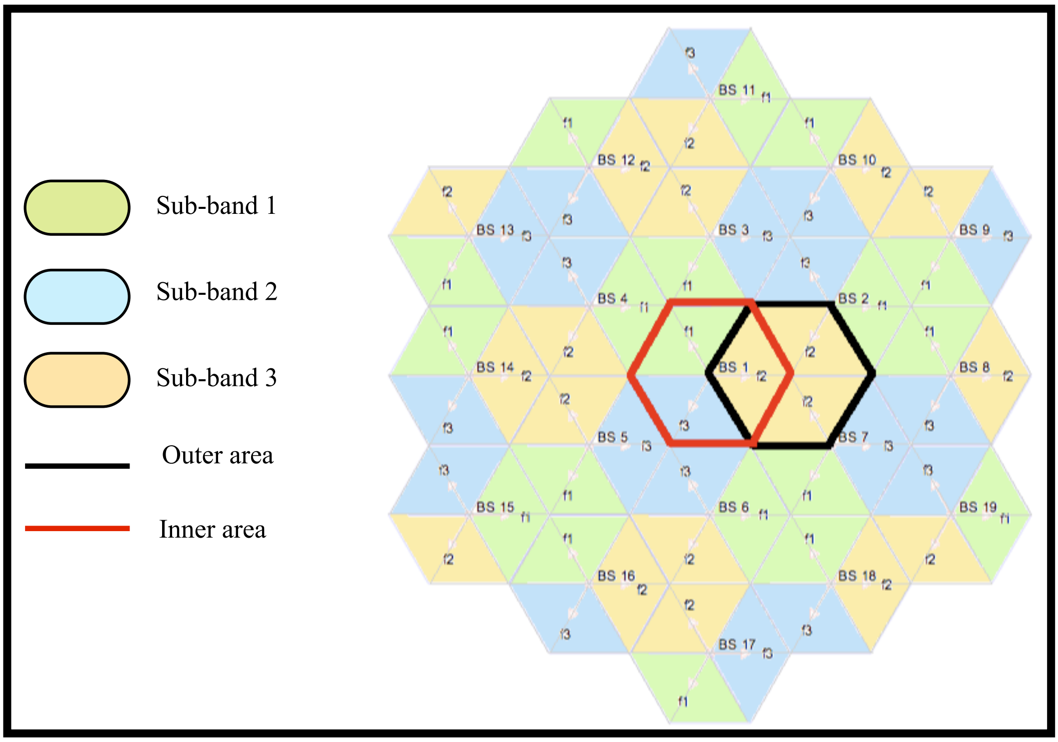

Figure 35. Reuse 1/3/3 (2)

This case is the opposite from reuse 3/3/1, in the sense that sectors in the inner area are orthogonalized while not the ones of the outer area. Applying coordination between BS in the outer area may improve the capacity of the system.

We will call fixed reuses those schemes in which all base stations transmit always with the whole bandwidth assigned to each sector, once established the frequency planning (one of these cases), thus, these assigned bands or sub-bands are not split, but they remain fixed. Furthermore, users are not orthogonalized in time nor frequency (more than they actually are because of the frequency planning). We will compare fixed reuses with the coordinated ones.

7.6 Channel models

The ROCKET project also considers different propagation scenarios which can be associated to different available channel models in the literature. They consider the following ones:

- ITU channel models
- SUI channel models
- IEEE 802.11n channel models
- 3GPP channel models
- Winner I,II channel models
- IEEE 802.16m channel models

According to the associations between the scenarios described in [ROCKET-1D109] and the previous models, we have implemented in our simulations the channel models proposed by the WINNER II project (Wireless World Initiative New Radio) [WINNER] but we have also completed some details about the shadowing using some expressions specified in [IEEE16j_EM]. WINNER is a consortium formed by 41 partners coordinated by Nokia Siemens Networks working towards enhancing the performance of mobile communication systems. We have used a public deliverable about channel models which is available in the website “http://www.ist-winner.org” of the WINNER II project: D1.1.2 WINNER II Channel Models.

7.6.1 Links and propagation scenarios

In all the transmission methods we will see, there will be three different links or signal paths to consider:

- From base station to mobile station (BS - MS): this is the unique link for direct transmissions, thus, without using relays.
- From base station to relay station (BS - RS): in relay transmissions, it is what we call first hop.
- From relay station to mobile station (RS - MS): in relay transmissions, it is what we call second hop.

We have also considered three different propagation scenarios: urban, suburban and rural. The cell radius and the channel model will be different for each one.

7.6.2 Break point distance

Some WINNER II models depend on the break point distance and on the effective break point distance. These models have more than one mathematical expression for the path loss, and depending on the distances between stations, if they are higher or lower than the break point distance, we apply an expression or the other one. The definition of these two distances are as follows. For the break point distance:

$$d_{BP} = \frac{4 \cdot h_{BS} \cdot h_{MS} \cdot f_c}{c} \tag{7.2}$$

where f_c is the centre frequency in Hz, c is the propagation velocity in free space and h_{BS} and h_{MS} are the heights of the base and mobile station, respectively. For the effective break point distance:

$$d'_{BP} = \frac{4 \cdot h'_{BS} \cdot h'_{MS} \cdot f_c}{c} \tag{7.3}$$

where h'_{BS} and h'_{MS} are the effective antenna heights at the base and the mobile station, respectively, which are computed as:

$$h'_{BS} = h_{BS} - 1.0 \tag{7.4}$$

$$h'_{MS} = h_{MS} - 1.0 \tag{7.5}$$

where the effective environment height in urban environments is assumed to be equal to 1.0 m.

All distances are defined as:

$$d = \max\{d, h_S\} \tag{7.6}$$

where h_S is the height of the emitter station. With this expression we assume as the minimum the distance of a user standing at the base of a station, which is 30 m for a RS and 32 m for a BS.

7.6.3 Channels description

In this section we are going to comment the main characteristics of each channel. WINNER II defines a wide variety of channels, named with the letters from A to D. In table 5 we summarize the ones we have used:

Name	Definition	Visibility	Frequency (GHz)
B5a	Stationary feeder, rooftop to rooftop	LOS	2-6
C1	Suburban macro-cell	LOS / NLOS	2-6
C2	Urban macro-cell	LOS/ NLOS	2-6
D1	Rural macro-cell	LOS/ NLOS	2-6

Table 5. WINNER II channel models presented in this work

Now, let's see the details of each one.

B5a model: stationary feeder, rooftop to rooftop

This model has to be applied to signals where the line of sight (LOS) is very clear. Antenna heights does not affect noticeably to the path-loss since it is a connection very similar to the free space one. Directive antennas are very effective in reducing the delay spread and other multi-path impacts. Although it can be also applicable for omnidirectional antennas, the antennas we use are directional (we have already defined them in a previous section).

C1 model: suburban macro-cell

C1 model assumes that BS are placed well above the rooftops while MS are outdoors at the street level. It is a suburban scenario, so the eventual buildings are considered as low residential houses or not too high blocks. There may be found occasional open areas such as playgrounds or parks, and a modest vegetation.

C2: urban macro-cell

In the C2 model, BS are also placed well above the rooftops and MS are located outdoors at street level. In this case, the MS is surrounded by buildings, since this is a urban scenario. These buildings could be organized in a grid or placed in irregular positions, and they are higher than the ones considered in C1 suburban model, as well as the density. However, both density and height are mostly homogeneous. In relation to the line of sight conditions, the obstructed line-of-sight is more probable in a urban scenario when comparing it with the rest, due to the diffraction over the rooftops.

D1: rural macro-cell

This model stands for radio propagation in large areas where radius may be up to 10 km. The building density in this case is low, unlike urban models, and their average height is also low. So to ensure a well coverage, antenna height has to be much higher than building height. From 20 to 70 m could be typical values of antenna height.

There is an important difference between this model and the suburban and urban ones, which is that MS are not typically outdoors, but inside buildings or vehicles. This could led to additional penetration losses. However, most of links are line of sight since due to the low density of obstacles.

These figures show a representation of the modelled path losses versus the free space losses:

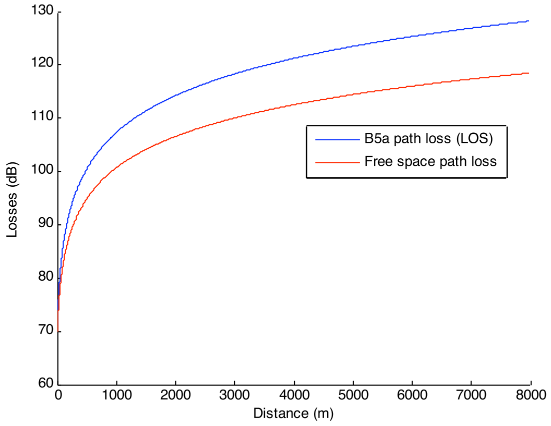

Figure 36. Representation of B5a vs free space path losses

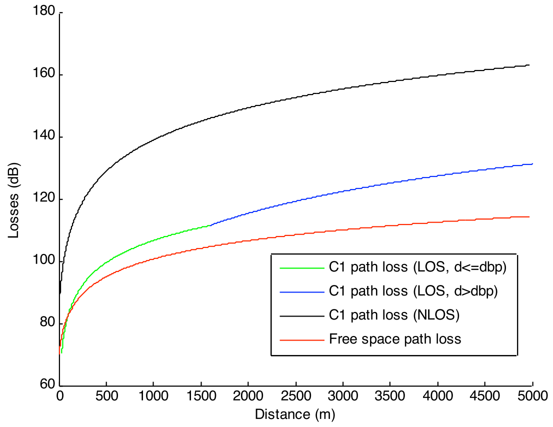

Figure 37. Representation of C1 vs free space path losses

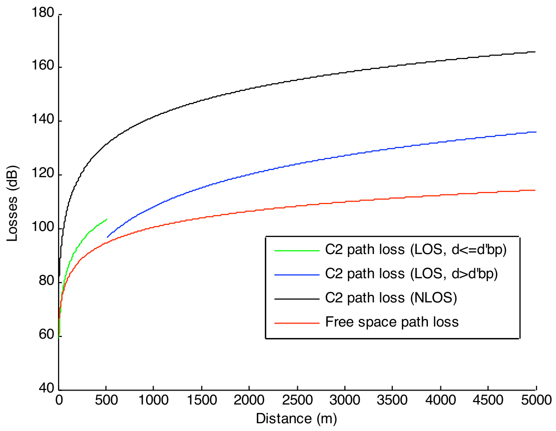

Figure 38. Representation of C2 vs free space path losses

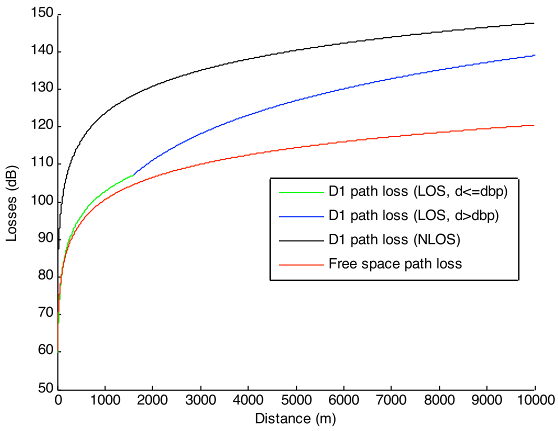

Figure 39. Representation of D1 vs free space path losses

7.6.4 Propagation conditions

As we already know, in the WINNER models there is the distinction between LOS or NLOS. Furthermore, there are also defined some probabilities for each model which express if a concrete user or mobile station is in LOS or NLOS.

For the links BS-MS and RS-MS, we have chosen the corresponding model according to the LOS probability associated to each model. The models associated to these links are C1, C2 and D1, and they have path loss definitions for each mode (LOS or NLOS). The LOS probabilities are defined depending on the distance of the mobile station. We have used three, one for each propagation scenario:

- Urban LOS probability: (C2)

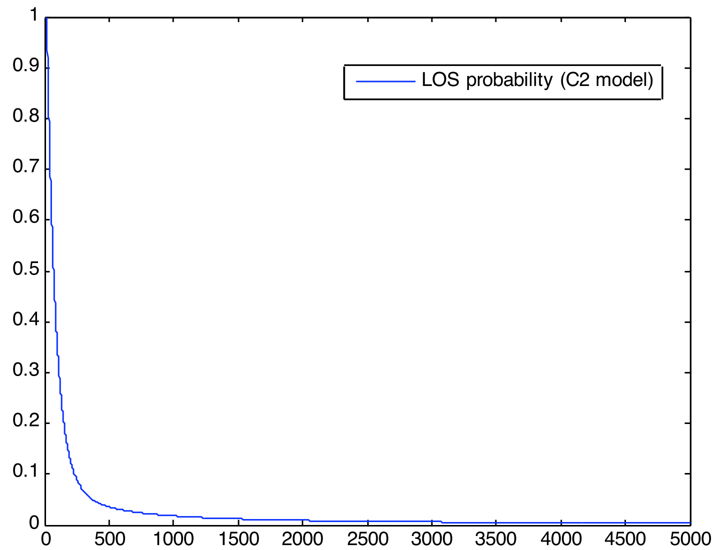

Figure 40. Representation of the C2 LOS probability

- Suburban LOS probability: (C1)

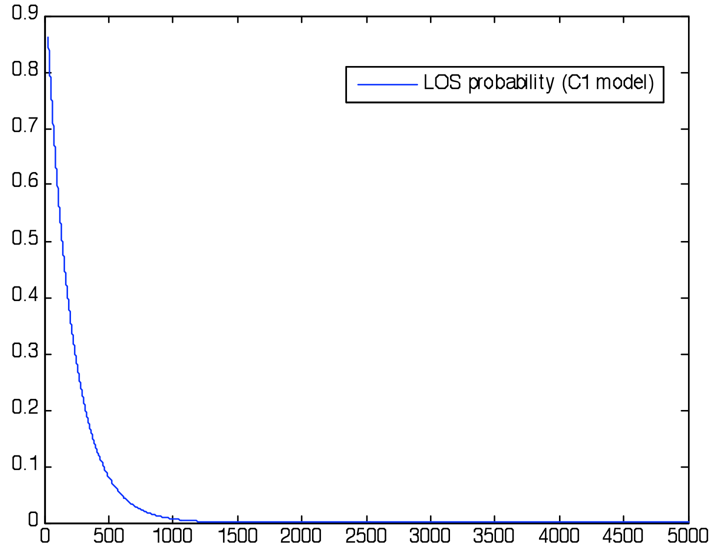

Figure 41. Representation of the C1 LOS probability

- Rural LOS probability: (D1)

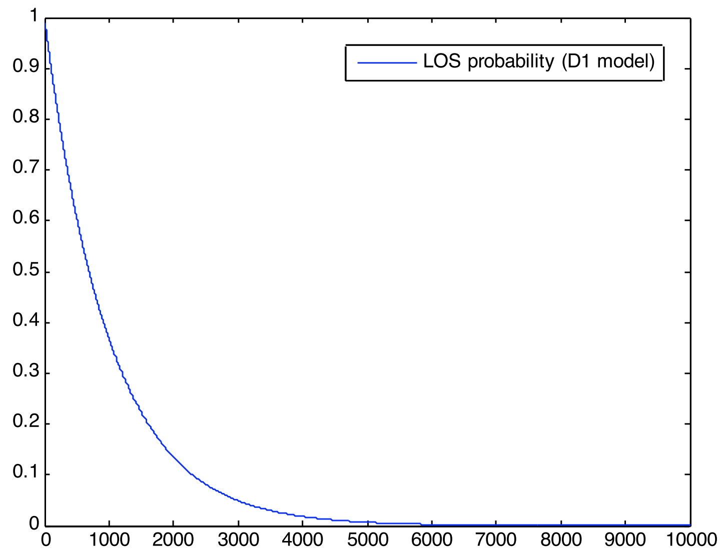

Figure 42. Representation of the D1 LOS probability

The link BS-RS is different, since we can place the relay stations wherever we want and the positions are fixed. So, we have considered that the 6 relay stations belonging to the same base station are in LOS while the rest are NLOS. In figure 43 we can see an example taking as reference the base station 1 (BS 1):

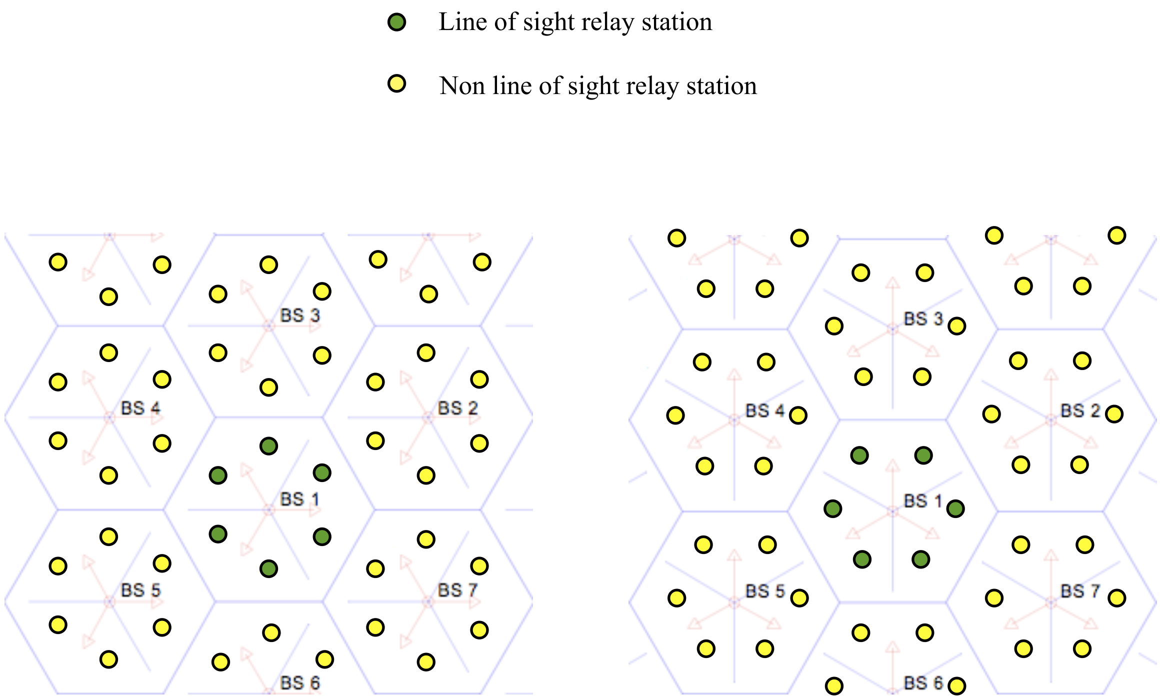

Figure 43. LOS / NLOS case for relays

7.6.5 Shadowing

The WINNER II models define expressions for the path loss but also specifies values for the standard deviation of the shadowing, which is considered as a lognormal distributed random variable. Even if we have used the exact expressions of the path loss, we have added for models C1 and C2 a correction for the standard deviation of the shadowing, which is defined in [IEEE16j_EM].

In figures 44-47 we can see the representation of the path loss of each channel model with the contribution of the shadowing.

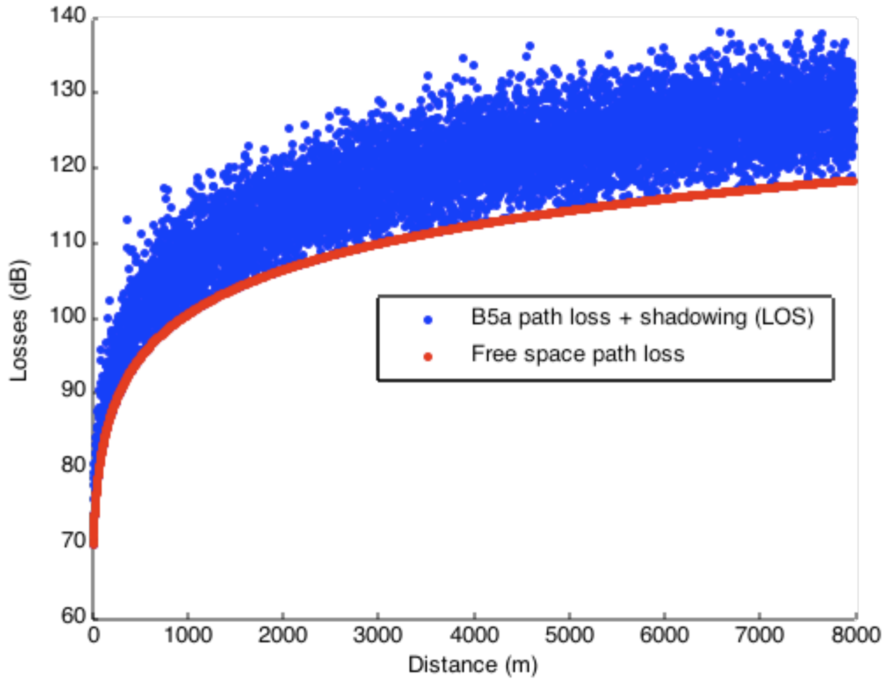

Figure 44. Representation of B5a path loss plus shadowing

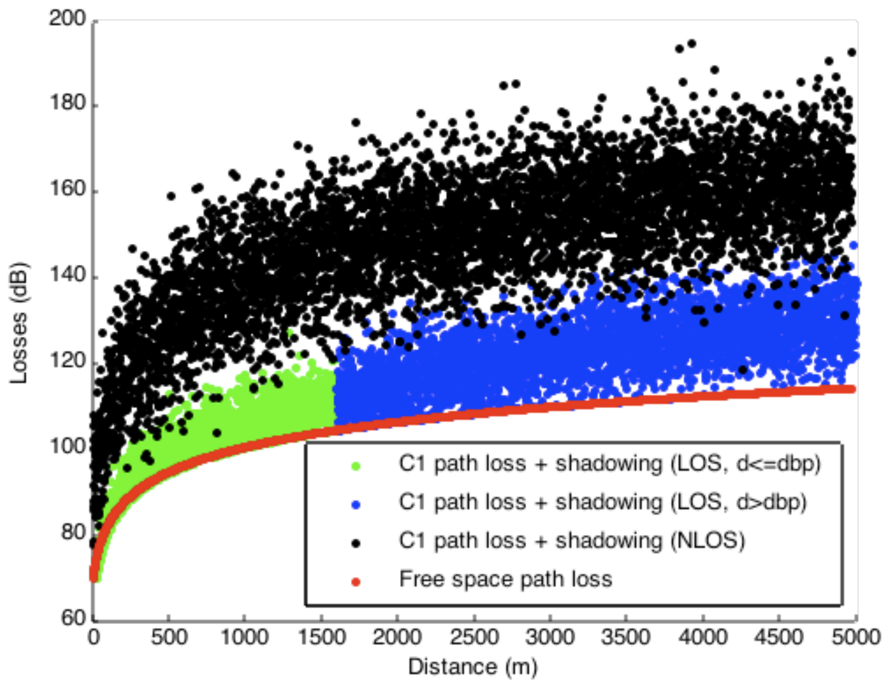

Figure 45. Representation of C1 path loss plus shadowing

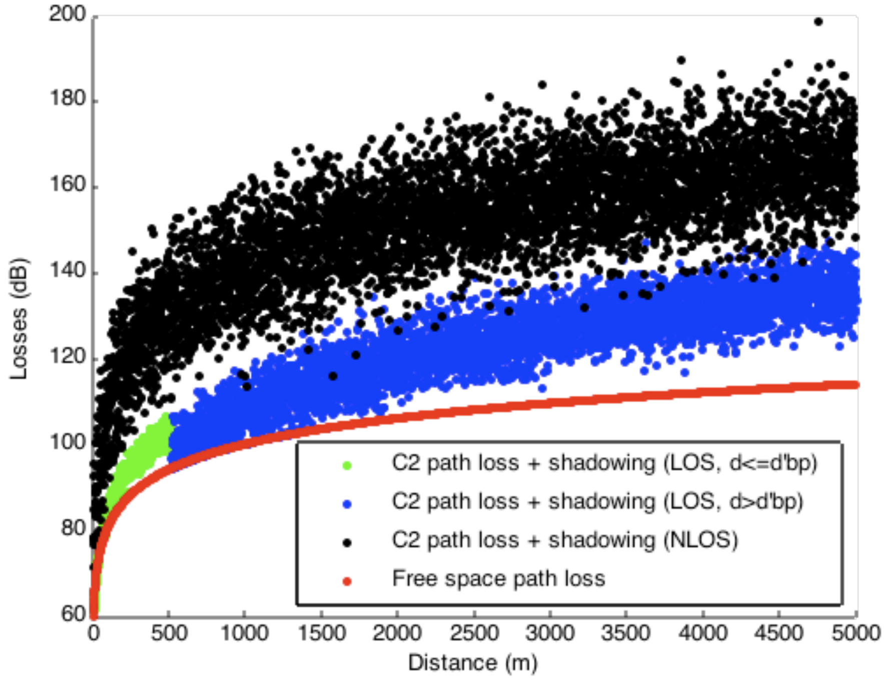

Figure 46. Representation of C2 path loss plus shadowing

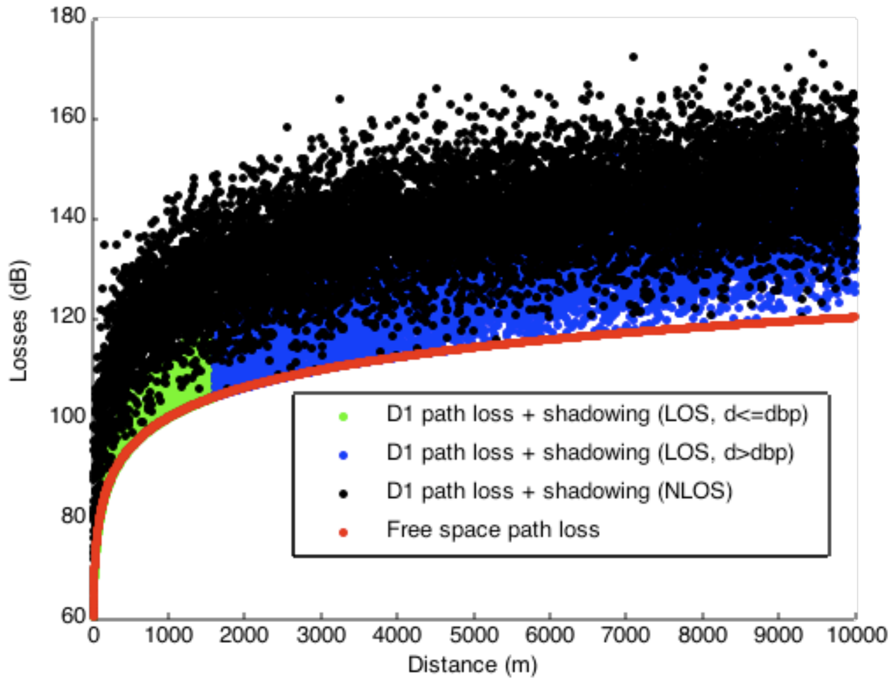

Figure 47. Representation of D1 path loss plus shadowing

7.6.6 Expressions for losses in an urban scenario:

Base station - mobile station (BS - MS)

LOS probability (C2 WINNER II):

$$P_{LOS} = \min\left\{\frac{18}{d},1\right\}\cdot\left(1-e^{\left(\frac{-d}{63}\right)}\right)+e^{\left(\frac{-d}{63}\right)} \tag{7.7}$$

PL for the LOS case (C2 WINNER II):

$$PL = 26\log_{10}(d)+39+20\log_{10}(f_c/5) \text{ for } 10\text{m} < d < d'_{BP}$$

$$PL = 40\log_{10}(d)+13.47-14\log_{10}(h_{BS})-14\log_{10}(h_{MS})+6\log_{10}(f_c/5) \text{ for } d'_{BP} < d < 5\text{km} \tag{7.8}$$

PL for the NLOS case (C2 WINNER II):

$$PL = (44.9-6.55\log_{10}(h_{BS}))\log_{10}(d)+34.46+5.83\log_{10}(h_{BS})+23\log_{10}(f_c/5) \tag{7.9}$$

Standard deviation of the shadowing (IEEE 802.16j):

$$\sigma = 7.5\cdot\left(1-e^{\frac{-\left(PL-PL_{free}\right)}{4}}\right)+1.5 \tag{7.10}$$

Base station - relay station (BS - RS)

PL for the LOS case (B5a WINNER II):

$$\begin{aligned} PL &= 23.5\log_{10}(d) + 42.5 + 20\log_{10}(f_c / 5) \\ \sigma &= 4 \end{aligned} \qquad (7.11)$$

PL for the NLOS case (C1 WINNER II):

$$PL = (44.9 - 6.55\log_{10}(h_{BS}))\log_{10}(d) + 31.46 + 5.83\log_{10}(h_{BS}) + 23\log_{10}(f_c / 5) \qquad (7.12)$$

Standard deviation of the shadowing (IEEE 802.16j):

$$\sigma = 8.2 \cdot \left(1 - e^{\frac{-\left(PL - PL_{free}\right)}{4}} \right) + 1.5 \qquad (7.13)$$

Relay station - mobile station (RS - MS)

LOS probability (C2 WINNER II):

$$P_{LOS} = \min\left\{\frac{18}{d},1\right\} \cdot \left(1 - e^{\left(\frac{-d}{63}\right)}\right) + e^{\left(\frac{-d}{63}\right)} \tag{7.14}$$

PL for the LOS case (C2 WINNER II):

$$PL = 26\log_{10}(d) + 39 + 20\log_{10}(f_c / 5) \text{ for } 10\text{m} < d < d'_{BP}$$

$$PL = 40\log_{10}(d) + 13.47 - 14\log_{10}(h_{BS}) - 14\log_{10}(h_{MS}) + 6\log_{10}(f_c / 5) \quad \text{for } d'_{BP} < d < 5\text{km} \tag{7.15}$$

PL for the NLOS case (C2 WINNER II):

$$PL = (44.9 - 6.55\log_{10}(h_{BS}))\log_{10}(d) + 34.46 + 5.83\log_{10}(h_{BS}) + 23\log_{10}(f_c / 5) \tag{7.16}$$

Standard deviation of the shadowing (IEEE 802.16j):

$$\sigma = 7.5 \cdot \left(1 - e^{\frac{-\left(PL - PL_{free}\right)}{4}}\right) + 1.5 \tag{7.17}$$

7.6.7 Expressions for losses in a suburban scenario:

<u>Base station - mobile station (BS - MS)</u>

LOS probability (C1 WINNER II):

$$P_{LOS} = e^{\left(\frac{-d}{200}\right)} \tag{7.18}$$

PL for the LOS case (C1 WINNER II):

$$PL = 23.8\log_{10}(d) + 41.2 + 20\log_{10}(f_c / 5) \quad \text{for } 30\text{m} < d < d_{BP}$$
$$\sigma = 4$$

$$PL = 40\log_{10}(d) + 11.65 - 16.2\log_{10}(h_{BS}) - 16.2\log_{10}(h_{MS}) + 3.8\log_{10}(f_c / 5) \quad \text{for } d_{BP} < d < 5\text{km}$$
$$\sigma = 6$$

(7.19)

PL for the NLOS case (C1 WINNER II):

$$PL = (44.9 - 6.55\log_{10}(h_{BS}))\log_{10}(d) + 31.46 + 5.83\log_{10}(h_{BS}) + 23\log_{10}(f_c / 5) \tag{7.20}$$

Standard deviation of the shadowing (IEEE 802.16j):

$$\sigma = 8.2 \cdot \left(1 - e^{\frac{-\left(PL - PL_{free}\right)}{4}}\right) + 1.5 \tag{7.21}$$

Base station - relay station (BS - RS)

PL for the LOS case (B5a WINNER II):

$$PL = 23.5\log_{10}(d) + 42.5 + 20\log_{10}(f_c / 5)$$
$$\sigma = 4 \tag{7.22}$$

PL for the NLOS case (C1 WINNER II):

$$PL = (44.9 - 6.55\log_{10}(h_{BS}))\log_{10}(d) + 31.46 + 5.83\log_{10}(h_{BS}) + 23\log_{10}(f_c / 5) \tag{7.23}$$

Standard deviation of the shadowing (IEEE 802.16j):

$$\sigma = 8.2 \cdot \left(1 - e^{\frac{-\left(PL - PL_{free}\right)}{4}}\right) + 1.5 \tag{7.24}$$

Relay station - mobile station (RS - MS)

LOS probability (C1 WINNER II):

$$P_{LOS} = e^{\left(\frac{-d}{200}\right)} \qquad (7.25)$$

PL for the LOS case (C1 WINNER II):

$$PL = 23.8\log_{10}(d) + 41.2 + 20\log_{10}(f_c/5) \quad \text{for } 30\text{m} < d < d_{BP}$$
$$\sigma = 4$$
$$PL = 40\log_{10}(d) + 11.65 - 16.2\log_{10}(h_{BS}) - 16.2\log_{10}(h_{MS}) + 3.8\log_{10}(f_c/5) \quad \text{for } d_{BP} < d < 5\text{km}$$
$$\sigma = 6$$
$$(7.26)$$

PL for the NLOS case (C1 WINNER II):

$$PL = (44.9 - 6.55\log_{10}(h_{BS}))\log_{10}(d) + 31.46 + 5.83\log_{10}(h_{BS}) + 23\log_{10}(f_c/5) \qquad (7.27)$$

Standard deviation of the shadowing (IEEE 802.16j):

$$\sigma = 8.2 \cdot \left(1 - e^{\frac{-(PL - PL_{free})}{4}}\right) + 1.5 \qquad (7.28)$$

7.6.8 Expressions for losses in a rural scenario:

<u>Base station - mobile station (BS - MS)</u>

LOS probability (D1 WINNER II):

$$P_{LOS} = e^{\left(\frac{-d}{1000}\right)} \tag{7.29}$$

PL for the LOS case (D1 WINNER II):

$$PL = 21.5\log_{10}(d) + 44.2 + 20\log_{10}(f_c / 5) \quad \text{for } 10\text{m} < d < d_{BP}$$
$$\sigma = 4$$
$$PL = 40\log_{10}(d) + 10.5 - 18.5\log_{10}(h_{BS}) - 18.5\log_{10}(h_{MS}) + 1.5\log_{10}(f_c / 5) \quad \text{for } d_{BP} < d < 10\text{km}$$
$$\sigma = 6$$

(7.30)

PL for the NLOS case (D1 WINNER II):

$$PL = 25.1\log_{10}(d) + 55.4 - 0.13(h_{BS} - 25)\log_{10}(d / 100) - 0.9(h_{MS} - 1.5) + 21.3\log_{10}(f_c / 5)$$
$$\sigma = 8$$

(7.31)

Base station - relay station (BS - RS)

PL for the LOS case (B5a WINNER II):

$$PL = 23.5\log_{10}(d) + 42.5 + 20\log_{10}(f_c / 5)$$
$$\sigma = 4 \tag{7.32}$$

PL for the NLOS case (D1 WINNER II):

$$PL = 25.1\log_{10}(d) + 55.4 - 0.13(h_{BS} - 25)\log_{10}(d/100) - 0.9(h_{MS} - 1.5) + 21.3\log_{10}(f_c / 5)$$
$$\sigma = 8 \tag{7.33}$$

Relay station - mobile station (RS - MS)

LOS probability (D1 WINNER II):

$$P_{LOS} = e^{\left(\frac{-d}{1000}\right)} \tag{7.34}$$

PL for the LOS case (D1 WINNER II):

$$PL = 21.5\log_{10}(d) + 44.2 + 20\log_{10}(f_c / 5) \quad \text{for } 10\text{m} < d < d_{BP}$$
$$\sigma = 4$$
$$PL = 40\log_{10}(d) + 10.5 - 18.5\log_{10}(h_{BS}) - 18.5\log_{10}(h_{MS}) + 1.5\log_{10}(f_c / 5) \quad \text{for } d_{BP} < d < 10\text{km}$$
$$\sigma = 6 \tag{7.35}$$

PL for the NLOS case (D1 WINNER II):

$$PL = 25.1\log_{10}(d) + 55.4 - 0.13(h_{BS} - 25)\log_{10}(d/100) - 0.9(h_{MS} - 1.5) + 21.3\log_{10}(f_c / 5)$$
$$\sigma = 8 \tag{7.36}$$

7.7 Users deployment

Users are placed randomly either in the inner area or in the outer one. The number of users per sector is 15. In outer coordination, note that for users placed near to the base stations (of coordinated sectors) seems better to transmit with all the available bandwidth, while for the users who are near to the centre of the coordinated area it is better to assign orthogonal resources in a coordinated way. We can see in figure 48 an example of a random user deployment over the outer coordinated area and we are going to focus on two particular users to show this fact. As we see, user 1 is placed in the centre of the area and user 2 under the base station.

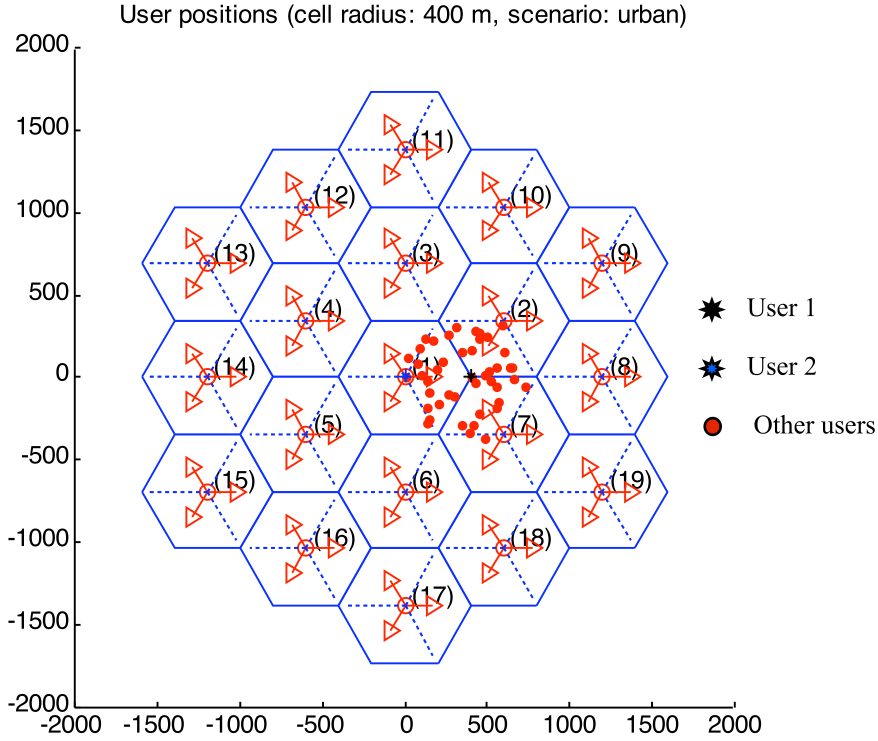

Figure 48. Example of user deployment

Figures 49 and 50 show the SNR of the signals from BSs 1, 2 and 7 received by the user 1 and 2 considered in figure 48.

Each figure corresponds to a different value for the front to back ratio (FtB), 20 dB and 30 dB. The different simulated realizations have been executed with the same seed for the random processes to avoid variations due to the effect of the shadowing.

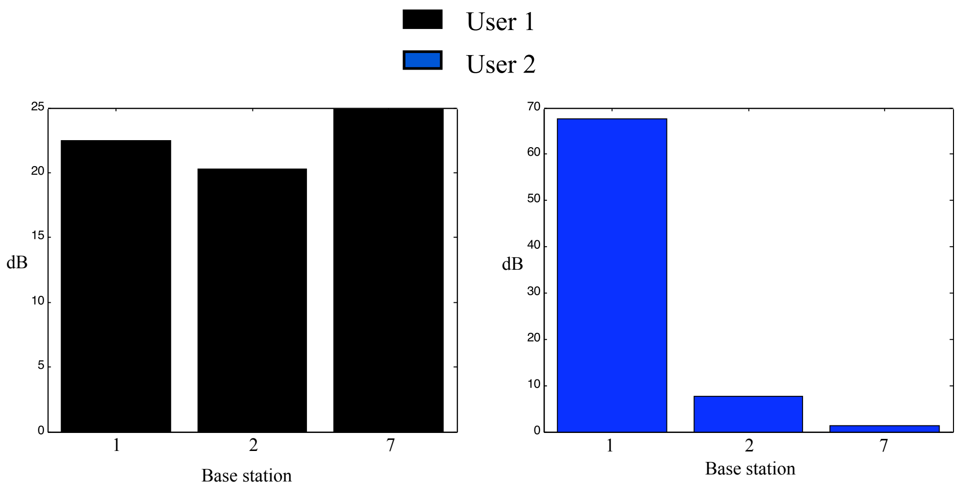

Figure 49. SNR of detected signals coming from coordinated sectors (FtB =20 dB)

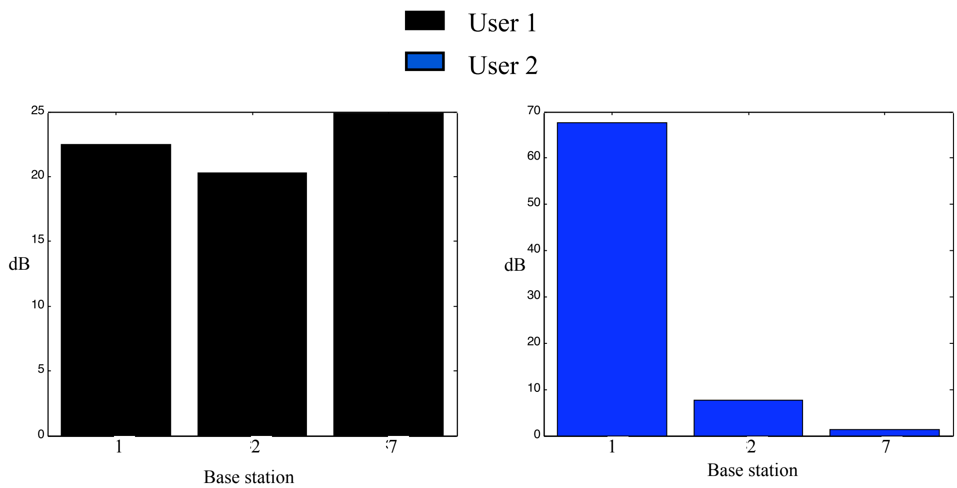

Figure 50. SNR of detected signals coming from coordinated sectors (FtB =30 dB)

We obtain almost the same results in both cases because antennas are always pointing in the direction of maximum gain or in a near one. We can observe that user 1 receives signals with low power in comparison with user 2, from the three stations in the coordinated area. These signals are very similar, so independently of the selected as useful signal, the rest will entail a high interference and the SNIR will be very bad. It would have sense to apply a coordination between these three sectors to not interfere each other. On the other hand, user 2 has a completely different situation. In this case, he receives a very strong signal from the antenna of his sector and a very low signal from the other two. These three BSs could use the same resources.

However, the situation changes when signals from out of the coordinated area are considered, thus, external interference (see subchapter 7.9), as we have done in this work. We are going to represent the SNR of all the detected signals. Now, the front to back ratio becomes a fundamental parameter.

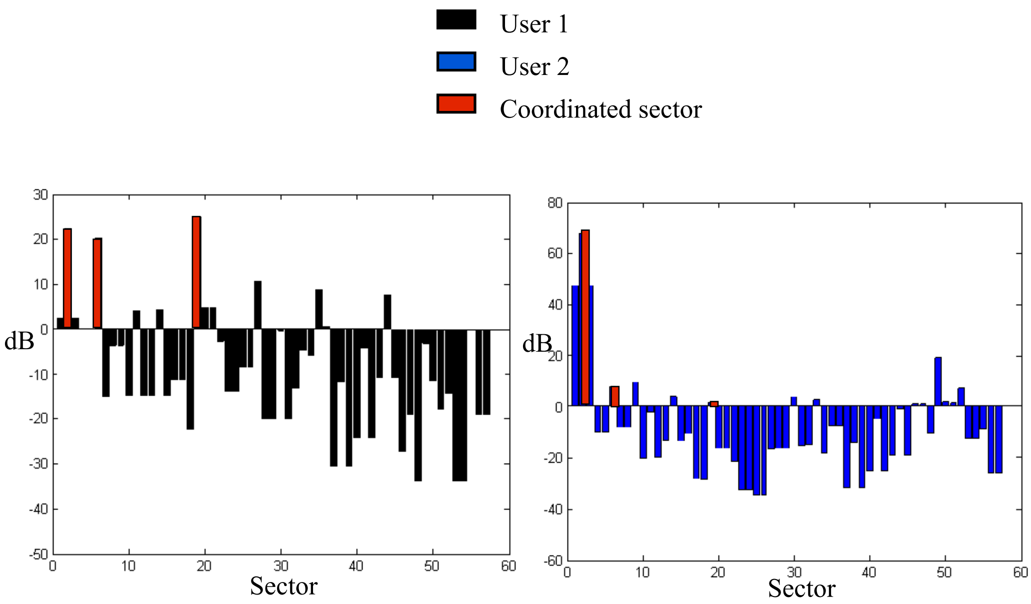

Figure 51. SNR of all detected signals (FtB =20 dB)

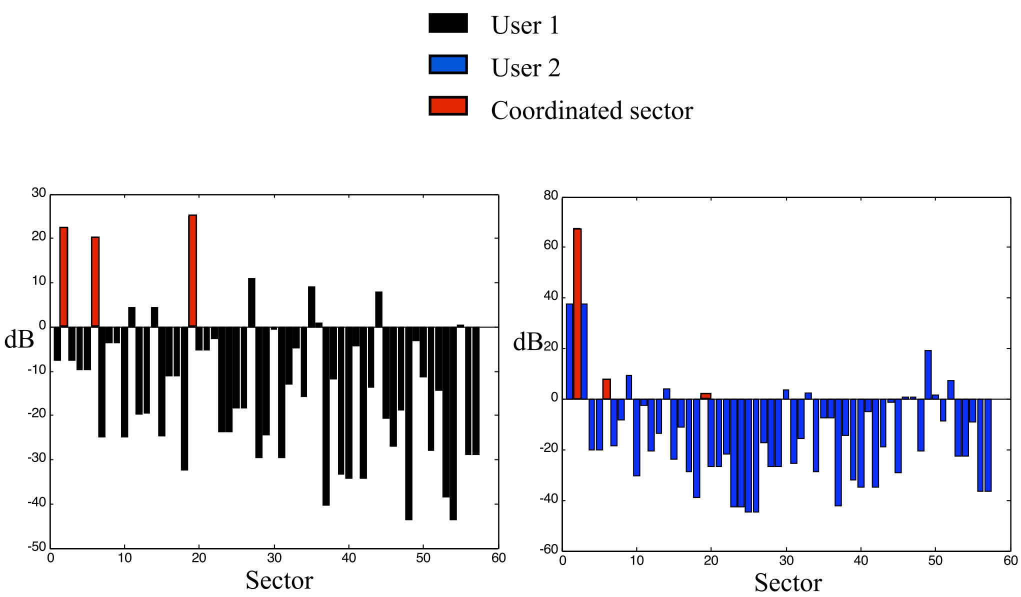

Figure 52. SNR of all detected signals (FtB =30 dB)

We can observe marked in red colour the signals from the coordinated sectors, the ones we saw in figures 49 and 50. Now, the situation has changed, because there appear other interfering sources with relevant power. These signals come from the adjacent sectors and from other non-coordinated base stations. The most harmful ones are the adjacent ones because they come from the nearest antennas. Theoretically, these signals shouldn't affect because the antenna is pointing in other direction, but in reality, there is being applied to them the maximum attenuation of the radiation pattern, that is, the front to back ratio.

If we compare figure 51 with figure 52 we observe how the signals from the adjacent sectors are attenuated 10 dB when we apply a FtB of 30 dB, instead of 20 dB. Furthermore, the power of the rest of signals coming from other base stations may be also decreased about 10 dB depending on the arrival direction.

7.8 Interfering power

7.8.1 Power per carrier allocation

In OFDMA systems each transmission has associated a set of subcarriers which conform different subchannels. We perform a uniform power allocation among all subcarriers available for each sector. However, each station transmit always a constant value of power, independently of the used bandwidth, thus, the number of assigned subcarriers. Therefore, if bandwidth becomes reduced, the power per carrier increases to obtain always the same total transmitted power. Let's see the difference between both situations in the figures 53 and 54.

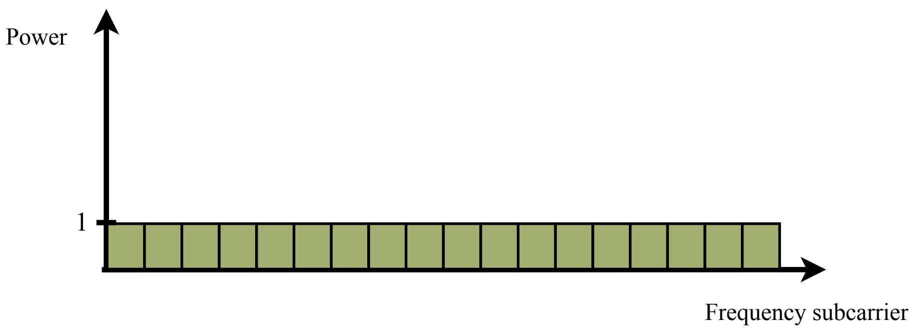

Figure 53. Transmission in one sector, using all the bandwidth.

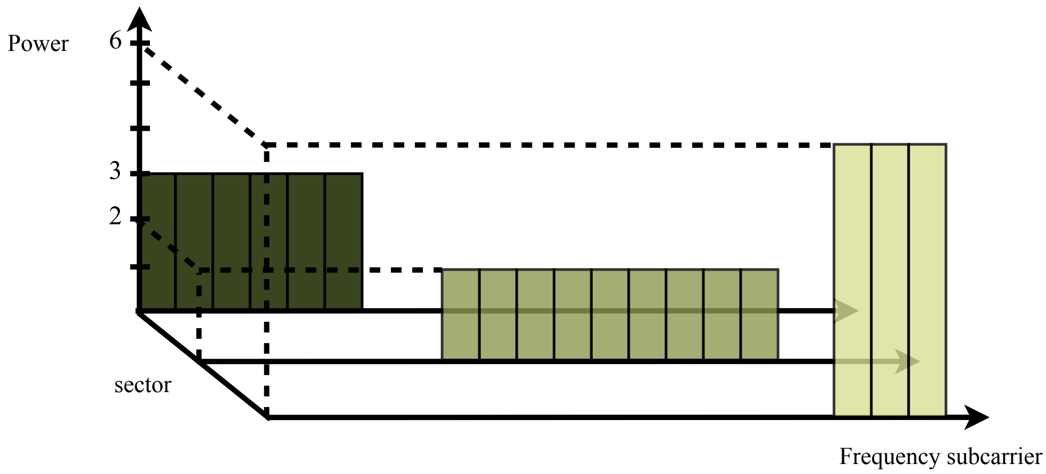

Figure 54. Transmission in three different sectors, different sub-bands.

In figure 53 we can see one base station transmitting in one sector, using all the bandwidth. In this case all subcarriers have the same power: one unit. We can see in figure 54 how the power per carrier increases depending on the transmission bandwidth. In the sector with the smallest assigned bandwidth the power per carrier has been multiplied by six, respect to the previous case. We improve the capacity, but at the price of increasing the power of the interfering signals. However, interfering signals are far enough and therefore their influence is low.

7.8.2 SNR of detected signals

Now, let's compare the SNR of the signals in a reuse 1 and reuses 1/3 for a certain user. We are going to see how it increases when power is multiplied by three and we are going to observe the signals which don't interfere because are transmitting in a different band. We are going to see how the detected interfering signals vary when we change the frequency reuse.

Figure 55 shows the position of the user and also the colour pattern which let us to identify the emitter base station for each signal.

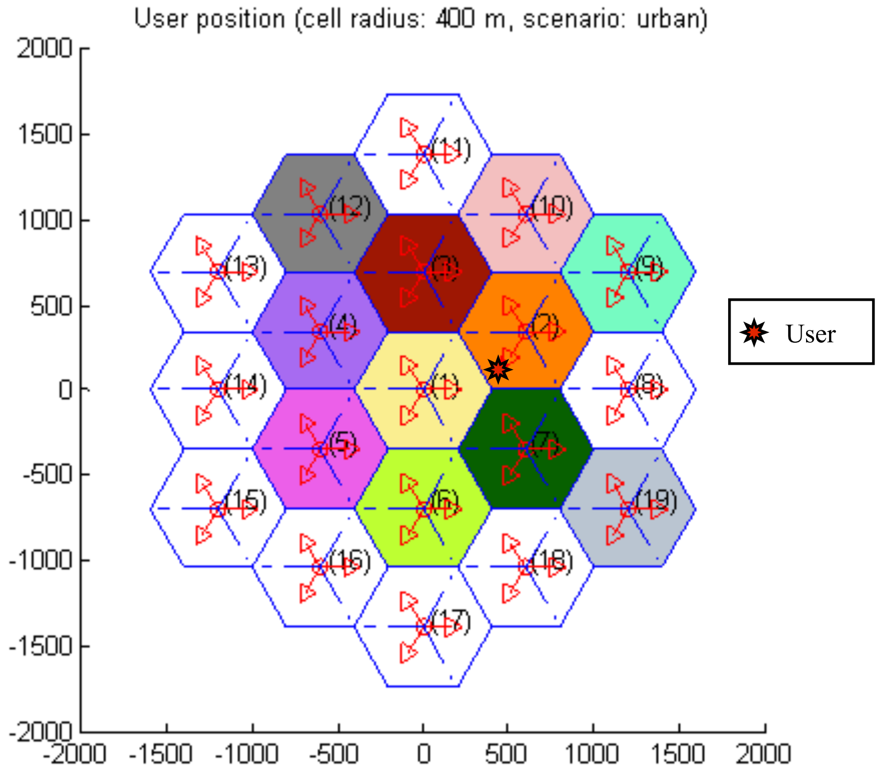

Figure 55. User position and colour pattern to identify the signals

Now we represent the SNR of all detected signals. We can see both representations: front to back ratio of 20 dB and 30 dB.

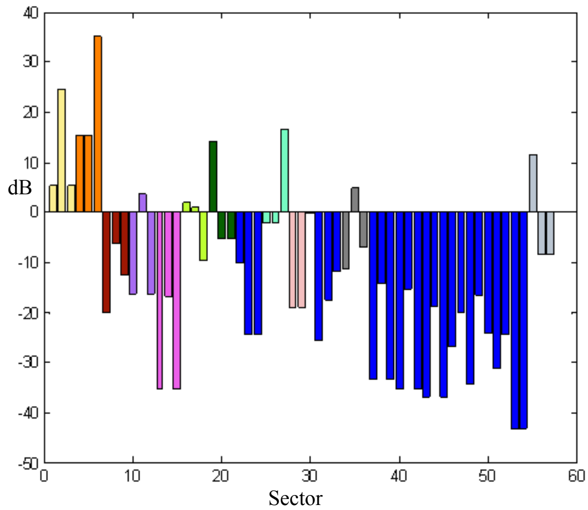

Figure 56. SNR of detected signals in reuse 1 (FtB = 20 dB)

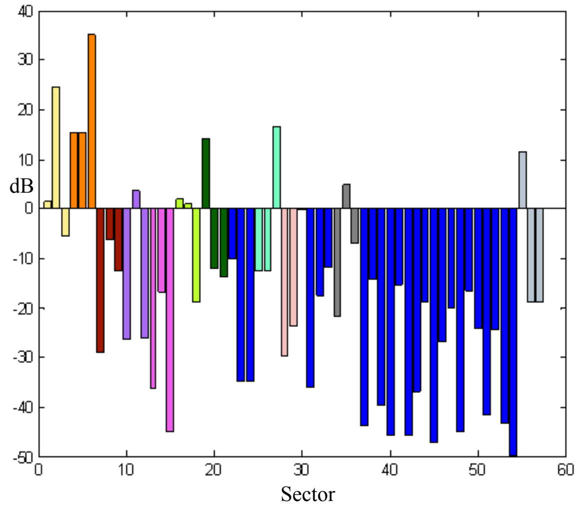

Figure 57. SNR of detected signals in reuse 1 (FtB = 30 dB)

We see in figures 56 and 57 that this user will be associated to BS 2. However, we detect a significant power from BS 1, 7, 9 and also from BS 19, which are more distant but they are directly pointing. Even if BS 10 is also pointing, the shadowing attenuates the signal. FtB of 30 dB reduces the SNR 10 dB in those stations whose signals come from directions with an angle greater than 110 º.

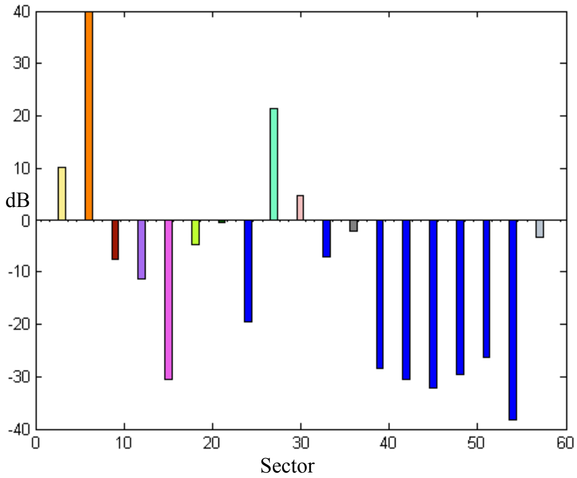

Figure 58. SNR of detected signals in reuse 133 (1) (FtB = 20 dB)

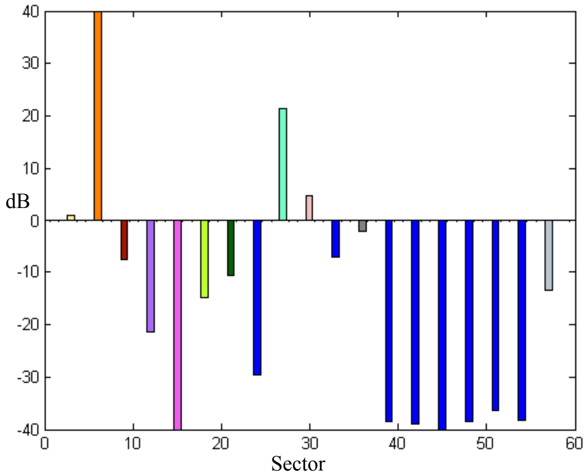

Figure 59. SNR of detected signals in reuse 133 (1) (FtB = 30 dB)

In figures 58 and 59, SNR is higher than in reuse 1 because the transmitted power has been multiplied by a factor three. There are also eliminated the interfering signals as the ones from BS 7 and 19 and also setting a FtB of 30 dB we almost eliminate the signal from BS 1 and others like BS 5.

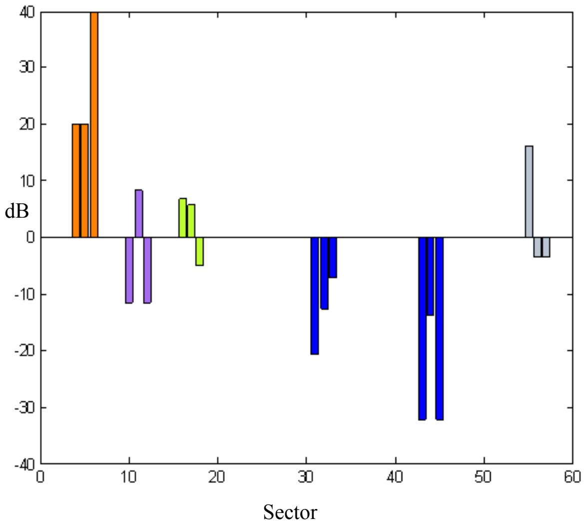

Figure 60. SNR of detected signals in reuse 331 (FtB = 20 dB)

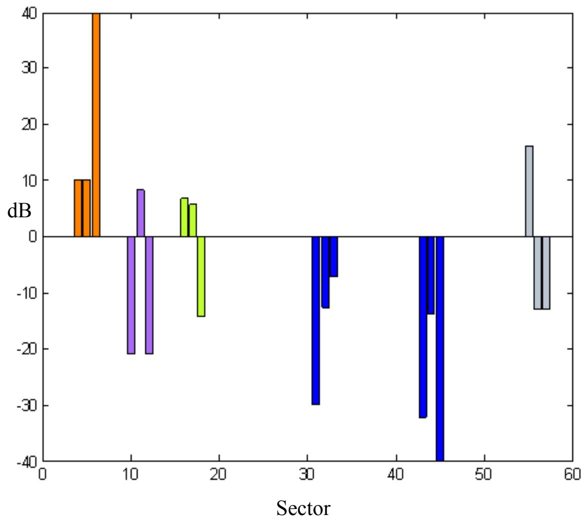

Figure 61. SNR of detected signals in reuse 331 (FtB = 30 dB)

In figures 60 and 61, we have the worst interfering signals: the ones which come from the adjacent sectors. However, they are attenuated by setting FtB of 30 dB. In this case, there is more interference than in the previous case.

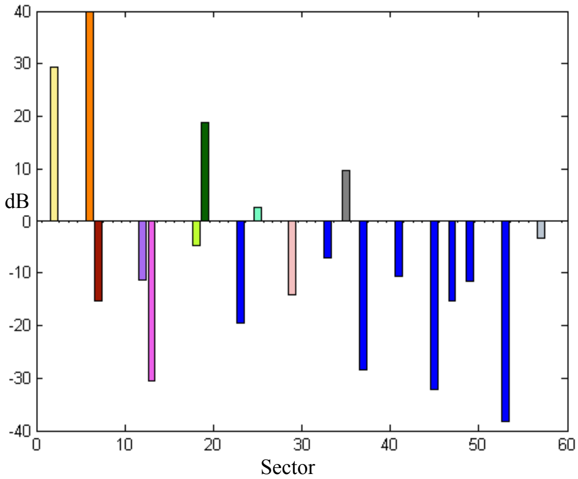

Figure 62. SNR of detected signals in reuse 133 (2) (FtB = 20 dB)

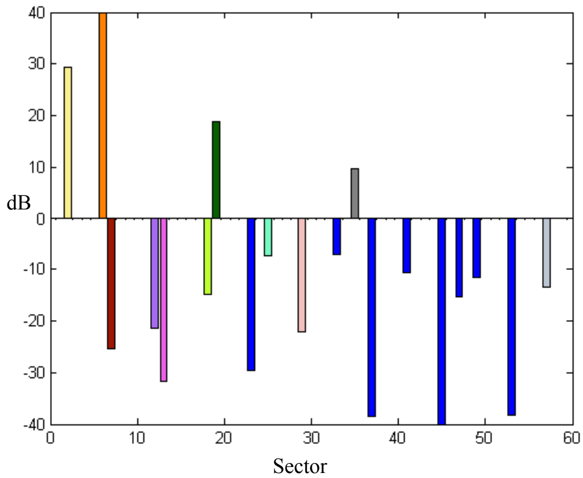

Figure 63. SNR of detected signals in reuse 133 (2) (FtB = 30 dB)

In relation to interfering powers and base stations the situation in figures 62 and 63 is similar to the reuse 133 (1) with a different distribution. The problem in this case is that the bases which are interfering the user are pointing directly and they can't be attenuated by setting a FtB of 30 dB. In this case, inter-cell coordination would be a good option. Of course it will depend on the user position, but the objective of these representation is indeed this one: to see a concrete example about the variation of the detected interfering powers and the number of interfering signals depending on the frequency reuse.

7.9 Interference models

Throughout this subchapter we are going to analyze the different interfering sources and how they affect to the receiver stations depending on the transmission scheme which is being used. By transmission schemes we understand transmission without relays and with them, considering also other criteria as the frequency reuse and the hop (the first or the second one, in the transmission with relays).

We have classified the possible interfering signals in two groups: internal and external interference. The first group corresponds to signals that come from sectors within the coordinated area (including from RS within this sector). The second corresponds to the rest of signals.

7.9.1 Transmission without relays (direct transmission)

- Reuse 1

All base stations and sectors have assigned the whole bandwidth of the system. However, we can differentiate two situations:

- The base stations in the coordinated area transmit using all the bandwidth of the system (as in fixed reuse 1 or a coordinated scheme which selects a non-orthogonal transmission).

- Even if coordinated sectors have available the whole bandwidth, they can be orthogonalized in time or frequency.

In the first situation we will be affected by internal and external interference. In the second one, sectors in the coordinated area are orthogonalized in time or frequency, so that there is not internal interference, only the external one.

Now, we are going to identify these two groups of interference: internal and external.

- Internal interference, from base stations in the coordinated area:

These interfering signals come only from the coordinated sectors. We have denoted it as I_{int}.

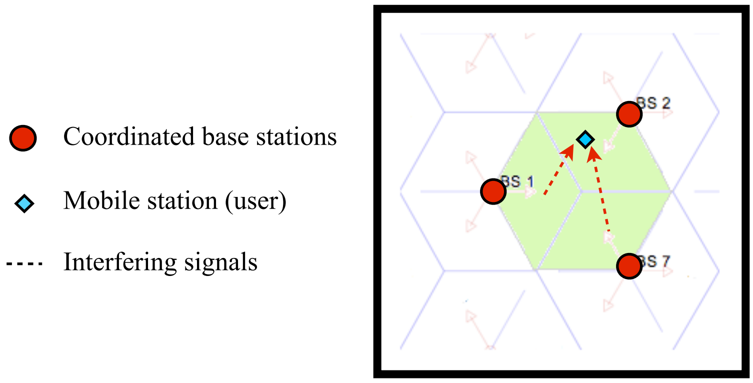

Figure 64. Representation of the interference I_{int}

The internal interfering signals are perfectly determined, since we know exactly who is transmitting and how long it does it.

However, it is different when we consider the external ones. If all base stations transmit using the whole available bandwidth, the external interference will be perfectly known. That will be the case for the fixed reuses. However, when we apply the coordinated schemes we can't know which stations are transmitting (maybe some of them are not transmitting because the optimization procedure does not assign them a sub-band or a time-slot) but it is still worse that we can't know the concrete bandwidth assignation for each sector, and some stations will be transmitting more power by carrier, depending on the assigned bandwidth[20]. The point is that, regarding a particular sub-band at the receiver, the interfering signals (in this sub-band) will have different power depending on their particular bandwidth allocation, and we can't know this information.

We assume that for a wide simulation area, signals from outside the coordinated area arrive from all directions and with a random assigned bandwidth, but statistically it is reasonably equivalent to have all stations transmitting on the whole band. In figure 65 we can see a simple example for this reasoning: we can observe see three base stations transmitting in different sub-bands and the same ones transmitting in the whole band. The power per carrier is lower in the second one but summing the interfering powers we obtain an equivalent situation.

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[20] *The total power emitted by a BS antenna has to be always the same, independently of the used bandwidth. See section 7.8.1.*

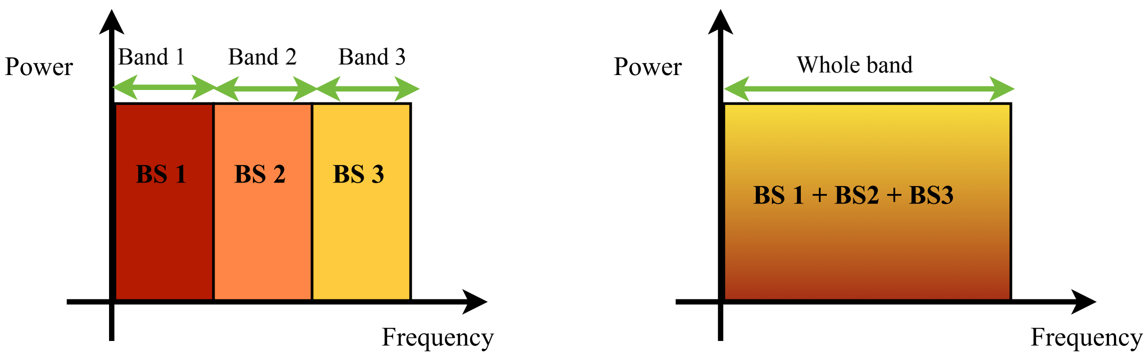

Figure 65. BS transmitting in different sub-bands (left) and in the whole band (right)

These two situations are completely equivalent because the sub-bands are equal, but if they were different, since there are a high number of sectors transmitting at the same time with different sub-band allocations statistically the stations would compensate each other obtaining an, at least approximative uniform interference power pattern. Therefore, we simplify the problem considering all base stations from outside the coordinated area transmitting at the same time with all the available bandwidth.

Then, we have to define only one kind of external interference, which is:

- External interference, from base stations outside the coordinated area:

These interfering signals come only from the non-coordinated sectors (even if they belong to a coordinated base station). We have denoted it as $I_{ext.}$

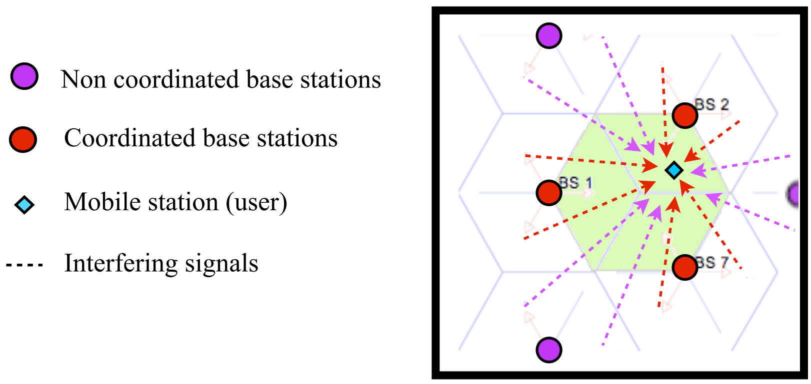

Figure 66. Representation of the interference I_{ext}

●Reuse $1/N_s$

The band is split equally in N_s sub-bands, where N_s is the number of sectors in the coordinated area. In our case it is the same number of coordinated sectors. In coordinated schemes over reuse $1/N_s$ the sub-band has to be the same for coordinated sectors, as we commented in section 4.5. In fixed reuses, they could be different.

We have only external interference if sectors are orthogonalized or also internal if they aren't.

- Internal interference, from base stations of the coordinated area:

These interfering signals come only from the coordinated sectors. However, there is an important difference between the intern interference we have described for a reuse 1 and this one: in this case, the assigned bandwidth is a $1/N_s$ portion of the whole one, and the power per carrier is increased by a N_s factor. So we have denoted this interference as I'_{int}.

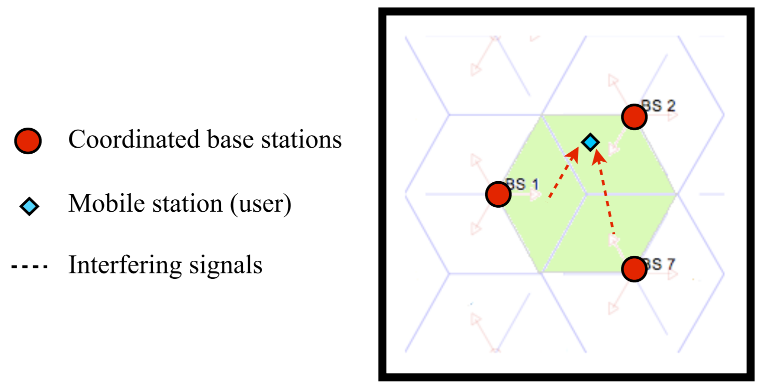

Figure 67. Representation of the interference I'_{int}

- Interference from the base stations outside the coordinated area:

These interfering signals go from base stations to the mobile ones. They come only from the non-coordinated sectors. In the case of fixed reuses $1/N_s$ we know exactly which sectors interfere the coordinated area. However, when we apply a coordinated scheme, we assume again that these stations transmit during all the time with all their assigned bandwidth, thus, $1/N_s$ of the whole bandwidth of the system. As a consequence, the subcarriers increase their power by a factor N_s respect to the reuse 1.

In both cases, fixed or dynamic reuse, the interference only will come from the sectors which transmit in the same sub-band than the station which the user is associated to. So the number of stations which interfere a concrete sector is divided by N_s. We have denoted this interference as $I'_{ext.}$

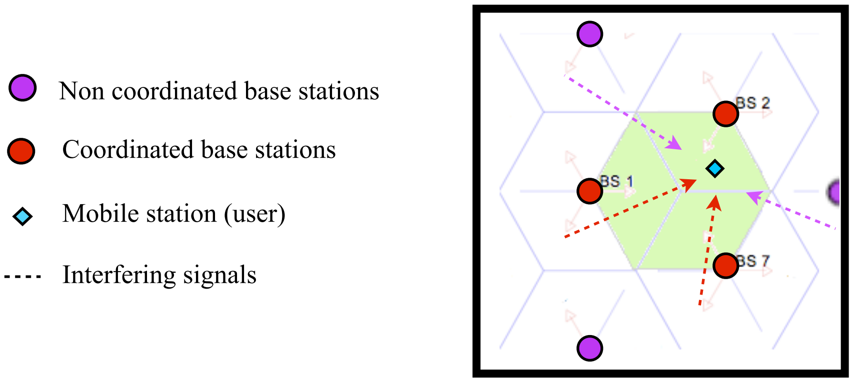

Figure 68. Representation of the interference I'_{ext}

7.9.2 Transmission with relays

- Reuse 1

In this case we also have to differentiate the following two situations:

- The base stations in the coordinated area transmit using all the bandwidth of the system.
- Even if all base stations have available the whole bandwidth, the coordinated sectors can be orthogonalized in time or frequency.

When we use the relays in the first situation, the phase durations have to be equal for each coordinated sector. Respect to the phases, we have to consider:

> - First phase: the base stations transmit to the relays. There is interference of the coordinated sectors, thus, internal interference from the base stations to the relays, and also external interference.
>
> - Second phase: the relays transmit to the users. In this case, to avoid the high interference of the neighbour relays we have decided to orthogonalize the relay transmissions. Then, there is not internal interference from the relays to the users. Of course, there is external interference.

The second situation, where the coordinated sectors are orthogonalized, is the simplest one, because it always implies only external interference. Also, since the coordinated sectors are orthogonalized, there is not interference from the relays to the users in the coordinated area, and every sector decide if it transmits using the relays or not independently.

Now, let's describe the different interfering sources and signals. Let us start by the internal interference.

- Internal interference, from base stations of the coordinated area:

In the transmission with relays this interference affects only to relays. The interfering signals go from base stations to the relay ones. We have denoted it as $I_{int\text{-}relay}$

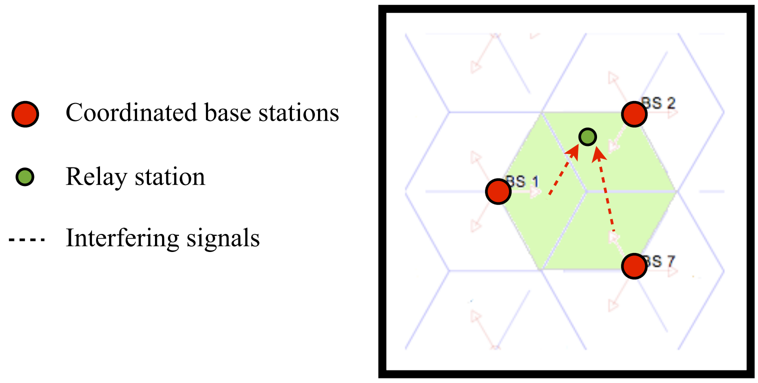

Figure 69. Representation of the interference $I_{int\text{-}relay}$

All these internal signals are totally determined.

However, concerning to the external interference, we have the same problem than for direct transmission: we can't know the scheme they are using, in terms of frequency band allocations. But in this case, it is still more complicated because we don't know which sectors are using the relays and which are not. Then, we consider only transmissions of the base stations. Actually, all of them are always transmitting in the whole bandwidth.

The interference we have to deal with is:

- External interference, from base stations outside the coordinated area:

We have to differentiate two different figures with this kind of interference: the signal which goes from base stations to the relay ones and the signal which goes to the users. Let us denote them as $I_{ext\text{-}relay}$ and $I_{ext\text{-}user}$, respectively.

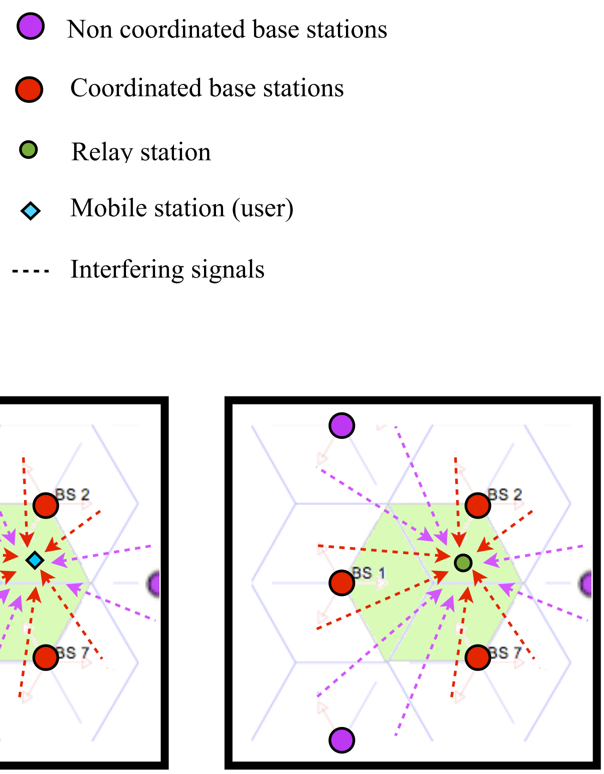

Figure 70. Representation of the interference $I_{ext\text{-}user}$ (left) and $I_{ext\text{-}relay}$ (right)

● Reuse $1/N_s$

In this case, the band is split equally in N_s sub-bands. We have the same situations than for direct transmission.

Let us define the interfering signals:

- Internal interference, from base stations of the coordinated area:

In the transmission with relays this interference affects only to the relay stations. Their power per carrier is increased by a N_s factor. We can denote it as $I'_{int\text{-}relay}$

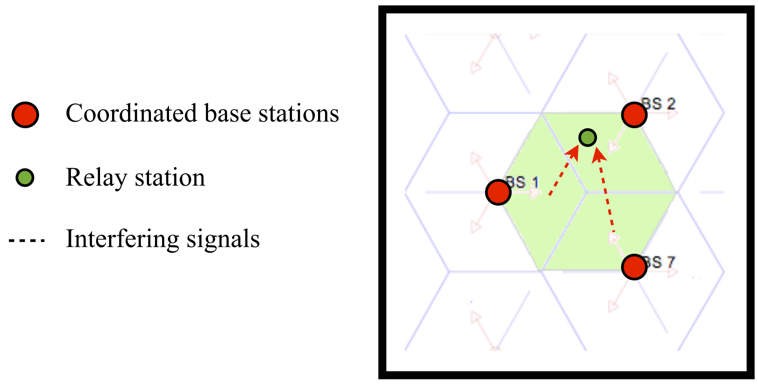

Figure 71. Representation of the interference $I'_{int\text{-}relay}$

- Interference from the base stations outside the coordinated area:

The interfering sources will be only the base stations. However, only those which transmit in the same sub-band, but with a power per carrier increased by a N_s factor:

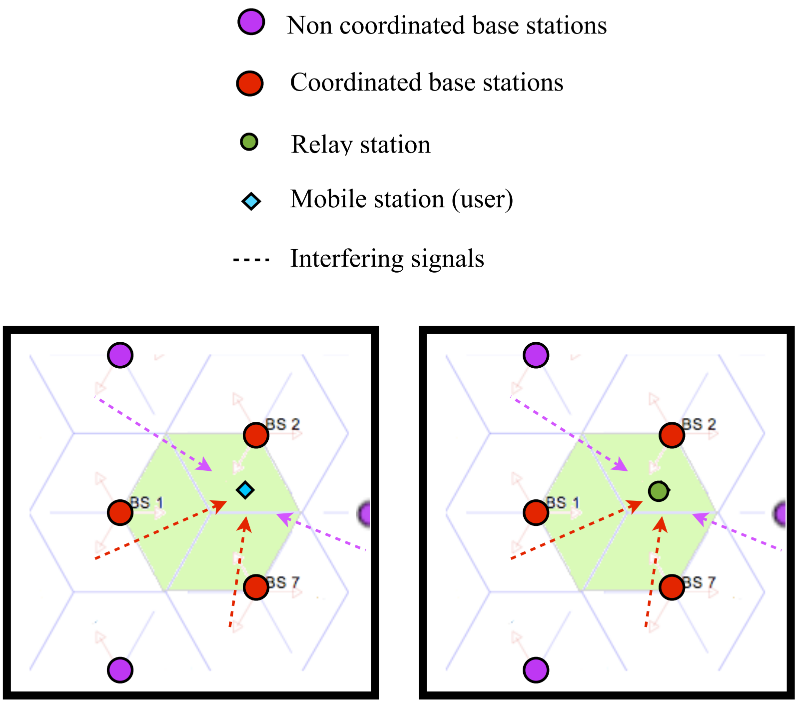

Figure 72. Representation of the interference $I'\_base_{ext\text{-}user}$ (left) and $I'\_base_{ext\text{-}relay}$ (right)

8. RESULTS

In this chapter we are going to present simulation results for the scenarios and parameters defined in chapter 7. Our main purpose is to compare the performance of the coordinated approach versus the conventional static frequency planning setups. Different conditions or situations are considered and they are described in the following. We have introduced two new coordinated schemes: coordinated OFDMA without extra combinations and OFDMA simplified. The first one is the same than coordinated OFDMA but not applying the combinations we presented in subchapter 4.4, only choosing the orthogonal or the non-orthogonal phase. The second one is the same but not optimizing the bandwidth assignation, thus, in the orthogonal phase, it splits the band equally in three parts, one for each sector. It is a scheme very similar to the one presented in [Sankaran09], which we described in chapter 2.

For outer coordination, offset sectors difficult the scalability of the coordination scheme. On the other hand, the interference from neighbour cells is going to be controlled by the coordination scheme. For such a reason, in the case of outer coordination, simulations will be focused mainly on converging sectors. It is not a problem, since converging and offset sectors offer the same performance. As we commented in section 7.3.2, generally the highly mixed frequency pattern does not offer better possibilities in outer coordination than converging configuration. However, we have commented some cases in which it does.

For inner coordination, scalability is possible for either converging and offset sectors. Note, however, that when all the sectors belong to the same BS there is no reason to limit the exchange of information between the sectors. Therefore, more sophisticated approaches could be considered, as for instance cooperation instead of coordination.

We will evaluate the proposed framework in terms of spectral efficiency for three different scheduling policies: maximization of the sum-rate, proportional fair and round robin per sector.

Firstly, we will evaluate the impact of coordination when the optimization objective is the maximization of the sum-rate within the coordinated area. This is the scheme with the lowest fairness, as the user with better channel conditions will be prioritized over the rest.

Secondly, we will show how introduce in the proposed framework linear utility functions or weights which include the satisfaction level experienced by the users given its served (long term) throughput. In this case, users with lower transmitted rate will be prioritized over the opposite ones.

Finally, we will see the effect of decoupling the resource allocation and scheduling by means of a preselection of users. We serve one user by sector in each scheduling period, but all of them will be cyclically served, applying a round robin policy in each sector. In this case, all the users in the sector have the same transmission opportunities. Then, when users are selected, resources will be distributed among sectors maximizing the sum-rate in the coordinated area.

If latency constraints require so, we may still serve several users per sector within a frame by repeating the optimization process several times within a frame. This scheme corresponds actually to a TDMA access within the sector as we assign to the preselected user all the sector bandwidth, but it could be applied also to OFDMA access by applying the RRM coordination to time-frequency resource units with smaller frequency granularity. Another option (sub-optimal) would be to consider that the sector bandwidth is equally split among the users in the sector. In the simulations we will considered, however, that the preselected user receive all the sector bandwidth.

Results of the cumulative distribution function will show us the advantages of using proportional fair or round robin scheduling policies, even if the results of the spectral efficiency are lower than for the sum-rate maximization method.

There is also presented some statistical information about the use of the four main transmission schemes we combine: orthogonal or non-orthogonal transmission or the mixed approaches we described in subchapter 4.4. We have shown the results for a suburban scenario.

Finally, we particularize the results for suburban scenario and round robin per sector scheduling for different relay positions (angle and distance from the BS) and a fixed cell radius (1000 or 1500 meters). It is interesting to find the optimal position to deploy the relays.

8.1 Spectral efficiency (maximizing the sum-rate)

The goal of this subchapter is to evaluate the performance of the coordinated framework in terms of spectral efficiency, when the maximization objective is the sum-rate of the coordinated area.

As we proved in sections 4.2.2, 4.3.2 and 5.2.2, in this approach the best user in each sector is selected at each transmission time. All the sector resources are given to this user and so an expanded multiuser diversity gain is achieved. We compare the performance of these approaches with the conventional uncoordinated schemes for reuse 1 and reuse 1/3. For reuse 1/3 the three possible frequency patterns named as 1/3/3(1), 3/3/1 and 1/3/3(2) are considered. As the goal is the maximization of the spectrum efficiency, we consider for these schemes also opportunistic scheduling (the best user according to the experienced signal to noise interference ratio is selected at each sector for each transmission time). The scheduling and resource allocation for these conventional schemes is done, however, individually by its sector, that is in an uncoordinated manner.

In order to understand better the interference impact, we present first a set of results achieved when the interference outside the coordinated area is neglected (which is a situation presented often in the literature). In a real cellular system, we need to cope with the interference from coordinated sectors and also from uncoordinated sectors. In such a situation, we will show that the antenna pattern, in particular the front to back ratio, has a high impact on the gain that coordinated approaches may offer.

8.1.1 Without external interference

Outer coordination and converging sectors:

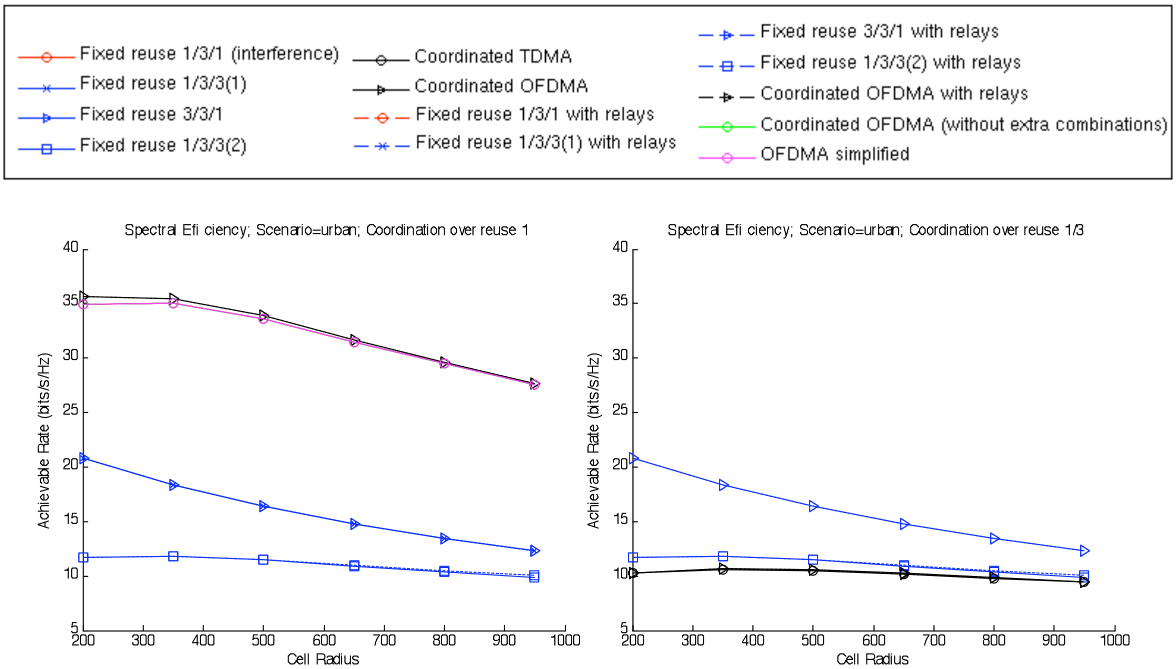

Figure 73. Urban scenario: outer coordination and converging sectors, without external interference and FtB=20 dB

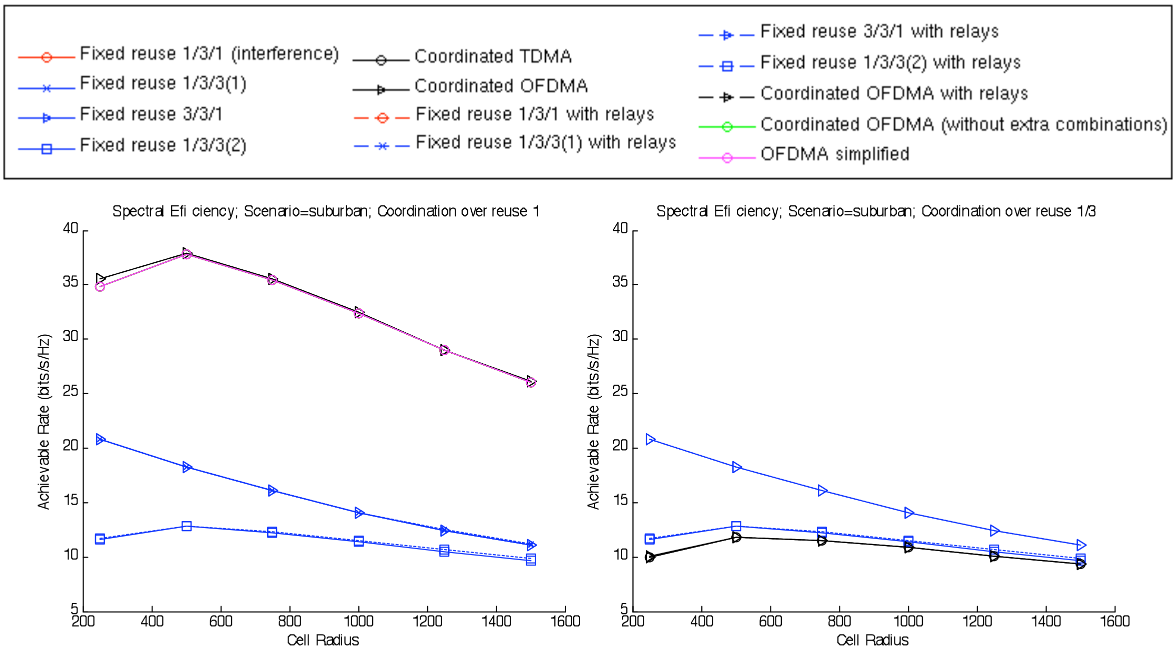

Figure 74. Suburban scenario: outer coordination and converging sectors, without external interference and FtB=20 dB

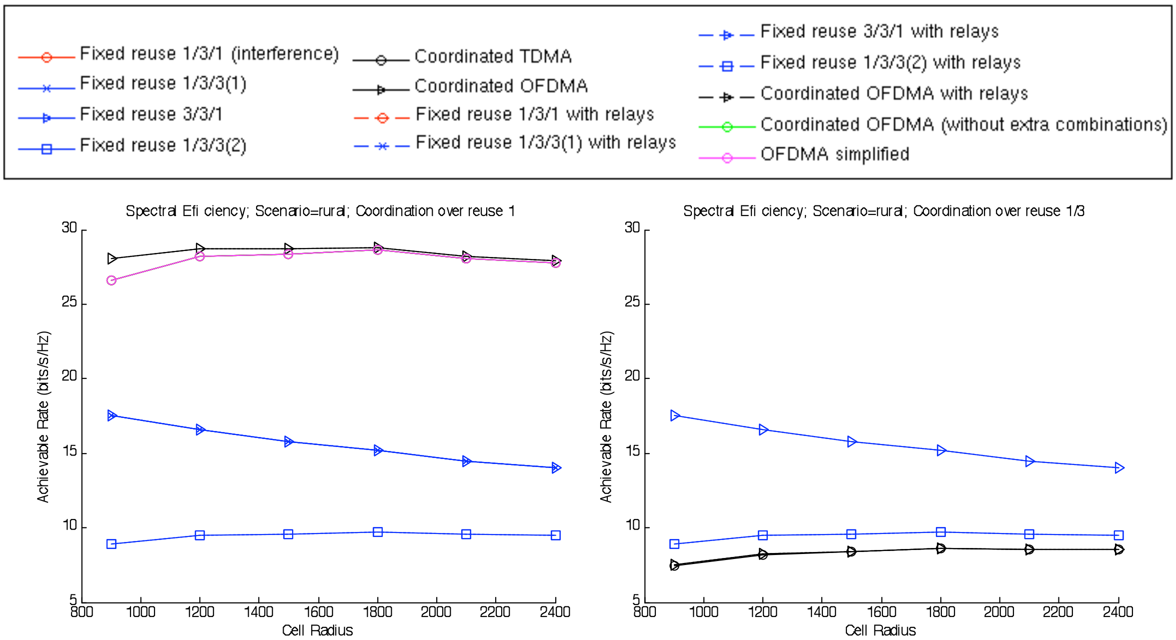

Figure 75. Rural scenario: outer coordination and converging sectors, without external interference and FtB=20 dB

All the schemes have the same behaviour when we change the scenario (urban, suburban or rural). However, in rural scenario, the achievable rate goes down slower with the cell radius than in the other cases. We can see how coordinated OFDMA over reuse 1 is the best option for all radius values but is very near to fixed reuse 1/3/1 and TDMA which actually coincide. That is because TDMA chooses always the non-orthogonal phase to transmit, which is equivalent to the mentioned fixed reuse. The rest of fixed reuses are below these results. When no external interference is considered, 1/3/3(1) and 3/3/1 are equivalent, but 1/3/3(2) is below them. That is because the maximum bandwidth in the coordinated area is one third of the whole one and all sectors transmit in the same sub-band, what means that they interfere each other, even if antennas are sectorial. When we apply coordinated OFDMA over reuse 1/3 we don't appreciate any improvement.

Relays are not offering any improvement. Their solution is the same than direct transmission. We will see that maximizing the throughput, relay transmission is worse than the direct one since we are serving the best users, those who are near the BS.

Inner coordination and offset sectors:

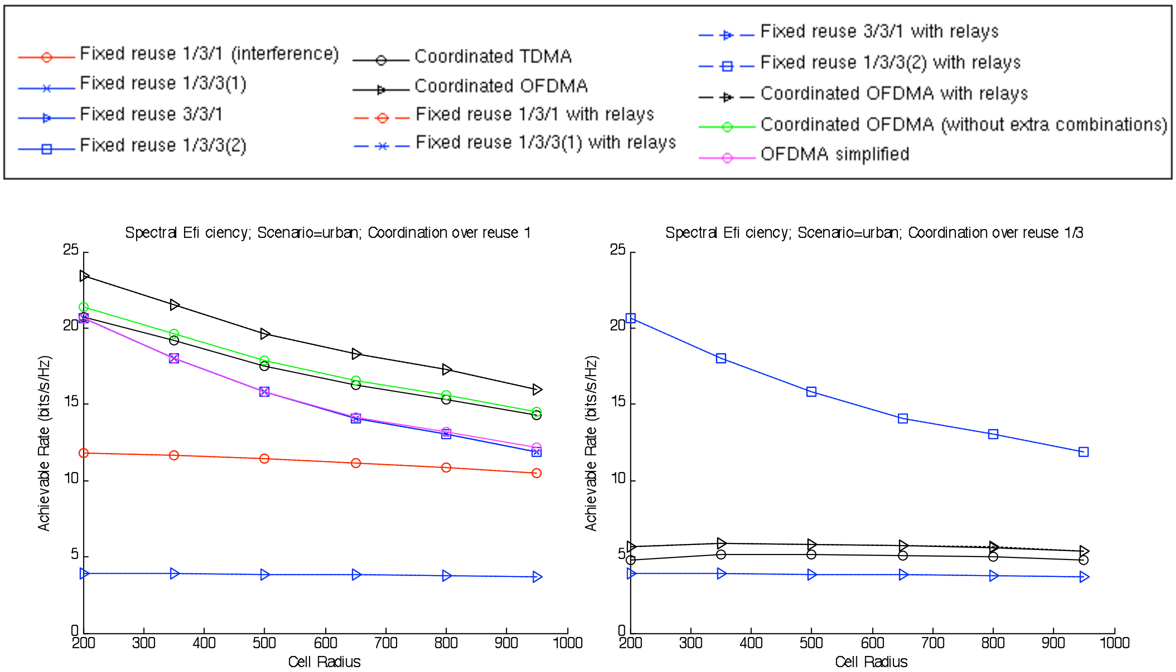

Figure 76. Urban scenario: inner coordination and offset sectors, without external interference and FtB=20 dB

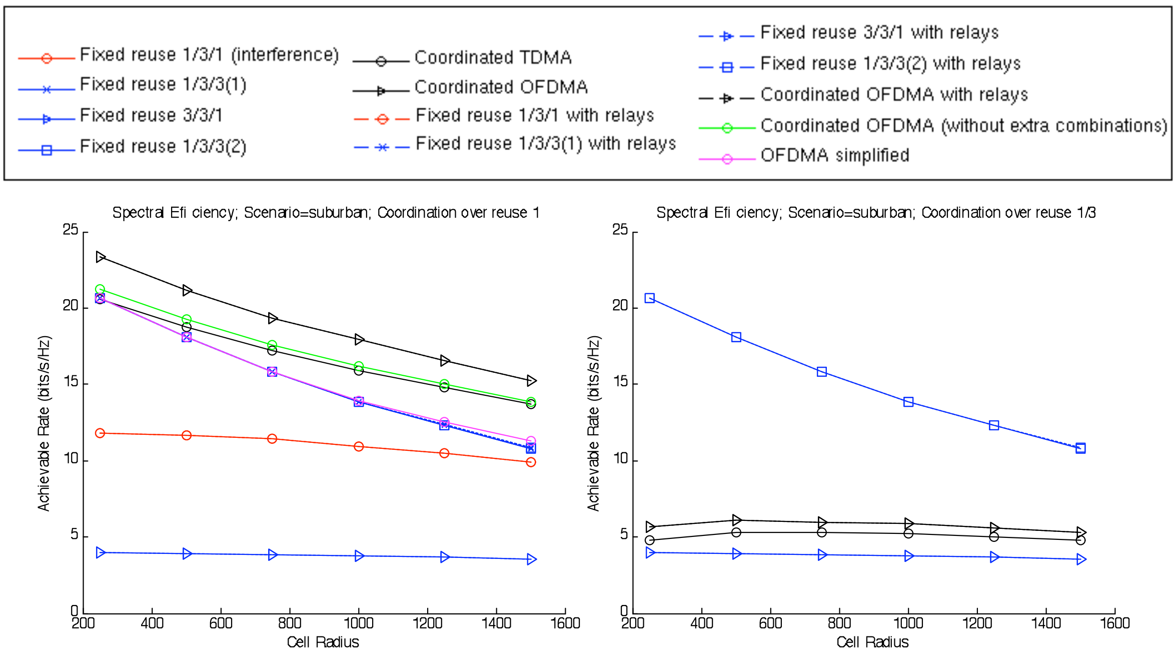

Figure 77. Suburban scenario: inner coordination and offset sectors, without external interference and FtB=20 dB

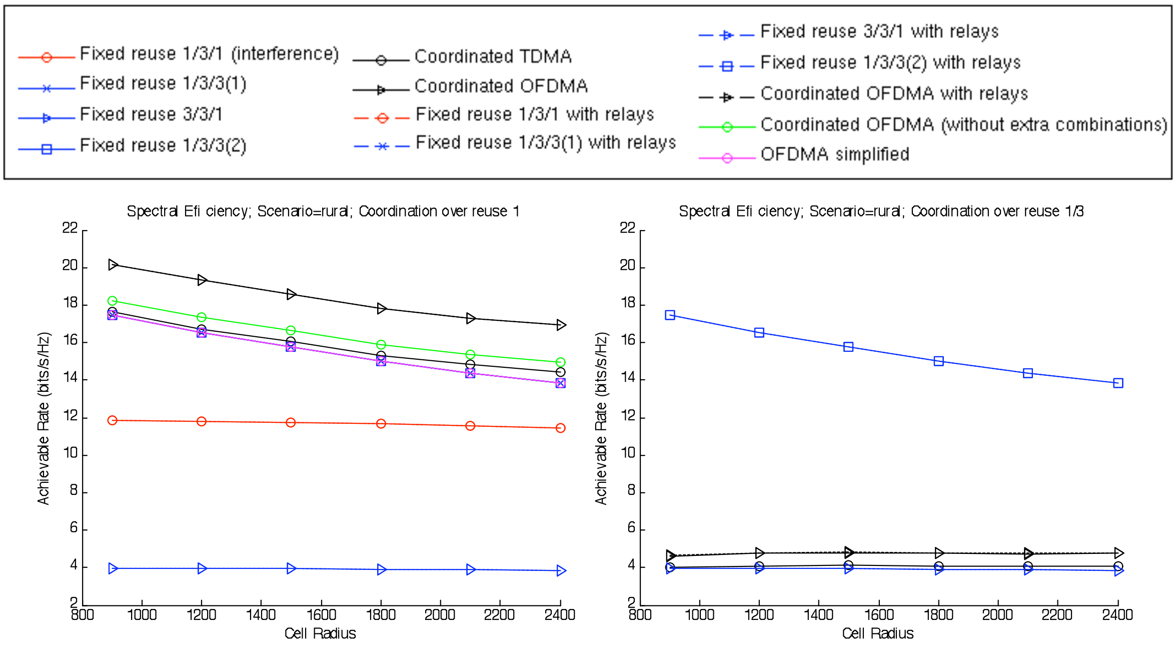

Figure 78. Rural scenario: inner coordination and offset sectors, without external interference and FtB=20 dB

In this case, coordinated OFDMA is much better than fixed reuse 1/3/1. However, fixed reuse 1/3/3(1) is a quite good option in this case. However, coordinated schemes are better except the OFDMA simplified, which coincides with the fixed reuse. We can see how TDMA performs worse than coordinated OFDMA without extra combinations, and we can see the difference between this one and coordinated OFDMA. In this case, 1/3/3 (1) and 1/3/3 (2) coincide, and they outperform fixed reuse 3/3/1, because now this scheme starts from a third of the total bandwidth and it has interference from the coordinated sectors.

In this case, we can see how TDMA and OFDMA over reuse 1/3 are better than fixed reuse 3/3/1, even if for rural scenario, TDMA is almost equal to it.

Relays are not offering any improvement.

8.1.2 With external interference

Outer coordination and converging sectors:

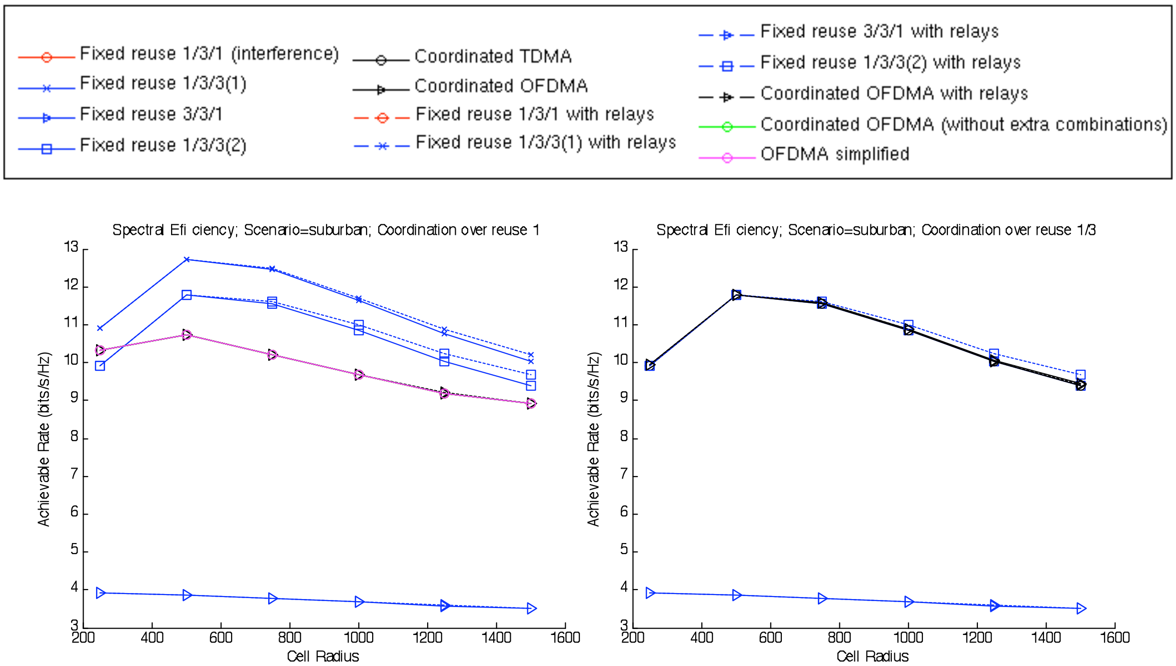

Figure 79. Suburban scenario: outer coordination and converging sectors, with external interference and FtB=20 dB

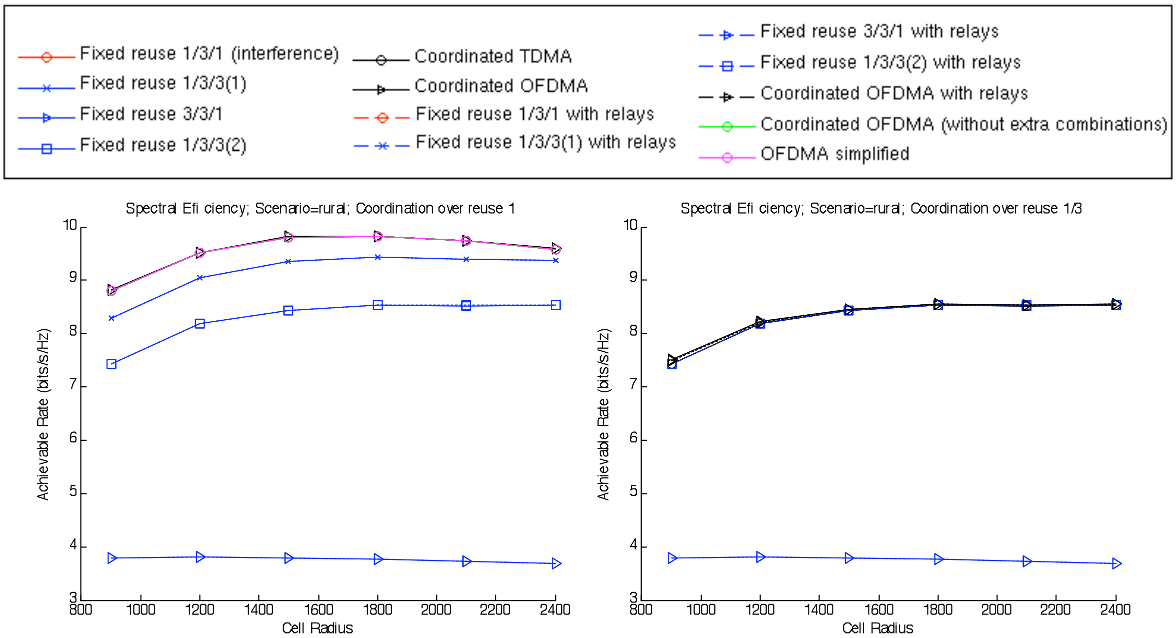

Figure 80. Rural scenario: outer coordination and converging sectors, with external interference and FtB=20 dB

External interference acts as an additional noise, and all results are lower.

When considering external interference and a FtB of 20 dB, in urban and suburban scenarios, fixed reuses 1/3/3(1) and 1/3/3(2) are better than reuse 1/3/1, which coincides with all coordinated schemes. We can see the suburban case in figure 79. However, it happens the opposite in rural scenarios, see figure 80.

Coordinated OFDMA is still very near to reuse 1 and now any fixed reuse 1/3 coincide, as happened in the case without external interference. The most penalized by interference is 3/3/1, which was equal to 1/3/3 (1) when we didn't consider the external interference, and now it is the worst option. 1/3/3(2) is the less affected by it, and now is very near to 1/3/3 (1), even if it starts from a third of the total bandwidth. However, if we remember its frequency pattern, all neighbour cells transmit in a different sub-band, so that external interference is combatted by nature.

Coordinated schemes over reuse 1/3 are not offering a better solution.

Relays enhance the spectral efficiency for high cell radius values.

However, when we apply a FtB of 30 dB, the situation in urban and suburban changes, as we can see in figure 81.

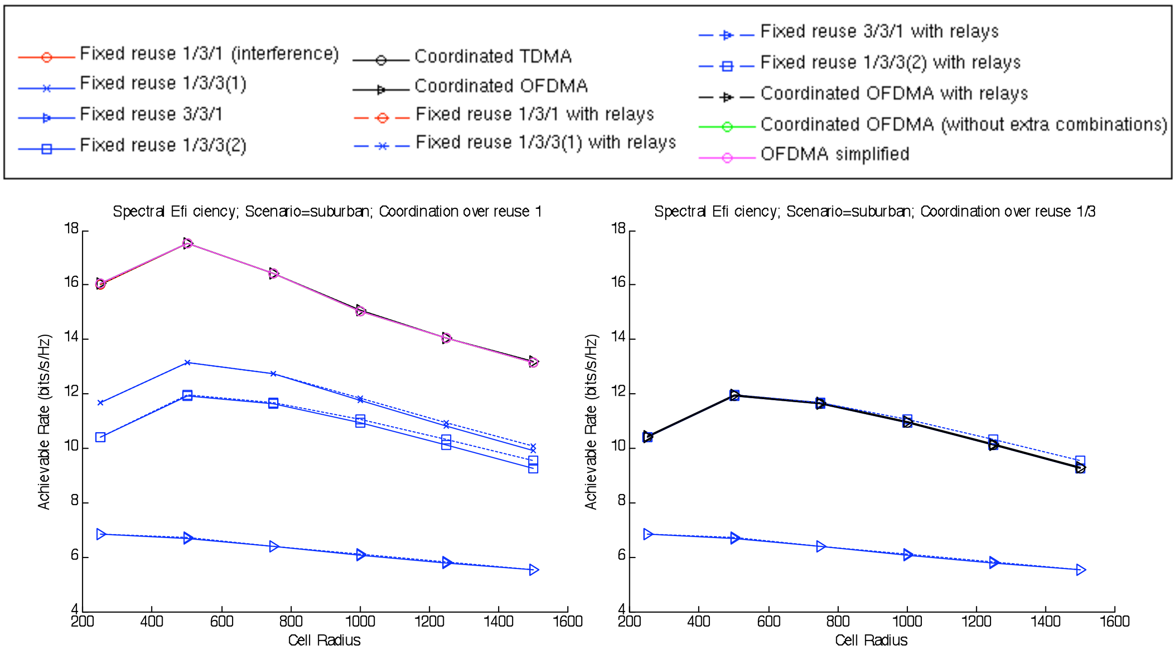

Figure 81. Suburban scenario: outer coordination and converging sectors, with external interference and FtB=30 dB

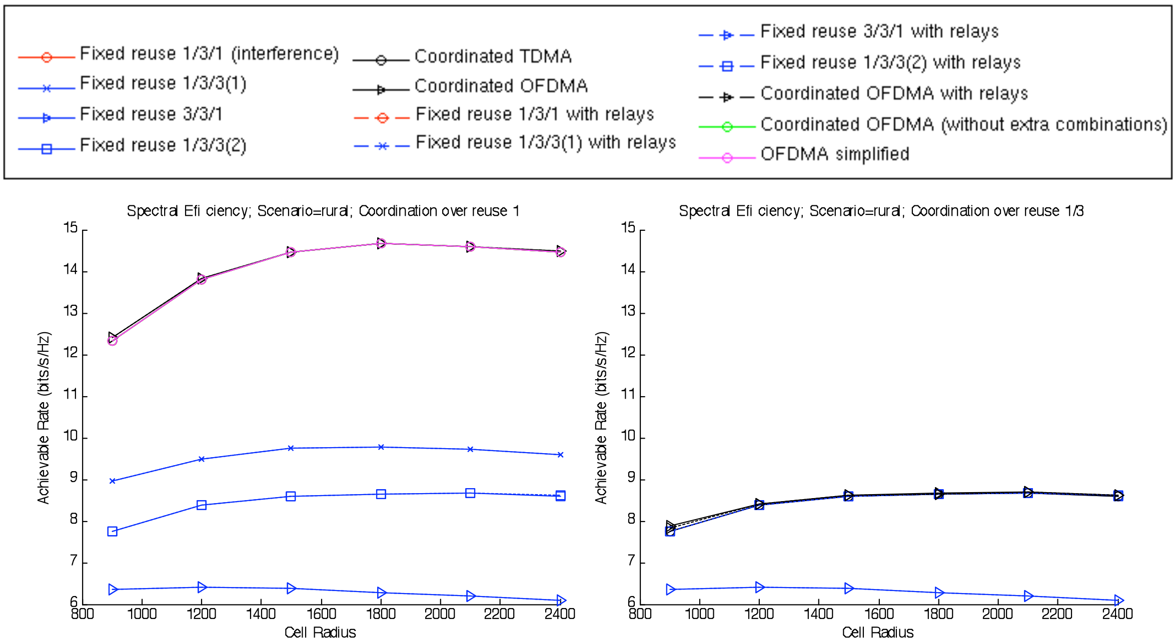

Figure 82. Rural scenario: outer coordination and converging sectors, with external interference and FtB=30 dB

When considering a FtB of 30 dB, coordinated schemes don't offer better results than fixed reuse 1/3/1. However, we can see how coordinated schemes and reuse 1/3/1 outperform clearly fixed reuses 1/3, due to the reduction of interference by means of the antenna radiation pattern. In rural scenario is still better.

Coordinated schemes over reuse 1/3 don't improve the results of the fixed ones.

Relays are not offering a good option.

Inner coordination and offset sectors:

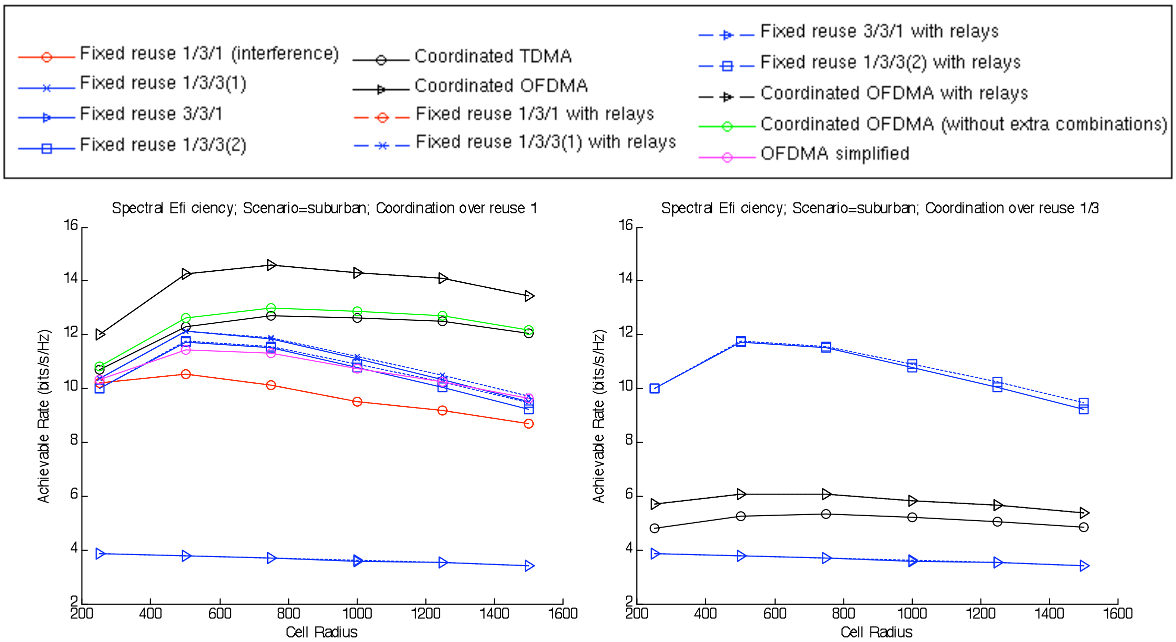

Figure 83. Suburban scenario: inner coordination and offset sectors, with external interference and FtB=20 dB

In this case, as in the case without extern interference and FtB of 20 dB, coordinated OFDMA is the best option with difference, in all scenarios. Urban and rural have the same behaviour than suburban, which we can see in figure 83. We can also appreciate the difference between OFDMA, the simplified one, and OFDMA without extra combinations. TDMA is still below this one.

All coordinated schemes over reuse 1/3 improve fixed reuse 3/3/1.

The use of relays don't improve the results.

When we apply a FtB of 30 dB, see figure 84, reuse 1/3/1 and coordinated schemes offer much better results. OFDMA is still the best option. TDMA and OFDMA without extra combinations coincide and are the second best option. However, we can't appreciate an improvement in coordinated schemes over reuse 1/3.

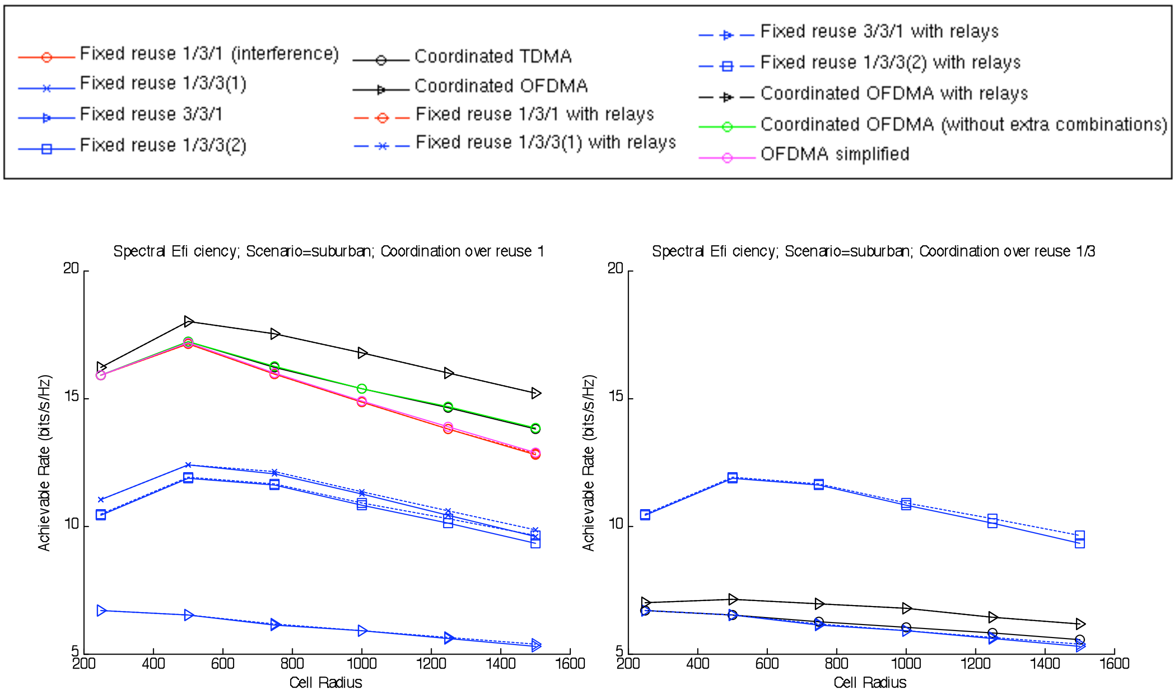

Figure 84. Suburban scenario: inner coordination and offset sectors, with external interference and FtB=30 dB

8.2 Spectral efficiency (proportional fair)

The goal of this subchapter is to evaluate the spectral efficiency performance of the coordinated framework when linear utility network functions are considered, what we call proportional fair scheduling.

8.2.1 Without external interference

Outer coordination and converging sectors:

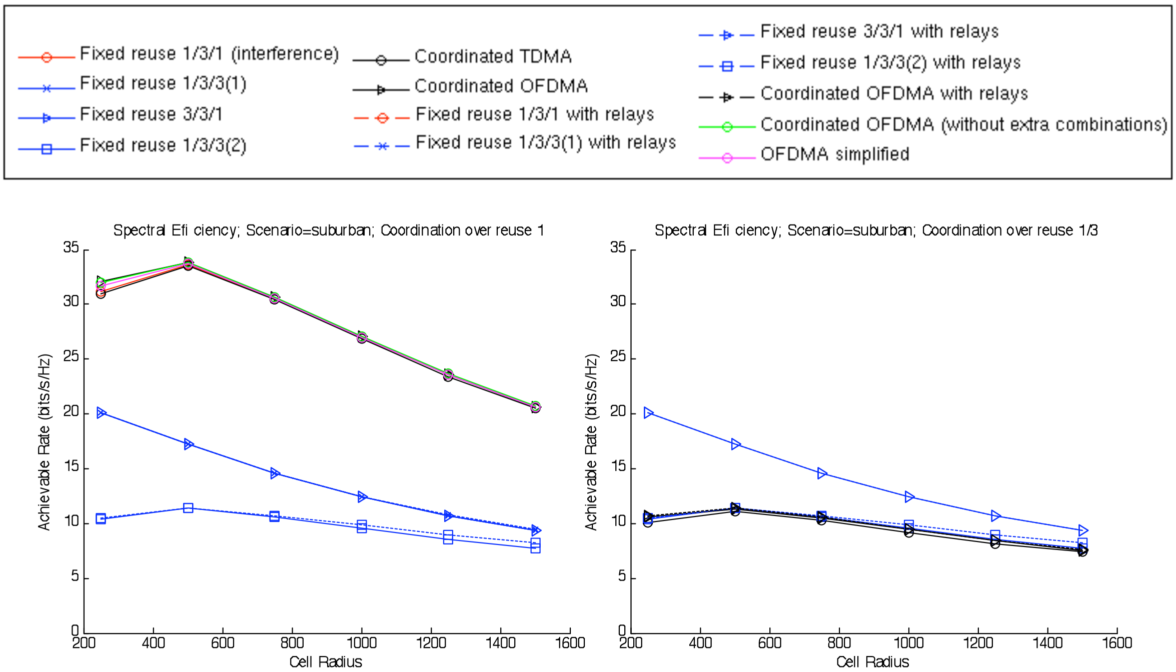

Figure 85. Suburban scenario: outer coordination and converging sectors, without external interference and FtB=20 dB

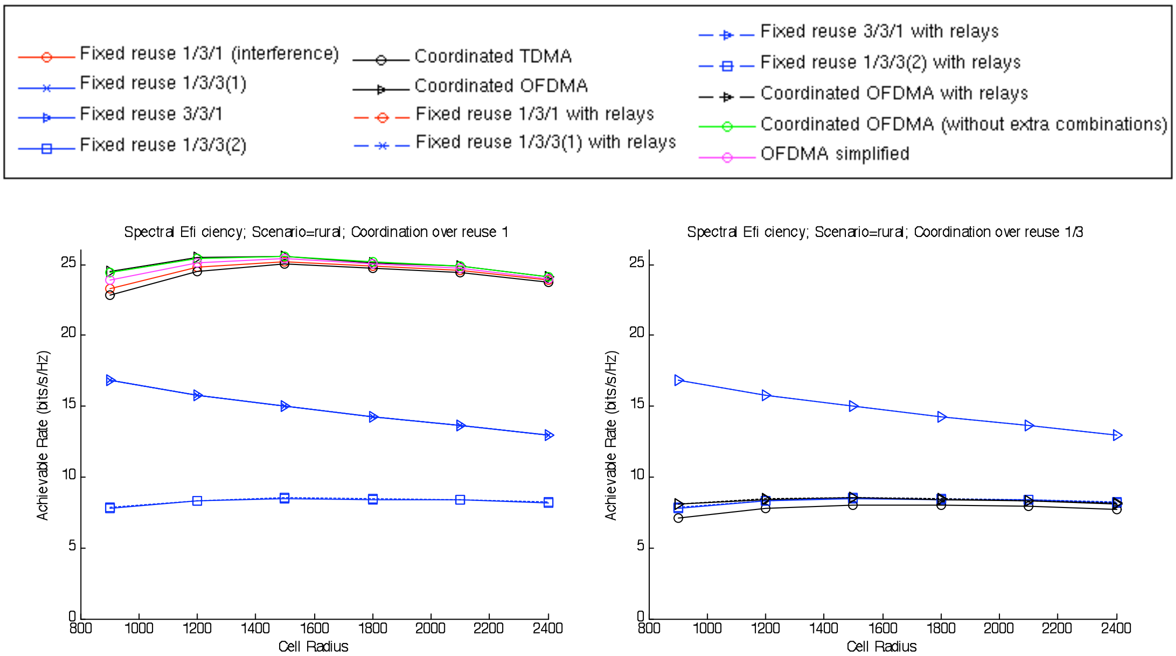

Figure 86. Rural scenario: outer coordination and converging sectors, without external interference and FtB=20 dB

These results are very similar to the sum-rate maximization. The achievable rates are very similar, even if slightly lower in this case. Coordinated schemes almost coincide with fixed reuse 1/3/1 and coordinated schemes over reuse 1/3 don't outperform the fixed ones.

Inner coordination and offset sectors:

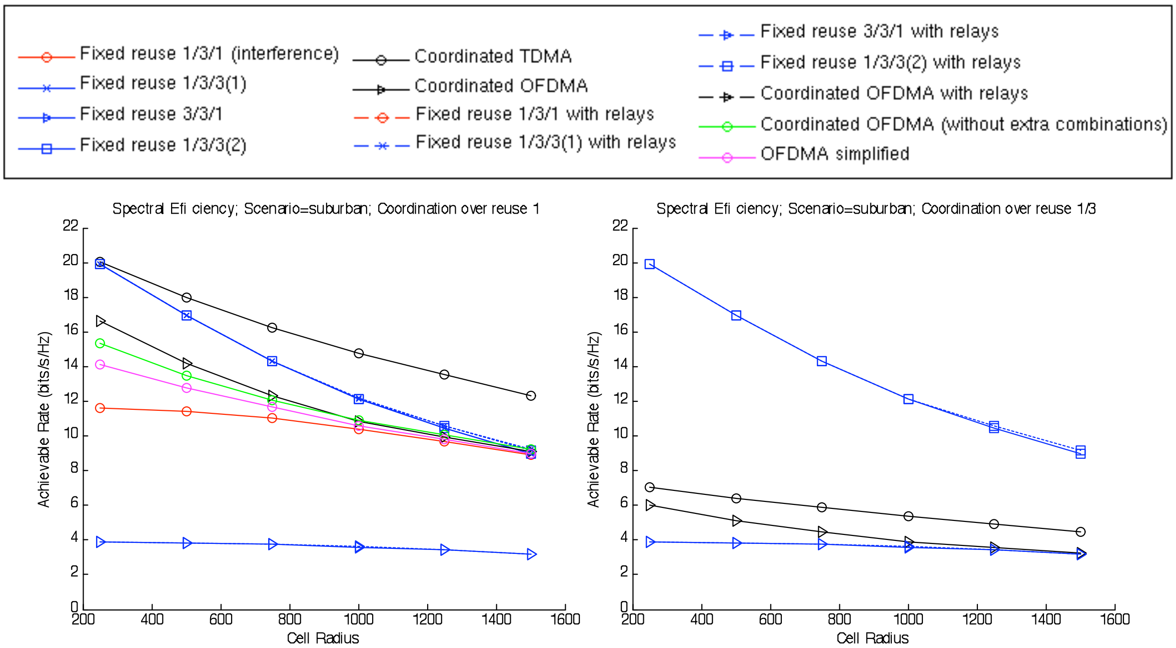

Figure 87. Suburban scenario: inner coordination and offset sectors, without external interference and FtB=20 dB

For inner coordination, all the achievable rates are also lower than in the previous scheduling method.

TDMA is the best option for all cell radius, followed by fixed reuses 1/3/3(2) and 1/3/3(1), which coincide. Coordinated OFDMA is over fixed reuse 1/3/1. It is the first case we find where coordinated TDMA outperforms OFDMA. That is because the user weights in both situations are different and they are serving different users.

8.2.2 With external interference

Outer coordination and converging sectors:

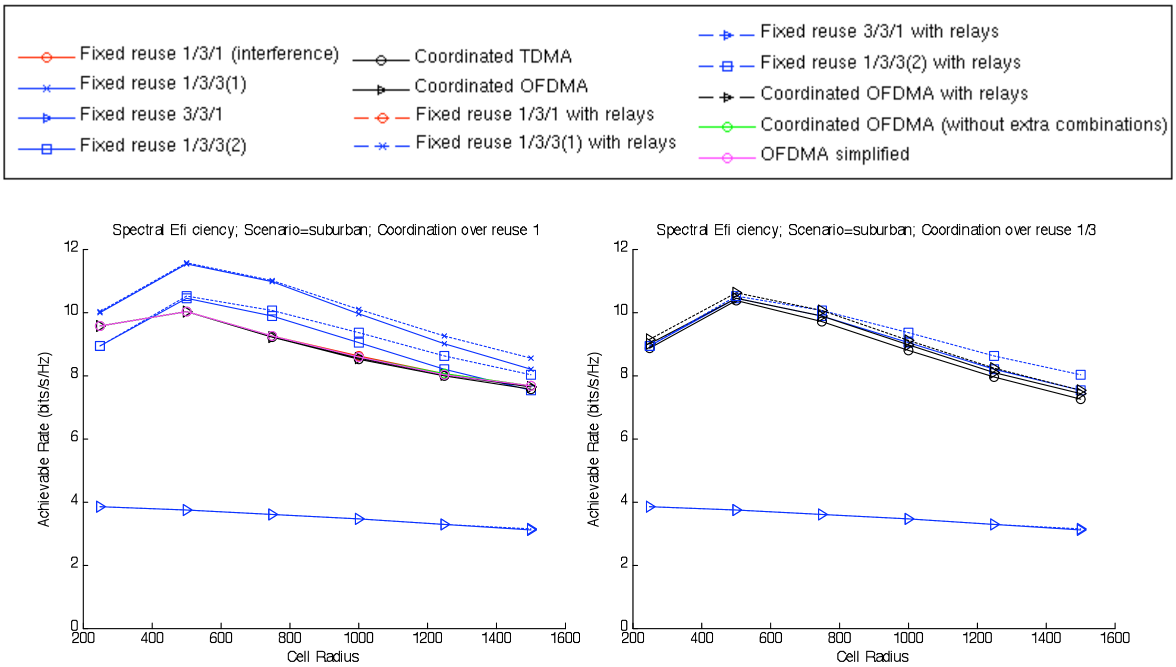

Figure 88. Suburban scenario: outer coordination and converging sectors, with external interference and FtB=20 dB

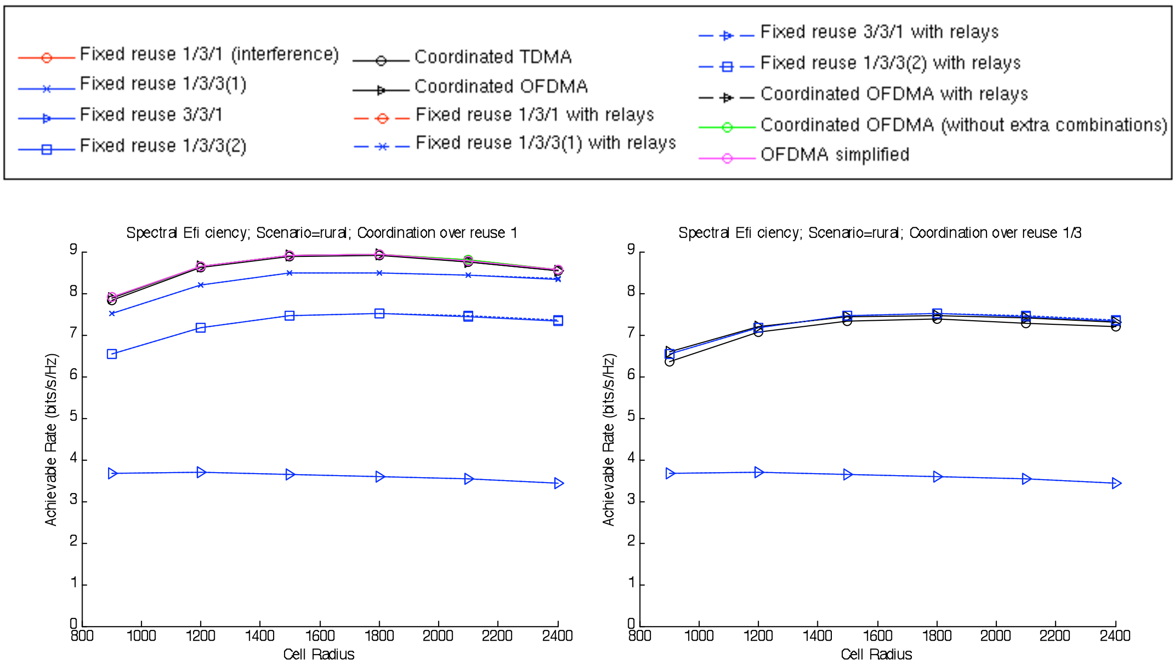

Figure 89. Rural scenario: outer coordination and converging sectors, with external interference and FtB=20 dB

We can see in figure 88 the effect of the external interference suburban scenarios for outer coordination: fixed reuses 1/3/3(1) and 1/3/3(2) are better than reuse 1/3/1 and the coordinated schemes. Even if it is not represented, urban scenario has exactly the same behaviour than suburban. In rural scenarios this interference has less impact. We saw for the sum-rate maximization than applying a FtB of 30 dB the situation for urban and suburban was inverted, and in rural scenarios the results were still better. We can see in figures 90 and 91 that the same is happening for this scheduling policy.

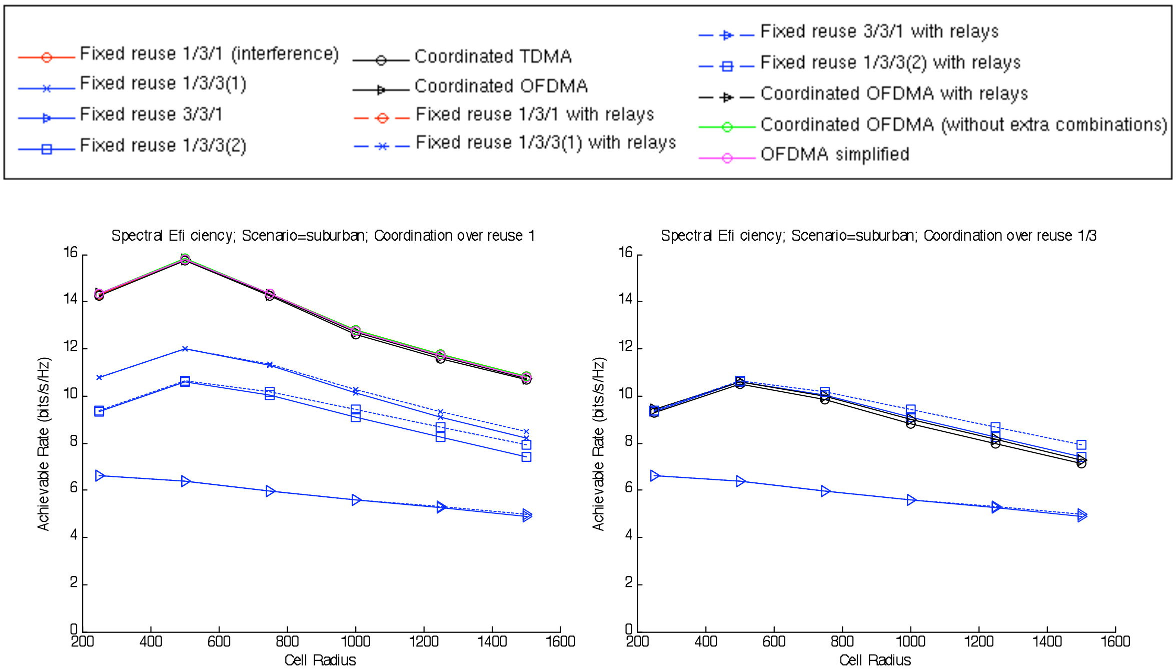

Figure 90. Suburban scenario: outer coordination and converging sectors, with external interference and FtB=30 dB

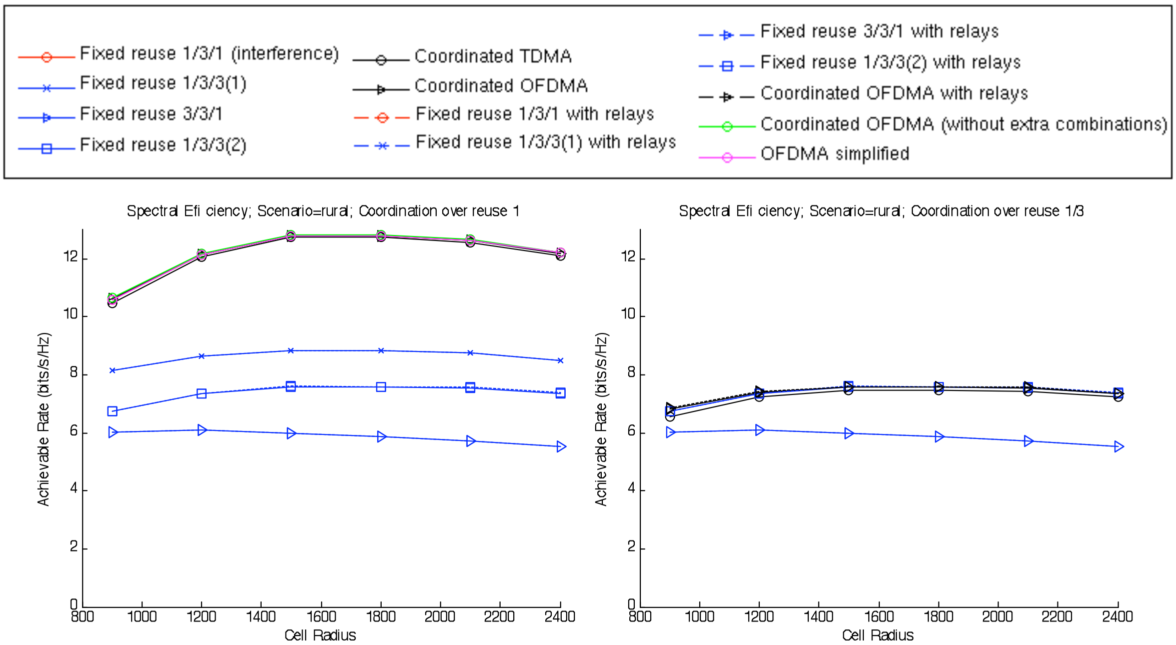

Figure 91. Rural scenario: outer coordination and converging sectors, with external interference and FtB=30 dB

Even if coordinated schemes offer the same results than fixed reuse 1/3/1, applying a FtB of 30 dB, the external interference is more rejected and they outperform all fixed reuses 1/3. In rural scenario, where external interference is expected to be lower, we can see much more improvement.

Inner coordination and offset sectors:

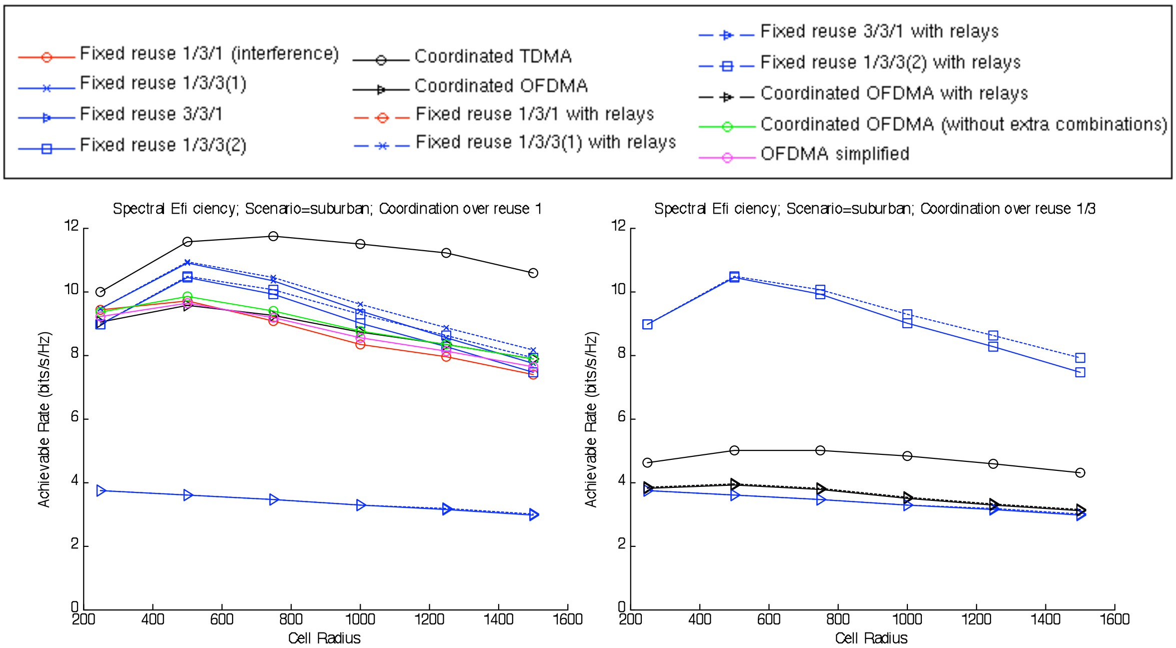

Figure 92. Suburban scenario: inner coordination and offset sectors, with external interference and FtB=20 dB

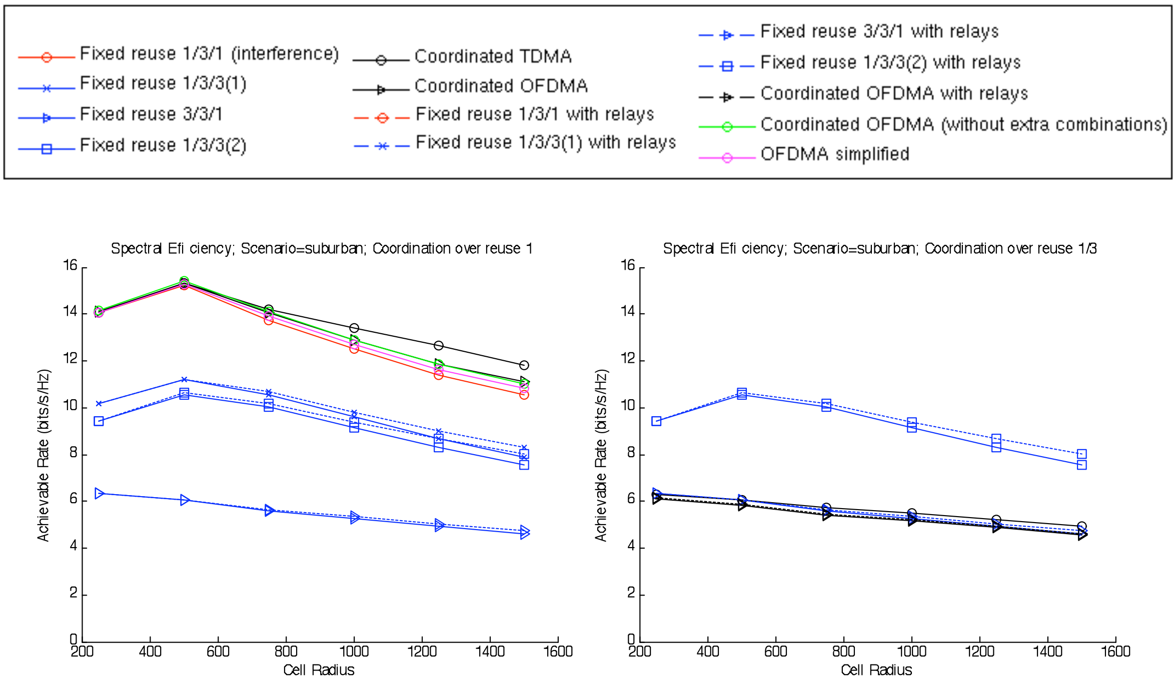

Figure 93. Suburban scenario: inner coordination and offset sectors, with external interference and FtB=30 dB

In inner coordination with external interference, when we use a FtB of 20 dB, TDMA is the best option. We still have similar results than for the maximization of the sum-rate. The rest of coordinated schemes are below fixed reuses 1/3. When we use a FtB of 30 dB, we are reducing the interference, internal and external, and coordinated OFDMA and fixed reuse 1/3/1 achieve much better results, almost reaching the TDMA rate, while fixed reuses 1/3, but fixed reuse 3/3/1, achieve a similar ones.

8.3 Spectral efficiency (round robin in each sector)

This subchapter presents spectral efficiency results corresponding to the case where every sector preselects one user at each scheduling opportunity. The coordination in this case would provide the best transmission strategy for the set composed by the preselected users at every sector.

Note that by doing so we will maximize not the system spectral efficiency but the spectral efficiency averaged over all the possible spatial positions within a sector, as all the users/ positions in one sector has the same transmission opportunities. Using this approach, the intra sector scheduling and the sector RRM coordination are decoupled. This fact presents the disadvantage that we do not optimize the composition of the users set at each transmission opportunity, but it presents the great advantage that computational complexity of the optimization is greatly simplified.

8.3.1 Without external interference

Outer coordination and converging sectors:

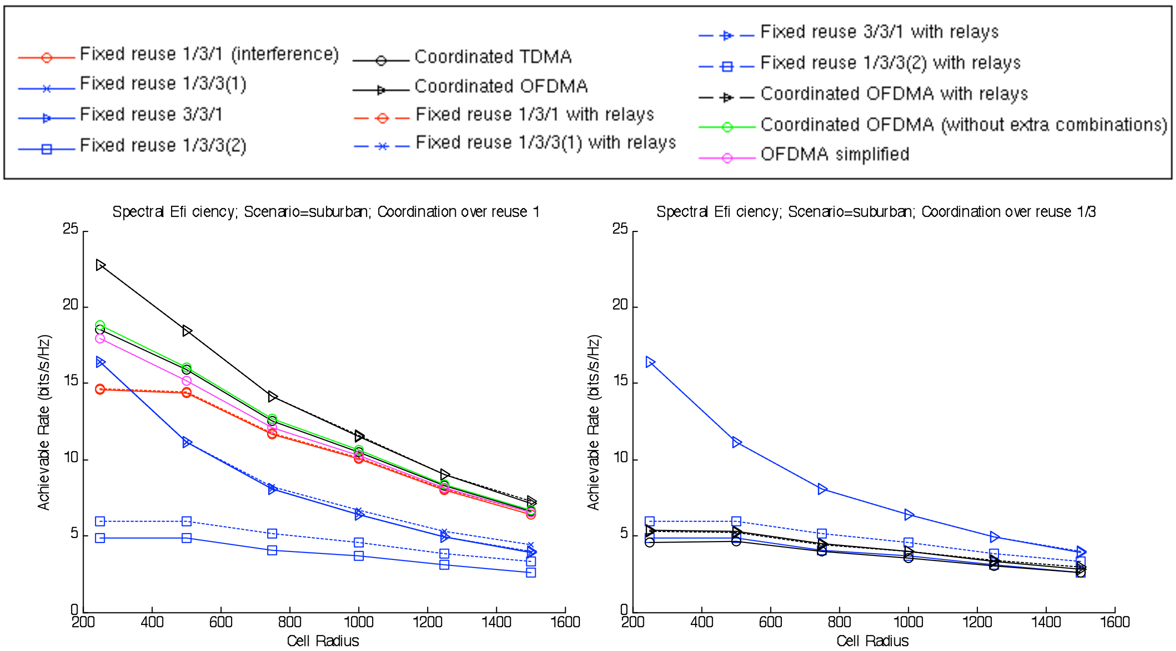

Figure 94. Suburban scenario: outer coordination and converging sectors, without external interference and FtB=20 dB

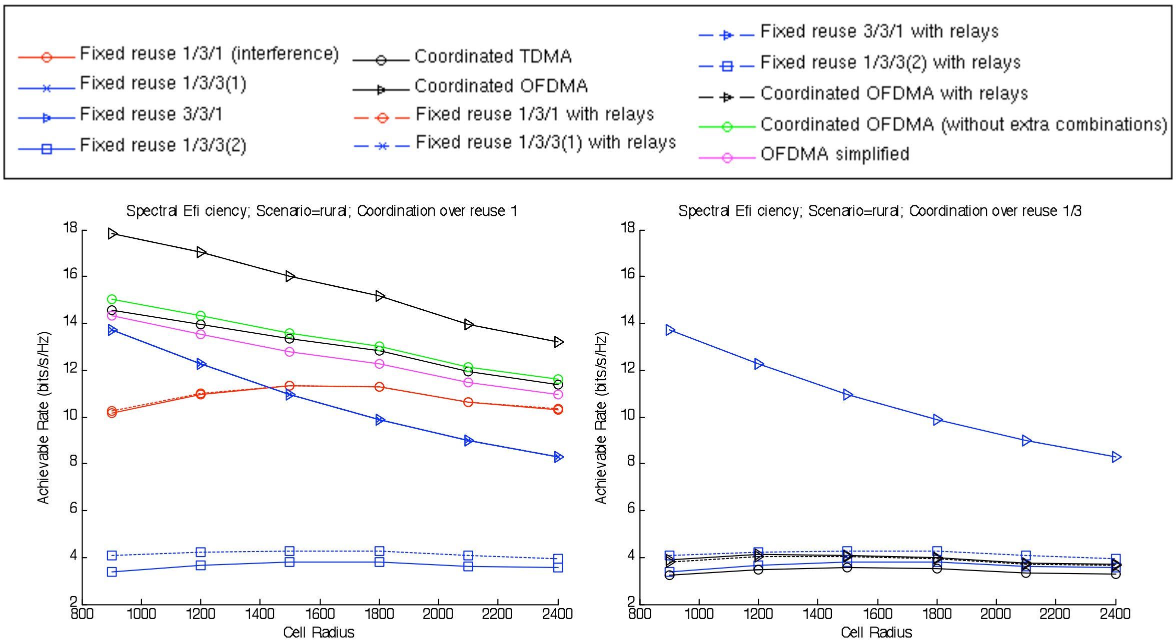

Figure 95. Rural scenario: outer coordination and converging sectors, without external interference and FtB=20 dB

When there is not external interference, always OFDMA outperforms the rest of schemes. The other coordinated ones are below in the following order: coordinated OFDMA without extra combinations, TDMA and OFDMA simplified. They are always better than fixed reuses.

For small cell radius, fixed reuse 1/3/1 is worse than 3/3/1 and 1/3/3 (1), which coincide, but there is a point where it happens the opposite. That is because increasing the cell radius, interference from neighbour cells is reduced.

We can see a little improvement by using the relays in fixed reuse 1/3/3 (2) but not in the coordinated schemes. It is interesting to see that coordinated OFDMA over reuse 1/3 is better than fixed reuse 1/3/3(2) but not when it uses relays.

Inner coordination and offset sectors:

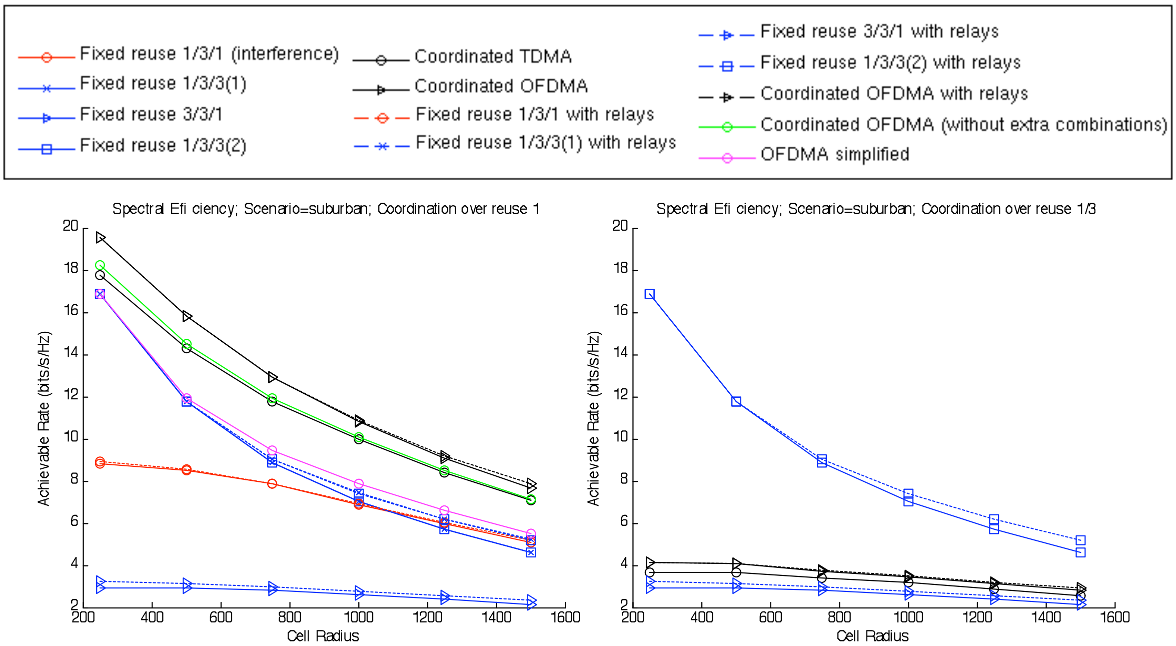

Figure 96. Suburban scenario: inner coordination and offset sectors, without external interference and FtB=20 dB

As in previous cases, coordinated OFDMA for inner coordination is better than all the other schemes. All coordinated schemes are better than fixed reuse 1/3/3(2) which is the best option for fixed reuses. Now, 1/3/1 is always below this one, unlike the previous case.

Relays don't offer a clearly better option.

8.3.2 With external interference

Outer coordination and converging sectors:

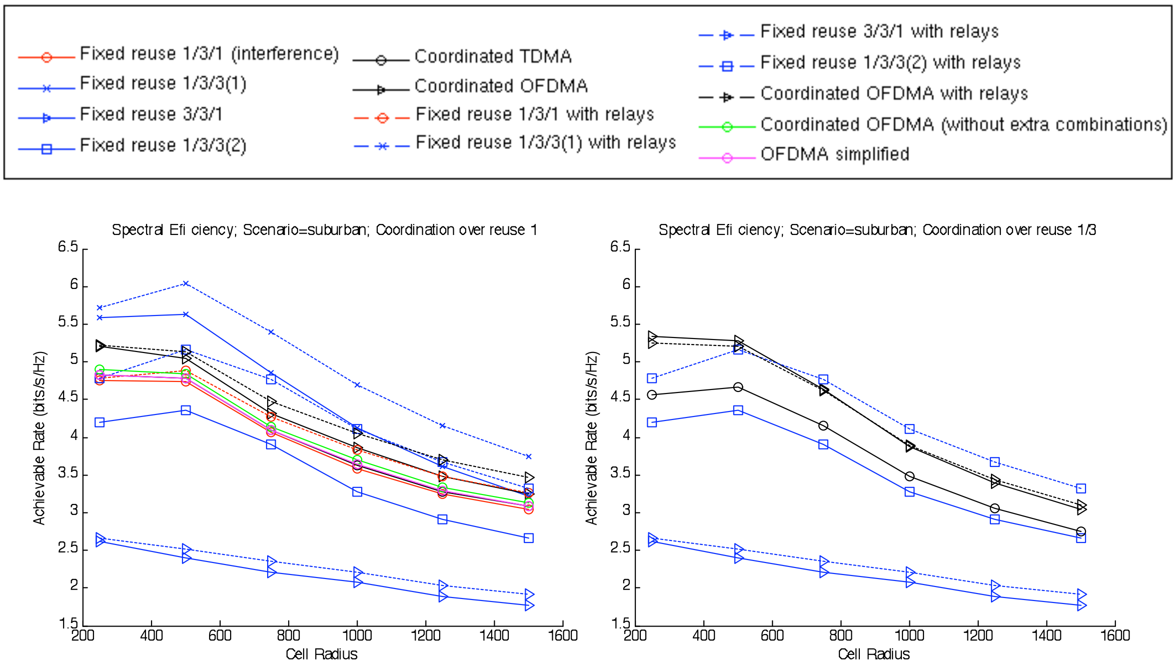

Figure 97. Suburban scenario: outer coordination and converging sectors, with external interference and FtB=20 dB

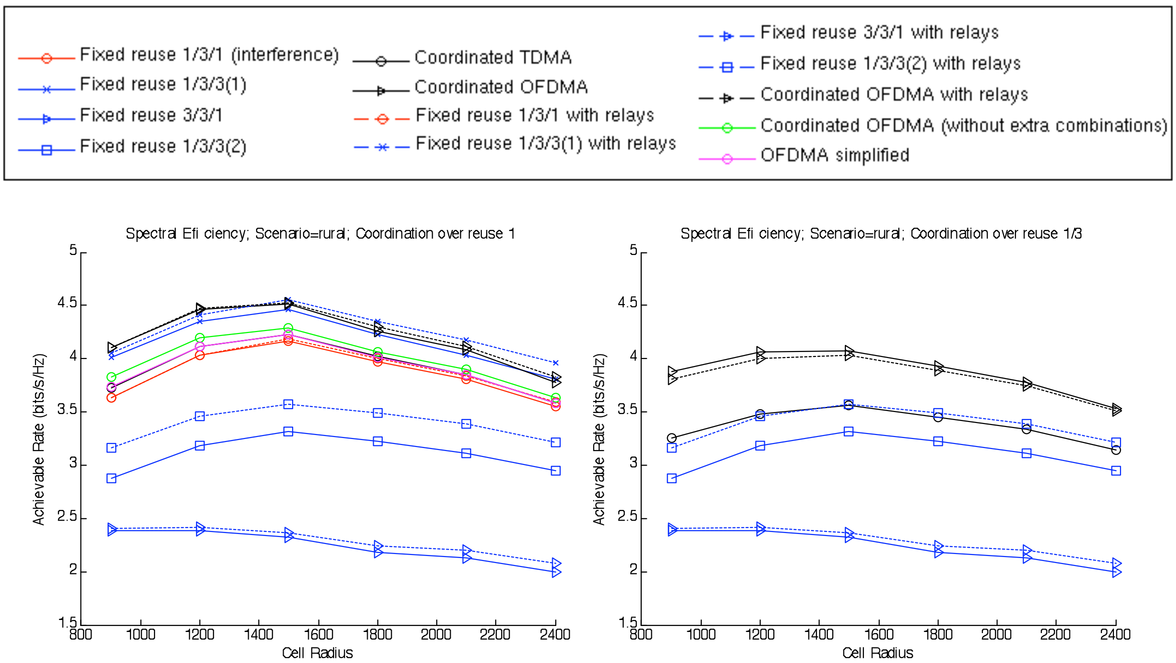

Figure 98. Rural scenario: outer coordination and converging sectors, with external interference and FtB=20 dB

For outer coordination with external interference and FtB of 20 dB, in urban and suburban scenarios, fixed reuse 1/3/3(1) is better than all coordinated schemes, even if for high values of cell radius, coordinated OFDMA with relays is better than 1/3/3(1) without relays. For rural scenarios they are similar.

Coordinated schemes over reuse 1/3 improve significantly the results of all fixed reuses, but they are similar to fixed reuses with relays. Actually, relays are a good option for fixed reuses. The most relevant aspect is that coordinated OFDMA over reuse 1/3 is better than OFDMA over reuse 1 for urban and suburban scenarios. This is the only case where it happens.

We can see in figures 99 and 100 the results when we apply a FtB of 30 dB.

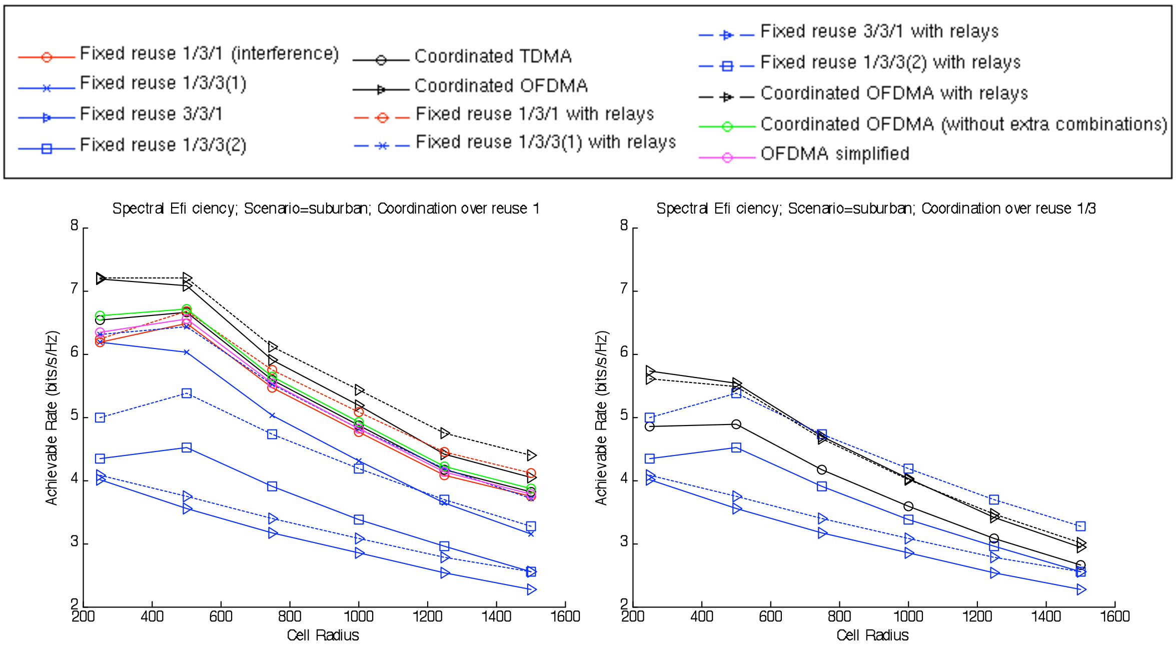

Figure 99. Suburban scenario: outer coordination and converging sectors, with external interference and FtB=30 dB

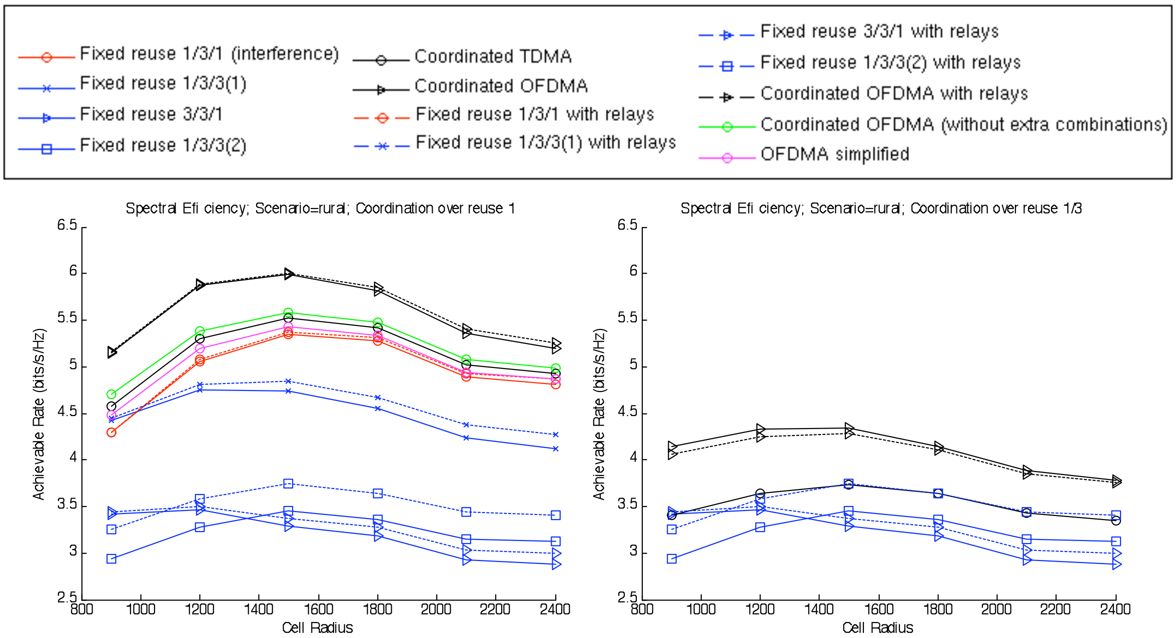

Figure 100. Rural scenario: outer coordination and converging sectors, with external interference and FtB=30 dB

Even if we have to deal with external interference, coordinated OFDMA, with and without relays are the best option in all cases, unlike the previous section, where fixed reuse 1/3/3 (1) was the best scheme in terms of spectral efficiency. Now, we are using a FtB of 30 dB, and we are rejecting more interference than in the previous case.

We can see how relays are improving almost all the direct transmissions, specially the fixed reuses.

Coordinated schemes over reuse 1/3 are similar to fixed reuses for urban and suburban scenarios, but they are better in rural ones.

Outer coordination and offset sectors:

When starting this chapter, we said that outer coordination with converging sectors and offset sectors provide almost the same results. Actually, the only clear difference is for fixed reuse 1/3/1 and round robin per sector scheduling. Figure 101 shows the achievable rate for coordinated OFDMA and fixed reuse 1/3/1.

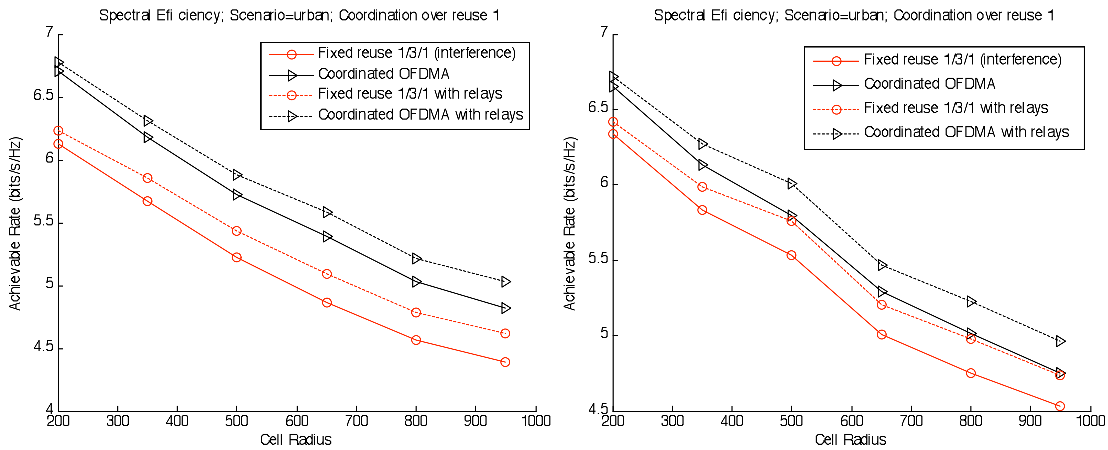

Figure 101. Urban scenario: outer coordination, converging (left) and offset (right) sectors, with external interference and FtB=30 dB

We can see how fixed reuse 1/3/1 performs slightly better with offset sectors. The orientation of the antennas in the offset configuration try to reduce the interference from the neighbour sectors. For a reuse 1/3/1 it is noticeable, however, for coordinated OFDMA it does not represent any change, since we are already controlling this interference using coordination in both cases (converging and offset sectors), so, interference in OFDMA schemes (either in converging or offset configuration) has not the same impact as in fixed reuse 1/3/1.

Inner coordination and offset sectors:

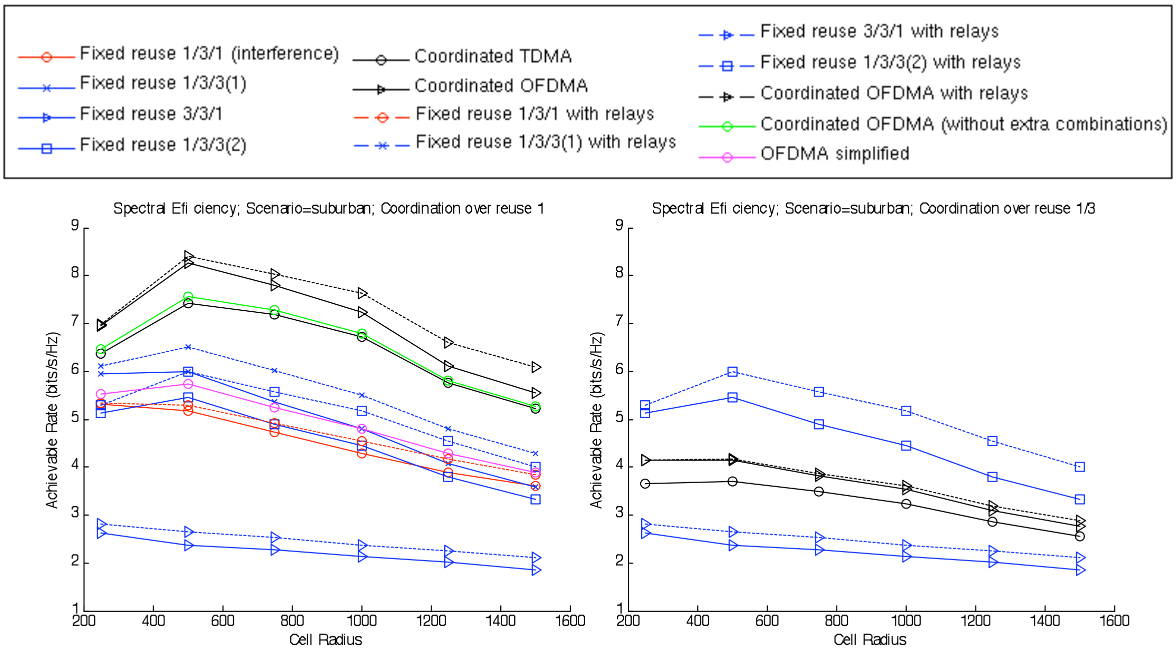

Figure 102. Suburban scenario: inner coordination and offset sectors, with external interference and FtB=20 dB

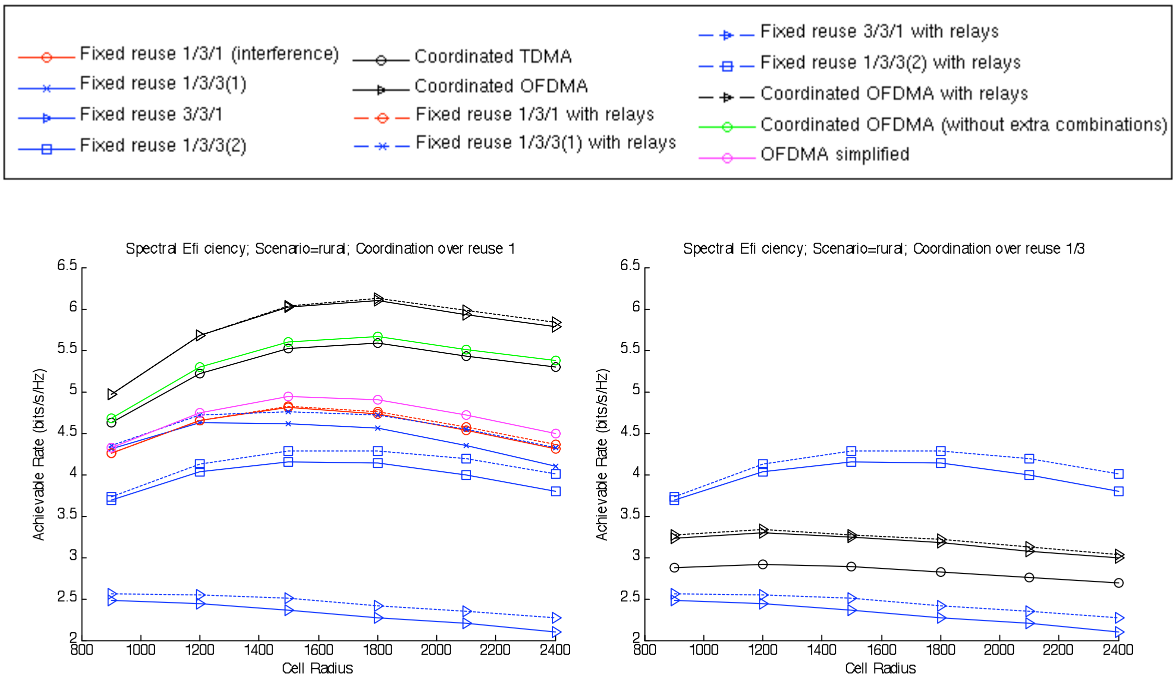

Figure 103. Rural scenario: inner coordination and offset sectors, with external interference and FtB=20 dB

In this case, with a FtB of 20 dB, coordinated OFDMA with relays is always the best option. We can see the improvement due to the use of relays, even if for rural scenarios is not so significant. OFDMA simplified is slightly better than fixed reuse 1/3/1 and OFDMA without extra combinations is also better than TDMA.

Coordinated schemes over reuse 1/3 are a good option respect to fixed reuse 3/3/1. OFDMA is better than TDMA.

Figure 104 represent the results for a suburban scenario when we apply a FtB of 30 dB.

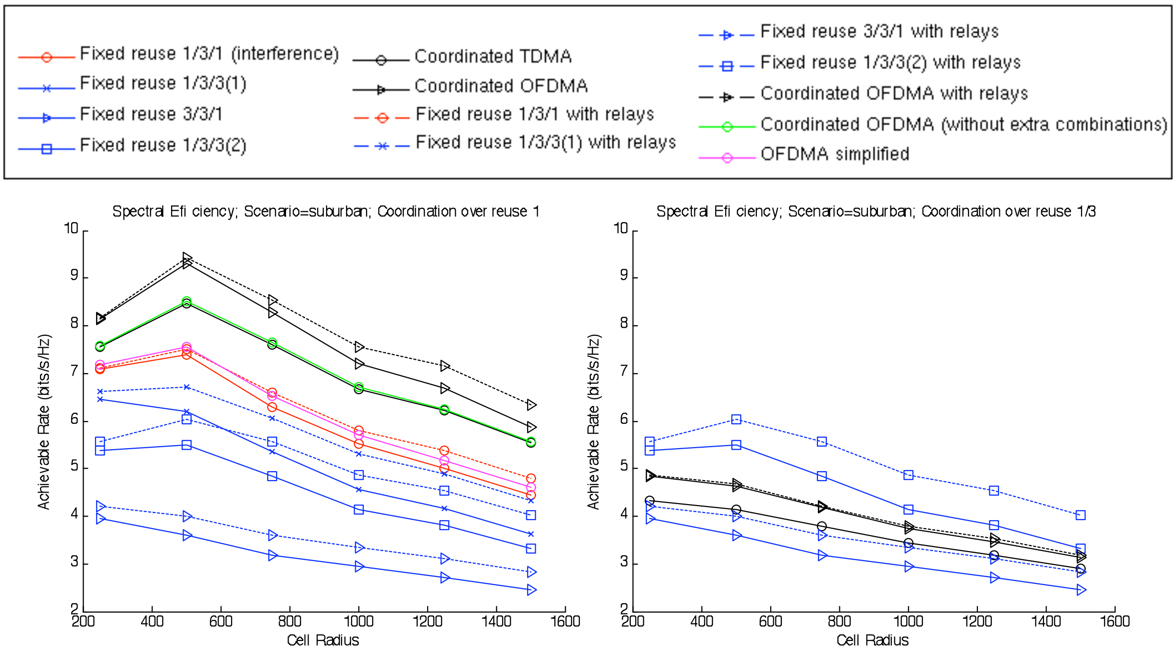

Figure 104. Suburban scenario: inner coordination and offset sectors, with external interference and FtB=30 dB

In this case, we can appreciate a very similar behaviour than for a FtB of 20 dB. However, we can see how all the achievable rates have been increased over 1 bit/s/Hz in all schemes for all scenarios.

8.4 Cumulative distribution function

We are going to present some situations and scenarios where there is appreciated the difference of all the scheduling methods we have presented in terms of quality of service. We are going to see the advantages of those scheduling methods that were worst when we compared the spectral efficiency.

The previous results showed the mean spectral efficiency of the coordinated area. Now, are going to represent the cumulative distribution function of the rate for a fixed cell value. Then, we can see with more detail the distribution of the users rate.

The simulated scenario is suburban, the value of the cell radius is 1500 meters and the schemes represented are all with relays, which in the worst case, will perform equally than direct transmissions, since it is always chosen the best transmission option in each scheme.

Each figure corresponds to a different scheduling method.

Outer coordination and converging sectors:

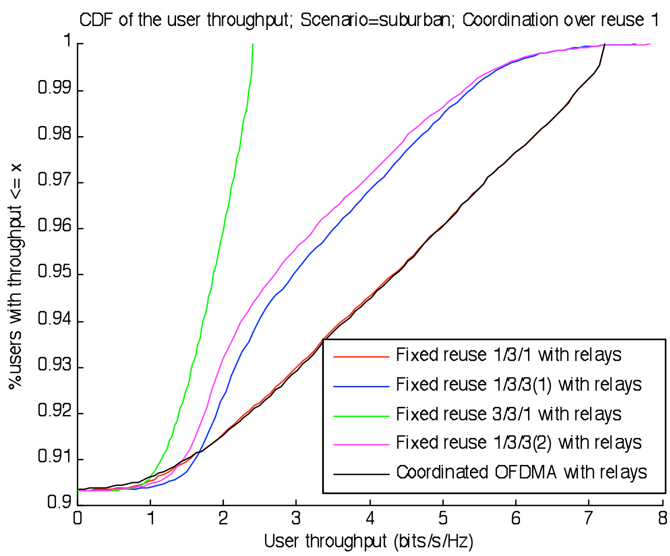

Figure 105. Cdf representation, maximize sum-rate, outer coordination and converging sectors, with external interference and FtB=30 dB

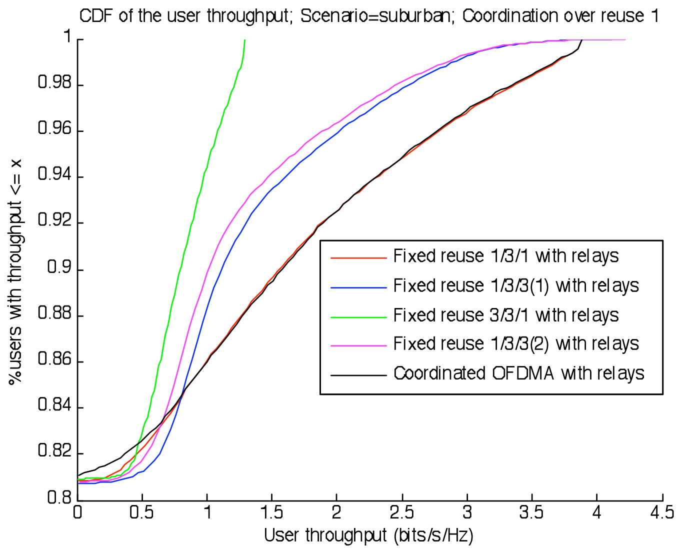

Figure 106. Cdf representation, proportional fair, outer coordination and converging sectors, with external interference and FtB=30 dB

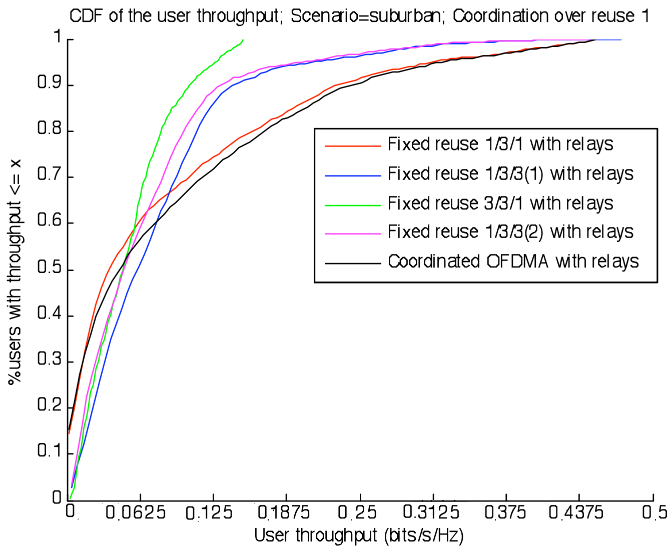

Figure 107. Cdf representation, round robin per sector, outer coordination and converging sectors, with external interference and FtB=30 dB

First of all, we can see the maximum throughput per user of each method: maximizing the sum-rate we reach 7.2 bits/s/Hz for coordinated OFDMA, with proportional fair 4 bits/s/Hz and 0.5 bits/s/Hz with round robin per sector. We have to consider that maximizing the sum-rate, we are assigning always the resources to the same user, so the throughput is very high when comparing it to the other scheduling methods, where we are serving different users. Proportional fair is able to reach a higher value than round robin because, even if it is more fair than maximizing the sum-rate, it still assigns more preference to users with a good connection. Moreover, in round robin, a certain user don't transmit again until all the rest have already done it. Then, the throughput is very low.

Generally, coordinated OFDMA and fixed reuse 1/3/1 provide higher throughput values for a higher percentage of users than fixed reuses 1/3 in all cases.

Then, considering coordinated OFDMA, if we focus on a user throughput of 4 bits/s/Hz, the percentages of users below this value are:

-Maximizing the sum-rate: 94.5%

-Proportional fair: 100%

-Round robin per sector: -

Maximizing the sum-rate, we are serving with a throughput greater than 4 bits/s/Hz a 5.5% of the users, while the rest are below this value. In proportional fair this is the maximum achievable user throughput. In round robin, any user reaches this value.

We can see that maximizing the sum-rate we can provide high throughput values to a high percentage of users than the other schemes. However, it happens only for <u>high throughput values</u>. Therefore, if we focus on a lower throughput value, as if we consider a lower throughput value, as 2 bits/s/Hz:

-Maximizing the sum-rate: 91.5%

-Proportional fair: 92%

-Round robin per sector: -

Maximizing the sum-rate and proportional fair are now very similar. However, proportional fair becomes better than maximizing the sum-rate if we decrease again this value, to 0.25 bits/s/Hz:

-Maximizing the sum-rate: 90.5%

-Proportional fair: 81.5%

-Round robin per sector: 90%

It is clearly seen that proportional fair is serving more users with this throughput, because it also accepts those users who have worse link conditions. Round robin is also serving more users at this rate than maximizing the sum-rate.

Finally, if we focus on a lower throughput value, we see that round robin is still better than the other methods, in terms of percentage of served users, for instance, 0.05 bits/s/Hz:

-Maximizing the sum-rate: 90.5%

-Proportional fair: 81%

-Round robin per sector: 50%

Round robin is serving more users than the others with this throughput. If we continue decreasing the throughput value, we will see that the percentage of served users still increases while the others don't. That is because the other two methods serve only to those users who are above a certain limit of the link conditions, while round robin is serving to all users.

Inner coordination and offset sectors:

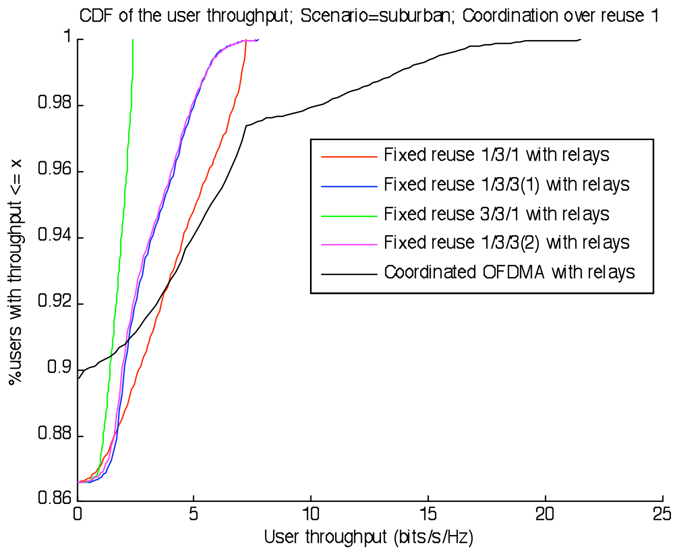

Figure 108. Cdf representation, maximize sum-rate, inner coordination and offset sectors, with external interference and FtB=30 dB

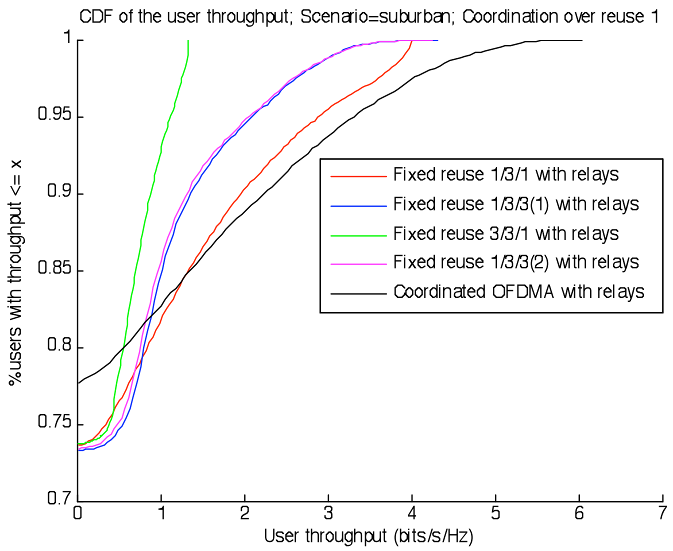

Figure 109. Cdf representation, proportional fair, inner coordination and offset sectors, with external interference and FtB=30 dB

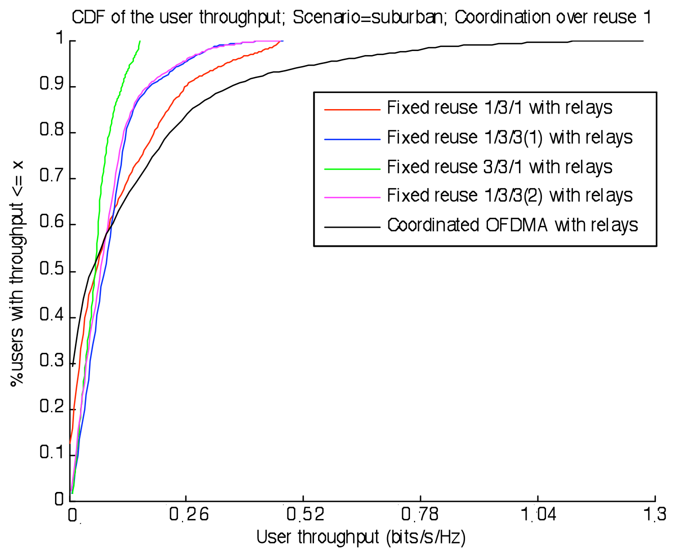

Figure 110. Cdf representation, round robin per sector, inner coordination and offset sectors, with external interference and FtB=30 dB

The general observations for the scheduling methods are the same than for outer coordination and converging sectors. However, in this case, we can see how the coordinated OFDMA provides much higher user throughput values than fixed reuses. Actually, these values are even higher than for outer coordination, specially for the sum-rate maximization, but we can observe the slope change that shows that high throughput values are only achieved by a very low number of users.

8.5 Statistics about transmission schemes (maximize sum-rate)

We explained in subchapters 4.3 and 4.4 the coordinated approach for OFDMA. It consisted of four main transmission schemes: orthogonal, non-orthogonal and other two mixed combinations. Along this subchapter, we are going to see the percentage of scheduling periods that use each one. There is considered only the suburban scenario.

8.5.1 Without external interference and FtB=20 dB

For the scheduling that maximizes the sum-rate, we have presented only the results for coordinated OFDMA without relays. OFDMA with relays provides exactly the same solution in most of the cases. Otherwise, the maximum difference is about 0.05%.

Outer coordination and converging sectors:

Orthogonal	Non-orthogonal
0%	90%
2 All BW / 1 off	2 orth / 1 all BW
5%	5%

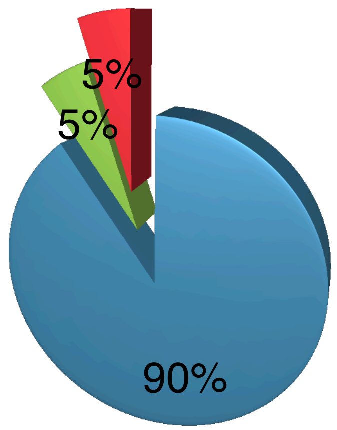

Figure 111. MSR statistics: outer coordination, converging sectors, OFDMA without relays, without external interference and FtB=20dB

Inner coordination and offset sectors:

Orthogonal	Non-orthogonal
29%	2%
2 All BW / 1 off	2 orth / 1 all BW
0%	69%

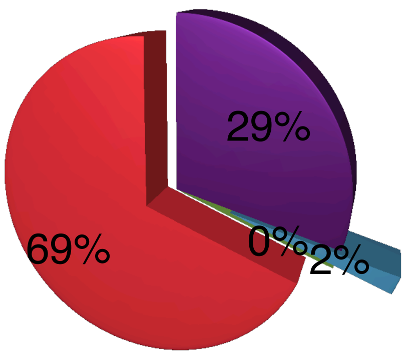

Figure 112. MSR statistics: inner coordination, offset sectors, OFDMA without relays, without external interference and FtB=20dB

8.5.2 With external interference and FtB=20 dB

Orthogonal	Non-orthogonal
0%	99%
2 All BW / 1 off	2 orth / 1 all BW
0%	1%

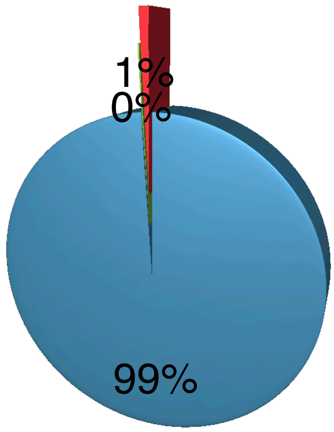

Figure 113. MSR statistics: outer coordination, converging sectors, OFDMA without relays, with external interference and FtB=20dB

Orthogonal	Non-orthogonal
31%	7%
2 All BW / 1 off	2 orth / 1 all BW
0%	61%

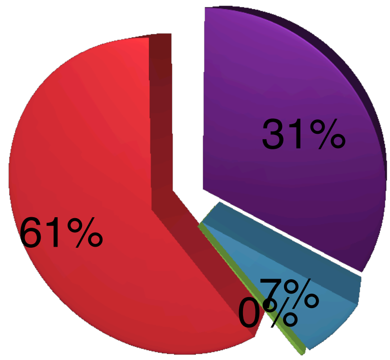

Figure 114. MSR statistics: inner coordination, offset sectors, OFDMA without relays, with external interference and FtB=20dB

8.5.3 With external interference and FtB=30 dB

Orthogonal	Non-orthogonal
0%	97%
2 All BW / 1 off	2 orth / 1 all BW
1%	2%

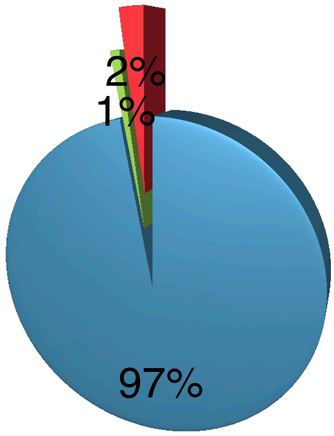

Figure 115. MSR statistics: outer coordination, converging sectors, OFDMA without relays, with external interference and FtB=30dB

Orthogonal	Non-orthogonal
7%	48%
2 All BW / 1 off	2 orth / 1 all BW
4%	41%

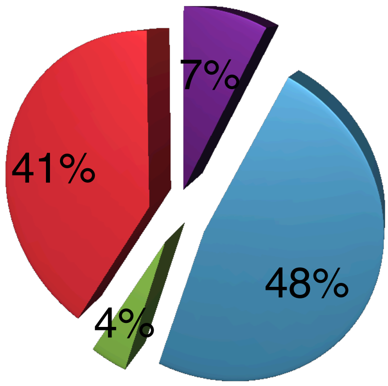

Figure 116. MSR statistics: inner coordination, offset sectors, OFDMA without relays, with external interference and FtB=30dB

We are going to comment the statistics about the transmission schemes for the maximization of the sum-rate in a suburban scenario.

We saw in subchapter 8.1 how was the spectral efficiency for outer coordination and converging sectors. We observed that coordinated OFDMA provided almost the same results than fixed reuse 1/3/1 in all cases and all scenarios. We saw that in some cases OFDMA outperformed the fixed reuse for low values of the cell radius. We can see that the percentage of the non-orthogonal phase for this configuration is about 90% or more. The implementation of this phase is completely equivalent to the fixed reuse 1/3/1. The orthogonal part is never used, since it is favourable for the users who are far from the BS, and we are serving the nearest ones with this scheduling policy. The mixed combinations are used sometimes, and they make the difference between both schemes.

For inner coordination and offset sectors we see different distributions for each situation. First of all, when there is not external interference, the non-orthogonal phase is used a 2%, the combination "2 all bandwidth / 1 off" is not used. So, there are used only orthogonal combinations. That is because the users who are near to the BS are highly interfered by the coordinated sectors, and orthogonal transmissions have to be carried out. It is interesting to see that the combination "2 orthogonal / 1 all bandwidth" is more used, and offers a high gain, if we see the comparison between the coordinated OFDMA and the coordinated OFDMA without combinations in subchapter 8.1.

When we consider the external interference with a FtB of 20 dB, we still have a high interference. Actually, the most important interfering sources in this configuration are the coordinated sectors. Even if the spectral efficiency was quite lower in this case, the percentages of use are similar to the previous case, without external interference. We obtain the most interesting result when we apply a FtB of 30 dB. The non-orthogonal transmissions increase from 7% to 48%. In this case, the interference from coordinated sectors, thus, the most important one, is reduced, so we can use non-orthogonal transmissions, because we don't harm the neighbour sectors.

8.6 Statistics about transmission schemes (proportional fair)

As in the previous case, we are going to present only the results for coordinated OFDMA without relays. OFDMA with relays provides almost the same solution, as we saw in the results of spectral efficiency.

8.6.1 Without external interference and FtB=20 dB

Outer coordination and converging sectors:

Orthogonal	Non-orthogonal
0%	80%
2 All BW / 1 off	2 orth / 1 all BW
18%	2%

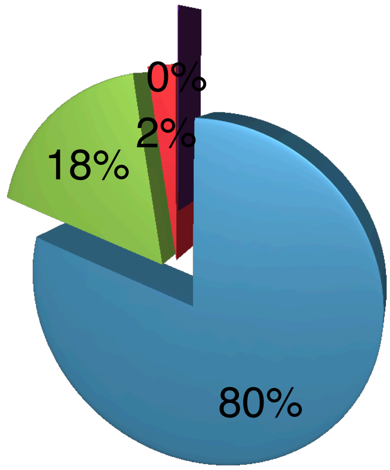

Figure 117. PF statistics: outer coordination, converging sectors, OFDMA without relays, without external interference and FtB=20dB

Orthogonal	Non-orthogonal
56%	11%
2 All BW / 1 off	2 orth / 1 all BW
25%	8%

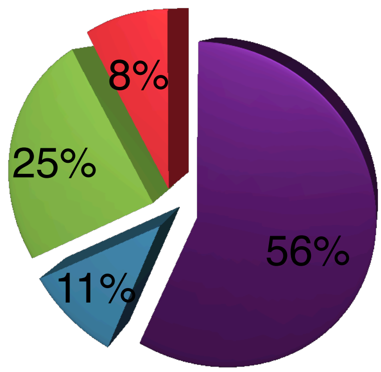

Figure 118. PF statistics: inner coordination, offset sectors, OFDMA without relays, without external interference and FtB=20dB

8.6.2 With external interference and FtB=20 dB

Orthogonal	Non-orthogonal
0%	94%
2 All BW / 1 off	2 orth / 1 all BW
5%	1%

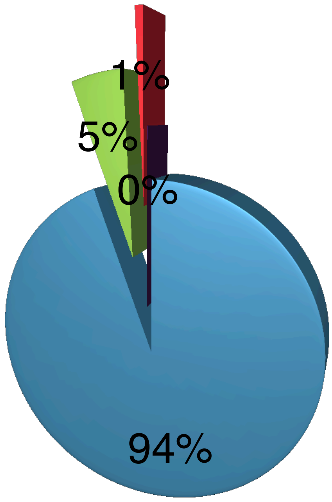

Figure 119. PF statistics: outer coordination, converging sectors, OFDMA without relays, with external interference and FtB=20dB

Orthogonal	Non-orthogonal
24%	25%
2 All BW / 1 off	2 orth / 1 all BW
41%	9%

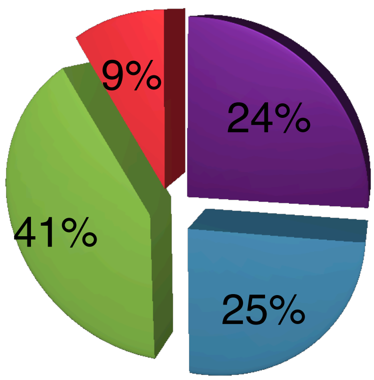

Figure 120. PF statistics: inner coordination, offset sectors, OFDMA without relays, with external interference and FtB=20dB

8.6.3 With external interference and FtB=30 dB

Outer coordination and converging sectors:

Orthogonal	Non-orthogonal
0%	90%
2 All BW / 1 off	2 orth / 1 all BW
9%	1%

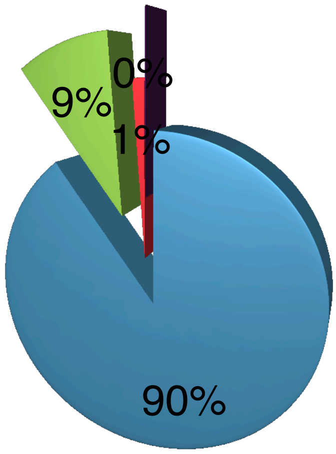

Figure 121. PF statistics: outer coordination, converging sectors, OFDMA without relays, with external interference and FtB=30dB

Orthogonal	Non-orthogonal
3%	51%
2 All BW / 1 off	2 orth / 1 all BW
39%	8%

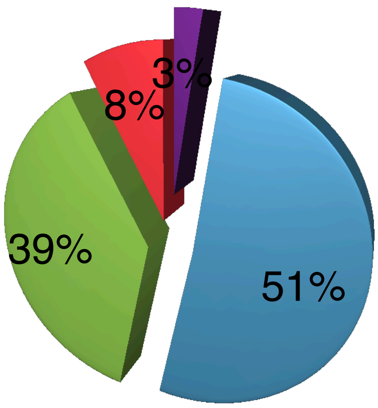

Figure 122. PF statistics: inner coordination, offset sectors, OFDMA without relays, with external interference and FtB=30dB

We are going to comment the statistics about the transmission schemes for a proportional fair scheduling in a suburban scenario.

Outer coordination and converging sectors behave very similarly to the sum-rate maximization, in the sense that a very high percentage of scheduling periods are using the non-orthogonal phase. In that case it was because there were served the users who were very near to the BS. Now, this percentage is slightly reduced because when the best users are penalized (the coordination procedure assigns them a low weight value), others who are farther will be served. There are mainly used the two mixed combinations, specially “2 all bandwidth / 1 off”. This combination is quite used, also when there is applied inner coordination and offset sectors. Its feasible to suppose that users are going served in a decreasing order according to their channel condition; first, users who are near the BS and the broadside, and later, the ones who are near the BS but also near to the frontier of the neighbour sectors. The combination that switches off one BS could be very good for these users.

Inner coordination without external interference uses mainly the orthogonal phase, while this percentage decreases when we introduce external interference with a FtB of 20 dB, and even more when we change to a FtB of 30 dB. The non-orthogonal has the opposite behaviour. It is the same than sum-rate maximization scheduling. Users who are near the BS have mainly interference from the coordinated sectors, and using a FtB of 30 dB it is reduced.

8.7 Statistics about transmission schemes (round robin per sector)

8.7.1 Without external interference and FtB=20 dB

Outer coordination and converging sectors:

Orthogonal	Non-orthogonal
8%	13%
2 All BW / 1 off	2 orth / 1 all BW
27%	52%

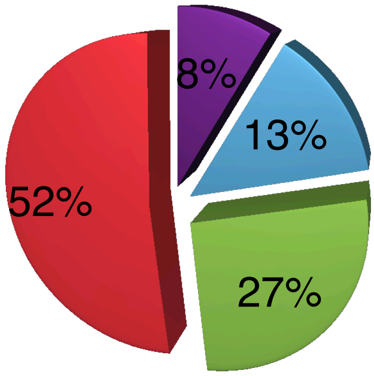

Figure 123. RR statistics: outer coordination, converging sectors, OFDMA without relays, without external interference and FtB=20dB

Orthogonal	Non-orthogonal
9%	15%
2 All BW / 1 off	2 orth / 1 all BW
27%	50%

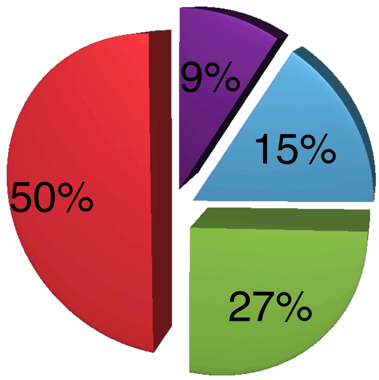

Figure 124. RR statistics: outer coordination, converging sectors, OFDMA with relays, without external interference and FtB=20dB

Inner coordination and offset sectors:

Orthogonal	Non-orthogonal
37%	12%
2 All BW / 1 off	2 orth / 1 all BW
3%	49%

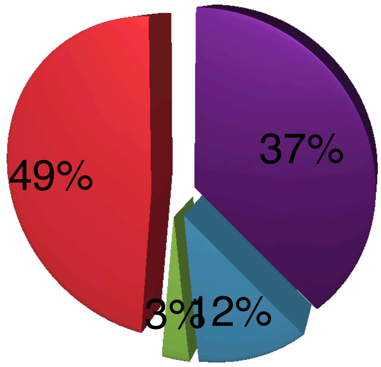

Figure 125. RR statistics: inner coordination, offset sectors, OFDMA without relays, without external interference and FtB=20dB

Orthogonal	Non-orthogonal
41%	10%
2 All BW / 1 off	2 orth / 1 all BW
3%	46%

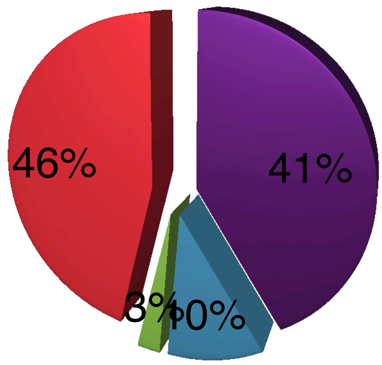

Figure 126. RR statistics: inner coordination, offset sectors, OFDMA with relays, without external interference and FtB=20dB

8.7.2 With external interference and FtB=20 dB

Outer coordination and converging sectors:

Orthogonal	Non-orthogonal
5%	40%
2 All BW / 1 off	2 orth / 1 all BW
9%	45%

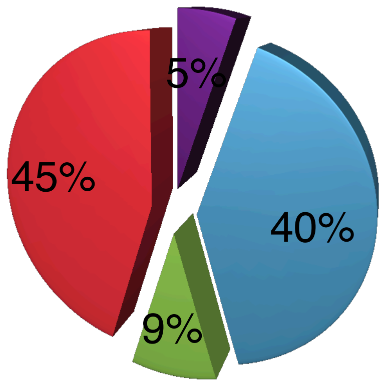

Figure 127. RR statistics: outer coordination, converging sectors, OFDMA without relays, with external interference and FtB=20dB

Orthogonal	Non-orthogonal
10%	48%
2 All BW / 1 off	2 orth / 1 all BW
8%	34%

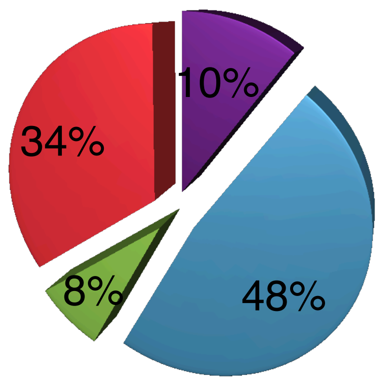

Figure 128. RR statistics: outer coordination, converging sectors, OFDMA with relays, with external interference and FtB=20dB

Inner coordination and offset sectors:

Orthogonal	Non-orthogonal
32%	19%
2 All BW / 1 off	2 orth / 1 all BW
6%	43%

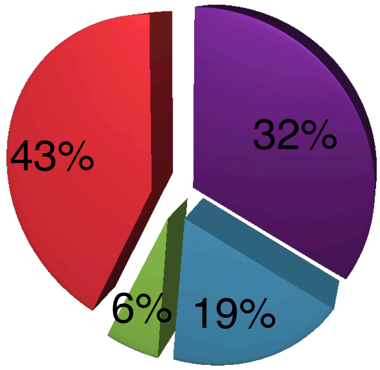

Figure 129. RR statistics: inner coordination, offset sectors, OFDMA without relays, with external interference and FtB=20dB

Orthogonal	Non-orthogonal
52%	9%
2 All BW / 1 off	2 orth / 1 all BW
5%	34%

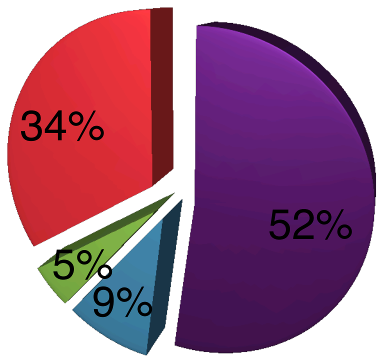

Figure 130. RR statistics: inner coordination, offset sectors, OFDMA with relays, with external interference and FtB=20dB

8.7.3 With external interference and FtB=30 dB

Outer coordination and converging sectors:

Orthogonal	Non-orthogonal
6%	33%
2 All BW / 1 off	2 orth / 1 all BW
13%	47%

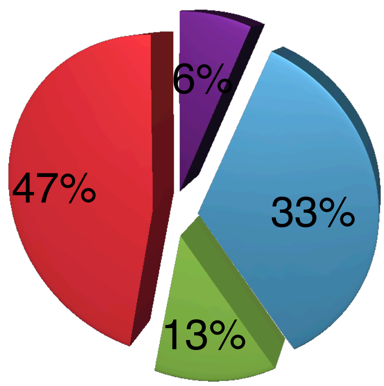

Figure 131. RR statistics: outer coordination, converging sectors, OFDMA without relays, with external interference and FtB=30dB

Orthogonal	Non-orthogonal
13%	41%
2 All BW / 1 off	2 orth / 1 all BW
11%	36%

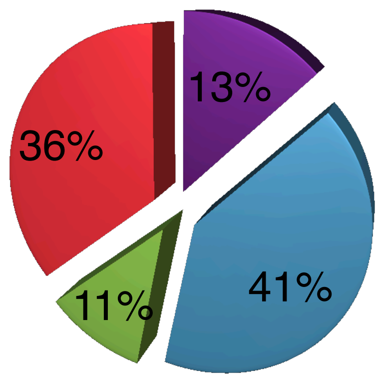

Figure 132. RR statistics: outer coordination, converging sectors, OFDMA with relays, with external interference and FtB=30dB

Inner coordination and offset sectors:

Orthogonal	Non-orthogonal
13%	36%
2 All BW / 1 off	2 orth / 1 all BW
12%	39%

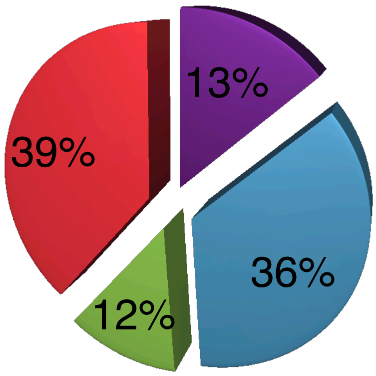

Figure 133. RR statistics: inner coordination, offset sectors, OFDMA without relays, with external interference and FtB=30dB

Orthogonal	Non-orthogonal
30%	26%
2 All BW / 1 off	2 orth / 1 all BW
11%	33%

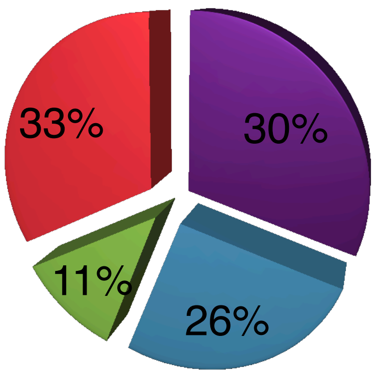

Figure 134. RR statistics: inner coordination, offset sectors, OFDMA with relays, with external interference and FtB=30dB

Now, we are going to comment the percentages for the round robin per sector. Let us start by non considering the external interference. When we apply outer coordination, OFDMA with relays and without them present almost the same percentages. The most used is "2 orthogonal / 1 all bandwidth". We can see that in this scheduling method, we serve users that are not near the BS, because we have to use mechanisms to orthogonalize them. Actually, we can see that this combination is very used in all situations with outer coordination. It is a useful scheme, since it combines the orthogonalization of the most interfered users with the transmission in all the band from the less interfered one, and we can check that it obtains higher rates than schemes that reduce the bandwidth for all users.

When we apply inner coordination, the mixed combination maintains its percentage but the orthogonal transmission is increased, by the reason we commented in 8.5.1: the interference from the coordinated sectors is high, not only for the users who are near to the BS.

If we consider the external interference and outer coordination the percentages are similar to the case without interference. However, non-orthogonal transmissions become more used, and even more if relays are introduced. In any case, they don't reach the values of the maximization of the sum-rate.

For inner optimization, the results are almost equal to the ones without external interference. However, when we apply a FtB of 30 dB, we eliminate an important part of the interference and non-orthogonal schemes can be used more often.

8.8 Relay positions

These figures show the throughput difference between direct and relay transmission for all schemes. They are obtained for a suburban scenario and cell radius of 1000 and 1500 meters. Simulations have been carried out using the same seed for all schemes and relay positions to see clearly the variation introduced by the distance between the relay and the BS.

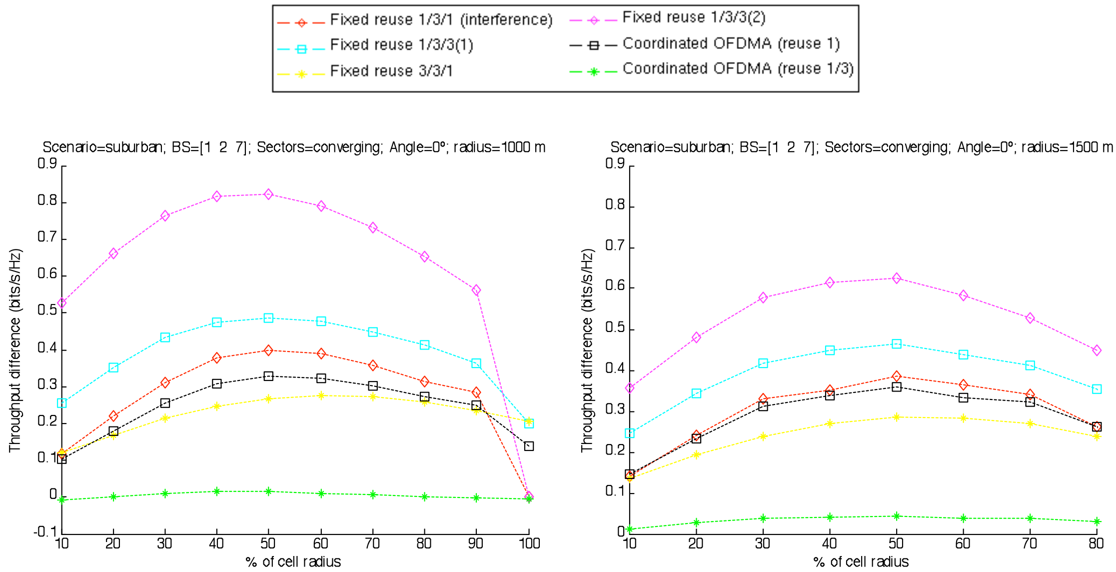

Figure 135. Relay positions. Outer coordination, converging sectors and angle 0º

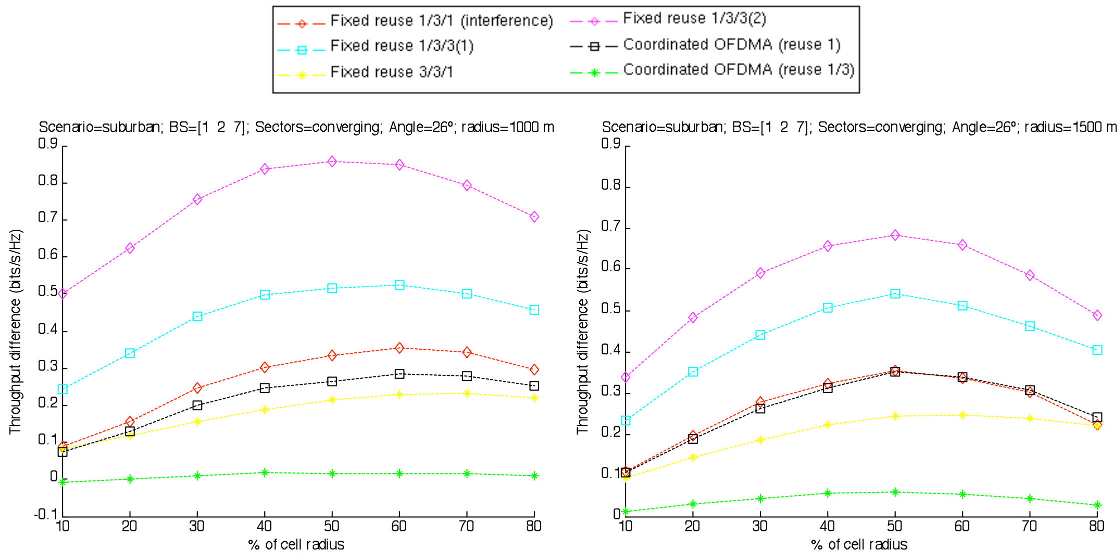

Figure 136. Relay positions. Outer coordination, converging sectors and angle 26º

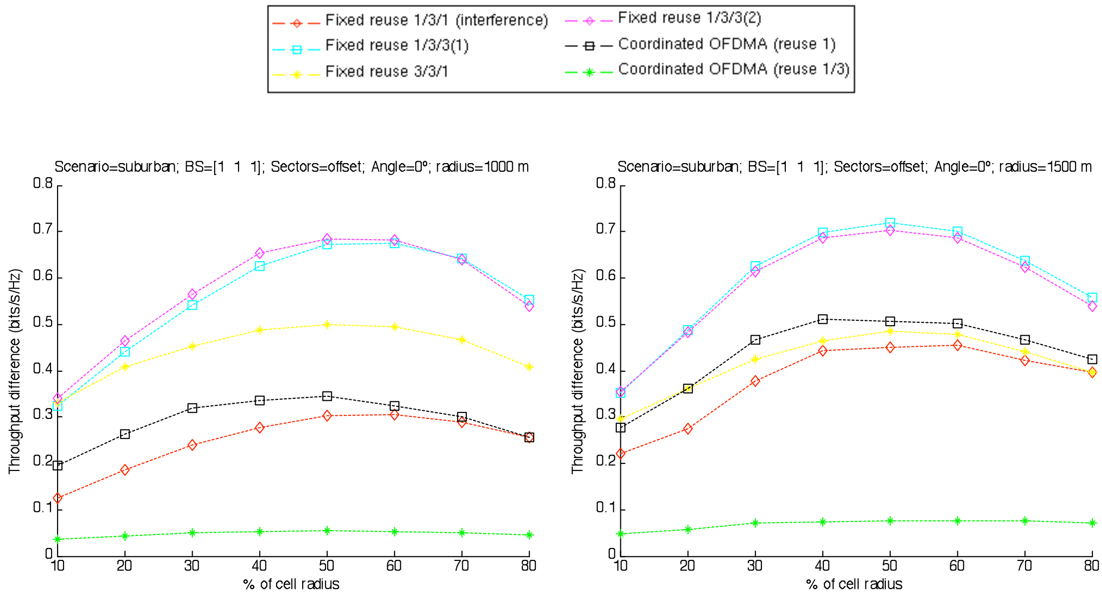

Figure 137. Relay positions. Inner coordination, offset sectors and angle 0º

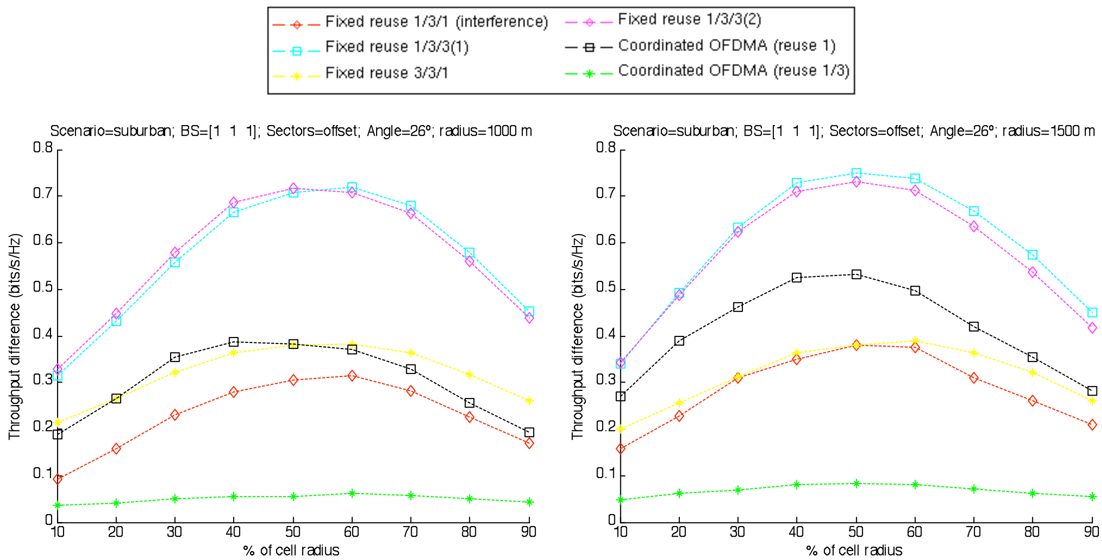

Figure 138. Relay positions. Inner coordination, offset sectors and angle 26º

From previous figures the following observations can be made:

The reuse pattern that benefits more from the use of relays is the fixed reuse 1/3.

The optimum relay position is around 50% of the cell radius, with slightly shifts to the right (distance greater than 50% of the cell radius) for outer coordination and converging sectors with the relay place in the 26º angle with respect to the broadside, and slightly shifts to the left (distance less than 50% of the cell radius) when the relay is at 0º or inner coordination with offset sectors is considered (either if the relay is placed at 0º or 26º)

The relay gain is quite similar for both angles 0º and 26º of the relay position, but it is greater for inner coordination than for outer coordination.

The case of shared relays has not addressed specifically. However, the performance observed for outer coordination-converging sectors with the relay placed at 0º with respect to the broadside and a distance equal to 100% of the cell radius can be taken as an upper bound (since the used power is greater if we considered one relay per sector) of the performance of shared relays. In the coordinated approach, placing the relay at a distance equal to 100% of the cell radius implies to lose approximately the 50% of the gain due to the relay. The performance for a shared relay would be still lower than that.

9. CONCLUSIONS

As a general conclusion we can state that sector coordination presents the ability to react to the instantaneous variability of the network caused by link propagation conditions and the spatial MS distribution. Armed with proper balancing of resources to better accommodate these effects, coordination enables a more efficient use of the network spectrum. This efficiency can be translated into either a cell radius increase at no performance penalty, with the consequent reduction of deployment costs, or an increase of user satisfaction due to better QoS provisioning.

The maximum user throughput decreases when we change the scheduling policy from maximizing the sum-rate to the proportional fair, and even more when we apply a round robin per sector. However, we have seen that in terms of served users, round robin is the best option. Maximizing the sum-rate we only serve to those users with good link conditions, but with round robin, we serve users with any kind of link, even if they are very bad, so the total spectral efficiency in the coordinated area decreases. Proportional fair serves more users than maximizing the sum-rate, but much less than round robin. However, the total spectral efficiency is very similar to the maximized one. There are applications which need high data rates in certain moments, and others which need lower rates but continuous. So, depending on the application, we can choose the most suitable method.

We can appreciate the significance of the external interference in outer coordination for almost all schemes. When a FtB of 20 dB is considered, 1/3/3(1) is better than coordinated OFDMA, because the interference is penalizing, but not in the second, because the antenna patterns help us to combat it.

When focusing in maximization of the spectral efficiency of the system, each sector selects the user with the best propagation conditions. In outer coordination, the solution to the optimization problem is that all the sectors transmit using the whole bandwidth, that is, the coordination leads to fixed reuse 1. We can see it in spectral efficiency plots, where its result almost coincided with fixed reuse 1/3/1, or in the percentage of use of each transmission scheme, where up to a 90% was applied the non-orthogonal phase. The improvement is very low, and it's only noticeable for small cell radius.

However, in inner coordination, users with the best propagation conditions are highly affected by the coordinated sectors, so for no external interference, or external interference with FtB of 20 dB, the best option is to apply orthogonal schemes (orthogonal phase or the mixed one, where two users are orthogonalized). Moreover, when a FtB of 30 dB is applied, this interference is reduced and non-orthogonal schemes are used more often. In this case, coordinated OFDMA outperforms still more fixed reuse 1/3/1.

When we apply the proportional fair scheduling, the results are very similar to the ones maximizing the sum-rate, but generally a little bit lower. We are still serving the best users in the coordinated area, but now in decreasing order, as we give some preference to the ones who haven't transmitted. For outer coordination and converging sectors, the behaviour of all schemes are equal to the ones of sum-rate maximization. The same for inner coordination and offset sectors, with the difference that TDMA outperforms all schemes, specially in the cases of no external interference or with external interference and FtB of 20 dB. It is due to the order and the choice of served users.

In the maximization of the sector average spectral efficiency (all the users in the sector are given the same transmission opportunities), sector coordination outperforms almost always both fixed reuse 1 and fixed reuse 1/3. When external interference is not considered, both outer and inner coordination provide very similar results. However, when it is considered, outer coordination behaves very different when FtB is 20 dB or 30 dB, as the previous methods. When inner coordination is applied, external interference is not as important as the coordinated one, and coordinated schemes outperform clearly fixed reuses.

The use of relays doesn't improve at all the results for the sum-rate maximization scheduling method. Since transmissions are performed to the users who are near the BS, it is worth to transmit to them directly, not using the relays. In proportional fair, we are in the same situation: they don't bring a significant advantage, since we are still serving the best users.

In round robin per sector, relays provide better results than direct transmissions, specially for users who are far from the BS, and they are useful when there is considered external interference, thus, in adverse conditions.

The optimum relay position in terms of average spectral efficiency has been found to be around the middle of the cell. The performance for the two cases of 0º or 26º between the broadside and the LoS of the relay is very similar. The gain for both cases decreases as the RS is placed at the extreme of the cells, making the option of one shared relay between 3 sectors not desirable. In conclusion, one relay per sector is the recommended deployment in terms of the trade off relay density and performance for the scheduling policy considered.

ANNEX 1: OFDM and OFDMA

IEEE 802.16 is able to work either with single carrier modulations or with OFDM, depending on its version. In this annex, lets define OFDM and OFDMA. The difference between OFDM (Orthogonal Frequency-Division Multiplexing) and OFDMA (Orthogonal Frequency-Division Multiplexing Access) is that OFDMA is a multi-user version of OFDM. Actually, OFDMA is a multiple access technique which assigns different subsets of sub-carriers to users, depending on the demand of each one, while OFDM is the modulation. Furthermore, OFDM is a multi-carrier modulation, whose key concept is the use of orthogonal subcarriers for sending several data symbols in parallel. The OFDM transmission technique is used for broadband wireless systems. It is used in IEEE 802.11 a/g in wireless local area networks, it is the base for the discrete multi-tone system in ADSL and as we already know, WiMAX standards have proposed various OFDM based methods for fixed and mobile environments.

The main goal of any multi-carrier modulation such as OFDM is to provide high data rate communications without inter-symbol interference. To achieve this goal, the symbol time has to be larger than the channel delay spread, which is the time interval during which reflections with significant energy arrive. Since in a wideband system the symbol time is much smaller than the delay spread, is preferable to form orthogonal sub-channels operating at a lower rate. The first idea we could have is to divide the band into sub-bands performing different sub-channels as in frequency division multiplexed (FDM) systems. However, divide the band is not so easy because there are required very high quality filters. Moreover, as we are going to see in a few lines, OFDM has an efficient and flexible management of the intersymbol interference, so that it improves the conventional frequency division multiplexed (FDM) systems. The spectral efficiency is higher and the implementation is quite simple. Figure 139 shows how are distributed in frequency the subchannels (SbC) in a FDM system:

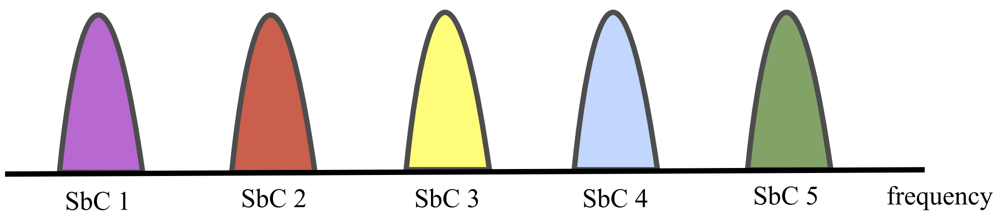

Figure 139. FDM spectrum

We can see how there are portions of the spectrum which are not being used. Therefore, they can't be used because the frequency filters are not perfect and there has to be a guard band. However, OFDM allows subchannels to be overlapped and use parts of the spectrum which were not used in FDM. We can see it in figure 140:

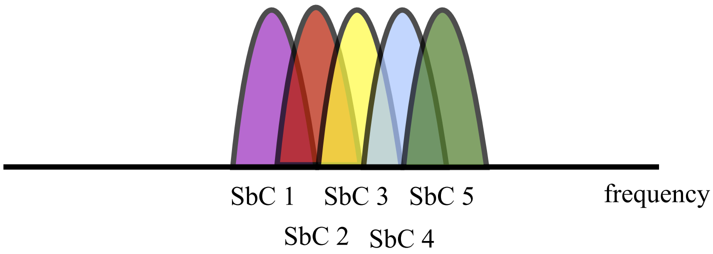

Figure 140. OFDM spectrum

Furthermore, even if the sub-bands are overlapped, we can obtain separately the information corresponding to each subcarrier, due to the orthogonality of the subcarriers. They are orthogonal because we do the sampling at specific points in the frequency domain. In figure 141 we can see how at the points where we sample there is only the contribution of one subcarrier while absolutely all the rest have zero value.

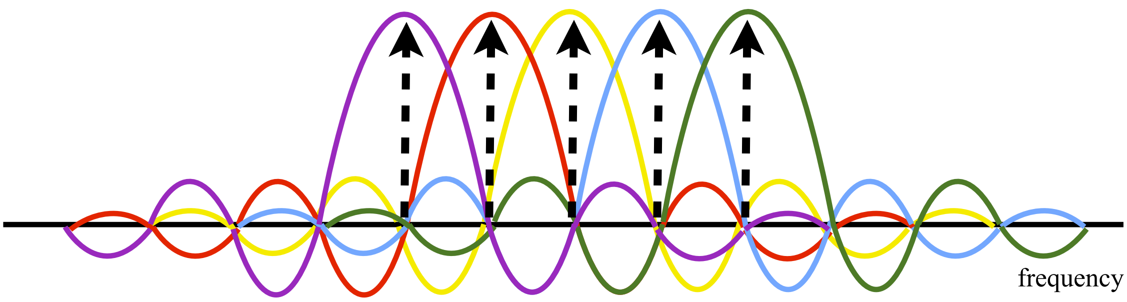

Figure 141. OFDM orthogonal subcarriers which are overlapped without interference

The process to build an OFDM symbol was initially very complicated because there was not available the necessary accuracy to obtain the subcarriers because of the oscillators, since technology was based on analogic processes. However, when digital computation was applied, most of the problems were solved because the samples of the OFDM signal can be obtained by using the inverse fast Fourier transform (IFFT) and recover them by applying the opposite operation, the fast Fourier transform (FFT). Actually, the high impact of OFDM on the communications is because thousands of carriers may be multiplexed by implementing the IFFT in a unique chip.

Let us show the transmission scheme by means of figure 142. The temporal signal is formed by different time slots in which the OFDM symbols are allocated (T_s) and also with some fractions of time called cyclic prefix period (T_{cp}), where there is not useful signal. This is a guard time during which there take place eventual reflections due to the channel memory which may cause inter-symbol interference (ISI). Then, we won't check the information during the cyclic prefix, since we know that it is interfered, but in spite leaving it without a transmitted signal, it is easier to implement it by repeating the last part of the useful OFDM symbol. The reason for this is one of the most interesting key points of OFDM: since we are working with sampled signals, the result of the IFFT we perform to obtain the OFDM symbol is also the result of a circular convolution, so by construction, we already obtain the OFDM symbol cyclically repeated. In figure 142 we can also see how different subcarrier signals are placed into the symbol cyclic prefix periods.

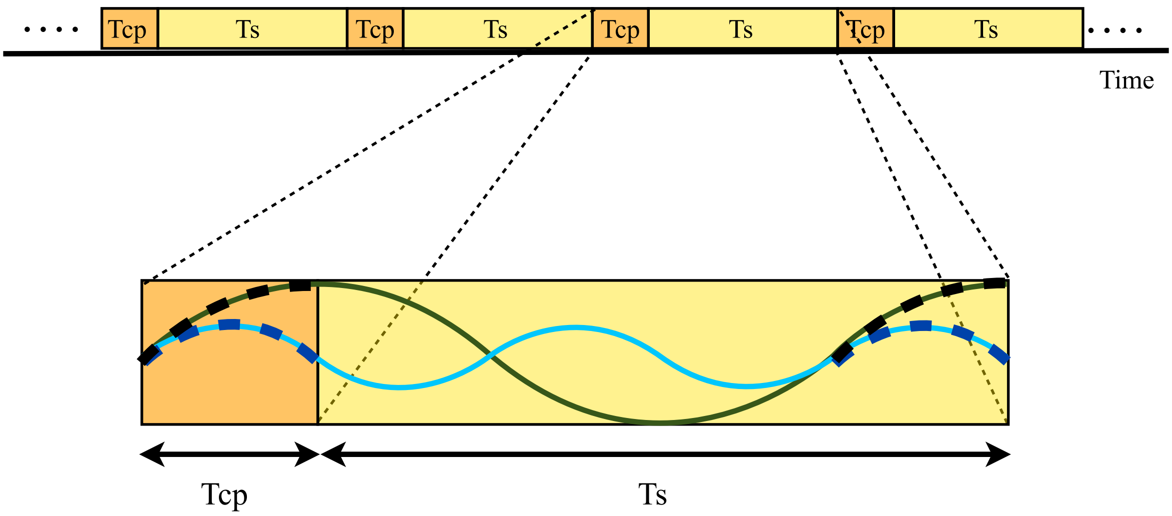

Figure 142. Symbol and cyclic prefix periods

We can see that during the cyclic prefix, there is repeated the last part of the OFDM symbol. These part of the signal will be surely interfered. During the symbol period, the temporal signal is described in the following way:

$$x(t) = \sum_{k=0}^{N-1} s_k e^{j\omega_k t} = \sum_{k=0}^{N-1} s_k e^{jk\frac{2\pi}{T_s}t}, \quad \omega_k = k\frac{2\pi}{T_s}, \quad k = 0,\ldots,N-1 \qquad (A1.1)$$

It is clearly seen that we are performing the inverse Fourier transform operation over S_k, which represent the N symbols to be transmitted in a certain slot. They could be symbols of a 16-QAM constellation, or one of the listed in section A2.4.5. The constellation used may be different for each subcarrier as we will comment in A2.4.5. We can also observe the frequency of the sub-carriers:

$$\omega_k = k\frac{2\pi}{T_s} \qquad (A1.2)$$

Where is seen that the adjacent subcarrier separation is the inverse of the symbol period T_s.

However, we have said before that this technique is usually applied to sampled signals. So if we want to obtain N samples:

$$x[n] = x\left(n\frac{T_s}{N}\right) = \sum_{k=0}^{N-1} s_k e^{jk\frac{2\pi}{T_s}n\frac{T_s}{N}} = \sum_{k=0}^{N-1} s_k e^{j\frac{2\pi}{T_s}kn}, \quad n = 0,\ldots,N-1 \qquad (A1.3)$$

Once defined the temporal signal, we can see the frequency-time representation for the OFDM resource allocation:

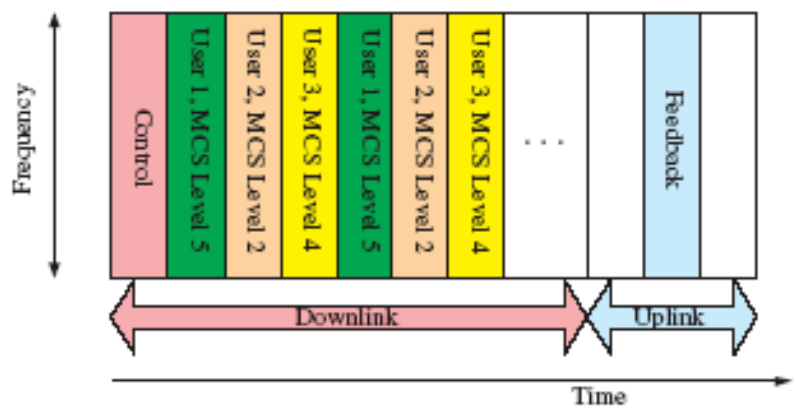

Figure 143. Frequency-time representation for OFDM

We can see how users are orthogonalized in time, while each one uses all the available subcarriers building the OFDM symbols in the way we have described. We can also see how users may use different modulation and coding schemes (MCS).

Moreover, in the next figure we can see the difference between OFDM and OFDMA:

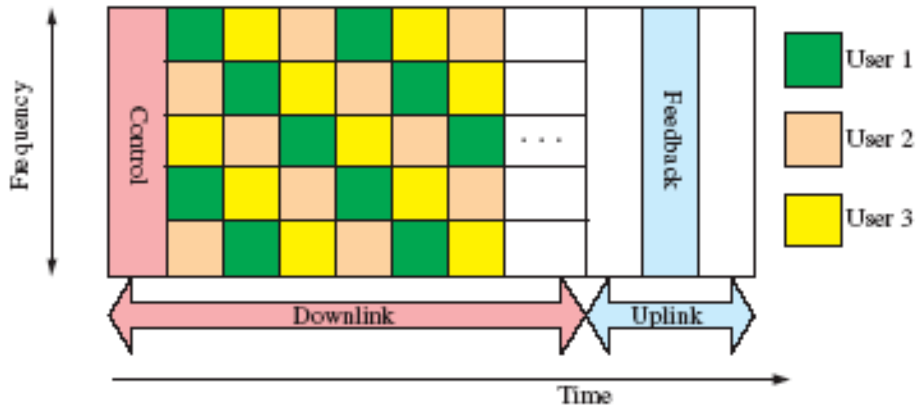

Figure 144. Frequency-time representation for OFDMA

In this case, subcarriers are distributed among different users. Spectral efficiency would be surely improved, since we could assign only the best subcarriers for each user. In the previous case there could be sub-bands which may be not useful for a certain user but they could be for another one. There also could be assigned more sub-carriers to some users than others, depending on their demand satisfying, for example, QoS services.

There is a hierarchy which involves the creation of an OFDM symbol. Let us define some terms about it:

- Subcarrier: they are the operative tones spread over the band. An OFDM symbol is made up of subcarriers. However, not all of them are used in data transmission (data subcarriers), but there are also pilot subcarriers (for channel estimation) and null subcarriers (used as guard bands).

- Subchannel: it is a set of subcarriers.

- Slot: it is the minimum data allocation unit. It spans both the time domain (OFDM symbol) and the frequency domain (subchannel).

- Data region: It is a two dimensional rectangular allocation of a group of subchannels in a group of OFDMA symbols.

- Group: set of clusters or subcarriers.

- Permutation zone: OFDMA symbols that use the same permutation scheme.

The subcarriers can be selected and grouped in different ways. That is what we call permutations, and there are considered mainly three. We can group them depending if subcarriers are selected in distributed or adjacent positions:

Distributed subcarrier permutation:

- FUSC: Full Usage of Subchannels (only in downlink). Achieves the best frequency diversity by spreading tones over the entire band. Pilot tones are allocated first and then the remaining subcarriers are divided into data subcarriers.

- PUSC: Partial Usage of Subchannels (uplink and downlink). It groups tones into clusters to enable fractional frequency reuse, still distributing the tones across the band for each subchannel. In this case, the set of used subcarriers (data and pilots) is first partitioned into subchannels, and then the pilot subcarriers are allocated within each subchannel.

Adjacent subcarrier permutation:

- AMC: Adaptive Modulation and Coding (uplink and downlink). Uses only adjacent tones for each subchannel. When it is used with fast feedback channels, it can rapidly assign a modulation and coding combination in each subchannel, depending on the channel fading state, since subcarriers are contiguous. So there can be applied waterpouring algorithms, combined with advanced antenna systems (AAS) and beam forming.

Finally, we are going to introduce the concept of scalable OFDMA (SOFDMA), which was proposed to the IEEE 802.16 WirelessMAN OFDMA mode by the task group 802.16e, as we commented in (evolution of WiMAX). As it says the name, the idea of SOFDMA is to apply a scalable sub-channelization structure so that the size of the FFT may change according to the channel bandwidth. Thus, small sizes of the FFT led us to low bandwidth channels and the opposite. Therefore, the number of sub-channels scales with the bandwidth and the FFT size.

Applying these concept, OFDMA still increases its inherent flexibility to address the different needs of a wide variety of applications and usage model requirements. Also, for sure performance is reduced if there is not used the scalability, as well as cost becomes increased.

In table 6 we show the values of the scalable OFDMA parameters recommended in the 802.16m standard [IEEE 802.16m-09/0034r2]:

Parameter	***Value***				
Bandwidth (MHz)	*5*	*7*	*8.75*	*10*	*20*
Sampling frequency (MHz)	*5.6*	*8*	*10*	*11.2*	*22.4*
Sampling factor	*28/25*	*8/7*	*8/7*	*28/25*	*28/25*
FFT size (samples)	*512*	*1024*	*1024*	*1024*	*2048*
Subcarrier frequency spacing	*10.938*	*7.813*	*9.766*	*10.938*	*10.938*

Table 6. SOFDMA recommended parameters

We can appreciate the wide variety of available bandwidth (from 5 to 20 MHz) and FFT sizes (from 512 to 2048 samples).

Moreover, WirelessMAN OFDMA also supports a wide range of frame sizes, which let us manage the ratio between useful signal and overhead per frame and also guarantee lower bounds for the number of OFDM symbols per frame, among others.

Table 7 summarizes them:

Frame duration (ms)	***OFDM frame number of symbols***
2	*19*
2.5	*24*
4	*39*
5	*49*
8	*79*
10	*99*
12.5	*124*
20	*198*

Table 7. Available frame sizes for SOFDMA

ANNEX 2: WiMAX and its evolution 802.16m

Nowadays, there has been an important growing in the demand of broadband accesses. The new applications require a good quality connection, in any moment, in any place. That is how WiMAX emerges, offering a broadband wireless connection with a large coverage, low cost and which has evolved until be also capable of offering full mobility.

A2.1 WiMAX vs 802.16

Surely, we have heard about WiMAX and IEEE 802.16 as the same. They are related, but different. 802.16 is a group formed in 1998 by the Institute of Electrical and Electronic Engineers (IEEE). Its objective was to develop a standard for the Wireless Metropolitan Area Network using the 10 GHz to 66 GHz band. Since its creation, a wide family of related standards has been developed until nowadays.

On the other hand, an industry association, which was called WiMAX Forum, was established in mid 2001 with the aim of coordinate testing and ensure the certification of interoperability of WiMAX equipment to the standards of the IEEE 802.16, ETSI HiperMAN and WiBro/Mobile WiMAX standards [www.wimax.com]. It's formed by different working groups, each one targeting an specific matter: marketing, technical, certification, regulatory, technical, global, etc.

So, 802.16 standards describe the specifications while the WiMAX group, what we could name as "industry" is in charge of developing them and making them interoperable. This one is only a marketing trend focused on promoting the adoption of broadband wireless, while it describes the IEEE 802.16 based technology.

A2.2 Applications of WiMAX

Point-to-point and point-to-multipoint network topologies let WiMAX to flexibly address different kind of applications.

The main point-to-point application for WiMAX is the back-haul traffic, where antennas can be used to connect BS from the cell sites to wider area networks. It can be done across long distances, for example, from rural areas or where other lower-capacity cell sites are placed. Point-to-point links may be daisy-chained before reaching the wider area network, and could also be used to connect the wider area network to a single user (which can be a company) who may need a special high capacity link.

WiMAX can also offer a wide variety of point-to-multipoint applications. One of them is to provide a high speed internet access either to consumers or to small business, that new internet applications may need. Since WiMAX offers higher bandwidth and greater range than Wi-Fi, it can also be used as a back-haul to connect Wi-Fi hotspots to internet, as an alternative to the wired ones. Furthermore, it is used also in last mile coverage deployments such as cable, DSL, T and E-carrier systems and optical fiber. The key point is that WiMAX technology can reach points and places where they can't. It leads to a ubiquitous, low cost and fast to implant broadband access.

A2.3 The evolution of 802.16 standards

The first specification for 802.16 was oriented to provide a high data rate point to point communication with LOS (Line of Sight) condition between fixed locations. This standard was suitable for situations where a wired communication is not recommended. As it has been evolving, it has been becoming a very flexible and scalable system in terms of frequency and bandwidth, what has facilitated its coexistence with other air interface technologies and adaptation to spectrum regulations. Furthermore, new developed techniques have been applied to these standards to enhance the transmission rate and other features as quality of service and mobility.

Table 8 resumes the features of some important standards which come from the evolution of IEEE 802.16.

	IEEE 802.16	***IEEE 802.16a***	***IEEE 802.16-2004***	***IEEE 802-16e***
Publication date	April 2002	April 2003	October 2004	February 2006
Mobility	Only for fixed stations	Only for fixed stations	Only for fixed stations	Either for fixed or mobile stations
Frequency bands	10-66 GHz	2-11 GHz	10-66 GHz and 2-11 GHz	2 - 6 GHz
Channel bandwidth	28 MHz	1.25 - 28 MHz	1.25 - 28 MHz	1.25 - 20 MHz
Propagation conditions	LOS	LOS / NLOS	LOS / NLOS	LOS / NLOS
Duplexing	TDD / FDD	TDD / FDD	TDD / FDD	TDD / FDD

Table 8. Features of IEEE 802.16 standard

We can see that initially WiMAX was used only for fixed stations until 802.16e introduced mobility. Also initially only line of sight conditions (LOS) were possible, because at high frequencies losses by obstacles are significant, but as the standards have evolved, other bands have been introduced, as well as variable channel bandwidths, and finally it is possible to work also in NLOS.

There are two features which all standards share: all 802.16 modes allow TDD and FDD duplexing and all of them work with adaptive modulation (see section A2.4.5), thus, the possibility to change the modulation scheme according to the channel conditions. Now, let's comment with more detail all the referring to modulations, multiplexing and access modes for each standard, as well as particular features of each one.

A2.3.1 IEEE 802.16

The modulation used in the first proposal of the 802.16 standard is the single carrier (SC). It implies that multiplexing has to be done in the time domain. Furthermore, there are used two modes: time division multiplexing (TDM) for the downlink and time division multiple access (TDMA) in the uplink. In TDM all users share the same bandwidth but they are allocated in different time slots. Signals come always from the same source and users only have to accede to its assigned slot to read it. However, in the uplink, signals may come from different sources and slots have to be assigned based on fixed or contention modes which are established in TDMA.

The security is very low in this standard and relies on the directivity of the antennas.

A2.3.2 IEEE 802.16a and IEEE 802.16-2004

Standard 802.16-2004 consolidates both IEEE 802.16 and 802.16a standards. It combines single carrier modulation, as in 802.16, but also allows orthogonal frequency division multiplexing (OFDM) and orthogonal frequency division multiplexing access (OFDMA) (see annex 1), which were already introduced in 802.16a. Then, there are available three possible operation modes:

- WirelessMAN-SCa: it uses single carrier (SC) modulation with TDM or TDMA for the downlink and TDMA for the uplink.
- WirelessMAN-OFDM: it uses OFDM with a 256 point fast Fourier transform (FFT) and TDMA channel access.
- WirelessMAN-OFDMA: it uses OFDMA with 2048 point FFT and the channel access is already provided by OFDMA.

IEEE 802.16-2004 improves security in communications, offering a two-way authentication. It employs data encryption standard (DES) and advanced encryption standard (AES).

A2.3.3 IEEE 802.16e

Standard IEEE 802.16e (also called IEEE 802.16-2005) proposes hardware and software not compatibles with IEEE 802.16-2004. In relation to the modulations, it uses two modes we have commented for IEEE 802.16-2004 (SC and OFDM 256 FFT) and also it employs an OFDM mode with 2048 FFT points. However, the most important advance it introduces is the scalable orthogonal frequency division multiplexing access (SOFDMA), also described in annex 1, which performs a flexible system that can vary the size of the FFT employed (from 128 to 2048 points).

IEEE 802.16e It supports a higher number of users than 802.16-2004 and it introduces new advanced antenna techniques, new performance models as power-save, idle and sleep modes, as well as quality of service (QoS) capabilities.

A2.4 IEEE 802.16m

The 802.16m standard is still in progress. It tries to describe an advanced interface for data rates of 100 Mbps for mobile stations and 1 Gbps for fixed ones, using sophisticated features as advanced antenna techniques (also used in 802.16e) and advanced radio resource management (RRM). Furthermore, our work is focused on developing RRM techniques to improve the capacity and spectral efficiency based on the recommendations and technical possibilities defined in the IEEE 802.16m standard.

A2.4.1 Channelization and duplexing modes

As we have commented, the IEEE 802.16m amendment shall support scalable bandwidths, whose accepted range is from 1.25 to 20 MHz.

It also shall work with both Time Division Duplex (TDD) mode and Frequency Division Duplex (FDD) mode. This one, can be either full-duplex or half-duplex (H-FDD), depending on the capacity of the mobile station to be able to transmit and receive simultaneously or not, respectively. A base station supporting FDD mode shall be able to support at the same time half duplex and full duplex terminals operating on the same RF carrier, while a mobile station supporting FDD mode shall use either H-FDD or FDD.

A2.4.2 Operating frequencies

IEEE 802.16m systems shall operate with frequencies lower than 6 GHz, even if they are licensed and identified for IMT-Advanced services. Then, 802.16m technologies shall be capable of coexisting with other IMT-Advanced or IMT-2000 systems.

A2.4.3 Advanced radio resource management

IEEE 802.16m amendment shall enable an advanced radio resource management (RRM) to make possible an efficient utilization of the radio resources. By using interference management, measurement and reporting techniques and establishing flexible resource allocation mechanisms as the one we propose in the present work, the efficient utilization of the radio resources may be achieved.

IEEE 802.16m shall also enable the collection of reliable statistics at system, user, flow or packet level to make possible an advanced RRM. This data may be obtained over different time-scales, and it could be for instance channel occupancy, dropped call statistics, position and mobility statistics, battery life among others.

In relation to the interference management, IEEE 802.16m shall support interference mitigation schemes as flexible and adaptive frequency reuse schemes, as the one we propose, in which resources are assigned depending on user conditions.

A2.4.4 Multi-hop relay networks

IEEE 802.16m aims to develop an air interface providing a high transmission rate, much higher than the one defined in the IEEE 802.16e standard. The deployment requirements include a high coverage, and the avoidance of coverage holes. Intelligent relays are an effective technology to achieve these goals, by increasing the SINR at the receiver side and adding new access points to the network. Figure 145 shows how by using relays coverage can be extended and, furthermore, signal level at the cell edge can be improved.

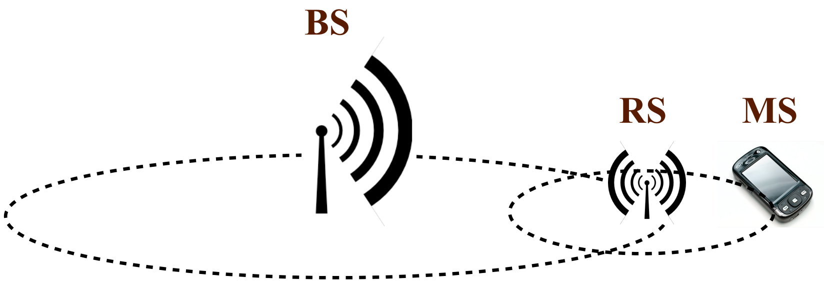

Figure 145. Coverage extension by using relay stations.

Even if we could place more BS to achieve our objectives, it is a high cost solution and the wire-line back-haul may not be available everywhere. Moreover, we could place repeaters, but at the expenses of amplifying also the interference and without the capacity to manage control signals or to process data. Then, to achieve a more cost-effective solution, relay stations (RS) capable of decoding and forwarding the signals from source to destination (through radio interface) should be considered. These relay station don't need a wire-line back-haul and its deployment cost is much lower than for base stations. By using intelligent resource scheduling and coordinated transmissions the system performance could be enhanced.

A2.4.5 Adaptive modulation

Since its early versions, WiMAX has applied adaptive modulation techniques which consist of optimizing the throughput considering the propagation conditions. Even when the transmission is based on single carrier modulations or OFDM it can be done by adjusting the coding scheme and the signal modulation of each carrier or sub-carrier, according to the Signal to Noise plus Interference Ratio (SINR) of the link. In this way, if channel conditions are good, there can be chosen higher order modulations to improve the capacity. During a signal fade or for users close to the cell boundary, the WiMAX system can apply a lower order modulation scheme with heavier coding to maintain the connection quality.

The supported modulation schemes in WiMAX are BPSK, 8-PSK, QPSK, 16-QAM, 32-QAM and 64-QAM. They can be applied separately to each sub-carrier according to the commented premises.

A2.4.6 Legacy frame structure

IEEE 802.16m allows the coexistence with other IEEE 802.16 standards as 802.16-2009 which incorporate different preambles and headers. This is supported by adding an offset between the start of the legacy frame and the start of the IEEE 802.16m frame. It is defined in a unit of subframes.

Then, two time zones (an integer number of subframes) are differentiated in each 802.16m radio frame, called LZone and MZone. They are always multiplexed in time (TDM). Specifically, the DL zone is divided in two time zones (DL LZone and DL MZone) and the same for the UL. We can apply the same idea to TDD and FDD.

During the LZones, it is allowed the transmissions (DL or UL) of terminals either working with 802.16-2009 or 802.16m, while during the MZones only 802.16m transmissions are possible. The duration of each zone is variable and, of course, in absence of 802.16-2009 systems, there are only defined MZones in the frames.

ANNEX 3: CHANNEL CAPACITY

A3.1 Information and entropy

Let us start this chapter by introducing the idea of *information*. It is a concept associated to the probability and the uncertainty of the events, in a way that a more certain event gives us a larger "amount" of information than a less certain one. A feasible example could be the following phrase:

"It will rain tomorrow"

This phrase would give us more information if we listened it in a desert, than in a rainy forest, so that the information is directly related to the probability of raining in the place.

The mathematical concept of information tries to describe quantitatively the uncertainty of an event, in this case a random event which has associated some probabilities or a similar kind of data. In the mathematical definition, there have been considered three conditions:

- Information has to be always equal or higher than zero.
- It has to be a decreasing function: information is an inverse function of probability.
- If there are two independent events, information has to be the sum of them.

And there is a function which fulfils all of them: the logarithm function. Then, the formal definition of information is:

$$I(x) = \log\frac{1}{P(x)} = -\log P(x) \qquad (A3.1)$$

where $P(x)$ is the probability of the event x.

We can check the three conditions:

- The expression of information is always equal or greater than zero, since the probability values are limited: $P(x) \in [0,1]$. We can see the representation of the possible values for the information expression *(A3.1)*:

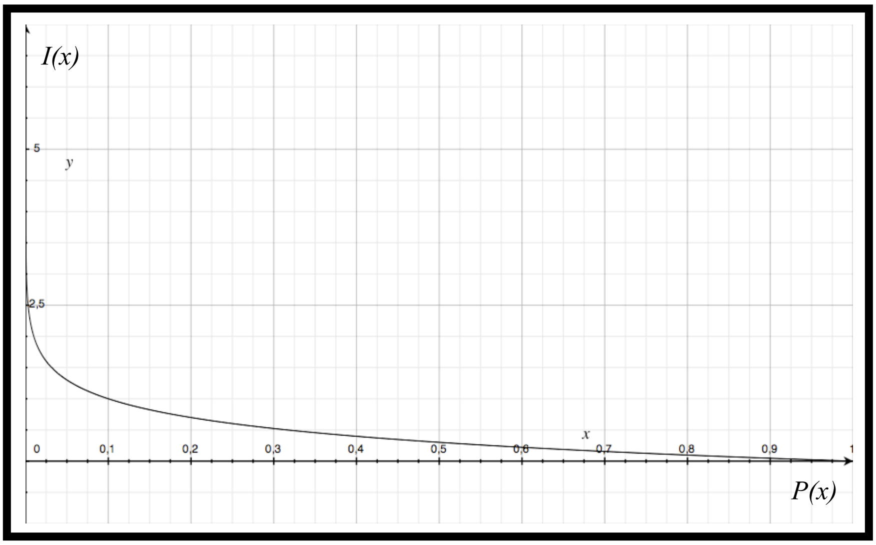

Figure 146. Representation of the information expression: $I(x) = \log \frac{1}{P(x)}$

- We can also see that it's a decreasing function: as probability increases, information decreases.

- For independent events:

$$I(x \cap y) = -\log P(x \cap y) = -\log(P(x)P(y)) = -\log P(x) - \log P(y) = I(x) + I(y) \quad (A3.2)$$

We can also change the basis, and define information in bits ($\log_2$), nats (ln), or whatever we want.

Now, let's consider a discrete memoryless source which generates random symbols from an alphabet X of N symbols. Each generated symbol has associated a probability and is independent of all the preceding and the succeeding ones.

Then, for a single observation x_i, we can compute the given information:

$$I(x_i) = -\log P(x_i) \quad (A3.3)$$

However, a more interesting parameter is to find the average amount of information for an alphabet or a source. That is what we call “entropy”:

$$H(X) = E\left\{I(x_i)\right\} = \sum_{i=1}^{N} P(x_i)I(x_i) = \sum_{i=1}^{N} P(x_i)\log\frac{1}{P(x_i)} \quad (A3.4)$$

We can extend this idea to random variables which are not discrete, by means of the probability density function. We define the entropy, the differential entropy, as:

$$H(X) = \int_{-\infty}^{\infty} f_x(x)\log\frac{1}{f_x(x)}\partial x \quad (A3.5)$$

We have seen that entropy and probabilities are directly related, so what would happen if we applied the conditional probabilities? It would have sense that having two variables, any information of one of them couldn’t decrease the information about the other one, so conditional entropy should be always smaller than entropy. Considering two alphabets *X* and *Y*, if we define the conditional information as:

$$I(x_i / y_j) = \log\frac{1}{P(x_i / y_j)} \quad (A3.6)$$

The conditional entropy is directly defined as:

$$H(X / Y) = E\left[I(x_i / y_j)\right] = \sum_i\sum_j P(x_i;y_j)\frac{1}{P(x_i / y_j)} = \sum_i\sum_j P(x_i;y_j)\frac{P(y_j)}{P(y_j / x_i)P(x_i)} \quad (A3.7)$$

It can be easily proved that always $H(X/Y) \leq H(X)$, and the equality is reached for two independent variables: *P(X/Y)=P(X)*.

It is interesting to comment that for a discrete memoryless channel where *X* represents the input symbols and *Y* represents the output ones, *H(X/Y)* is known as the "equivocation", thus, the average amount of information which has been lost because of the channel.

A3.2 Mutual information

Once defined the average amount of information of a random variable, we can try to find a kind of measurement to relate the information shared between two random variables, thus, how affects the knowledge of one variable to the other one. This measurement is, actually, the mutual information. It should fulfil two main conditions:

- Considering *x* and *y* two independent random variables, the knowledge of one of them does not imply any knowledge about the other one, so the mutual information should be equal to zero:

$$I(x;y) = 0 \tag{A3.8}$$

- On the other hand, if knowing *x* we can also know *y*, so that *P(y/x)*=1, the mutual information should be equal to:

$$I(x;y) = I(y) \tag{A3.9}$$

Then, the following definition could be valid:

$$I(x;y) = \log \frac{P(x \cap y)}{P(x)P(y)} = \log \frac{P(x/y)}{P(x)} = \log \frac{P(y/x)}{P(y)} = I(y;x) \tag{A3.10}$$

We can extend this definition to two alphabets, X and Y, in a similar way than we have done with entropy, and obtain the average mutual information:

$$I(X;Y) = E\left[I(X;Y)\right] = \sum_i \sum_j P(x_i;y_j) \frac{\log P(x_i / y_j)}{P(x_i)} = \sum_i \sum_j P(x_i;y_j) \frac{\log P(y_j / x_i)}{P(y_j)} \quad (A3.11)$$

And we can easily find that

$$I(X;Y) = H(X) - H(X/Y) = H(Y) - H(Y/X) \quad (A3.12)$$

Even if the proof is out of the scope of this work, we state that the channel capacity of a discrete memoryless channel is the maximum average mutual information, considering all the possible probability distributions at the input of the channel.

Let's consider one channel and the two alphabets X and Y, whose probability distributions are $P(x)$ and $P(y)$. If those alphabets correspond to the input symbols and the output ones, respectively, the channel capacity would be:

$$C = \max_{P(x)} I(X;Y) \quad (A3.13)$$

A3.3 Capacity of an additive white Gaussian channel (AWGC)

Here's one of the simplest kind of channels. The only contribution of the channel to the signal is the addition of a white Gaussian noise, generally with zero mean. That will be our case. Then, we can easily represent the general scheme for this kind of channel in the following way:

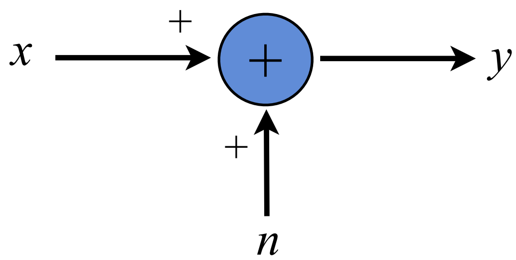

Figure 147. Scheme of an additive white Gaussian channel (AWGC)

Where ***x***, which is a random variable, represents the signal at the input of the channel, ***y*** represents the signal at the output and ***n*** the additive noise.

Their respective probability density functions (p.d.f.'s) are $f_x(x)$, $f_y(y)$ and $f_n(n)$, with ***n*** as a Gaussian random variable, so ***n*** ~ $N(0,\sigma_n^2)$ and because of the independence between ***x*** and ***n***, the p.d.f. of ***y*** is $f_y(y) = f_x(\lambda) * f_x(\lambda)|_{\lambda=y}$.

Now, taking the arbitrary p.d.f. of ***x***, we can define its differential entropy as:

$$H(X) = \int_{-\infty}^{\infty} f_x(x)\log\frac{1}{f_x(x)}\partial x \tag{A3.14}$$

But the key point of this chapter is the following: for a random variable ***x***, with p.d.f. $f_x(x)$ and a finite variance σ_x^2, its differential entropy is upper-bounded by:

$$H(X) \le \frac{1}{2}\log(2\pi e\sigma_x^2) \tag{A3.15}$$

And the equality is reached "if and only if" x follows a Gaussian distribution, thus x ~ N (μ, σ_x^2). The proof is given by finding the variational solution to

$$f_x(x) \equiv \arg\max_{f_x(x)} \int_{-\infty}^{\infty} f_x(x)\log\frac{1}{f_x(x)}\partial x \tag{A3.16}$$

with the following constraints:

$$\int_{-\infty}^{\infty} (x-\mu)^2 f_x(x)\partial x = \sigma_x^2 \qquad (A3.17)$$

$$\int_{-\infty}^{\infty} f_x(x)\partial x = 1 \qquad (A3.18)$$

$$f_x(x) \geq 0 \qquad (A3.19)$$

However, we can also find it easier, stating that:

$$\int_{-\infty}^{\infty} f_x(x)\log\frac{f_x(x)}{g(x)}\partial x \geq 0 \qquad (A3.20)$$

for any p.d.f. $g(x)$, and reaching the equality "if and only if" $f_x(x) = g(x)$, $\forall x$ [21].

That's the same than:

$$\int_{-\infty}^{\infty} f_x(x)\log\frac{g(x)}{f_x(x)}\partial x \leq \int_{-\infty}^{\infty} f_x(x)\left[\frac{g(x)}{f_x(x)}-1\right]\partial x = 0 \qquad (A3.21)$$

$$\int_{-\infty}^{\infty} f_x(x)\log\frac{1}{f_x(x)}\partial x \leq \int_{-\infty}^{\infty} f_x(x)\log\frac{1}{g(x)}\partial x \qquad (A3.22)$$

$$H(X) \leq \int_{-\infty}^{\infty} f_x(x)\log\frac{1}{g(x)}\partial x \qquad (A3.23)$$

with equality "iif" $f_x(x) = g(x)$, $\forall x$

---

[21] *Because of the fundamental inequality:* $\ln x \leq x-1$ *(see annex 4).*

The following step is to see, in a crafty manner, why an arbitrary entropy is always smaller than the entropy of a Gaussian random variable. We have to consider two random variables ***x*** and ***y***, with the same mean and variance (μ, σ^2), but $f_x(x)$ is the p.d.f. of ***x*** (a generic one), and ***y*** is a Gaussian random variable.

$$\begin{aligned} H(Y) &= \int_{-\infty}^{\infty} f_y(y)\log\frac{1}{f_y(y)}\partial y = \int_{-\infty}^{\infty} f_y(y)\left(\frac{1}{2}\log(2\pi\sigma^2)+\frac{(y-\mu)^2}{2\sigma^2}\right)\partial y = \\ &\frac{1}{2}\log(2\pi\sigma^2)\int_{-\infty}^{\infty} f_y(y)\partial y + \int_{-\infty}^{\infty} f_y(y)\frac{(y-\mu)^2}{2\sigma^2}\partial y = \frac{1}{2}\log(2\pi\sigma^2)+\int_{-\infty}^{\infty} f_y(y)\frac{(y-\mu)^2}{2\sigma^2}\partial y = \end{aligned} \quad (A3.24)$$

and now, the interesting part [Vázquez08]:

$$\begin{aligned} H(Y) &= \frac{1}{2}\log(2\pi\sigma^2)+\frac{1}{2\sigma^2}E\left[(y-\mu)^2\right] = \frac{1}{2}\log(2\pi\sigma^2)+\frac{1}{2\sigma^2}E\left[(x-\mu)^2\right] = \\ &\int_{-\infty}^{\infty} f_x(x)\log\frac{1}{f_y(x)}\partial x \geq \int_{-\infty}^{\infty} f_x(x)\log\frac{1}{f_x(x)}\partial x = H(X) \end{aligned} \quad (A3.25)$$

with equality “iif” $f_x(x) = f_y(x)$, $\forall x$

Finally, taking the function

$$g(x) = \frac{1}{\sqrt{2\pi}\sigma_x} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma_x}\right)^2} \quad (A3.26)$$

$$\begin{aligned} H(X) &\leq \int_{-\infty}^{\infty} f_x(x)\log\frac{1}{g(x)}\partial x = \frac{1}{2}\log(2\pi\sigma_x^2)+\frac{\log e}{2\sigma_x^2}\int_{-\infty}^{\infty}(x-\mu)^2 f_x(x)\partial x = \\ &\frac{1}{2}\log(2\pi\sigma_x^2)+\frac{\log e}{2\sigma_x^2}\sigma_x^2 = \frac{1}{2}\log(2\pi e\sigma_x^2) \end{aligned} \quad (A3.27)$$

with equality “iif” $f_x(x) = f_y(x)$, $\forall x$

Going back on the first scheme,

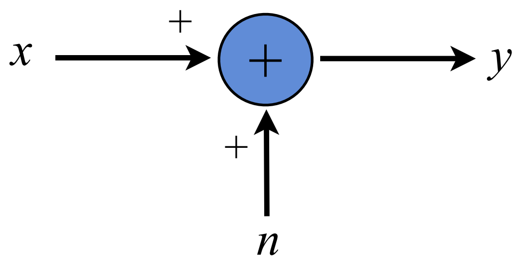

Figure 148. Scheme of an additive white Gaussian channel (AWGC) (2)

The definition of the mutual information for the Gaussian channel would be:

$$I(A_x;A_y) = H(Y) - H(Y/X) \tag{A3.28}$$

For a given $\boldsymbol{x}$, $\boldsymbol{y}$ would be a Gaussian random variable with the variance of the noise and mean $\boldsymbol{x}$. So that $\boldsymbol{y} \sim \mathrm{N}(\boldsymbol{x}, \sigma_n^2)$. Then:

$$H(Y/X) = \frac{1}{2}\log(2\pi e\sigma_n^2) \tag{A3.29}$$

We also know that $\boldsymbol{y} = \boldsymbol{x} + \boldsymbol{n}$, and $\boldsymbol{x}$, $\boldsymbol{n}$ are independent random variables, so the variance of $\boldsymbol{y}$ is:

$$\sigma_y^2 = \sigma_x^2 + \sigma_n^2 \tag{A3.30}$$

Finally, to find the capacity, we have to find the probability distribution at the input that maximizes the mutual information: the Gaussian distribution.

Let's be

$\boldsymbol{x} \sim \mathrm{N}(\mu, \sigma_x^2)$

$\boldsymbol{n} \sim \mathrm{N}(0, \sigma_n^2)$

Then, $\boldsymbol{y} = \boldsymbol{x} + \boldsymbol{n} \sim \mathrm{N}(\mu, \sigma_x^2 + \sigma_n^2)$, so that

$$C = H(Y) - H(Y / X) =$$
$$\frac{1}{2}\log(2\pi e\left(\sigma_x^2 + \sigma_n^2\right)) - \frac{1}{2}\log(2\pi e\sigma_n^2) = \frac{1}{2}\log\left(1 + \frac{\sigma_x^2}{\sigma_n^2}\right) = \frac{1}{2}\log\left(1 + SNR\right) \text{bits/channel-use}$$

(A3.31)

If the bandwidth of the channel is B, there are a maximum of 2B channel-uses per second, and finally, the capacity in bits/s/Hz is:

$$C = \log\left(1 + SNR\right) \text{bits/s/Hz} \qquad (A3.32)$$

where:

$$SNR = \frac{\sigma_x^2}{\sigma_n^2} \qquad (A3.33)$$

Interfering signals would be considered as noise and their variance or power (σ_i^2) could be added to the variance of the noise (σ_n^2) because they are independent, so we could extend the definition of capacity considering also interfering signals:

$$C = \log\left(1 + SINR\right) \text{bits/s/Hz} \qquad (A3.34)$$

where we define also the signal to noise plus interference ratio:

$$SINR = \frac{\sigma_x^2}{\sigma_n^2 + \sigma_i^2} \qquad (A3.35)$$

A3.4 Capacity of an OFDM system

As we have commented in subchapter 6.1, we have implemented the PUSC or FUSC modes, because our only knowledge about the link is the path loss for each mobile or relay station. Then, as it is proposed in [Calvo09], one practical strategy is to perform uniform power allocation among groups of tones sufficiently far apart such that their individual fading states are uncorrelated and frequency diversity is enabled. Also, when we described OFDMA we said that when we use N different subcarriers, we are trying to obtain N channels with flat fading (generally each one has a different coefficient, of course), then, considering uncorrelated fading states, in the best case we could reach the capacity of N parallel and independent AWGN channels (additive white Gaussian noise):

$$C_{eq} \leq \sum_{i=1}^{N} \log(1 + SINR_i) \quad bits / s / Hz \tag{A3.36}$$

We can also express the maximum instantaneous rate as:

$$R_{eq} \leq \sum_{i=1}^{N} \frac{1}{T} \log(1 + SINR_i) \quad bits / s \tag{A3.37}$$

Where T would be the symbol rate of the parallel AWGN channels. For us, it is going to be interpreted as the period of an OFDM symbol.

Now, we multiply and divide by the number of subcarriers *N*,

$$R_{eq} \leq \sum_{i=1}^{N} \frac{1}{T} \log(1 + SINR_i) = \frac{1}{N} \sum_{i=1}^{N} \frac{N}{T} \log(1 + SINR_i) \tag{A3.38}$$

We know that the number of subcarriers is the same that the total used bandwidth divided by the subcarrier spacing (*K [Hz]*), which we can consider as constant.

Then,

$$\frac{1}{N}\sum_{i=1}^{N}\frac{N}{T}\log(1+SINR_i)=\frac{1}{N}\sum_{i=1}^{N}\frac{B}{TK}\log(1+SINR_i) \qquad (A3.39)$$

Where the product of the symbol period and the subcarrier separation K is the only OFDM system parameter. We check that for TK=1 the expression stands for the capacity of N parallel AWGN channels with a bandwidth B. But, as it is said in [Schafhuber04], in real OFDM systems, TK is greater than one, due to the redundancy of guard periods or the cyclic prefixes between OFDM symbols. However, we can consider it typically very close to 1, actually, for DVB-T, values of 1.03 are possible. Furthermore, we can interpret the result (A3.39) as N parallel AWGN channels with an effective bandwidth:

$$B_{eff}=\frac{B}{TK} \qquad (A3.40)$$

In our simulations we have consider B_{eff}=B, but we have applied a SNR penalty which we are going to comment in a few lines.

Then, starting from the following expression:

$$R_{eq}\le\frac{1}{N}\sum_{i=1}^{N}B\log(1+SINR_i) \qquad (A3.41)$$

Coding the information using a sufficiently large number of tones makes the instantaneous achievable rate R_{eq} be upper-bounded by the ergodic capacity, which is the average considering all the possible fading realizations the frequency domain. The proof, which we can also see in [Calvo09], follows the law of the large numbers: for large N values we can affirm the following statement with convergence in probability:

$$R_{eq}\le\frac{1}{N}\sum_{i=1}^{N}B\log(1+SINR_i)\rightarrow E\left\{B\log(1+SINR)\right\} \qquad (A3.42)$$

Thus, channel capacity well be approximated by the ergodic capacity:

$$R_{eq} \simeq E\left\{B\log(1+SINR)\right\} \tag{A3.43}$$

Then, for a single user receiver, we can state:

$$E\left\{B\log\left(1+SINR\right)\right\} = E\left\{B\log\left(1+2^{\log SINR}\right)\right\} \geq \log\left(1+2^{E\{\log SINR\}}\right) \tag{A3.44}$$

Where the inequality comes from the convexity of $\log\left(1+2^{x}\right)$. The SINR is given by:

$$SINR = \frac{P_u\left|h_u\right|^2}{\sigma^2 + \sum_{j=1}^{N-1} P_{I,j}\left|h_{I,j}\right|^2} = \frac{SNR_u\left|h_u\right|^2}{1+\sum_{j=1}^{N-1} SNR_{I,j}\left|h_{i,j}\right|^2} \tag{A3.45}$$

Introducing *(A3.45)* in the expression *(A3.44)*:

$$\begin{aligned} R_{eq} &\geq \log\left(1+2^{E\{\log SINR\}}\right) = \\ &\log\left(1+2^{E\{\log SNR_u\}+E\left\{\log\left|h_u\right|^2\right\}-E\left\{\log\left(1+\sum_{j=1}^{N-1} SNR_{I,j}\left|h_{i,j}\right|^2\right)\right\}}\right) \overset{(a)}{\geq} \\ &\log\left(1+SNR_u\cdot 2^{E\left\{\log\left|h_u\right|^2\right\}}\cdot 2^{-E\left\{\log\left(1+\sum_{j=1}^{N-1} SNR_{I,j}\left|h_{i,j}\right|^2\right)\right\}}\right) = \\ &\log\left(1+\rho_u\cdot SNR_u\left(1+\sum_{j=1}^{N-1} SNR_{I,j}\right)^{-1}\right) \end{aligned} \tag{A3.46}$$

where inequality *(a)* follows from the concavity of log(.), We simulate the impact of per-carrier fading by means of the following constant:

$$\rho_u = e^{E\left\{\log_2 |h_u|^2\right\}} \tag{A3.47}$$

which is a particularization of the expression:

$$\rho_u = e^{E\left\{\log_2\left(\lambda_u\left(\mathbf{HH}^+\right)\right)\right\}} \tag{A3.48}$$

where λ_u are the *u*-th ordered eigenvalues of the matrix $\mathbf{HH}^+$.

We can find it in [Calvo09], where it is said that these channel-dependent coefficients can be accurately performed offline by using Monte Carlo methods, but in case of *n* x 1 or 1 x *n* antenna configuration, which is our case, and Rayleigh fading, can be shown that:

$$\rho_u(n) = e^{-\Psi + \sum_{i=1}^{n-1}\frac{1}{i}\delta[u-1]} \tag{A3.49}$$

Where $\Psi = 0.577215665$ is the Euler-Mascheroni constant. Then, we differentiate two propagation constants, depending on the number of transmitting antennas:

- RS-MS link (one antenna)

$$\rho(1) = e^{-\Psi} = 0.561459484 \tag{A3.50}$$

- BS-MS or BS-RS link (two antennas)

$$\rho(2) = e^{-\Psi+1} = 1.526205111 \tag{A3.51}$$

Finally, we also add a constant γ to simulate the SNR degradation due to imperfect coding. The value of this SNR penalty is 4 dB. We can find its definition on [Simoens09], ch. 5.

Moreover, we can define the SINR in two different ways: considering only the internal interference, as in [Muñoz09], where only the interfering transmissions from BS in the coordinated area are considered, or also the external interference, which comes from the rest of BS in all the simulated area. In the first case, the SNR would be:

$$SINR = \frac{SNR_u}{1 + SNR_I} = \frac{SNR_u}{1 + SNR_{Iint}} \tag{A3.52}$$

And in the second:

$$SINR = \frac{SNR_u}{1 + SNR_I} = \frac{SNR_u}{1 + SNR_{Iint} + SNR_{Iext}} \tag{A3.53}$$

Where SNR_{Iint} is the SNR of interfering signals corresponding to BSs from coordinated area and SNR_{Iext} corresponds to the ones from outside the coordinated area.

From now on, we will consider always the external interference in our notation. However, we will present also the results without considering it. In that case, the only change in the expressions would be:

$$SNR_{Iext} = 0 \tag{A3.54}$$

ANNEX 4: FUNDAMENTAL INEQUALITY

There is a very common inequality in Information or Communication Theory. It has been called fundamental inequality. We can see it in the following expression:

$$\ln x \le x - 1 \qquad (A4.1)$$

A formal proof of this inequality could be finding a unique maximum in the following function:

$$f(x) \equiv \ln x - (x - 1) \qquad (A4.2)$$

The maximum is 0, and it's reached for x=1. It's more intuitive if we see it graphically:

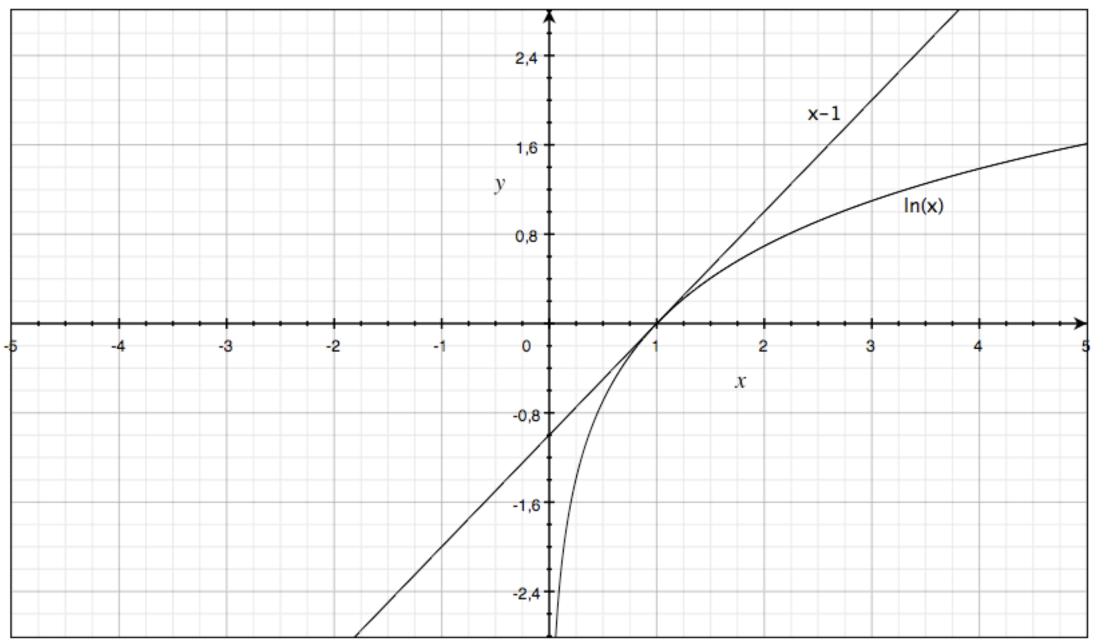

Figure 149. Representation of functions $x - 1$ *and* $\ln x$

The equality is only reached for x=1.

Now, let's be *A(x)* and *B(x)* two different probability distributions. Then, applying the previous inequality, we have:

$$\sum A(x)\log\frac{B(x)}{A(x)} = \frac{1}{\ln 2}\sum A(x)\ln\frac{B(x)}{A(x)} \le \frac{1}{\ln 2}\sum A(x)\left[\frac{B(x)}{A(x)} - 1\right] = \frac{1}{\ln 2}\sum A(x)\frac{B(x)}{A(x)} - \frac{1}{\ln 2}\sum A(x) = 0$$

(A4.3)

Don't forget that *A(x)*, and *B(x)* are probability distributions, so the sum is equal to 1. Then, we can wee that the first inequality leads us to this one:

$$\sum A(x)\log\frac{1}{A(x)} \le \sum A(x)\log\frac{1}{B(x)} \qquad (A4.4)$$

Finally, changing a little bit this expression, we obtain the "relative entropy", the "divergence" or "Kullback-Leibler pseudo-distance", which is defined for two probability distributions, and it has the form:

$$D(A\,/\,/B) \equiv \sum A(x)\log\frac{A(x)}{B(x)} \ge 0 \qquad (A4.5)$$

and the equality will be reached "if and only if" *A(x)=B(x)*.

So we have seen the fundamental inequality represented into three different ways.

ANNEX 5: CONVEX OPTIMIZATION

Convex optimization has become an important computational tool in engineering. It's capable to solve very large and practical engineering problems with efficiency and reliability. In this annex, we are going to define briefly what is a convex problem and two important methods to face and solve these kind of problems by decomposing the original problem into simple ones.

A5.1 Convex problems

A high number of design problems can be represented of the form [Hindi]:

$$\begin{array}{lll} \min & f_0(x) & \\ \text{subjected to} & f_i(x) \le 0, & i = 1,\ldots,m \\ & h_i(x) = 0, & i = 1,\ldots,p \end{array} \qquad (A5.1)$$

Where x is the optimization variable, f_0 is the objective or cost function, $f_i(x) < 0$ are the inequality constraints and $h_i(x) = 0$ are the equality constraints. These are explicit constraints, while there are also implicit constraints: $x \in \text{dom } f_i$, $x \in \text{dom } h_i$, thus, x has to be included in the set:

$$D = \text{dom } f_0 \cap \ldots \cap \text{dom } f_m \cap \text{dom } h_1 \cap \ldots \cap \text{dom } h_p \qquad (A5.2)$$

Geometrically, we can consider that it corresponds to minimize f_0 over the set described by the intersection of the sublevel sets of the f_i's with surfaces described by the solution sets of the h_i's.

A point x is feasible if it satisfies the constrains; the feasible set C is the set of all feasible points and the problem is feasible if there are feasible points. The problem is unconstrained if p and m are zero.

A convex optimization problem is a particularization of the problem *(A5.1)*. Concretely, if functions f_0... f_m are convex and functions h_1...h_p are affine, the problem is said to be convex.

A function f:$\mathbf{R}^n \rightarrow \mathbf{R}^m$ is affine if it has the form linear plus constant:

$$f(x)=Ax+b \qquad (A5.3)$$

If F:$\mathbf{R}^n \rightarrow \mathbf{R}^{pxq}$ is a matrix valued function, it is affine if it has the form:

$$F(x)=A_0+x_1A_1+\ldots+x_nA_n \qquad (A5.4)$$

A function f:$\mathbf{R}^n \rightarrow \mathbf{R}$ is convex if:

1) The domain of the function is a convex set. It happens when any two points in its domain, $x,y \in$ dom f, and two scalars λ, μ > 0 for which λ+μ = 1, then, $\lambda x+\mu y \in$ dom f.

   Figure 150 shows an example of convex set and figure 151 a non convex one, because there is a line segment between x and y that is not joining the segment that connects $f(x)$ and $f(y)$.

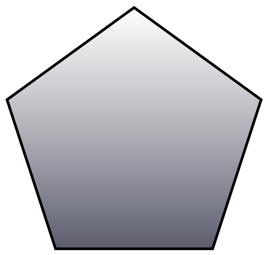

Figure 150. Convex set

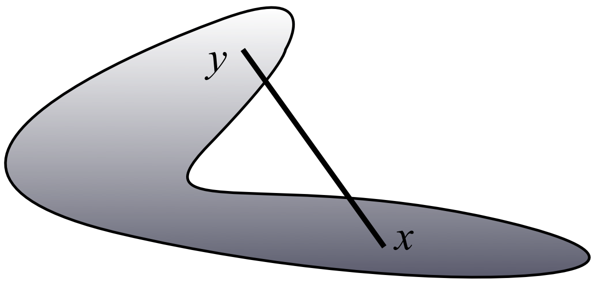

Figure 151. Non convex set

2) For any two points in its domain, $x,y \in$ dom f, and a scalar $\theta \in [0,1]$,

$$f(\theta x+(1-\theta)y) \leq \theta f(x)+(1-\theta)f(y) \qquad (A5.5)$$

f is concave if $-f$ is convex. Figure 189 shows a convex shape:

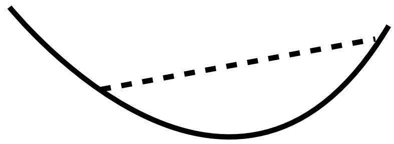

Figure 152. Convex shape

The objective of convex optimization problems is to find the optimal solution, which we denote as x^*. This is the feasible point for which the objective function reaches its minimum possible value: $p^*=f(x^*)$, accomplishing all the constraints. If the problem is unfeasible, it is generally adopted the convention that $f^*=+\infty$.

We find a locally optimal point x when, for some $R>0$:

$$x, y \in C, \|y - x\| \leq R \Rightarrow f_0(y) \geq f_0(x) \qquad (A5.6)$$

We find a globally optimal point x when:

$$x, y \in C \Rightarrow f_0(y) \geq f_0(x) \qquad (A5.7)$$

Let be *(A5.1)* our optimization problem. If f_i are all convex and h_i are affine, any local optimum value is, in fact, global.

A5.2 Decomposition methods

Many times, it's not simple to face the whole problem, and decomposition methods have been developed to simplify it. They consist of splitting the original problem in several smaller sub-problems, that, coordinated by a master problem can lead us to a global optimum. We are going to present two methods we have used throughout this work: primal and dual decomposition.

A5.2.1 Primal decomposition

Let be a problem of the form [Morell08]:

$$\min_{\{\mathbf{y}_j,\mathbf{x}_j\}} \sum_{j=1}^{J} f_j(x_j)$$

$$\begin{aligned} s.t.\quad & \mathbf{x_j} \in \chi_j, \quad j=1,\dots,J \\ & \mathbf{A_j x_j} \le y_j, \quad j=1,\dots,J \\ & \sum_{j=1}^{J} \mathbf{y_j} \le \mathbf{b} \end{aligned} \qquad (A5.8)$$

The optimization variables are $\left\{y_j, x_j\right\}$, f_j:$\mathbf{R}^{n_j}\rightarrow\mathbf{R}$, χ_j are subsets in $\mathbf{R}^{n_j}$, $\mathbf{A_j}$ is a real rxn_j matrix and b, $\{y_j\}\in\mathbf{R}^r$

If we fix $\{y_j\}$ values, we can separate the problem:

$$\min_{\{\mathbf{y}_j\}} \sum_{j=1}^{J} \min_{\substack{\mathbf{x}_j\in\chi_j \\ \mathbf{A_j x_j}\le y_j}} f_j(x_j)$$

$$s.t.\quad \sum_{j=1}^{J} \mathbf{y_j} \le \mathbf{b},\ \ \mathbf{y_j}\in\gamma_j \quad j=1,\dots,J \qquad (A5.9)$$

Considering the feasible solutions for the inner minimization problems or sub-problems:

$$p(\mathbf{y_j}) = \sum_{j=1}^{J} \min_{\substack{\mathbf{x}_j\in\chi_j \\ \mathbf{A_j x_j}\le y_j}} f_j(x_j) \qquad (A5.10)$$

They depend on the variables $\mathbf{y_j}$, as we can see in the second constraint. Then, considering the domain of p_j, γ_j, we can reformulate the original problem *(A5.8)* as:

$$\begin{aligned} &\min_{\{\mathbf{y}_j\}} \sum_{j=1}^{J} p_j(\mathbf{y_j}) \\ &s.t. \quad \sum_{j=1}^{J} \mathbf{y_j} \le \mathbf{b}, \ \mathbf{y_j} \in \gamma_j \quad j = 1,\dots,J \end{aligned} \tag{A5.11}$$

This is the master problem which coordinates the sub-problems, which are expected to be simpler than the global original one.

A5.2.2 Dual decomposition

Let be a problem of the form [Morell08]:

$$\begin{aligned} &\min_{\{\mathbf{x}_j\}} \sum_{j=1}^{J} f_j(x_j) \\ &s.t. \quad \mathbf{x_j} \in \chi_j, \quad j = 1,\dots,J \\ &\qquad \sum_{j=1}^{J} \mathbf{h_j}(\mathbf{x_j}) \le \mathbf{b} \end{aligned} \tag{A5.12}$$

Where h_j:$\mathbf{R}^{n_j} \rightarrow \mathbf{R^r}$, and b$\in \mathbf{R}^r$.

In this case we obtain a dual function by means of the Lagrangian relaxation of the coupling constraint [Ber99]:

$$q(\mu) = \sum_{j=1}^{J} \min_{\mathbf{x_j} \in \chi_j} \left\{ f_j(\mathbf{x_j}) + \mu^T \mathbf{h_j}(\mathbf{x_j}) \right\} - \mu^T \mathbf{b} \tag{A5.13}$$

This function is separable for each $\boldsymbol{x_j}$. Then, we define the subproblems as:

$$q_j(\mu) = \min_{\mathbf{x_j} \in \chi_j} \left\{ f_j(\mathbf{x_j}) + \mu^T \mathbf{h_j}(\mathbf{x_j}) \right\} \tag{A5.14}$$

We assume that for all values of μ, there exists a vector $\boldsymbol{x_j}$ which attains all the minimums of *(A5.14),* we call them $\boldsymbol{x_j^*(\mu)}$. We can introduce them in *(A5.14)* and it becomes:

$$q_j(\mu) = f_j(\mathbf{x_j^*}(\mu)) + \mu^T \mathbf{h_j}(\mathbf{x_j^*}(\mu)) \qquad \textit{(A5.15)}$$

Finally, the dual master problem is:

$$\begin{aligned} &\max_{\mu} \;\; q(\mu) = \sum_{j=1}^{J} q_j(\mu) - \mu^T \mathbf{b} \\ &s.t. \quad \mu \geq 0 \end{aligned} \qquad \textit{(A5.16)}$$

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