

A Two-Step Method for the Optimization of Antenna Azimuth/Tilt and Frequency Planning in OFDMA Multihop Networks

Fernando Gordejuela-Sánchez
CWIND (Centre for Wireless
Network Design, <http://cwind.org>)
University of Bedfordshire, Luton, UK
+44 (0)1582 743288

David López-Pérez
CWIND (Centre for Wireless
Network Design, <http://cwind.org>)
University of Bedfordshire, Luton, UK
+44 (0)1582 743288

Jie Zhang
CWIND (Centre for Wireless
Network Design, <http://cwind.org>)
University of Bedfordshire, Luton, UK
+44 (0)1582 743288

Fernando.Sanchez@beds.ac.uk

David.Lopez@beds.ac.uk

Jie.Zhang@beds.ac.uk

ABSTRACT

During the network planning process, it is very important to identify the key network design factors and define how to take them into account to achieve optimally performing networks. The introduction of Relay Stations (RSs) in OFDMA-based networks will bring numerous advantages such as coverage extension and capacity enhancement due to the deployment of new cells and the reduction of distance between transmitter and receiver. However, the use of RSs will also bring new challenges to the network designers, for example, interference management in multihop communications. This work establishes the fundamentals of a new approach that will adapt the tilt, azimuth, and frequency assignment in OFDMA networks - in the form of subchannel planning - according to the changing conditions of the traffic and the radio channel in a novel two-step process for network design. An example of deployment is presented in this paper.

Categories and Subject Descriptors

C.4 [Performance of Systems]: *Design studies, modeling techniques, reliability, availability, and serviceability.*

General Terms

Algorithms, Performance, Design.

Keywords

Network planning, optimization, interference avoidance, antenna tilt, azimuth, OFDMA, Multihop.

1. INTRODUCTION

OFDMA is a physical layer technology that supports several key features necessary for delivering broadband services at high mobility, for example, scalable channel bandwidth, high spectral efficiency, simple implementation and multi-path robustness due to subcarrier orthogonality [1]. LTE (downlink) and Mobile WiMAX are broadband *Wireless Metropolitan Area Network*

(WMAN) based on OFDMA capable of providing wide coverage area, flexibility, high data rates, *Quality of Service (QoS)* and seamless mobility between different networks.

The relay topology is a kind of multihop communication that introduces RSs into the network, which forward the information from some *Mobile Stations (MSs)* to the legacy *Base Stations (BSs)* that are connected to the core network. The BSs will provide resources to both the RSs and the MSs to which is directly connected. The RS will help to extend the coverage and enhance the capacity of the system [1]. This results in more reliable communications with larger throughput, capacity improvement and terminal power saving. However, there are also some important challenges that the network designers must face before deploying a relay network. A major concern is the management of interference [2], which can considerably downgrade the performance of the system. Therefore, the power, frequency and antenna configuration of the RSs must be carefully selected to mitigate this problem.

In order to successfully compete to other existing and future wire-line and wireless services, the network designers need to fully consider the technical constraints that influence the whole design process of this kind of networks: IEEE 802.16j. The number of combinations of network elements and parameters that can be configured by the operator (e.g. antenna tilt/azimuth, subchannel assignment) constitutes the solution space of the design process. The size of such space determines the degree of complexity of finding appropriate configurations. Since, in WMAN scenarios, the number of options is large, it is very unlikely that the optimal solution can be found using a manual method [3]. The problem is even more complex with the relay-based configuration [2]. Therefore, automated procedures for network design are desirable.

Some approaches on technologies such as GSM suggest the use of *Radio Frequency Planning (RFP)* in order to mitigate interference and enhance the system performance [4] [5]. Similarly, OFDMA supports reconfiguration of the subchannel usage with different frequency reuse schemes and subchannel allocation techniques in order to mitigate intercell interference. Some of these strategies are proposed in the existing literature on multihop communications. However, they only consider fixed reuse patterns or fixed assignment of subchannels in regular scenarios

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. IWCMC'09, June 21–24, 2009, Leipzig, Germany. Copyright © 2009 ACM 978-1-60558-569-7/09/06...\$5.00

This work is supported by the EU FP6 "RANPLAN-HEC" project. Grant number MEST-CT-2005-020958.

[6][7][8]. On the other hand, antenna azimuth and tilt optimization has been widely investigated as main part of advanced network planning and optimization tools [9][10][11], especially in the case of UMTS or other CDMA based networks where a frequency reuse factor of 1 is used. Nevertheless, frequency planning and tilt/azimuth configuration involve different reconfiguration costs, and although some approaches for a joint formulation can be found in the existing literature e.g. [12] [5], they focus on special cases or other technologies, and do not consider a precise formulation and computationally efficient methodology. This work goes beyond the study of fixed frame structures, and establishes the fundamentals of a novel approach that exploit the flexibility of the OFDMA physical layer by adapting the antenna azimuth/tilt and subchannel assignment, according to the changing conditions of the traffic and the radio channel. We propose a two-step method with the use of static Monte Carlo simulation that will allow intense *System Level Simulations (SLSS)* in a multihop environment.

The paper is organized as follows. Section 2, introduces the OFDMA technology. In Section 3, the optimization model used in this work is introduced. In Section 4, an example of deployment analysis is given. Finally, the conclusions are drawn in section 5.

2. OFDMA TECHNOLOGY

In OFDMA the available bandwidth is formed by orthogonal subcarriers, which are grouped into subchannels [1]. In the time domain, the frame is divided in several symbols. The slot is the minimum frequency-time resource that can be allocated by the base station. A single user is allocated a contiguous set of slots with the same *Modulation and Coding Scheme (MCS)* called burst. This particular matrix-like frame structure should be taken into account in the interference model when designing a network.

In order to accommodate the *relay links* (or backhaul link) and the *access links* (or users link), the OFDMA frame can be fragmented into several pieces and some of them are allocated to the relay links and the others to the access links in different combinations to avoid interference between communications. It is accepted that in most of the cases more than three hops in the communication (two RSs) is not practical due to the low radio resource efficiency and possible impairments in the communication such as delay [7].

In order to enhance the network performance, traditional frequency planning in the form of *dynamic subchannel planning* has recently been proposed for OFDMA networks [2], where a certain subset of subchannels is assigned to different sectors. This planning aims to balance the network load and decrease the interference levels, resulting this in a better system respond. With the addition of RSs, the network designers will also need to deal with the interference between the new links created in the multihop operation.

3. OPTIMIZATION FRAMEWORK

In general, the network design process consists of two parts, *planning* and *optimization*. The concept of planning involves finding the quality of the network performance for a given configuration, whereas optimization involves finding the configuration for which the network quality is optimal. The network planning and optimization problem is NP-hard as it is difficult to find a theoretical optimum in polynomial time [3].

There are several methods and algorithms in the existing literature to perform the latter task, among them, meta-heuristic algorithms seem a common approach, since they can provide optimal or at least a good solutions in reasonable time [5][9]. They do not guarantee the optimality of the solution, but they often perform well in practice when the number of variables becomes large.

This work proposes a two-step process for wireless network design in which a first step performs a frequency planning procedure, which is integrated within the simulation stage in an inner optimization loop. Other parameters that need a full network performance estimate are optimized in an outer optimization loop. Figure 1 shows the optimization framework introduced.

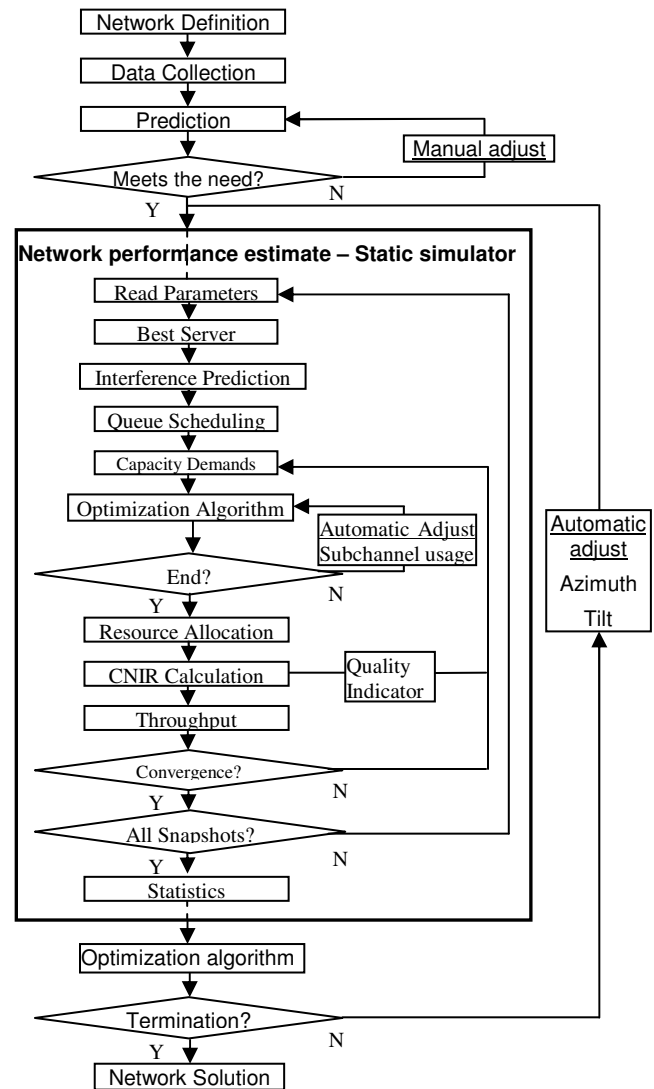


Figure 1. Optimization framework.

The first stage of the network life is the actual *definition of the network*. In this phase different criteria are defined, including description of the expected traffic, services, network topology, and deployment scenarios, as well as coverage, and capacity and quality requirements of the system. After this, a first manual network adjustment based on data collection from a digital map and propagation model tuning can be done.

The following network planning and optimization phase normally makes use of a tool for coverage and capacity predictions. This tool should support traffic, propagation, *Radio Resource Management (RRM)* models among other parameters. The objective of this tool is to estimate the network performance by calculating *Key Performance Indicators (KPI)* that can represent the network quality of a certain configuration. Static network simulation is often used in cellular network planning and optimization due to the high computational load of dynamic simulation [3].

In the described framework, we propose a static Monte Carlo simulation, which is an snapshot-based simulation approach. A snapshot represents an instant of the network performance with fixed position of MSs. The simulator takes multiple snapshots to statistically observe the network performance. Within each Monte Carlo snapshot, the throughput is calculated iteratively until the performance of the system converges. Since the resources used by one user in one sector may interfere with other users, the system converges when it is stable in the selection of MCSs and assignment of resources. In order to fulfill the service requirements of the user, a *Quality indicator (QI)* helps to set the adequate MCS for communication according to the performance obtained in the previous iteration.

Link level simulation results are imported in the form of *Look Up Tables (LUT)* for throughput calculation, which should include the effects of different wireless channels and effects like fading.

3.1 Inner Optimization Loop: Frequency Planning

At each iteration of this process, the first automatic adjustment of the framework is done. After the system is initialized, the best server of each user is identified and a number of MSs are associated to a sector (M_i). This is done by checking the pilot power strength of all stations, including RSs. The MS service requirements and the MCS estimated from the QI are taken into account in the optimization process. This is done in two stages, *interference prediction*, and *capacity demands*, which are described below. Note that the system intercell interference is characterized by a *Restriction Matrix W* [2] [9].

First of all, let us model an OFDMA network as a set of N sectors $S = \{S_0, S_1, S_2, \dots, S_{N-1}\}$, the users associated to a sector ($MS_i = \{0, m, \dots, M_i - 1\}$) and K available subchannels $\{0, k, \dots, K - 1\}$, where each sector S_i requires a certain number of subchannels D_i . The interference prediction stage characterizes the intercell interference of the network, represented by the matrix W of size $N \times N$, in which $w_{i,j}$ represents the intercell interference between sectors S_i, S_j .

Let us introduce the concept of *Interference Event (Ie)*. We consider a set of RS as a subset of a sector S_i ($RS_i = \{0, r, \dots, R_i - 1\}$, $RS_i \subset S_i$). Two sectors, S_i (server) and S_j (neighbour), interfere with each other ($Ie_{ij}++$) every time the power level of the carrier signal (from S_i to a served user UE_x) is smaller than the power level of a neighbouring interfering signal (from S_j to the same user) plus a given threshold (here 12 dB), and S_j is not a RS attached to S_i , (due to frame fragmentation) as the following pseudocode indicates. The threshold *Thres* is a protection margin against interference and it is set by the operator according to its planning targets.

if ($C_i < I_j + Thres$ && $S_j \notin RS_i$) then

$Ie_{ij}++$

Note that the power level of the server and neighboring cells is reported using *Measurement Reports (MR_{ij})*. The system intercell interference is modeled by W , as (1) indicates, in terms of percentage of time that cells interfere each other considering that the same subchannel is used.

$$w_{ij} = \frac{Ie_{ij}}{Mr_{ij}} \quad (1)$$

After the traffic class prioritization (queue scheduling), the optimal number of required subchannels D_i per sector S_i , is approximated in the capacity demand stage. The number of requested slots Rl_m for each user m of sector S_i is calculated, from the requested service capacity Rc_m (kbps) and slot efficiency Se_m (kbps):

$$Rl_m = \frac{Rc_m}{Se_m} \quad (2)$$

As (3) indicates, Se_m depends on the number of subcarriers per subchannel η_{sub} , and the bearer efficiency $\eta_{B(QI_m)}$ in terms of bits/symbol. The bearer efficiency depends on the MCS assigned to the user, and it is selected according to the QI feedback from previous iterations. T_{frame} is the frame duration.

$$Se_m = \frac{\eta_{sub} \cdot \eta_{B(QI_m)}}{T_{frame}} \quad (3)$$

The requested subchannels D_i per sector are calculated by dividing sum of all Rl_m within the sector S_i and the number of symbols per subchannel η_{sym} (see (4)).

$$D_i = \frac{1}{\eta_{sym}} \cdot \sum_{m=0}^{M_i-1} Rl_m \quad (4)$$

Once that the inputs has been obtained, the optimization routine can be defined as a *Mixed Integer Programming* problem, where the objective is to find the optimal solution that minimizes the given cost function representing the overall network interference:

$$\min \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} \sum_{k=0}^{K-1} \frac{w_{ij}}{D_i \cdot D_j} \cdot y_{i,j,k} \quad (5)$$

subject to:

$$\sum_{k=0}^{K-1} x_{i,k} = D_i \quad \forall k \quad (6)$$

$$x_{i,k} + x_{j,k} - 1 \leq y_{i,j,k} \quad \forall i, j, k \quad (7)$$

$$y_{i,j,k} \geq 0 \quad \forall i, j, k \quad (8)$$

$$x_{i,k} \in \{0,1\} \quad \forall i, k \quad (9)$$

where $x_{i,k}$ is a binary variable that indicates whether sector S_i uses subchannel k or not. Constraint (6) imposes that sector S_i must use D_i subchannels. Inequality (7) and (8) force that in an optimal solution, $y_{i,j,k} = 1$ if and only if both sectors S_i and S_j use

subchannel k , and $y_{i,j,k} = 0$ otherwise. Finally, the cost function is the sum of the interference between all pair of sectors S_i and S_j taking into account all the frequencies k . Since the capacity of the sectors is not considered when the restriction matrix W is built, the interference restrictions $w_{i,j}$ must be divided by the number of used subchannels D_i, D_j in both interfered sectors S_i, S_j , and thus, the bigger the number of subchannels per sector, the smaller the chance of interference.

3.2 Outer Optimization Loop: Antenna configuration

In the outer loop, the optimization algorithm test different configurations for different parameters that have higher reconfiguration costs in a real network evaluation - tilt or azimuth - and that need a full simulation of RRM procedures. Such parameters need to be discrete, and the resolution chosen will determine the size of the solution space. The algorithm stops when a series of penalty functions based on some criteria ($G = \{G_\phi, G_b, \dots, G_{H-1}\}$) that evaluate the network performance in a cost function meet the needs of the service provider:

$$\min \left\{ \sum_{h=0}^{H-1} F_{pen_h} \right\} \quad (10)$$

The different criteria is evaluated over all the users, which may be penalized differently. A binary variable d_h^m in $\{0, 1\}$ indicates if user m is evaluated by the cost function related to criterion G_h (see (11)). For example, the MSs will be either in transmission UL or reception DL state and the designer may want to penalize differently these two states.

$$F_{pen_h} = \sum_{i=0}^{N-1} \sum_{m=0}^{M_i-1} f_{pen_h}^m \cdot d_h^m \quad (11)$$

For the penalization of the network performance in the cost function, a threshold-based function avoids the excessive influence of very good or very bad users. Maximal penalty is applied when the value of the criterion t_h^m from user m is smaller than a lower bound T_{min} and no penalty exists when it is higher than a threshold T_{max} . In between these two values the function is linearly decreasing as (12) indicates.

$$f_{pen_h}^m = f_{pen_h}^m(t_h^m) = \begin{cases} 0 & \text{if } (T_{max_h}^m < t_h^m); \\ f_{max_h}^m \cdot \left(\frac{t_h^m - T_{max_h}^m}{T_{min_h}^m - T_{max_h}^m} \right) & \text{if } (T_{min_h}^m < t_h^m \leq T_{max_h}^m); \\ f_{max_h}^m & \text{if } (t_h^m \leq T_{min_h}^m); \end{cases} \quad (12)$$

Furthermore, different criteria can be grouped according to the main KPIs. We consider CINR (C), throughput (T) and RS resilience (R) in a three objective minimization problem as shown in (13). Different subsets of criteria ($G', G'', G''' \subset G$) related to the particular KPI nature will determine different constraints to the problem, e.g. services used or channel profile, which are shown in (14-17) and described below.

$$\min \left\{ \sum_{i=0}^{N-1} \sum_{m=0}^{M_i-1} \sum_{h'=0}^{H'-1} f_{pen(C)}^m \cdot d_{h'}^m + \sum_{i=0}^{N-1} \sum_{m=0}^{M_i-1} \sum_{h''=0}^{H''-1} f_{pen(T)}^m \cdot d_{h''}^m + \sum_{i=0}^{N-1} \sum_{r=0}^{R_i-1} \sum_{h'''=0}^{H'''-1} f_{pen(R)}^r \cdot d_{h'''}^r \right\} \quad (13)$$

subject to:

$$\sum_{h'=0}^{H'-1} d_{h'}^m = 1, \quad \forall m \quad (14)$$

$$1 < \sum_{h''=0}^{H''-1} d_{h''}^m \leq 2 \cdot Ser_{max} \quad \forall m \quad (15)$$

$$\sum_{h'''=0}^{H'''-1} d_{h'''}^r \leq 2 \quad \forall m \quad (16)$$

$$d_{h'}^m, d_{h''}^m, d_{h'''}^r \in \{0, 1\} \quad \forall m, h', h'', h''' \quad (17)$$

$F_{pen(C)}$ represents the wireless connection by penalizing the effective CINR perceived by the MSs over the burst. The thresholds T_{min} and T_{max} can be set to the CINR criterion for the minimum and maximum MCS in the LUTs.

The assumptions about the expected users made by the network provider in the network definition, such as the user profile and speed, influence the CINR calculation. Different MSs profiles may require different costs for the system due to the different channel conditions. Therefore the network designer may penalize each of them differently (note that different LUTs will apply in the SLS). Since each user will be in UL or DL and in certain channel conditions, constraint (14) indicates that only one penalty function will be applied.

In OFDMA different users can have the same ‘‘connectivity’’, by having similar CINR over their bursts, but they can have different burst sizes and thus, not the same throughput. The overall network performance will therefore depend on the service requirements, bandwidth available, scheduling and frequency reuse. As a result, a separate QoS indicator is needed in the cost function.

$F_{pen(T)}$ is the penalty function for the MSs throughput. T_{min} and T_{max} can be set to the maximum and minimum throughput request for each service. The use of this factor in the cost function provides a more flexible network design in which different business plans, based on certain services for some areas, can be applied. Constraint (15) indicates that the MS will use at least one service DL or UL, and a maximum of services (Ser_{max}) in both UL and DL which can be penalized in different ways. The services supported by our simulator module are VoIP, video conference, web browsing and FTP.

F_{max} can be set differently to the CINR criteria to give this objective more or less importance. Note that the final throughput perceived by a MS attached to a RS depends on two links, BS-RS and RS-MSs.

$F_{pen(R)}$ penalizes different degrees of network resiliency. In the event of having a failure in a RS, other RSs may cover the new empty area by extending the coverage of an alternative station. In addition, the RSs previously attached to the faulty station need to reconnect to a new one. These procedures incur in reconfiguration costs that are considered in this objective.

During the network planning some failure events can be simulated for each configuration. A failure in the multihop communication is more likely to happen for weak relay links connections. Note in (13) that the performance in this criterion is penalized over the BS-RS link, and therefore over the subset of RSs. Similarly to CINR criterion, different RS profiles can be penalized differently for every channel according to the LUTs provided, adjusting T_{min} and T_{max} to the CINR values to for the minimum and maximum MCS. Constraint (16) indicates that different penalties can be applied in both UL and DL.

4. EXPERIMENTAL EVALUATION

An example of network design process has been performed over a rectangular area of the city of Munich (3.3km \times 2.3km) using an IEEE 802.16j network. The used scenario is a non-regular OFDMA network at 3.5 GHz with a channel bandwidth of 10 MHz, composed of 3 BSs (of 3 sectors) and 8 RSs. Two different types of traffic pattern have been used to simulate the uneven distribution of the users across the scenario: one background traffic map and three different hot spots with a density of 50 user/km² and 70 user/km², respectively. The rest of parameters are shown in Table 1.

Table 1 Simulation Parameters

Parameter	Value	Parameter	Value
PMP Sectors	9	CPE Antenna Gain	0dBi
Relay Sectors	8	CPE Antenna Pattern	Omni
Carrier Frequency	3.5GHz	CPE Antenna Height	1.5m
Channel Bandwidth	10MHz	CPE Noise Figure	5dB
BS TX Power	43dBm	CPE Cable Loss	0dB
BS Antenna Gain	18dBi	σ (Shadow Fading)	8dB
BS Antenna Height	30m	Intra BS correlation	0.7
BS Noise Figure	4dB	Inter BS correlation	0.5
BS Cable Loss	3dBm	Path Loss Model	RayTrace
CPE Tx Power	23dBm	Traffic Map Density	50u/Km ²

Different configurations are searched by a Tabu Search algorithm in both the inner and outer optimization loop. The Tabu list size is chosen empirically in the initial tuning. The outer loop gets optimal or at least good values for antenna tilt and azimuth (in intervals of 10⁰) with the optimal or at least a good assignment of subchannels calculated in the inner loop. Figure 2 shows the pilot power and user status of a single snapshot in the solution found.

Hotspots and indoor coverage in the central area benefit from this configuration. However, there are a number of MSs with low CINR levels concentrated at the edge of the coverage areas, where they may have a poor channel quality. Note that the penalization is performed in different ranges and values, and depends on the network designer criteria as some objectives can be given more or less preference. Due to this fact diverse situations can be created. This solution is an example of throughput enhancement and network reliability, since RSs are well covered. Other strategies with different degrees of fairness for users or risky configurations for the operators can be set by tuning the values (F_{max} , T_{min} , T_{max}) in the penalty function.

One snapshot of a solution obtained without the use of the inner optimization loop is shown in Figure 3. Instead, the frequency planning process has been performed after the optimization of tilt and azimuth.

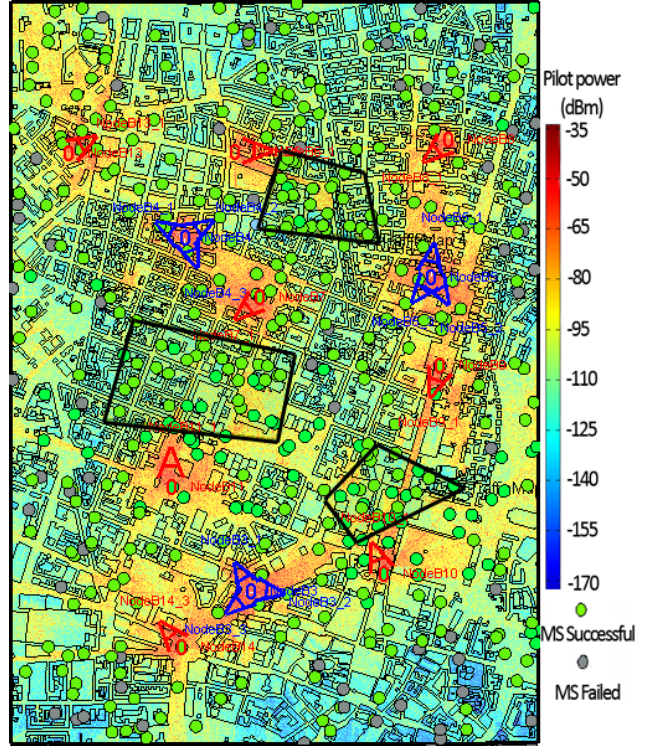


Figure 2. Optimal solution.

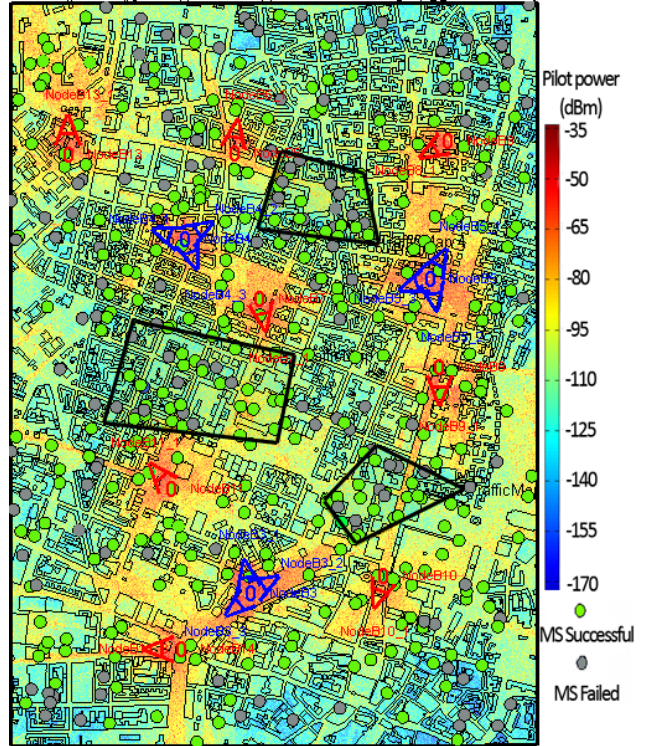


Figure 3. Solution without Inner optimization loop.

In this case, the throughput per user decreases specially in the MSs that are in the hotspots. The reason is that the tilt/azimuth set were calculated for a frequency reuse 1, and the subsequent automatic frequency planning has more difficulties to efficiently

allocate more subchannels to sectors with large traffic demands due to the lower CINR levels with such antenna configuration.

The tilt/azimuth values have been set to avoid interference between sectors as much as possible. For example, compared to the optimal solution in Figure 2, it can be observed that sectors avoid pointing each other. Also, in some cases, the BS antenna parameters are not set optimally for the relay link. As a result, the network is less resilient. Since the final throughput perceived by the MSs is the result of the communication in several links, the total throughput in this system is lower. The system throughput in this case is 802 Mbps while in the optimal solution is 1082 Mbps.

Figure 4 shows the distribution of users at different CINR levels. We can observe that the number of users that cannot get the minimum MCS for communication ($CINR < 0$) is sensibly higher in the solution without the inner loop. However, the main problem in this solution is the high number of users that have low CINR levels that only allow low MCSs. This is due to the inefficient interference management. These users ($CINR > 0$) will need large bursts to fulfill their service requirements and the OFDMA frame will be filled faster, thus leaving other users with the same situation in an “unsuccessful” state. This effect is critical in the two hotspots where the traffic is higher. The final number of successful and unsuccessful users will depend on the services requirements and system scheduling.

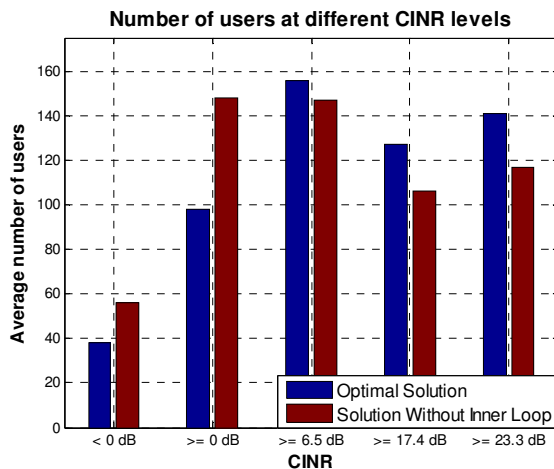


Figure 4. Distribution of users at different CINR levels.

Even though the final results will depend on the particular scenario, the described frequency planning procedure is designed to balance the network load, react against the emergence of hotspots and improve bad propagation conditions by reducing the interference levels. We have presented our framework with an integrated two-step method when other parameters need to be designed (tilt/azimuth in this case), in which every tested configuration present an optimal OFDMA subchannel assignment.

5. CONCLUSIONS

This article describes the impact of relays on the network planning and optimization process and shows how the design the problem can be simplified and translated it into a formal optimization routine with consideration of technology-specific factors. Relay networks involve a more complicated air interface than other kind of cellular networks, and need to be rigorously analyzed during

the process of network design to achieve an outstanding performance. The results of the relay scenario analyzed in this article highlight the complexity of the design process, as the operator needs to estimate a number of parameters, such as the number of users to serve or services that will be used. Frequency planning and base station configuration are integrated in a new framework that provides a new perspective to the network designer so a solution that suits its needs can be found.

We are working on extending the formulation of the optimization procedure to fully avoid the use of system level simulations with the use of the Restriction Matrix and thus, speed up the whole process. This can possibly lead to solutions of better quality and the analysis of larger and more complex scenarios.

6. REFERENCES

- [1] IEEE Standard for Metropolitan Area Networks, Part 16: Air Interface for Fixed and Mobile Broadband Wireless Systems. IEEE 802.16's Relay Task Group, 2008.
- [2] F. Gordejuela-Sanchez, D. Lopez-Perez and J. Zhang, "Frequency Planning in IEEE 802.16j Networks: An Optimization Framework and Performance Analysis," accepted in IEEE WCNC, 2009.
- [3] F. Gordejuela-Sanchez, A. Juttner and J. Zhang, "A Multiobjective Optimization Framework for IEEE 802.16 Network Design and Performance Analysis," IEEE Journal on Selected Areas in Communications (J-SAC), vol. 27, no. 2, pp. 1-15, February 2009.
- [4] A. Eisenblätter. Frequency Assignment in GSM Networks: Models, Heuristics, and Lower Bounds. PhD thesis, Technische Universität Berlin, Germany, 2001.
- [5] S. Hurley, "Planning Effective Cellular Mobile Radio Networks," IEEE Transactions in Vehicular Technology, Vol.51, No.2, pp. 243-253, March 2002.
- [6] L. Guan, J. Zhang, J. Li, G. Liu, P. Zhang, "Spectral efficient frequency allocation scheme in multihop cellular network," in 66th VTC Fall, 2007, pp.1446-1450.
- [7] Y. Li, Q. Miao, M. Peng and W. Wang, "Frequency allocation in two-hop cellular relaying networks," in 18th IEEE PIMRC, 2007, pp.1-5.
- [8] T. Liu, M. Rong, H. Shi, D. Yu, Y. Xue, E. Schulz, "Reuse partitioning in fixed twohop cellular relaying network," in IEEE WCNC, 2006, vol.1, pp.177-182.
- [9] A. Eisenblätter, H. F. Geerdes, T. Koch, A. Martin, and R. Wessly, "UMTS radio network evaluation and optimization beyond snapshots," Mathematical Methods of Operations Research, vol. 63, pp. 1-29, 2005.
- [10] R. K. Taplin, D. M. Ryan, S. M. Allen, S. Hurley, and N. J. Thomas, "Algorithms for the automatic design of WiMAX networks," in NGMAST, 2007.
- [11] I. Siomina, P. Värbrand, and D. Yuan, "Automated optimization of service coverage and base station antenna configuration in UMTS networks", IEEE Wireless Communications, vol. 13, pp. 16-25, 2006.
- [12] L. Chen, N. Martin, C. Cabrera, A. Srinivas, "Joint Topology Design and Frequency Allocation for Fixed Wireless SDR Networks", presented in SECON 2006, September 2006.