Planning and Deployment of WiMAX and Wi-Fi Networks for Health Sciences Education

PEDRO SEBASTIÃO, FERNANDO J. VELEZ, RUI COSTA, DANIEL ROBALO, CLAUDIO COMISSARIO, ANTONIO RODRIGUES

Optimal planning for the integration of WiMAX (Worldwide Interoperability for Microwave Access) and Wi-Fi (Wireless Fidelity) technologies enables real technical conditions to make a hybrid Wi-Fi/WiMAX network available at the Health Sciences Faculty of University of Beira Interior, supporting nomadic applications like videoconference, voice over IP and communication of high resolution video/image. A simple wireless planning tool is designed and used in this optimal planning, which facilitates the design and implementation of Wi-Fi and WiMAX networks in indoor and outdoor environments. The tool gives useful information through quick coverage/capacity based procedures, as the output is the number and position of the APs (access points)/BSs (base stations) or an estimation of the total cost of implementation, based on data provided by different manufacturers. While planning methodologies are already stable for Wi-Fi, and propagation models have already been widely validated, the propagation models available for WiMAX still need to be tuned, which motivates the need to carry out propagation measurements. For IEEE 802.16-2004 networks operating at 3.5 GHz, by comparing the measurement results with the ones obtained using the modified Friis and the SUI (Stanford University Interim) models, it was concluded that, for a suburban area of Covilhã, Portugal, the use of the modified Friis model with a propagation exponent ~3 is more appropriate than the use of the SUI one, although for coverage distances between 275 and 475 m the SUI model (SUI-B and mainly SUI-C) may still be used. WiMAX cellular planning exercises are presented for the zone of Covilhã. Carrier-to-noise-plus-interference issues are discussed, and Geographic Information Systems are applied to determine the existence of line-of-sight in rural and sparse urban areas. One of the main conclusions arising from this work is the strong need of using sectorial antennas to guarantee an adequate coverage and interference mitigation for several terrain types and environments, including hilly terrain.

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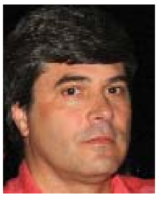

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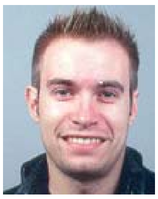

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1 Introduction

The present context of frequency spectrum management around the globe, as well as the need for making broadband access flexible for users, create opportunities for the entrance of new operators and offer diversification of innovative access technologies. Since WiMAX (Worldwide Interoperability for Microwave Access) operates in outdoor environments (and even in indoor ones, for the lower frequency bands) with high coverage ranges, it will allow for the exchange of truly wide and broadband multimedia content, simultaneously supporting all-IP (Internet Protocol) voice, data, streaming, image and video multi-rate communications.

WiMAX is the commercial name for IEEE 802.16. The IEEE 802.16-2004 base standard is called Fixed WiMAX and is dedicated to PtP (Point-to-Point) and PtM (Point-to-Multipoint) networks without mobility support while the IEEE 802.16e-2005 amendment is called Mobile WiMAX and is dedicated to PtM networks that support mobility. WiMAX uses OFDM (Orthogonal Frequency Division Multiplexing), OFDMA (Orthogonal Frequency Division Multiple Access) and dynamic modulation scaling, ie. the system is able to adapt itself to the best modulation/coding schemes by considering carrier-to-noise-plus-interference versus throughput constraints.

In Fixed WiMAX, channels of 3.5, 5, 7 and 10 MHz are defined. As link distances of the order of tens of kilometres can be guaranteed, WiMAX is a good solution for broadband backhauling; it enables a distance range up to 50 km (in the PtP case) and cell coverage radius between 2 and 5 km (in the PtM case) while offering high throughputs.

In Portugal, the introduction of WiMAX gains special interest for emergency and security public services. With a service-oriented approach, where the needs of firemen, police, and ambulances are taken into account, it is possible to establish a framework for an initial planning of a wireless metropolitan area network where users will have access to interactive voice, data, video and multimedia communications. This will be enabled by using innovative terminals, similar to PDAs or Tablet PCs, which will combine voice with other types of services, including image and video. One example can be the communication of RT (Real-Time) image from an actual fire site to the fire department. During the summer time in Portugal, simultaneous fires in forests are a persistent calamity, and the authorities lack access to RT information on the evolution of fires in order to coordinate the fire brigades.

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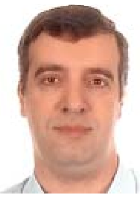

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A network was deployed for demonstration purposes in the city of Covilhã by using IEEE 802.16-2004 equipment with 3.5 MHz channels at 3.5 GHz [1]. This PtM network constitutes the basis for research and demonstration of WiMAX scenarios, including the possibility of performing extensive field trials in the FDD (Frequency Division Duplexing) mode.

Despite their coverage range limitations, IEEE 802.11, Wi-Fi (Wireless Fidelity) networks have already proven to be easy and cheap to deploy in indoor hotspots (or for short coverage range outdoor environments). As the prices of equipment are low and the use of the frequency spectrum is free, the return of investment is guaranteed after a short period of time. However, for wider coverage ranges, there is a need for hybrid networks combining another wireless standard, eg. UMTS (Universal Mobile Telecommunications System) together with or instead of IEEE 802.16 [1], [2]. Future scenarios with a large scale deployment of such network infrastructures justify the development of new dimensioning methodologies for ubiquitous indoor and outdoor broadband wireless access. To fulfil part of these needs, this work aimed at enabling future hybrid Wi-Fi/WiMAX networks while addressing a wireless planning tool developed for this purpose. The WiMAX and Wi-Fi integrated infrastructure is a high capacity experimental implementation that provides indoor-to-outdoor roaming in the context of telemedicine and health sciences education.

While the Wi-Fi component, defined by the IEEE 802.11a, 802.11b or 802.11g standards [3], is already totally incorporated into the planning tool, the WiMAX functionalities are still being developed. The aspects related to service quality will certainly lead to the inclusion of IEEE 802.11e functionalities into the tool, allowing for the mapping of WiMAX service classes to Wi-Fi. The tool will simultaneously present cellular planning results for outdoor WiMAX and indoor/outdoor Wi-Fi for a given zone, eg. in the area surrounding a University Campus (or a Hospital), and inside its buildings. For a given coverage region and expected user capacity, the WPT (Wireless Planning Tool) estimates the adequate position of APs (Access Points) seeking for cost minimisation, based on data provided by manufacturers [4].

In the initial phase of WiMAX deployment, the operator's experience with large scale networks is limited and measurement based cellular planning procedures, extracted from the experimental networks and prototypes, enable the validation of the proposed planning algorithms and tools. The configuration of the WiMAX classes of service facilitates the optimisation of QoS (Quality of Service) parameters of each type of traffic stream. In terms of QoS support, IEEE 802.16e includes a fifth service class, not included in IEEE 802.16-2004, which supports other services, eg. VoIP with silence suppression.

The remaining of the paper is organized as follows. Section 2 presents the set of e-Learning applications, whose support motivated the conception of the hybrid wired/wireless network at FCS (The Health Sciences Faculty) of UBI (University of Beira Interior). Section 3 addresses outdoor and indoor propagation models. As IEEE 802.16-2004 equipment was made available, and frequency carriers at the 3.5 GHz band were assigned by the Portuguese regulator for R&D purposes, a comparison was performed between the values obtained from the measurements and the theorethical curves for the modified Friis and Stanford University Interim models. Section 4 starts by presenting the conception and implementation details of the Wi-Fi and WiMAX platforms of the WPT. As system capacity aspects are a key element for the deployment and planning of these networks, Section 5 addresses manual and automatic algorithms for the choice of the placement of access point positions (while guaranteeing a given throughput). In Section 6, after presenting our WiMAX cellular planning scenario, carrier-to-noise-plus-interference issues are addressed. As the existence of obstacles, eg. mountains, trees and buildings can affect the LoS (line-of-sight) propagation, GIS (Geographic Information System) based dimensioning is used for rural and sparse urban areas, in mixed hilly/flat zones. Finally, conclusions are presented in Section 7.

2 e-Learning Applications

FCS from UBI was the first in Portugal to adopt an e-Learning approach across its entire medical science programme of studies. This learning methodology does not involve classrooms filled with students listening to a lecturer or written tests. Instead, online trainers and tutors publish study material and reference information on the University's Intranet, and can be in touch with students at any time, seven days a week. Furthermore, classrooms are fully equipped for self-study development, and this methodology can actually be considered as a b-Learning (blended learning) one.

Supporting such an innovative e-Learning environment requires a fixed and wireless network infrastructure that can handle considerable volumes of videoconference, e-mail, self-Learning material, and video images over secure, reliable, easy-to-use and highly flexible LAN (Local Area Networks) and MAN (Metropolitan Area Networks), see Figure 1.

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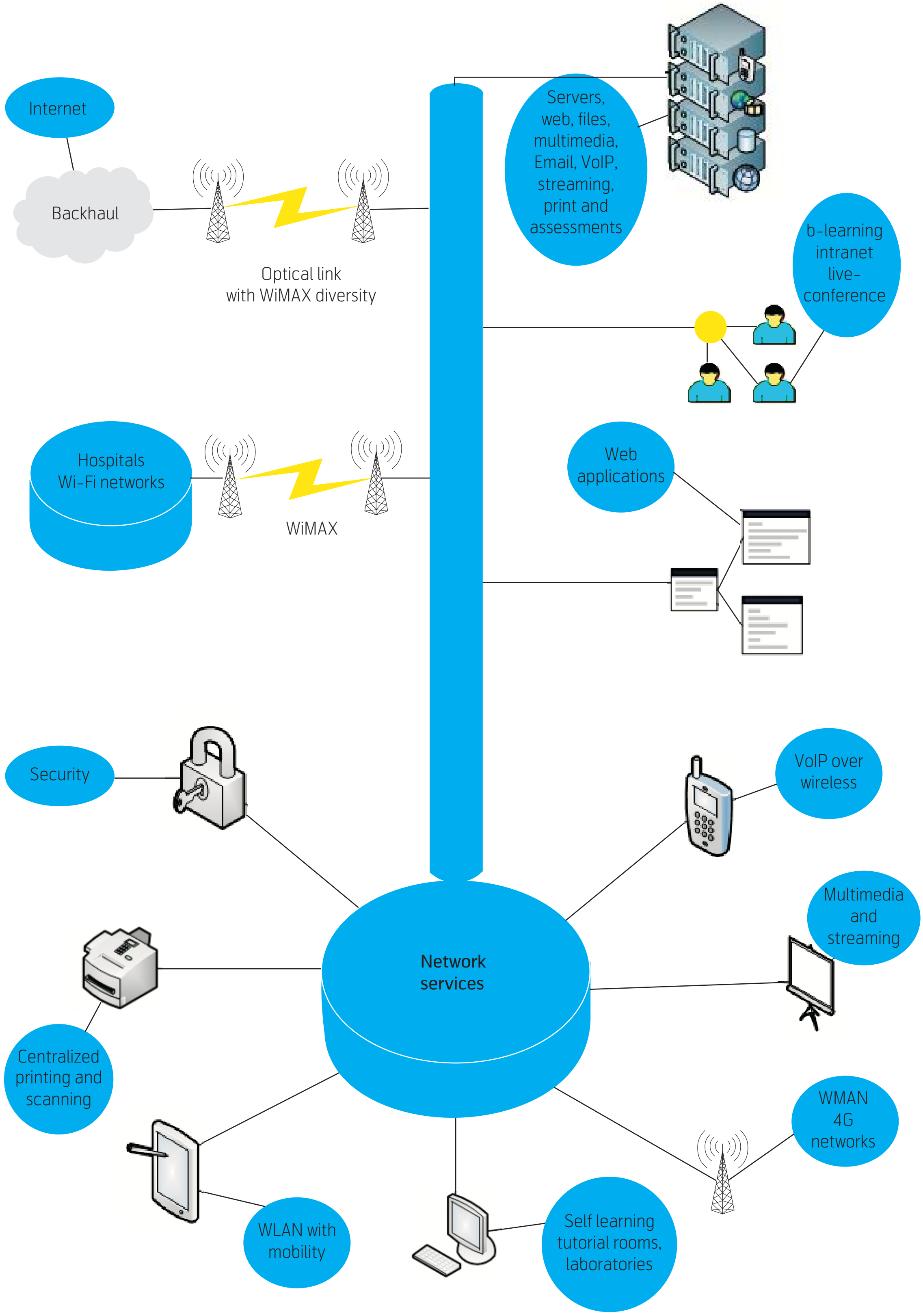

Figure 1 Network architecture and services for the contemporary FCS network. A high volume of traffic is handled over secure, reliable, easy-to-use and highly flexible hybrid networks

A HP ProCurve Switch 5304xl, WESM (Wireless Edge Services Module) together with 12 ProCurve Radio Port 230 units (Wi-Fi access point and router) enable the wired interoperability LAN platform.

Unified network management is provided for users on both the wired and wireless networks through ProCurve Manager Plus, Mobility Manager and Identity Driven Manager. By using this solution [5], the Faculty now benefits from network access control that is enforced at the edge, but readily commanded

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Figure 2 Telemedicine and WLAN communications are supported by Tablet PCs and Ultra Mobile PCs at the FCS tutorial rooms. Trainers and tutors may walk while discussing the course subjects with the students

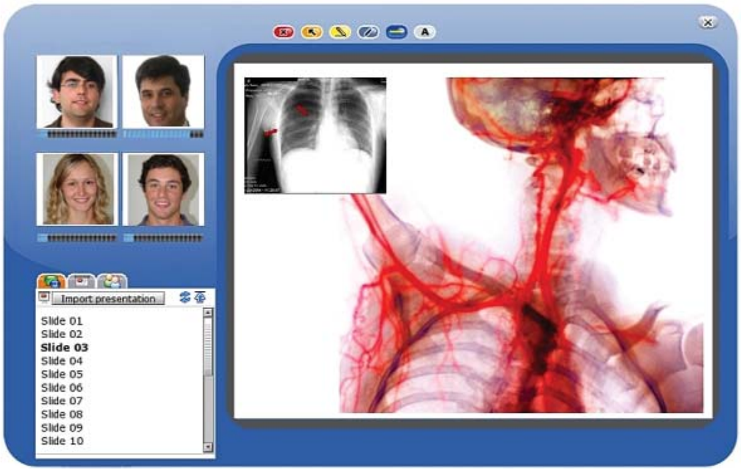

Figure 3 Telemedicine and Self-Learning: the hybrid network facilitates user access to multimedia contents in an efficient and seamless way

from the centre. Network integrity is preserved, assets protected, while productivity and efficiency is increased. The Faculty building is now equipped with a highly reliable and secure network that satisfies the needs of 600 medical students and about 50 members of the staff, Figures 2-3.

Together with PtP wireless optical/WiMAX links and the PtM cell in the city of Covilhã, this innovative network is also flexible enough to satisfy any future demands of the FCS student population, which is growing to 1,000 users. It really does complement the modern teaching facilities, laboratories and library available at the Faculty.

3 Propagation Models

3.1 Outdoor Propagation Models

The average path loss is computed by using empirical radio frequency propagation models. This enables to position APs, for each pixel of the coverage map, corresponding to a given area on the field, urban or building plan. For outdoor environments, obstacles such as building materials, foliage and clutter, also contribute to increase the path loss [6-7]. In this context, two outdoor propagation models have special relevance [6]; the SUI (Standford University Interim) and the MMDS (Multichannel Multipoint Distribution Service) empirical path loss. In this study only the former will be considered.

In NLoS (Non Line-of-Sight) channel conditions, signals may undergo scattering, diffraction, polarization changes and reflection impairments, which affect their level and phase at the receiver. Usually these impairments are not important when there is LoS between the transmitter and the receiver.

Over the years, various models have been developed to characterize RF (Radio Frequency) environments and allow for the prediction of the RF signal strengths. These empirical models are used to predict large-scale coverage for radio communications systems in cellular applications and provide estimates for PL (Path Loss) by considering the distance between the transmitter and receiver, terrain factors, antenna height, and operation frequencies. Nevertheless, according to [7] none of these models address the needs of broadband fixed wireless adequately. This fact motivated the development of a new empirical model by AT&T. This model was the basis of an industry-accepted model, and is considered in the IEEE 802.16 standard. The adoption of the AT&T wireless model by IEEE is referred as 'Channel Models for Fixed Wireless Applications' in [8]. The AT&T wireless PL model includes, as parameters, antenna heights, carrier frequency and types of terrain [7]. Apart from the modified Friis model (where the propagation exponent γ instead of taking a value of 2 is replaced by a different empirical value), one possible option for the WPT is therefore the SUI model, which is an extension of the earlier work of AT&T wireless propagation model [7].

The SUI model uses three basic terrain types:

- Category A – Hilly / moderate-to-heavy tree density;
- Category B – Hilly / light tree density or flat / moderate-to-heavy tree density;
- Category C – Flat / light tree density.

These terrain categories provide a simple method to estimate more accurately the PL of the RF channel in an NLoS situation. Being statistical in nature, the model is able to represent the range of PLs experienced within an actual RF link. SUI propagation models were explored for the design, development, and testing of WiMAX links in six different scenarios, SUI-1 to SUI-6 [9]. By using these propagation models, it is then possible to predict more accurately the coverage probability achieved within a BS (Base Station) site sector. These models do not replace detailed site planning efforts (and site surveying), but can provide an estimate before the actual planning of the network. Besides, it is very important to perform RF planning activities to adequately evaluate specific environment factors, co-channel interference, actual clutter and terrain effects.

This model facilitates using several frequencies and TSs (Terminal Stations) heights. The path loss is given (in dB) by [6]

$$PL(d) = \overline{PL}(d_0)\ [\text{dB}] + 10 \cdot \gamma \cdot \log(d/d_0) + X_f + X_h + S \quad (1)$$

with the following parameters

$$\overline{PL}(d_0)\ [\text{dB}] = 20 \cdot \log(4\pi d_0/\lambda) \quad (2)$$

and

$$\gamma = a - b \cdot h_b + c/h_b, \quad (3)$$

where d is the distance between the BS and a given point, in metres, $d_0 = 100$ m, $\lambda = c/f$ is the wave length, $c = 3\times10^8$ ms^{-1}, f is the carrier frequency, h_b is the BS height above ground, in metres ($10 < h_b < 80$ m), and a, b, and c are parameters which are chosen according to three terrain types [6]. The terms X_f and X_h are correction factors for frequency and TS antenna height above the ground, respectively. These correction factors are defined in [6]. The term S is a lognormal distributed random variable with zero mean and standard deviation σ_s, with typical values varying from 8.2 to 10.6 dB, depending on the type of terrain [6]. The average received power is given by $\overline{PR}(d) = PE - \overline{PL}(d)$, where $\overline{PE}$ is the average transmission power and $PL(d)$ is the average path loss (attenuation factor). In other commercially available planning tools models with high complexity can be used, namely, the NLoS dominant ray path loss one [6], [10]. However, in order to obtain the most efficient cellular planning tools it is important to compare these models with the simplest ones and validate them against experimental results.

3.2 Indoor Propagation Models

In indoor environments, the radio wave propagation is strongly influenced by the layout of the building and its materials; hence, the adoption of a propagation model takes the several obstacles into account (doors, walls, closets, machines, furniture, etc.), and their attenuation coefficients [11-12]. Extra details on indoor propagation models can be found in [13-15].

In these environments, the average received power in a given position depends on the average attenuation factor, $\overline{PL}(d)$ between the AP and TS, expressed in dB [11]

$$\overline{PL}(d) = \overline{PL}(d_0)[\text{dB}] + 10\gamma\log(d/d_0) + FAF[\text{dB}] + \sum_i PAF[\text{dB}]' \quad (4)$$

where $d_0 = 1$ m, γ represents the value of the propagation exponent (for the same floor it is equal to 3.5), FAF[dB] is the floor attenuation factor (for the same floor it is equal to 12.9 dB), and PAF[dB] is the obstacle attenuation factor. PAF can be obtained from [11] but is only applicable for some materials. The average path loss attenuation for the reference distance is given by eq. (2). The threshold values for received and transmitted powers were extracted from [16].

3.3 Experimental Results

Figure 4 presents some of the PtM WiMAX equipment installed in the FCS of University of Beira Interior, Covilhã, near the Hospital. A BreezeMAX 3000 OFDM micro BS and self-installable BreezeMAX CPEs (Customer Premise Equipments) operating at 3.5 GHz are shown. The appropriate Ethernet and RF cables were also used, as well as a GPS (Global Positioning System) device, a 12-240 V power inverter (to feed the CPE), and a portable PC, used as a terminal and running an FTP (File Transfer Protocol) application. The BreezeCONFIG software and a tool for acquiring GPS positions were used to collect the data.

In the FCS backhaul network, there was an FTP server and a DHCP (Dynamic Host Configuration Protocol) server for automatically assigning an IP address to the users' CPEs. The BS antenna gain is 10 dBi (360° azimuth, 8° elevation, vertical polarization). The TS antenna is a beam switching array of six 9 dBi, 60° antennas, integrated into the CPE. Field trials were performed in the suburban area of Covilhã, in a zone with approximately 2.80 × 1.55 km^2.

Figure 4 IEEE 802.16-2004 PtM equipment operating at 3.5 GHz in the experimental setup: the antenna and the ODU (outdoor unit) are shown in the left hand picture while the BS and CPE (Customer Premise Equipment) are presented in the right hand side

Initial results for the Signal-to-Noise Ratio, *SNR*, and the throughput were obtained at the TSs that roam around the suburban area surrounding the FCS.

There is a direct correspondence between the *SNR* values, the modulation and coding schemes, and the achieved data rate (eg. ~6 Mbps for 16-QAM). The BreezeMAX duplexing frequency range is 3499.5-3553.5 MHz and 3550-3600 MHz for DL (downlink), and 3399.5-3453.5 MHz and 3450-3500 MHz for UL (uplink) [16]. In these particular field tests, our outdoor unit (ODU) is operating at 3551.75 MHz (DL), and 3451.75 MHz (UL). The ODU transmitter power was 28 dBm.

At distances far from the base station, the experimental regions with reasonable quality of signal coverage basically coincide with the LoS regions. However, for distances up to ~550 m even NLoS regions near the boundary between LoS and NLoS areas can be covered [17]. Another important issue is the comparison between the results for the curve fitting of the signal-to-noise ratio and the curves obtained from the application of the propagation models (SUI model and modified Friis equation), as depicted in Figure 5 for distances up to ~1.6 km [17]. Within the modified Friis model different propagation environments are modelled by different propagation exponents, γ, which vary from $\gamma = 2$, corresponding to free space conditions, eg. rural areas, to $\gamma = 3$ in urban areas (no shadowing) and $\gamma = 4$ in shadowed urban areas [11].

For the SUI model, one considers $h_m = 2$ m, $h_b = 13.3$ m and $S = 8.8$ dB. Besides, for both models, one considers a total antenna gain (transmitter plus receiver) of 17 dBi, a transmiter power of 28 dBm, a bandwidth of 3.5 MHz, and a noise figure of 3 dB.

To try and understand the results, it is important to analyse the terrain profile around the BS location at FCS. While at southeast of the BS the terrain is flat, at northwest it is continuously hilly, with increasing altitudes. The ring with a radius of ~550 m from the BS is part of the suburban region of Covilhã, with a moderate density of buildings. The second coverage ring, for distances larger than 550 m, corresponds to a rural area (and the small airport) at Southeast, and to a dense urban area at northwest. However, this dense urban area corresponds to zones predominantly in LoS with the BS as the terrain height continuously increasing from the BS to this zone. At southeast, the zones up to a distance of ~550 m are predominantly in NLoS owing to the shadowing effect of the FCS roof. However, at northwest of the BS, this ring is predominantly in LoS (as for higher distances), as the terrain height increases. For distances larger than 550 m measurements were taken mostly at locations with LoS coverage.

A curve fitting approach was used to interpret measurement results from Figure 5 (in dB). The coefficient -8.259 for $\log(d)$ corresponds to a very low power decay rate. If the modified Friis equation is considered, the experimental results take values similar to the curve for $\gamma = 4$ for distance in the interval

[60, 150] m, and similar to the ones from the curve for $\gamma = 3$ for distances in the interval [300, 500] m.

Then, for larger coverage distances, values correspond to modified Friis equation propagation exponents between 2 and 3. It seems that the results consecutively correspond to i) shadowed urban areas, ii) urban areas (with no shadowing), and iii) approximately free space, which is partially true if we consider the actual terrain. Unlike the SUI model, in this case, distances shorter than 100 m are considered.

Despite the fact that use of the SUI model is recommended for WiMAX, the comparison of experimental results with the SUI model is harder since they only coincide for distances in the interval [275, 475] m. Figure 6 seems to indicate that use of the modified Friis model with $\gamma = 3$ will produce a better approximation in most cases, as presented in [17].

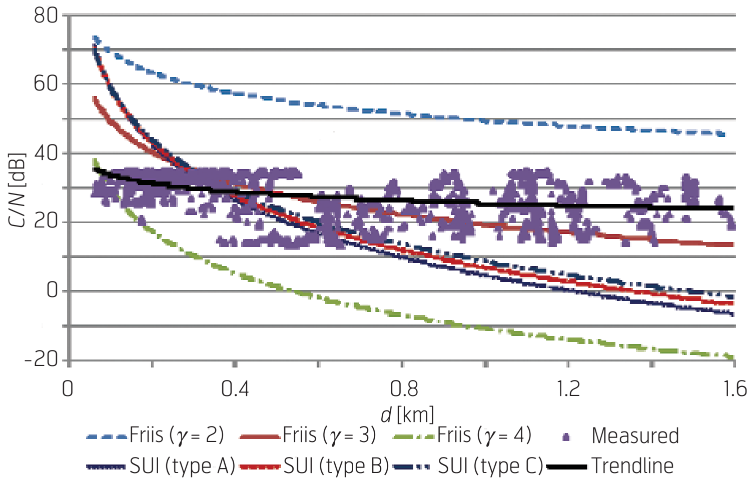

Figure 5 Trend curve for the measured SNR in the locations around FCS: while the curve for the modified Friis models with γ=3 fits to the experimental results for a wide range of distances the SUI model can only be used for distances in the interval [275, 475] m

4 Wireless Planning Tool

The WPT includes a C# and a GIS platform, as depicted in Figure 6. The C# platform helps in the planning process of indoor/outdoor wireless local area networks (Wi-Fi). It optimises the number of APs or BSs and their positions, as well as the total cost of the equipment by considering the choice of different Wi-Fi technology suppliers. The ArcGIS platform enables the network planning of WiMAX outdoor networks by relating the geographical data of a given location to the number of BSs needed to cover that location.

The Wi-Fi platform is user friendly and facilitates the development of the cellular design process into two different modes: manual and automatic. In the manual mode the designer decides case by case the position of APs while in the automatic one the positioning of APs is defined by the WPT itself. The manual distribution mode was implemented to enable trying and testing different possibilities for the received signal power distribution. The options given to the user include the manipulation of APs, obstacles, CAs (Covered Areas) and TSs positions. This mode is very attractive to case-by-case development and configuration of the area to be covered. For the automatic distribution mode, depending on obstacles, the user's position and their capacity, the tool defines the positioning and number of AP needed to optimise the coverage and/or the associated capacity.

The inputs of the tool are the file with the building or campus plan, in digital format, the position and type of obstacle materials, the total covered area, and the most probable position of TSs (eg. laptops, PCs, and PDAs), and the type of user's applications. For outdoor design, besides the plan, the maps have to include the elevation of the terrain.

The WPT development comprises two main scopes:

- Technical – It defines the position of APs by using one of the following options: either the distribution of signal power according to a given propagation model or the consideration of the capacity of user's applications and his/her most probable position.

- Economic – It generates a budget according to the quantities and types of equipment and the information provided by the suppliers.

The tool was developed to help network designers with a fast, technical and economic planning tool. It supports the IEEE 802.11 a/b/g standards and WiMAX as well. It estimates the TR (Transmission Data Rate) needed by the network according to the capacity model. Items such as obstacles, APs charac-

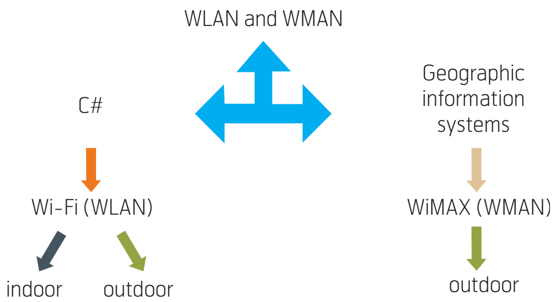

Figure 6 Conception of the Wi-Fi and WiMAX cellular planning tools: while the WLAN platform was developed in C# the WMAN one uses ArcGIS as a working environment

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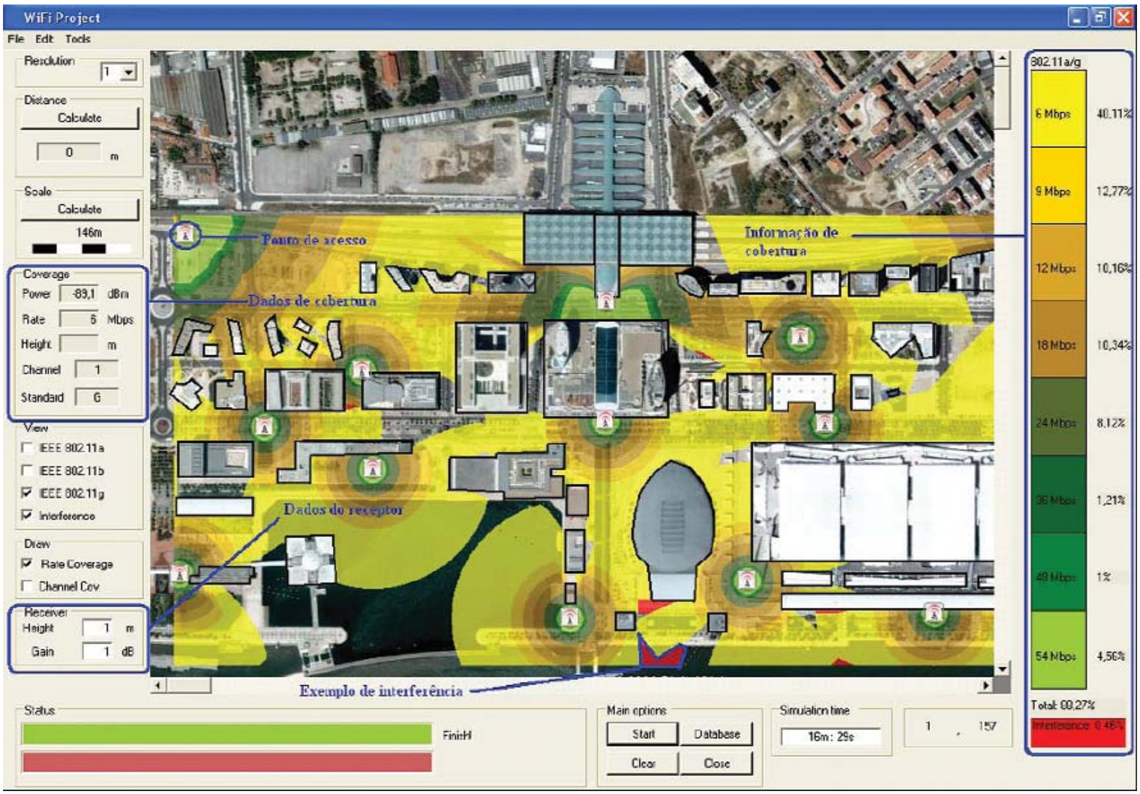

Figure 7 WPT layout with outdoor application for a Wi-Fi network in Parque das Nações, Lisbon, Portugal. The received power level distribution and the system capacity for each area are depicted

teristics, and network card types can also be directly updated into the tool. Different propagation models can also be introduced and tested.

Figure 7 presents an example of the actual layout of the WPT in an outdoor application in Parque da Nações, Lisbon. The heights of the campus terrain are also considered. The WPT has several menus that enable the user to insert the appropriate parameters according to several options.

It helps in the process of making a complete plan for the coverage of a given area based solely on a file of the plan, the obstacles, their materials, and the locations for the wireless terminals. As an output, the program generates a layout showing the received power/capacity, and the positions of APs.

For the positioning of APs over the plan two optimization methods were developed that allow for the minimization of their total number. One of the methods considers the received power in each position of the coverage area plan by using empirical propagation models. The other method enables choosing the most probable position of each user and its capacity according to the foreseen applications.

This tool is still being developed in order to include additonal wireless standards, eg. the possibility of upgrading the tool for QoS support, with the inclusion of IEEE 802.11e, and for different frequency bands, was also foreseen, and can be easily implemented.

The total capacity was determined according to the number of users in a given area, the type of application being used, and the USF (user simultaneous factor) for each application.

The Wi-Fi component of the WPT was developed by using C# graphic methods [18] and it interacts with a SQL Server 2000 Data Base [19]. There are however other tools for Wi-Fi planning in the market which involve higher complexity and costs (eg. [20]), and do not comprise both technical and economic/budget issues as the proposed WPT.

The WiMAX platform uses ArcGIS as a working environment. ArcGIS allowed the development of the toolbar that works as a base for network planning. The radio characteristics of the system are studied, including the link budget, the radio capacity, and the definition of the radio propagation models.

The planning tool is made available as a toolbar in ArcGIS that allows the user to choose several parameters, from the number of base stations to the number of users, allowing for network operation in different environments, providing important similarities with real-life situations.

5 Capacity Models and Planning Algorithms

The total capacity required for each AP (or BS) is defined by using experimental measurements for the application's transmission throughputs for VoIP (Voice over IP), Video over IP, FTP, E-mail, WWW (World Wide Web), and FT (File Transfer). The total capacity supported by each AP is obtained as a function of the number of users assigned to it, and of the average duration of the applications.

The planning of a WLAN is mainly focused in the coverage of all PCs/wireless terminals. Usually, the suppliers of wireless equipment visit the place and make a site survey with a laptop. The procedure consists in verifying if the signal power level surpasses a given threshold for all relevant locations. However, sometimes, this strategy is not enough to produce the most profitable planning, and the evaluation of the user's traffic is also important to define the number of APs and their positions. As an example, Table 1 presents the average transmission throughput corresponding to a group of three applications [4].

The values seem to be very high but this is due to overhead bits used in RTP (Real Time Transport Protocol), UDP (User Datagram Protocol), IP, MAC (Media Access Control) and PHY (Physical) headers. Protocol overhead is especially significant in the case of VoIP because the data packets are small compared to the overhead.

For WLAN, the WPT defines the total number of APs and their positions by assuming a given USF for each application and a correspondence between the received power threshold and the maximum transmission throughput [16].

For a given usage scenario the choice of the USF for each application depends on the percentage of simultaneous users. A placement algorithm is used to choose the AP positions [4]. In the automatic mode, the algorithm guarantees the fulfilment of a given throughput (in Mbps). The distribution of APs is made by applying one of two different methods: either dynamic or static. If no value is defined for the throughput threshold the algorithm uses the default value of the standard. The purpose of the dynamic algorithm is to properly choose APs positions in the coverage area defined by the network designer. As wireless terminals are either portable or nomadic, and their position is random, the algorithm sets the optimized number (and location) of APs to cover a given area.

The static algorithm is the best approach when the spots are fixed, ie. there are several users associated to one spot. In this context, the required throughput can be obtained for each spot. In the case of the WMAN platform, cellular planning procedures also simultaneously account for coverage and throughput requirements for users of each cell.

Applications	Transmission throughput [kbps]
VoIP (G.711, sampling of 20 ms, no silence suppression)	80
Video over IP (MPEG 4)	1024
FTP+WWW+E-mail+FT	500

Table 1 Average transmission throughput for each application at the IP layer

6 WiMAX Cellular Planning

6.1 Framework and Scenario

A radio network planning process was conceived with the objective to install a Fixed + WiMAX PtM wireless network covering the whole district of Covilhã, a zone of 550 km^2, and in particular to cover the city area in detail by considering IEEE 802.16-2004 coverage [1]. The final aim is to guarantee a PtM connection from the FCS-UBI located in Covilhã to the whole city centre. While the overall cellular structure is mainly dedicated to emergency and security public services, urban micro-cells will specifically support e-Learning and e-health services, among others.

The territorial framework of the frequency band license assigned to our laboratory for R&D purposes is the area under study in Beira Interior, from the south part of Castelo Branco up to the north part of the city of Guarda.

The process of cellular planning has to simultaneously account for carrier-to-noise and carrier-to-interference constraints [21]. A simple propagation model [11] is considered by modifying the Friis equation, where different propagation environments are modelled by different propagation exponents, γ, which vary from $\gamma = 2$ to 4 [11]. Conceptually, hexagonal cells were considered. The number of cells needed to cover the area under study is 24 and 14 cells, for a cell coverage radius of 3 and 4 km, respectively. These results were obtained by dividing the total area by the area of each hexagonal cell.

6.2 Carrier-to-Noise and Carrier-to-Interference Ratios

The analysis of the dependence of the carrier-to-noise ratio on the coverage distance, R, shows the limita-

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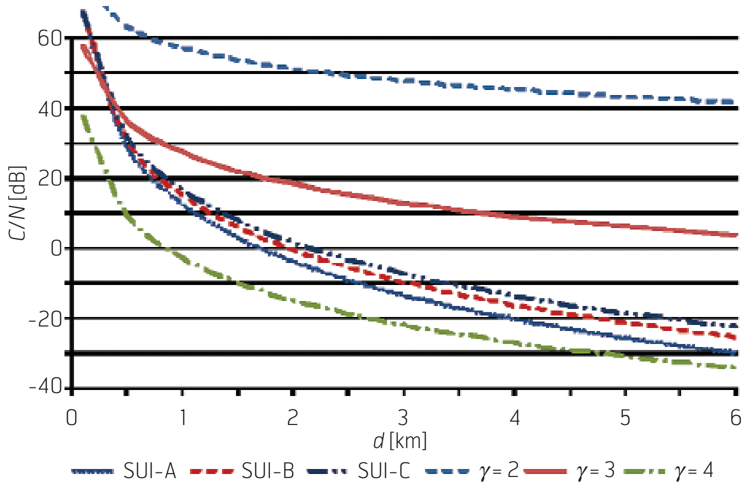

Figure 8 Carrier-to-noise ratio for f = 3.5 GHz: results are presented for the SUI and the modified Friis propagation models for distances up to 6 km. For the highest distances, the SUI model presents a behaviour that is in between the ones for the modified Friis one with γ =3 and γ = 4

tions on coverage, Figure 8. Besides the SUI model [14], the Friis free space equation is also used by replacing the propagation exponent 2 by γ [11]. Rain and fog attenuations are included into the modified Friis model, with specific attenutations of 0.015 and 0.010 dB/km, respectively.

With the modified Friis equation, it is shown that, for $(C/N)_{min} \approx$ 6-8 dB, the threshold for low order modulations, it is only possible to achieve $C/N > (C/N)_{min}$ with $\gamma = 2$ and $\gamma = 3$, although, for $\gamma = 3$, this is only achievable up to d = 6 km. For higher order modulations, typical values for (C/N)min are of the order of 15-16 dB [1], [2] and the maximum coverage distance decreases down to circa 2 km for $\gamma = 3$.

For distances greater than 1 km, the SUI model is less optimisitic than the modified Friis equation with $\gamma = 3$. In this case, maximum coverage distances can be lower than 1 km if high order modulations are used.

If the experimental results from Section 3 can be generalized for other environments, and $\gamma = 3$ is used for urban areas, while γ between 2 and 3 is used for 'almost' free space propagation, in open space, eg. rural areas, coverage is not a limitation. In urban areas, high coverage distances will be impossible, and cells with limited coverage distances, R, up to 3 km, have to be used. Besides, in urban areas a careful choice of the placement and height of the BSs transmitter antennas is needed in order to ensure a high percentage of LoS within the cells and to guarantee that the propagation exponent is of the order of $\gamma = 3$ (maximum). The use of GISs in the planning process is thus necessary. Details on the determination of the carrier-to-interference ratio are presented in [21].

6.3 LoS Dimensioning with GIS

6.3.1 Covilhã Rural and Urban Areas

GIS functionalities were incorporated for the choice of the best placement of BSs, including their height. By considering the use of the modified Friis model, an initial application was made for the district of Covilhã, an area of ~550 km^2. Because this zone is very hilly, cells with coverage distances around 3 km are used, differently from the whole region of Beira Interior, where larger cells were considered. By considering 18 sites and by using digital terrain models and ArcGIS 9.0, 3D Analyst, one obtains LoS coverage in ~70% of the area, see Figure 9. Omnidirectional antennas are mounted at 15 sites (although two of them only cover a 180° sector), while the remaining three sites have two 180° sectorial antennas. There is an average of 83% LoS coverage in villages, towns and cities. This guarantees propagation exponents of $\gamma = 2$ in rural areas and $\gamma = 3$ in dense urban areas. Furthermore, main roads in the access to the mountain are covered with LoS.

Another exercise using the ArcGIS platform, in a broader geographical scope, leads to results where micro-cells are overlaid with the macro-cellular structure, Figure 10. A comparison is performed between the use of omnidirectional cells and tri-sectorial ones. The height of BS antennas is 30 m, and the sum of the transmitter and receiver antenna gains is higher than in the experimental setup. Besides, the transmitter power in urban areas is ~18 dB lower than in rural areas. The SUI-C model was considered. In terms of interference mitigation, the advantages of using a solution with sectorial antennas are clear because the area of interference is reduced from 42% in the omnidirectional case, down to 9.3%, see Table 2, while the covered area increases from 52.3 to 85.0%.

6.3.2 Region of Beira Interior

For the WiMAX cellular coverage of the whole region of Beira Interior many combinations of the

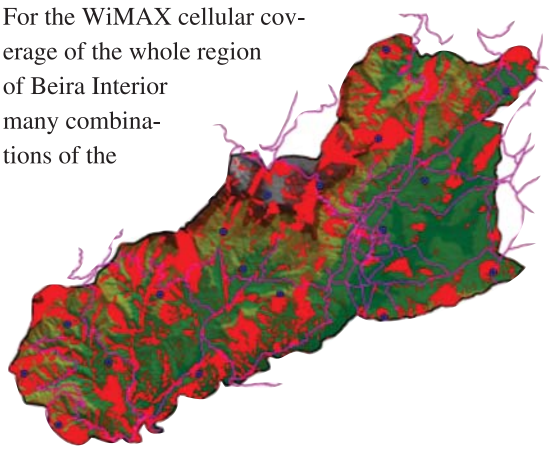

Figure 9 LoS discovery for the district of Covilhã: the blue dots represent the BSs and the red areas depict the zones where there is NLoS to any BS

placement of BSs and types of antennas can be explored. One specific exercise compares the use of omnidirectional antennas with the use of sectorial ones over the whole region.

The advantages of using the latter in terms of interference mitigation are clear because the area of interference is reduced by 36.1%, from 36.4 to 0.3%, while the covered area increases from 50.8 to 86.9%. Finally, it is important to note that, as the SUI model is pessimistic in terms of long distance propagation, the results for coverage are appropriate from an engineering perspective, as they represent a worst case situation. However, results for interference would be worst if a more optimistic model was used for propagation at 3.5 GHz.

Figure 10 The use of sectorial antennas in the district of Covilhã clearly leads to the increase of the coverage without interference

7 Conclusion

Optimal planning for the integration of WiMAX and Wi-Fi technologies enables the interoperability of these hybrid networks to be made available to the students, providing excellent theoretical, laboratorial, simulation and practical lessons through multimedia and IP communications, eg. videoconference, VoIP, and communication of high resolution video/image with the support of terminal mobility, a must for the practice and teaching of health sciences.

A simple planning tool was presented that facilitates the design of WLAN and WMAN topologies via a practical approach. Basically, it is possible to obtain the signal coverage and throughput maps from the plan of a given zone.

Results from field trials show that, at 3.5 GHz, the propagation at distances higher than 550 m is mainly in LoS; hence, a need is identified to use lower frequency bands to achieve the objective of having appropriate NLoS propagation within WiMAX networks. For this zone, and for some distance ranges, by using a curve fitting approach, we conclude that the modified Friis model can be used with a propagation exponent $\gamma = 3$. From the analysis of the results, we also conclude that the Stanford University Interim model may be considered for distances in the interval [275, 475] m, mainly SUI-C but also SUI-B, as the mean square error is reasonable.

From the examples presented the strong need to use sectorial antennas to guarantee an adequate coverage and interference mitigation for several terrain types and environments, including hilly terrains has been verified.

Type of Antenna	Coverage area [%]		Non-covered area [%]
	Without interference	With interference	
Omnidirectional	52.3	42.0	5.7
Sectorial	85.0	9.3	5.7

Table 2 Coverage and interference areas in the second exercise for the district of Covilhã

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