Frequency Planning with an Optimized Frequency Reuse Distance for Fixed WiMAX Networks

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Abstract. This paper propose a methodology based on Integer Linear Programming to perform the frequency assignment in WiMAX networks. In a first step the reuse frequency distance is calculated. The obtained results for the performance of WiMAX networks using the frequency assignments obtained with the proposed methodology are similar with those obtained with frequency assignment obtained from professional radio planning tools.

1 INTRODUCTION

At present broadband wireless networks are one of the best technological alternatives to meet the communication needs of end users located in suburban and rural areas with poor connectivity services. In the case of Mexico, there are many areas within its territory that result inaccessible to wired networks which are the main offering option for broadband connectivity in the country. These areas have lacked connectivity services due to the high complexity and cost of providing such services. Finally this situation results in a lag in the development of these areas.

In order to increase the broadband penetration level in Mexico, the federal government is currently deploying a nationwide network of broadband wireless access based on WiMAX technology. This network is called "Redes Estatales de Educación Salud y Gobierno (REESyG)". With the purpose of operate these networks the federal government has booked the frequency spectrum from 3300 to 3350 MHz (50 MHz bandwidth) in all the country [1].

One of the key factors that define the performance of a wireless broadband network is the level of interference present in the network. The level of interference directly affects the transmission rate and limits the performance. The interference present in a network depends on the used frequency assignment plan [2]. In a network with a reduced number of sites, assignment of frequencies to different sectors of the network can be done manually. But with a large number of sites the frequency assignment problem becomes a major design challenge. In the case of the REESyG it is estimated that may be taken into operation

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around 2000 sites in the country. This will require the design of efficient frequency assignment plans in order to ensure the coexistence of many sites in the same geographical area without reducing the global network performance.

As shown, the problem of frequency assignment is critical in the design and optimization of wireless broadband networks such as WiMAX. This paper proposes a methodology based on Integer Linear Programming to generate frequency assignment plans. This methodology is tuned to the WiMAX technology specifications and considers a fixed assignation of one channel for each sector of the network. The obtained frequencies assignment plans ensure an efficient use of the available electromagnetic spectrum resources by reducing the levels of interference in the network. An efficient assignment of the frequencies results in benefits to the end-user and to the network itself. Currently there are several professional-level tools for radio network planning that can address the issue of design of frequency plans. However, the proposal of this paper seeks to provide a simpler alternative to generate efficient frequency plans adjusted to the particular needs of the REESyG.

This paper is organized as follows. In the second section it is presented a procedure for determining the frequency reuse distance based on different scenarios of interference. The third section presents the proposed methodology for frequency assignment in WiMAX networks. Finally the fourth section presents the performance results of a network that operates with the frequency plan obtained with the proposed methodology.

2 DETERMINING THE REUSE DISTANCE

2.1 C/I ratio evaluation

Carrier to Interference ratio (C/I) provides a measure of the relationship between the average power of the transmitted signal and the average power of interference [3]. Interference is a disturbance affecting the performance of a radio system due to the close operation of one or more links that use the same frequency (co-channel interference) or an adjacent frequency (adjacent channel interference) as shown on Figure 1. Both the adjacent interference as co-channel interference can severely limit the capacity of a network. The design of an efficient frequency assignment plan must offer reduced interference levels for the network.

In Figure 1 above, ED indicates the wanted link and IE indicates the interfering link. The received power depends on the propagation loss, the power transmitted by the site and the gains of the transmitting and receiving antennas. In this paper we consider that the site use sector antennas of 90 degrees. A site is composed of 4 sites to provide coverage of 360 degrees.

The received power of a wanted signal is determined as [3]:

$$PrD(dBm) = PtI + GTD + GRD - Lbd \tag{1}$$

The received power of an interfering signal is determined as:

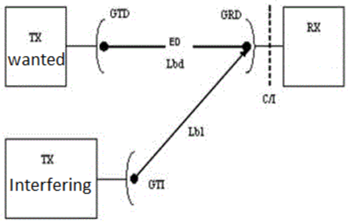

Fig. 1. Radio link operating with an interfering transmitter

$$PrI(dBm) = PtI + GTI + GRI - LbI \tag{2}$$

where:
PtD is the wanted transmitter power
PtI is interfering transmitter power
GTD is the antenna gain of the wanted transmitter
GTI is the gain of the interfering transmitter antenna
GRD is the receiver gain on the wanted link
GRI is the receiver gain in the interfering link
Lbd are the propagation losses of wanted link
LbI are de propagation losses of interfering link

$$\frac{C}{I}(dBm) = PrD - PrI \tag{3}$$

If multiple interference exists, the total interfering received power must be calculated, which is the result of the addition of partial interference sources. In this case the above equation can be expressed as:

$$\frac{C}{I}(dBm) = PrD - 10\log\left(\sum_{i=1}^{n} PrI_i\right) \tag{4}$$

where:

$$PrI_i = 10^{0.1PrI} \tag{5}$$

In the case of the WiMAX technology the C/I ratio of a link defines the highest modulation that can be used on it. Table 1 shows an example of the minimum C / I ratio required by a manufacturer of WiMAX equipment for a link to operate with different modulation schemes. Different manufacturers offer this type of tables to use their equipment.

From the point of view of the network planning, a main objective is to ensure links with high level modulations. So the C/I ratio in the network must be maintained above a threshold to ensure the operation of links with the wanted modulation. To achieve this goal is very important to define a distance for the

Modulation	Required $C/(N+I)$ dB
BPSK 1/2	3
QPSK 1/2	9.375
QPSK 3/4	12
16QAM 1/2	15.75
16QAM 3/4	18.375
64 QAM 2/3	22.5
64 QAM 3/4	24

Table 1. Minimum C/I ratio required to operate different modulation schemes on the platform redmax [4]

reuse of frequencies. Based on this distance it is possible to determine those areas of a network that can share the same frequency. The operating frequency assignment to each sector of the network must be such as to ensure that the C/I ratio is kept at the wanted levels.

In this work the propagation losses area calculated using the SUI model of the Stanford University. The IEEE 802.16 standard working group in conjunction with Stanford University developed a WiMAX channel model for suburban environments. One of the most important achievements was the SUI model for propagation loss (Stanford University Interim), which is an extension of previous work developed by AT & T Wireless and the analysis of it made by Erceg [5]. This model was adopted by the IEEE 802.16 working group as the recommended model for fixed WiMAX applications. For the propagation loss through the Extended SUI model it is required to know three values: the height of the antennas, the operating frequency and link distance. The model proposes three different types of scenarios: Erceg A, applicable to mountainous terrain with medium / high density of trees and urban areas; Erceg B, applicable for mountainous areas with low tree density or flat terrain with moderate / high density of trees and suburban areas; and Erceg C, applicable to flat terrain with low tree density and rural areas. In this work the Erceg B model was used because of the conditions of the analysis scenario in a zone of the Mexico City. For a complete treatment of the SUI model refer to [5,6].

2.2 Reuse distance calculation

To calculate the reuse distance an analysis was performed on a scenario consisting of four interfering sites named I1, I2, I3 and I4, and the wanted Tx transmitter site, each with 4 sectors of 90 degrees. This scenario is representative of most real scenarios where network deployment consider the frequency reuse and an analysis of C/I ratio is required. The analysis is performed only with those sectors that may radiate to the area where the interfered receiver is located, as shown in Figure 2. In this figure the analysis area is a 5Km x 5Km box, divided into cells with 0.5 Km by side. A cell represents the location of a receiver that wants to establish a link to the wanted transmitter Tx. The analysis considered that the interfering sectors were located at distances from 3Km up to 15Km from the transmitter.

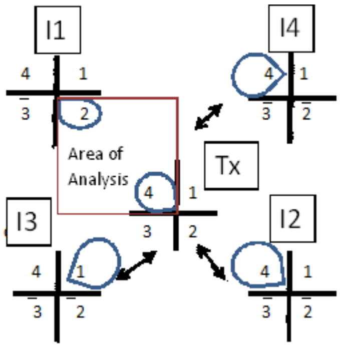

Fig. 2. Figure 2. Interference analysis scenario

For the C/I ratio evaluation were considered technical specifications of the transmitter and receiver, such as the sector antenna radiation pattern and transmitter power. Based on the equations 5 and 7 calculations of the C/I ratio were performed for each of the 100 cells in the analysis area. These calculation were performed for each interfering site in a separately way and also for the case when the four sites were interfering at the same time. The obtained results of C/I ratio let to establish the highest modulation that could be operated in a radio link for each of the 100 analyzed cells. Table 2 shows the percentage of cells with 64QAM 3/4 (the highest WiMAX modulation) for different distances of analysis, according to Figure 2, ranging from 3Km to the 15Km. This table presents the percentages of cells with 64QAM 3/4 modulation for the case of only one interfering site of type I2 and for the case of only one interfering site of the type I3 or I4 (because of their symmetry, interfering sites I3 and I4 affects in the same way).

These obtained results let to define the frequency reuse distance depending on the main wanted modulation in the operation of a WiMAX network. For example if it is wanted that more than 80% of the network operate with 64QAM 3/4 modulation, the frequency reuse distances should be of 9 Km for type I2 interfering sites and 5 Km for type I3 and I4 interfering sites.

3 CHANNEL ASSIGNMENT USING ILP

Once the frequency reuse distances were calculated, in this section the proposed methodology for the frequency or channels assignment in the WiMAX network is presented. The Assignment Problem for radio frequencies is complex. It requires sharing the available resources among all sites in the network efficiently and at the same time minimizing the interference within the network.

Analysis distance (Km)	Percentages of cells with 64QAM 3/4 modulation	
	I2 type interferent	I3, I4 types interferents
3	27.27	48.76
5	50.41	85.95
7	71.90	97.52
9	85.12	99.17
11	94.21	99.17
13	97.52	99.17
15	99.17	99.17

Table 2. Percentage of cells with 64qam 3/4 modulation for different distances and different interference analysis

Consider a wireless network system consisting of n sites each one is formed by m sectors. Let, R be the set of sites $R = \{r_1, \ldots, r_n\}$ and S be the set of sectors $S = \{s_1, \ldots, s_m\}$. Therefore the universe of sites-sectors in the network is defined by the set $N = R \times S = \{(r_1, s_1), (r_1, s_2), ..., (r_1, s_m), (r_2, s_1), ..., (r_n, s_m)\}$.

There will be a possible electromagnetic connectivity between the sector s_j belonging to the site r_i and the sector s_k belonging to the site r_l when the distance between these sectors is less or equal than a predefined distance d_γ. This predefined distance d_γ will be estimated according to the calculations of theC/I ratio in the previous section.

3.1 Electromagnetic Compatibility Matrix

The Electromagnetic Compatibility Matrix $C_{p \times p}$, where $p = |N|$ and $|\cdot|$ is the cardinality, defines in a certain way the behavior of the communication network. It is a square matrix formed by p site-sectors in the network and establishes the restrictions required to assign channels.

Without loss of generality, the entries or the matrix $c_{((r_i,s_j),(r_l,s_k))} = 1$ if the sector s_l of the site r_k is within the transmission range of a sector s_j belonging to the site r_i, and $c_{((r_i,s_j),(r_l,s_k))} = 0$ in other case.

Let us define the set $Ch = \{ch_1, ch_2, \ldots ch_q\}$, where q represents available frequency channels which can be assigned to a sector.

3.2 Design Variables

A channel ch_β has to be assigned to a sector s_j of the site r_i this is denoted by the decision variable $A_{((r_i,s_j),ch_\beta)}$.

This decision variable is a dummy variable i.e.

$A_{((r_i,s_j),ch_\beta)} = 1$ if the channel ch_β is assigned to the sector s_j of the site r_i and $A_{((r_i,s_j),ch_\beta)} = 0$ in other case. So a value equal to 1 in an entry of this matrix indicates that the pair of involved sectors can generate an unacceptable level of interference to the network if they use the same frequency channel. The proposed methodology of frequencies assignment takes the entries of this matrix as its first decision variable.

3.3 Set of Constraints

If according to the C matrix, two sectors may cause interference due to the use of the same channel, then a specific channel can be assigned to only one of those sectors. This is expresed as:

$$A_{((r_i,s_j),ch_\beta)} + A_{((r_l,s_k),ch_\alpha)} \leq 1 \,\forall \left\{ch_\beta = ch_\alpha \mid c_{((r_i,s_j),(r_l,s_k))} = 1\right\}. \quad (6)$$

Only one channel can be assigned to one sector, i.e.:

$$\sum_{\beta=1}^{q} A_{((r_i,s_j),ch_\beta)} \leq 1 \quad \forall\,(r_i,s_j) \in R \times S. \quad (7)$$

The objective function is to minimize the use of channels, with respect to A; it is defined as follows:

$$\min_A (A) := \sum_{\beta=1}^{q} 1 - \sum_{i=1}^{n}\sum_{j=1}^{m} A_{((r_i,s_j),ch_\beta)}$$

Now, we can define the integer-linear programming problem Θ:

$$\min_A (A) := \sum_{\beta=1}^{q} 1 - \sum_{i=1}^{n}\sum_{j=1}^{m} A_{((r_i,s_j),ch_\beta)}$$

subject to (6)-(7).

The integer-linear programming problem that we present here is a convex problem therefore we warranty to find a global minimum, for more details please refer to [8].

4 TESTING AND RESULTS

4.1 Frequency reuse distance

In order to validate the estimated values for the frequency reuse distance some simulations were conducted. These simulations include the verification of the reuse distance as a function of the accepted C/I ratio levels or as a function of the wanted modulations. These simulations were performed using the professional network radio planning tool Mentum Planet 5.2 [7].

The simulation scenario includes three interfering transmitters I1, I2 and I3, all of them located at a distance of 9 Km from the transmitter Tx. An analysis of C/I ratio is performed on the 5Km x 5Km square, shown in Figure 3.

Using equations (4) and (5) calculations for the C/I ratio were performed, with N = 100 radio links in each of the different positions of the receiver in the analysis area. With these results the better modulation in each link was defined in accordance with the requirements of minimum C/I ratio. Table 3 summarizes

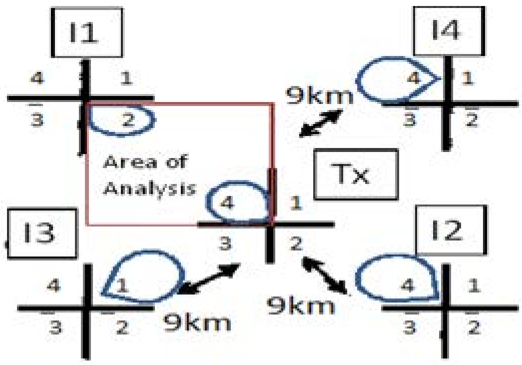

Fig. 3. Figure 3. Scenario for interference analysis.

	Modulation percentages for each modulation	
Modulation	Proposed estimation using SUI model	Mentum Planet
No link	12.39	1.89
BPSK 1/2	8.26	13.67
QPSK 1/2	4.13	8.48
QPSK 3/4	1.65	6.58
16QAM 1/2	0	2.92
16QAM 3/4	7.43	3.47
64 QAM 2/3	4.13	1.03
64 QAM 3/4	61.9	61.96

Table 3. Percentages of modulation usage in the analysis area.

the obtained results and presents also those results obtained with the Mentum Planet tool.

The obtained results confirm that there is high similarity between modulation levels that are estimated using the procedure described in Section 2 and the results obtained with Mentum Planet. It is important to point out that Mentum Planet uses different information layers in the propagation estimations. These layers include a digital terrain model and land usage layer (clutter). This additional information will allow more accurate propagation estimates. However it can be seen from Table 3 that the estimates for the higher modulations are very similar in both cases.

4.2 Frequencies assignment

Once the frequency reuse distance was defined, this information is fed to the process of frequency assignment to the sectors of the WiMAX network. In this case the defined reuse distances were set to 11 Km for type I2 interferers and to 9 Km for types I3 and I4 interferers. Thus it is expected that a percentage of about of 90% of the territory of the network coverage operate with a 64QAM 3/4 modulation.

The following analysis is performed in order to validate the results obtained from the proposed methodology for frequency assignment. In this case the frequency plan obtained with the proposed methodology is applied to a network with 5 sites, each with 4 sector antennas of 90 degrees. It is considered that the network operates under the IEEE 802.16-2004 (fixed WiMAX). There are 7 available channels to be assigned to the sectors because of the booked 50 MHz bandwidth for the operation of the REESyG and because of the 7 MHz of bandwidth for the WiMAX channels. Table 4 presents the frequency assignment plan obtained with the proposed methodology and also the plan obtained with the Mentum Planet tool. The used frequency channels are named 1, 2, 3, 4, 5, 6 and 7 and they are distributed in the available 50 MHz to operate de WiMAX network.

In order to evaluate the performance of the network many parameters can be used, but the most representative one to assess the impact of the frequency assignment plan is the Carrier to Interference ratio C/I in the downlink. Figure 4 shows a Mexico City map, where the analysis scenario was placed, and the 5 sites are shown. This map shows the C/I ratio values in the downlink values over a clutter layer for Mexico City. The frequency assignment plan used to generate this analysis was that obtained with the proposed methodology. This map shows the different C/I ratio levels in the area with coverage from the WiMAX network.

As shown in Figure 4, much of the territory covered by the WiMAX network achieves high C / I ratios. However, in order to perform a more formal comparison between the frequency assignment plan resulting from the application of the proposed methodology and the frequency plan obtained with Mentum Planet, the Table 5 presents the percentages of different modulation obtained in the WiMAX network using both frequency plans.

	Frequency assignment plans	
Sector	Assigned frequency channel with the Proposed Methodology	Assigned frequency channel with the Mentum Planet
1	4	7
2	2	3
3	5	4
4	3	5
5	3	6
6	7	4
7	4	7
8	2	2
9	4	5
10	2	7
11	3	6
12	1	1
13	5	3
14	4	1
15	1	2
16	4	5
17	1	1
18	4	2
19	5	3
20	3	4

Table 4. Frequency assignment using the proposed methodology and frequency assignment using mentum planet

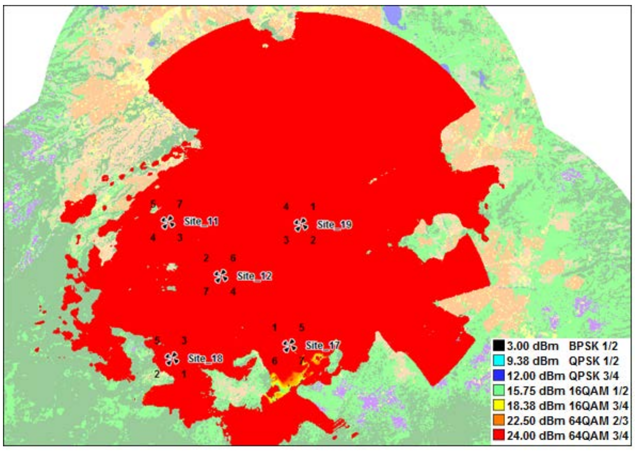

Fig. 4. C/I ratio for the downlink channel for the analyzed WiMAX network for 5 sites.

	Percentage of modulation usage in the coverage area	
Modulation	Using Mentum Planet frequency plan	Using the frequency plan obtained with the proposed methodology
BPSK 1/2	0	0.01
QPSK 1/2	0	0.01
QPSK 3/4	0.01	0.04
16QAM 1/2	0.14	0.05
16QAM 3/4	0.3	0.14
64 QAM 2/3	0.14	0.05
64 QAM 3/4	99.41	99.7

Table 5. Percentage of different modulation levels for 5 sites.

As can be seen from this table the percentages of use for the different modulations are very similar in both frequency plans. However it is important to note that in the frequency plan obtained from the proposed methodology uses only 6 channels as opposed to the proposal of Mentum Planet that uses all the 7 available channels. So in this case the proposed methodology offers a more efficient spectrum usage.

The proposed methodology was applied to a more complex network composed of 41 sites and 164 sectors. This network was designed to offer coverage to the majority of the populated zones of the Mexico City. Due to the number of sites, we decide to reduce the reuse distances to 9 Km for type I2 interferers and to 5 Km for types I3 and I4 interferers. The obtained results are shown in Table(6).

	Percentage of modulation usage in the coverage area	
Modulation	Using Mentum Planet frequency plan	Using the frequency plan obtained with the proposed methodology
BPSK 1/2	0.03	0
QPSK 1/2	0.06	0
QPSK 3/4	0.16	0.03
16QAM 1/2	0.22	0.14
16QAM 3/4	0.56	0.3
64 QAM 2/3	0.36	0.16
64 QAM 3/4	98.61	99.37

Table 6. Percentage of different modulation levels for 41 sites.

As we can see from Tables (5,6) in both cases, our proposed methodology offers a better efficient spectrum usage.

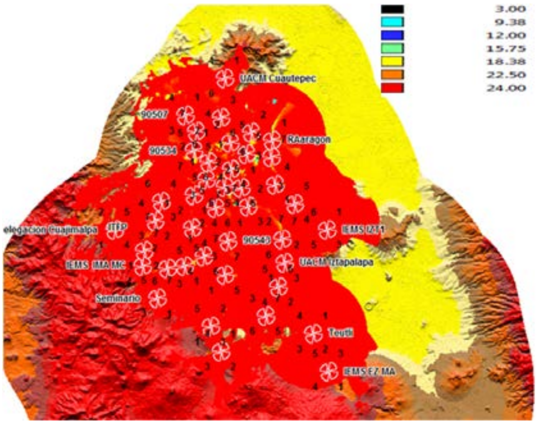

Fig. 5. C/I ratio for the downlink channel for the analyzed WiMAX network for 41 sites.

Figure 5 shows a Mexico City map, where the analysis scenario was placed, and the 41 sites are shown. The frequency assignment plan used to generate this analysis was that obtained with the proposed methodology. This map shows the different C/I ratio levels in the area with coverage from the WiMAX network for Mexico City.

5 Conclusions

The definition of the frequency reuse distance is very important to generate frequency plans to ensure that the network C/I ratio levels are maintained above a desired threshold. The frequency assignment methodology proposed offers similar performance level as the frequency plan generated with a professional tool for radio network design. However the proposed methodology achieves a more efficient use of the available spectrum.

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