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Dynamic Configuration and Optimization of WiMAX Networks with Relay Power Saving Modes: Measurement-Based Scenario in a Hilly Region

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Abstract This paper investigates the performances achievable by WiMAX networks deployed in various sectorization configurations, with and without relay stations (RSs). Further, it studies the dynamic adjustment of the configuration to serve traffic loads at different times of the day while maximising the use of opportunistic sleep modes by relays in conjunction with cell zooming, thereby saving energy. The configuration changes and invocation of opportunistic sleep modes also take into account coverage constraints. This paper first reports extensive propagation measurements that have been undertaken in Covilhã, a hilly area of Portugal which presents a realistic and challenging propagation scenario. Using this scenario as the topographical basis, practical cellular planning results are then obtained and compared, using the dominant path and ray tracing (RT) functionalities of Winprop^{TM}. It is shown that without RSs present, the supported throughput is lower in practice because coverage is not 100 %. Further, for the case with omnidirectional cells, coverage reduces to only approximately 60 % if RSs go into sleep mode, and for the tri-sectored cells case coverage drops from 95.75 to 81.90 % (based on RT calculations) if RSs go into sleep mode. There is, however, still a reasonable economic performance in all cases. Additional results demonstrate that savings typically of 47.6 % in RSs' average power consumption can be achieved. These savings are shown to result in a financial

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saving for the operator of 10 % of the combined operational and maintenance cost. However, it is observed that such solutions have to be used cautiously in hilly regions due to challenges in maintaining coverage.

Keywords WiMAX · Cellular planning · Economics · Green communications · Cell zooming · Relay power saving

1 Introduction

In the optimization of cellular planning for fixed Worldwide Interoperability for Microwave Access (WiMAX), the use of relay stations (RSs) reduces the necessary extent of wire-line backhaul, improving coverage significantly whilst achieving a competitive system throughput. Moreover, RSs have a much lower hardware complexity, and using them can significantly reduce the deployment cost of the system as well as its energy consumption. Consequently, in [1, 2], frequency reuse topologies have been explored for 2D broadband wireless access topologies in the absence and presence of relays, and the basic limits for system capacity and cost/revenue optimization have been discussed. The identification of these fundamental limits involves the study of the variation of the carrier-to-noise-plus-interference ratio (CNIR) as a function of the coverage and reuse distances, considering the propagation model and different modulation and coding schemes (MCSs).

Relays are also amenable to opportunistic utilization of power-saving modes. In [1], it has been shown that cell zooming may be used in conjunction with relay sleep modes to save energy during low traffic periods. However, the comparison between WiMAX topologies with and without the presence of relays in [1] did not consider the resulting loss in coverage due to removing relays, and did not consider real-world terrains. Such terrains may lead to increased loss to subscriber stations (SSs) due to significant shadowing, and may result in coverage gaps.

This work is an extended version of [3]. As compared with [3], in this paper propagation modelling through measurements is addressed in detail, and the dominant path (DP) model and ray tracing (RT) propagation functionalities are simultaneously considered in the cellular planning tool simulations. We obtain analytical results for the CNIR versus distance and maximum supported throughput. The results from cellular planning exercises are achieved using Winprop™ for WiMAX deployments, with and without relays, in Covilhã, Portugal, a very hilly region. Different MCSs are considered, and cellular planning exercises are performed for frequency reuse pattern $K = 3$. RS backhauling is supported through dedicating specific sub-frames within the radio transmissions to that purpose. Besides base station (BS)-to-SS communications, BS-to-RS and RS-to-SS communications are also guaranteed. Moreover, it is noted that there is usually less traffic load in the UL direction in wireless multimedia communications, leading to a 1:5 asymmetry factor between UL/DL as being most appropriate.

Despite the above, as considerable resources are needed for BS-to-RS communication, some configurations with no relays, e.g., with tri-sectored BSs, may still lead to better efficiency in theoretical terms. If there was no coverage difficulty, topologies with no relays would consequently still have a higher throughput performance. However, this is not always the case, and a detailed analysis of the achieved throughput versus coverage in the presence of interference is essential to understand the pros and cons of using relays in practical terms.

By switching-off RSs either during the night or the weekends [4], or when the traffic load is low [5], energy savings can be achieved. In these periods, although the transmitter power is kept the same, the central coverage area of the cell is zoomed out. During the night and weekends, the offered traffic significantly decreases and RSs may sleep whilst increasing the range of the central coverage zone of the cell. When a RS is in sleep mode, the air circulation and other energy consuming equipment can be switched-off. The coverage zones of the RSs in sleep mode zoom into zero coverage [4] and the central BS coverage zone zooms out to maintain coverage of the system. In [1], it has been shown that this special form of cell zooming may be exploited to save energy at low traffic times. The energy trade-offs arising from this solution need to be verified under simple assumptions for the energy consumptions of BSs and RSs. Moreover, cost/revenue optimizations for WiMAX planning also need to be investigated, as well as efficient ways of reducing interference between cells and the redesign of the frame structure.

The remaining of the paper is organized as follows. Section 2 addresses the empirical modified Friis propagation model for the performed spectrum measurements as well as the analyses of the histogram for the measurements of received power. Section 3 discusses the assumptions in terms of cellular topologies with relays and the sub-frame format. Results in terms of supported throughput are analysed in Sect. 4. Section 5 investigates coverage limitations for the topologies with no relays present with the RT functionality and DP model. The economic performance and energy efficiency trade-off is discussed in Sect. 6. Finally, Sect. 7 concludes the paper.

2 Modelling of the Propagation Environment

Accurate planning of BS sites and coverage prediction (macrocell, microcell, small cell) is fundamental for the deployment of new wireless communication systems (e.g., WiMAX, LTE) due to the need to provide reliable and high data rate services in different outdoor and indoor environments. In order to increase the effectiveness of empirical propagation models, field trials have been carried out aimed at keeping the mean prediction errors within acceptable values for the challenging hilly environment around the city of Covilhã.

2.1 Field Trials Experimental Setup

The WiMAX propagation has been characterized in different operating situations by means of field trials at 3.5 GHz. The measurement campaigns have been conducted in a suburban cell in Covilhã, Portugal. The setup for the field trials was based on an Alvarion BreezeMAX 3000 micro base station (μBS). During these experiments, the Alvarion outdoor data unit (ODU) was operating at 3551.75 MHz (downlink, DL) and 3451.75 MHz (uplink, UL), with a maximum transmitter power of 28 dBm and a radio frequency bandwidth $b_{rf} = 3.5$ MHz. For the μBS, we have considered a 10 dBi omnidirectional antenna, installed 28 m above ground level, at the top of a 7 m pole on the rooftop of the Health Science Faculty (HSF) of the University of Beira Interior. A summary of the equipment parameters considered during the field trials is presented in Table 1.

In place of a SS, a Rohde & Schwarz FSH8 portable spectrum analyser was used during the trials. In order to measure the received power at different locations, another 10 dBi

Table 1 Transmitter/receiver parameters for the field trials setup

Parameter	Value
b_{rf}	3.5 MHz
f	3.5 GHz
f_{DL}	3551.75 MHz
f_{UL}	3451.75 MHz
P_t	−2 dBW
G_t	10 dBi (BS)
BS antenna height	28 m
G_r	10 dBi
Receiver antenna height	2.3 m

Table 2 Spectrum analyser acquisition parameters

Parameter	Autumn 2011	Spring 2012
Sweep time (ms)	20	772
Number of data acquisitions	3	5
Duration of each acquisition (s)	5	25
Number of samples	750	162
Repeatability (or error) (dB)	±0.45	±1.00

omnidirectional antenna, connected to the spectrum analyser, was installed on the rooftop of the car, approximately 2.3 m above ground level. Geo-referencing was provided by a GPS receiver. The frequency range of the spectrum analyser covers 9 kHz to 8 GHz, with a sensitivity of −160 dBm. The sweep time can be configured between 200 µs and 100 s. The spectrum analyser measured channel power received at the measurement device antenna in the considered frequency band using the “channel power measurement” option.

In order to improve our acquisition methodology, instead of roaming the city at vehicular speed of up to 40 km/h (the approach taken in [6, 7]), we stopped the car approximately every 30–50 m to acquire the channel power several times at a steady position. Aside from improvements in spectrum measurement accuracy, this method provides an increased confidence in the geo-positioning process. GPS receivers have a margin of error usually of a few meters; this margin increases whenever the receiver is moving. Additionally, to improve the spectrum measurement accuracy, we have increased the value of sweep, i.e., the duration of the channel power measurements. From the chart of the repeatability/error as a function of the number of samples, extracted from [8], one obtains the acquisition parameters for different sweep times for the measurements campaign performed during Autumn 2011 and Spring 2012, as shown in Table 2.

In the latter measurements we reconfigured the spectrum analyser to increase its sensitivity by setting the resolution bandwidth to 100 Hz and the video bandwidth to 10 Hz. As a consequence, we have been able to measure values of the received power lower than −90 dBm.

Table 2 also presents the repeatability for a given number of samples [8]. For example, a repeatability of ±0.45 dB means that the measured value lies within a range of ±0.45 dB from the true value, with a confidence level of 99 % [8]. We have also verified that the histogram of the 80 measurements taken in a single location from Fig. 1 follows a

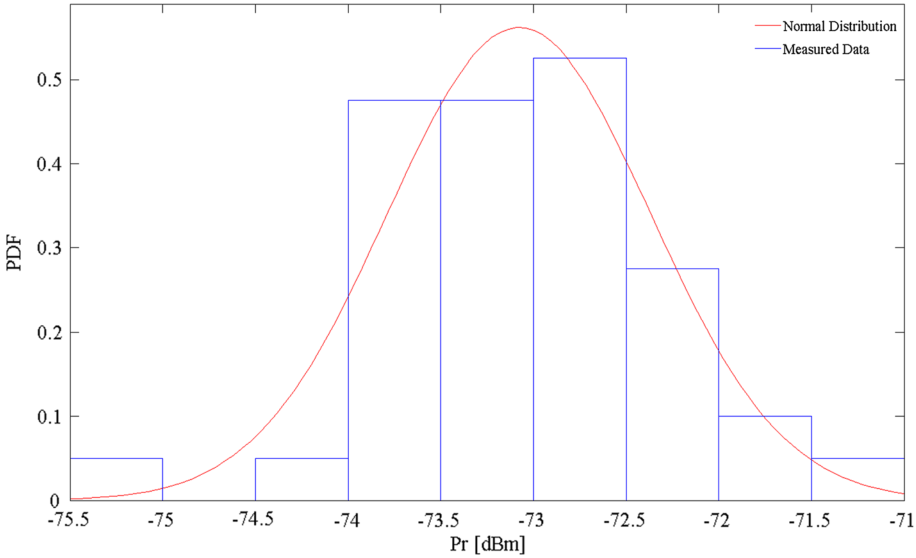

Fig. 1 Distribution of the terminal received power (dBm) for a measurement point taken in Covilhã. The superimposed Gaussian curve (in dB) suggests that the terminal received power approximately according to a log-normal distribution

Gaussian distribution with a confidence level of 95 %, with expectation $\mu = -73.08$ dBm (location of the peak) and standard deviation $\sigma = 0.711$ dB.

2.2 Measurements Results and Curve Fitting Approach

For the autumn 2011 measurements, we selected the straightest path moving away from the BS from the several routes that were followed. From the results, we achieved an adequate fit to the SUI-C model [9] for distances up to 900 m with low density of trees (and other foliage). For the spring 2012 measurements, we observed a substantial increase of foliage and even the existence of additional vegetation (as the trees had grown). In this case, the curve for the measurements of the received power (and the resulting path loss, PL) in the same range of distances fitted the SUI-A model [9]. For larger distances (of up to 1670 m), the influence of the foliage near the HSF was negligible. Figure 2 shows the variation of the measured and the modified Friis path loss with the distance (varying from 1.30 to 1.67 km) in the latter case.

Field trial measurements provide the value of the received power. To compute the path loss we have to consider the influence of the transmitter power and gains of the antennas, as well as the influence of the inclination of the SS antenna on the received power. The transmitter power is a known value. However, to subtract the antenna gains we have to consider the influence of the antenna vertical (or elevation) radiation pattern. Note that the horizontal radiation (or azimuth) pattern from the antenna is omnidirectional.

As it is shown in Fig. 3, different angles of incidence (or take-off angles), β, provide different values for the antenna gain. The maximum values of the antenna gain occur from values of β between $-10°$ (350°) and 10°, and 170° and 190°. When the incident beam moves away from the horizontal plane the antenna gain diminishes.

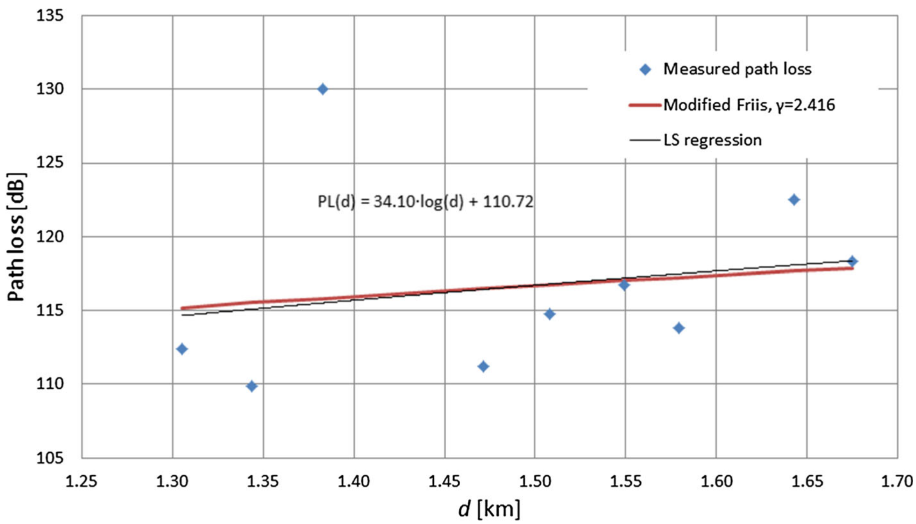

Fig. 2 Measured and modified Friis ($\gamma = 2.416$) path loss curve

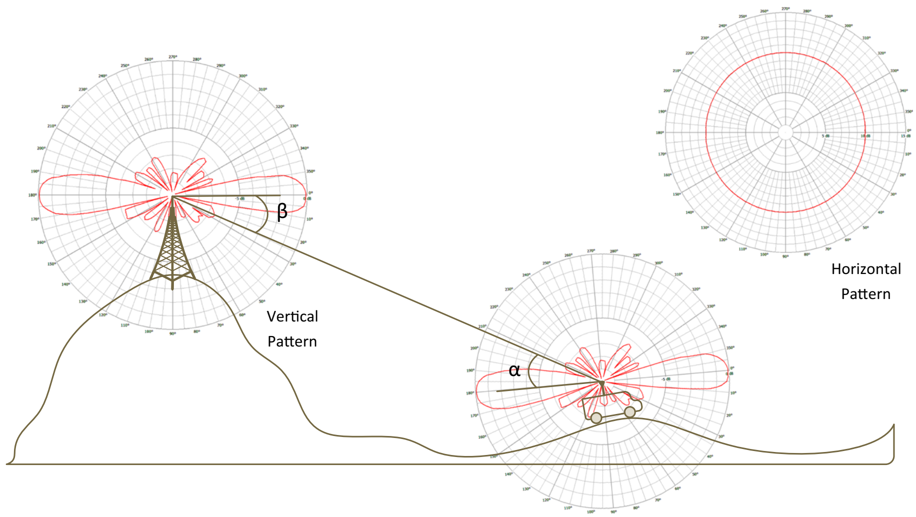

Fig. 3 Influence of the angles of incidence and arrival in the computation of the path loss

During the field trials, we have found that β varied between 2.5° and 24°, which corresponds to a decrease in the antenna gain of between 1.81 and 2.23 dB, respectively. Additionally, we have also considered the angle of arrival α between the SS and the BS antenna.

The terrain slope is also responsible for changes in the antenna gain, i.e., the angle of arrival, α, also incorporates the terrain slope. This can be positive or negative when the car is going uphill or downhill, respectively, or null when the terrain is flat. The angle of arrival is determined through an approach similar to the one considered to determine β. We have found that α varies between $-1.1°$ and 5.4°. As a consequence of this analysis, we have found that α and β are responsible for losses up to 4 dB. This methodology enables us to compensate for the antenna gains at different incident angles.

By comparing the results with known path loss models through least-square (LS) regression, we have achieved a fit to the modified Friis model with a propagation exponent, γ, varying from 2.416 in the case shown in Fig. 2, to 2.55 in other field trials.

3 Assumptions for the Analysis of System Capacity

To guarantee WiMAX communications with no coverage gaps near the cell edge (i.e., to enable BPSK with ½ MCS which is the lowest-order MCS, as shown in Table 3, where *AuxFactor* represents the reduction of the throughput at a distance d relatively to the throughput at the centre of the RS coverage zone), the value of the CNIR must be higher than 3.3 dB throughout the cell [1, 2] yielding a physical throughput of just 1.41 Mbps. Here, the radio frequency bandwidth, noise figure, and frequency are $b_{rf} = 3.5$ MHz, $NF = 3$ dB, and $f = 3.5$ GHz, respectively [1].

Based on the performed measurements, our modified Friis propagation model is assumed. Assumptions for the values of different parameters are $P_t = -2$ dBW, $\gamma = 2.55$ in suburban areas $G_{BS} = 10$ dBi, and $G_{SS} = 9$ dBi for BS-to-SS and SS-to-BS communications [1], and $P_t = -2$dBW, $G_{RS} = 17$ dBi for RS-to-SS communications, while $G_{BS} = 10$ dBi and $G_{RS} = 28$ dBi for BS-to-RS and RS-to-BS communications respectively. The difference between the receiver gains for the RS/BS and the RS/SS (or BS/SS) communications is justified by the use of a directional antenna in the RS, pointing directly towards the central BS; this antenna has a gain, $G_{RS\text{-}BS}$, of $\sim$28 dBi [1]. A summary of these parameters is presented in Table 4.

The worst-case interference scenario is considered, where the mobile is at the cell edge and the co-channel interference is the highest. On the one hand, the worst-case DL interference scenario occurs when the BS of the serving cell transmits to the SS at the cell edge, using a channel (or sub-channel) on which the SS is also receiving interference from the BSs of the six co-channel hexagonal neighbouring cells. On the other hand, for the UL, the worst-case interference scenario occurs when the SS is transmitting to the BS from the cell edge, and interfering SSs are at the cell edge at the closest distance from the central/serving cell.

Table 3 CNIRmin, physical throughput and *AuxFactor* for different values of the MCS ID for the communications to the SSs at the RS coverage zone (the bold example for 16-QAM½ is discussed in more detail in terms of coverage and capacity planning in later text)

ID	MCS	CNIRmin (dB)	Physical thr. (Mbps)	*AuxFactor* (d)
1	BPSK ½	3.3	1.41	1.41/5.64
2	BPSK ¾	5.5	2.12	2.12/5.64
3	QPSK ½	6.5	2.82	2.82/5.64
4	QPSK ¾	8.9	4.23	4.23/5.64
5	**16-QAM ½**	**12.2**	**5.64**	**1**
6	16-QAM ¾	15.0	8.47	1
7	64-QAM ⅔	19.8	11.29	1
8	64-QAM ¾	21.0	12.27	1

Table 4 Parameters for the analysis of the system capacity

Parameter	Value
b_{rf}	3.5 MHz
NF	3 dB
f	3.5 GHz
BS-to-SS and SS-to-BS	
P_t	−2 dBW (BS and RS)
G_{BS}	10 dBi (BS-to-SS/RS)
G_{SS}	9 dBi (SS-to-BS/RS)
BS-to-RS and RS-to-BS	
G_{RS}	17 dBi (RS-to-SS)
G_{RS-BS}	28 dBi (RS-to-BS and BS-to-RS)

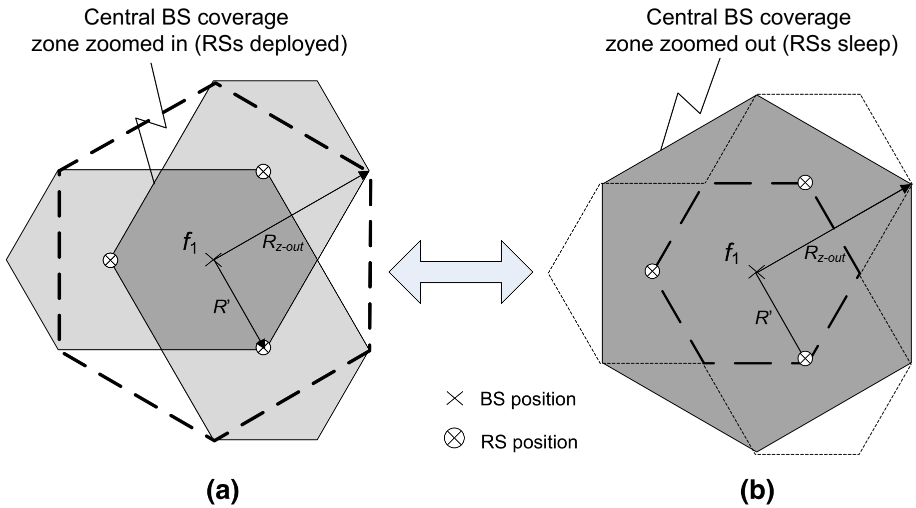

Fig. 4 **a** BS, RS and respective "hexagonal" coverage areas, **b** central coverage zone zooms out when RSs sleep

In the considered multihop context, with $K = 3$, a cell is composed by the central coverage zone, served by the BS, and three 240° sector coverage zones, served by individual RSs (RS_1, RS_2 and RS_3), as shown in Fig. 4a. While the BS antenna may be either omnidirectional or sectored (120° sectors), RS antennas for communication with BS are considered to be directional (e.g., 120° sectored or narrower beamwidth ones). This is to reduce the received interference from BSs and facilitate non-overlapping coverage with the central zone of the cell.

Although BS backhaul is assured through the usual means for mobile communications (e.g., cable or micro-wave radio link), RS backhauling is supported by using special and specific sub-frames within the radio channel created for that purpose. The duration of each sub-frame is 5 ms [1]. Our proposal on frames is inspired by the sub-frame structure from [10] and explores the inclusion of RS DL traffic/communications from RS to SS into the UL frequency sub-frame only considering single-hop between the RS and SSs. This is different from the proposal for IEEE 802.16j in [11], which enables multihop. Note, however, that there may be some similarities between the sub-frame structure proposed here and the frame structure with transparent relaying in IEEE 802.16j. With transparent relaying, the RSs do not forward framing information; hence do not increase the coverage of the wireless system; the main use of this mode is to facilitate capacity increase within the cell. The considered type of relay is of lower complexity, and only operates in a centralized scheduling mode and for topology up to two hops.

The aforementioned mode assumes that the RSs have some small buffering capability, such that multiple hops via the relay can be scheduled in different frames. For example, data can be transmitted from the BS to the RS in one frame, and the same data can be forwarded from the RS to the SS in the subsequent frame. These assumptions are also inspired in the IEEE 802.16-2004 frames, which consists of two sub-frames, operating in the frequency division duplexing (FDD) mode where the DL and the UL are transmitted simultaneously. Although the version of fixed WiMAX we consider here originally used FDD, our proposal implies that time division duplexing (TDD) needs to be additionally supported (over the FDD frame structure) for RS-to-SS communications.

Besides, the proposal for DL and UL frequency sub-frames from Fig. 5a, b (the cases of omnidirectional and tri-sectored BS antenna) assumes an asymmetry factor of 1:5 between the UL and DL. The advantage of using relays arises from the fact the co-channel interference now comes from cells at a larger distance [2]. The improvement of the present tri-sectored frame, relatively to the frame for the omnidirectional cells proposed in Fig. 5a [1, 2], corresponds to the increase of the throughput in the area covered by the RSs by a factor of the number of sectors, N_{sec}, as there is a carrier assigned to each sector. The N_{sec} increase takes place in both DL and UL, due to the use of a more favourable frame format.

The assumed type of RS is not standardized and available yet but this structure for frequency sub-frames is flexible enough to accommodate changes in the relay topology (e.g., facilitating the inclusion of mobile RSs), as RSs and SSs already incorporate TDD in the UL frequency sub-frame.

4 Supported Cell/Sector Physical Throughput

Under the frame format proposed in this paper for the tri-sectored BS case, communications using a given frequency carrier can be between a sector and a RS, a sector and a SS, or a RS and a SS. In the omnidirectional case (where the number of sectors $N_{sec} = 1$), the central zone BS provides shared access to or from three RSs within the same frequency carrier. Hence, to obtain the supported throughput, the contribution from the central cell results from multiplying the sector supported throughput by N_{sec}. Although the considered cells with three RSs are formed by one central hexagonal coverage zone plus three 240° RS zones, with radius R' each as shown in Fig. 4a, given that the RS coverage zones form 240° sectors the cells have an equivalent area corresponding to three omnidirectional (360°) coverage zones with radius R'. The equivalent supported throughput in a hexagonal coverage zone (or cell) with an area of $\left(3\sqrt{3}/2\right) \cdot R'^2$ is therefore given as [2]

$$\begin{aligned}\left(R_{b-\sup}\right)_{equiv} &= \frac{R_{b-tot}}{3} = \frac{N_{\sec} \cdot R_{b-central} + 3 \cdot R_{b-RS-zone}}{3} \\ &= \frac{1}{2} \cdot N_{\sec} \cdot R_{b-central-norm} + R_{b-RS-zone}\end{aligned} \quad (1)$$

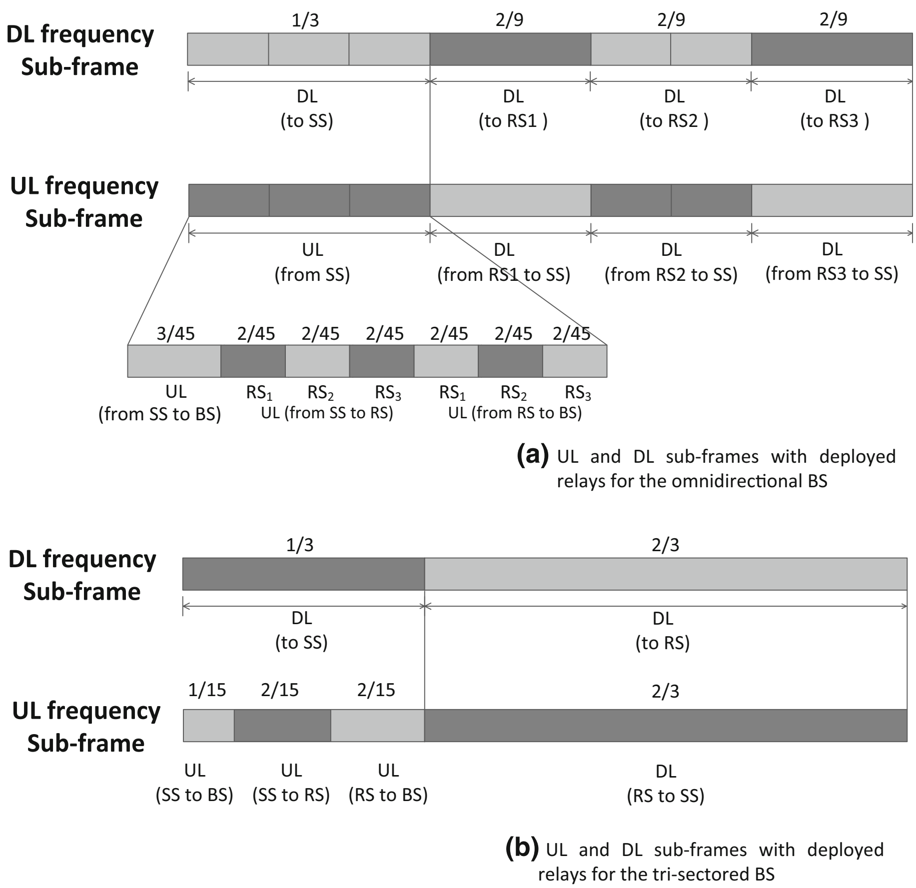

Fig. 5 Structure for UL and DL sub-frames with deployed relays, **a** omnidirectional BS, **b** the tri-sectored BS

where $R_{b\text{-}tot}$ is the total throughput in the multihop cell (formed by the central plus RS zones), $R_{b\text{-}central}$ is the computed throughput in the central coverage zone and $R_{b\text{-}RS\text{-}zone}$ is the computed throughput in the RSs coverage zone. Moreover, $R_{c-central-norm} = {}^{2}\!/\!{}_{3}R_{b-central}$ represents the throughput, as ${}^{2}\!/\!{}_{3}$ of the area of the central coverage zone assuming uniform user traffic distribution (over an area equal to the one from each RS zone). The use of sectored cells corresponds to N_{sec} increase in both DL and UL traffic, from or to the BS, due to the use of a more favourable frame format.

The approach from [1, 2] has been considered to compute the CNIR, corresponding to worst-case situations on the edge of the cell where higher co-channel interference takes place due to the proximity between co-cells. The physical throughput, $R_{b[\text{Mbps}]}$, was computed according to its correspondence to the values of CNIR from Table 3, yielding a stepwise behaviour that comes from the correspondence between $CNIR_{min}$, in dB, and the physical throughput for each MCS. Details on the study of the dependence of the carrier-to-interference on the reuse distance and the cell coverage radius can be found in [2]. By weighting the physical throughput achieved in each concentric cell coverage ring (or coverage area) by the size of the ring, as in Figure 8 of [2], the contribution from each transmission mode (or MCS) is included in an implicit function formulation to obtain the average supported throughput. For consecutive MCSs, the step distances are determined by looking at the correspondence between the minimum feasible values of the CNIR curves (for a given MCS), and the supported physical throughput, through an inversion procedure [2]. When a sectored BS antenna is considered, the number of interfering cells is decreased, and system capacity increases.

In practice, the throughput at a distance d from the RS, $R_b(d)$, depends on the supported MCS, and is given by [2]

$$R_b(d) = \frac{2}{9} N_{\mathrm{Sec}} \times R_b(R) \times AuxFactor(d), \quad (2)$$

where d is the distance to the RS and $R_b(R)$ is the maximum throughput at the edge of the central coverage zone, at a distance R from the BS and N_{sec} is the number of sectors of the central coverage zone ($N_{sec} = 1$ or 3 in the omnidirectional or tri-sectored cases, respectively). $AuxFactor$ (d) represents the reduction of the throughput at a distance d relatively to the throughput at the centre of the RS coverage zone and is given in Table 3 (example for a 16-QAM½ MCS at the central of the coverage zone).

For this example, Table 3 shows the values for $AuxFactor$ (d) if the MCS ID that may be guaranteed for the $CNIR(d)$ from the RS coverage area is within the range 1–8. The 16-QAM ½ MCS is shown in bold in Table 3. In practice, if the MCS supported at a distance d from the RS is higher than or equal to the one supported in the BS-to-RS link (16-QAM ½ in this example) in the omnidirectional case, the throughput for RS will be (2/9)·$R_b(R)$; otherwise, the throughput will be (2/9)·$(R_{b\text{-}sup})_{RS}$.

Additionally, when one considers the supported throughput according to the omnidirectional and tri-sectored BS sub-frames, it can be found that:

- The central BS throughput, BS to SS, is supported by 1/3 of the frame structure, so the DL throughput is obtained by multiplying the total obtained throughput by 1/3 in both the omnidirectional and the tri-sectored case.
- For the throughput from the BS to the RS (DL) and, from the RS to the SS (downlink at the UL frame), 2/9 and 2/3 of the frame structure are assigned for the omnidirectional and tri-sectored BS, respectively. As such, the throughput is obtained by multiplying these factors of 2/9 and 2/3 by the total obtained throughput.
- For the supported UL throughput from the SSs to the BS in the central coverage area, 3/45 = 1/15 of the frame structure is assigned to the UL, so the UL throughput is obtained by multiplying the total obtained throughput by 3/45 (or 1/15) in both the omnidirectional and the tri-sectored case.
- For the supported UL throughput from the SS to the RS, 2/45 and 2/15 of the frame structure are assigned for the omnidirectional and tri-sectored BS, respectively. As such, the throughput is obtained by multiplying the total obtained throughput by 2/9 and 2/3, for the omnidirectional and tri-sectored BSs, respectively.

Since the RS antennas are directional, the omnidirectional BS only receives interference from two RS at distance $D + R$. At the RS it is only possible to achieve a throughput of 2/45 $(R_{b\text{-}sup})_{SS}$ for the omnidirectional BS and 2/15 $(R_{b\text{-}sup})_{SS}$ for the tri-sectored BS, where $(R_{b\text{-}sup})_{SS}$ refers to the supported throughput from the SS to RS. This traffic will only reach the BS if the RS to BS radio link supports such a value of throughput.

Figure 6 shows results for the equivalent supported throughput as a function of R' and $R_{z\text{-}out}$ for the DL, $K = 3$ and the absence/presence of relays, where two different horizontal

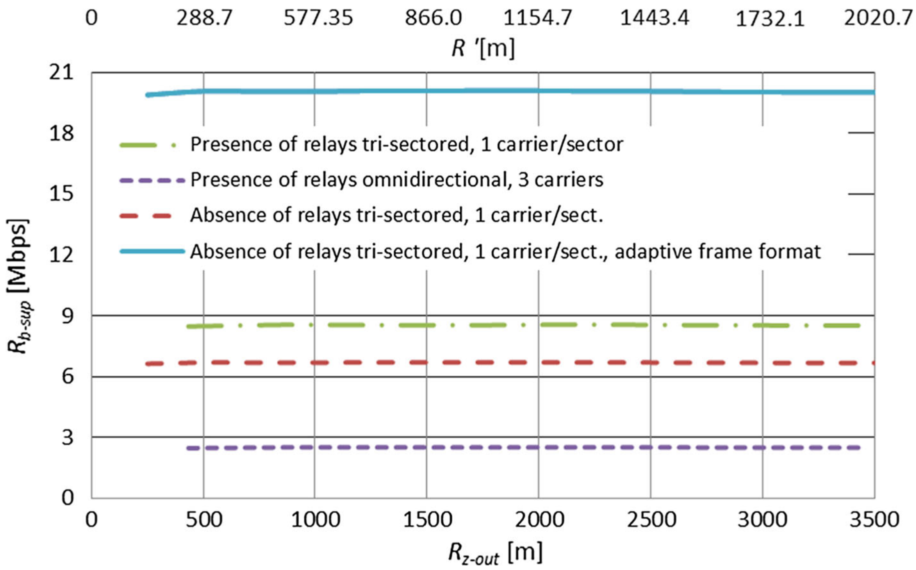

Fig. 6 Comparison of the equivalent supported throughput between the cells with relays and the zoomed-out cells, $K = 3$

axis are represented. While R' is the coverage distance for the central and RS coverage zones, $R_{z-out} = \sqrt{3}R'$ is the radius for the zoomed out cell, as shown in Fig. 4b. We have considered BSs with omnidirectional and tri-sectored antennas whilst first assuming that the frame format is not adaptively changed in the absence of relays.

For omnidirectional BS antennas, in the absence of relays, it was not possible to obtain the curve for the supported throughput for $K = 3$, as the cell is not totally covered with, at least, the BPSK ½ MCS, corresponding to $CNIR \geq 3.3$ dB. The curves for the cell throughput reach 0 Mbps for distances lower than the coverage distance, e.g., the non-covered zone is $\sim$7 % for $R_{z\text{-}out} = 2000$ m. In the presence of RSs, the supported throughput is very low for omnidirectional BS antennas (circa 2.5 Mbps). However, with tri-sectored BS antennas (1 carrier/sector), as the interference is decreased, the supported throughput reaches circa 6.7 Mbps in the absence of relays and more than 8.5 Mbps in the presence of RSs. When the RSs are switched-off, if the frame format needs to be kept there is a partial loss of capacity (as the part of the sub-frame dedicated to communication with RSs is being wasted).

Until now, it is assumed that only one carrier was used per cell per sector, i.e., the total bandwidth is $3 \times 3.5 = 10.5$ MHz and $3 \times 3.5 \times 3 = 31.5$ MHz, for omnidirectional and tri-sectored cells, respectively. However, in the omnidirectional case the operator is able to use three carriers, which results in $3 \times 10.5 = 31.5$ MHz (total bandwidth). As a consequence, the total throughput is obtained by multiplying the cell/sector throughput by three because there are three available carriers in the omnidirectional case; in the tri-sectored case the three sectors in the "zoomed out" cell have one carrier in each sector. Further, one needs to consider the effect of the DL sub-frame format in the resulting supported throughput, i.e., that the throughput is reduced by a factor of 1/3 in both cases [2]. All of these considerations yield an overall multiplying factor of 1.

For tri-sectored BS antennas, we have also considered the possibility of adaptively changing the frame format when the RSs are switched-off and only the BS equipment remains active. In this unlikely possibility [1], the theoretical supported throughput would reach $\sim$20 Mbps. This improvement leads to a theoretical advantage for the topologies with no relays that may possibly compensate the better/more regular coverage achieved in topologies with relays. The supported throughput is used in Sect. 6 to calculate the costs, revenues and profits.

5 Cellular Planning in Actual Environments

The Winprop™ simulations were performed by considering the DP model and the RT functionality with several reflections (up to six reflections at surfaces of walls/objects) while neglecting diffraction. Furthermore, Winprop™ simulations have used a detailed 553,527 pixel database for urban building data of the city of Covilhã, including 2528 buildings and a total area is 7.79 km^2, as shown in Fig. 7. It is a worth noting that the pixel database uses rectangular coordinates from Hayford-Gauss-Lisboa of the Portuguese Army surveying Institute (Instituto Geográfico do Exército, IGeoE) coordinate system, with a resolution of 25 m per pixel.

In Fig. 7, it can be observed that the city is located on a very hilly terrain at the bottom of the highest mountain in continental Portugal. Cellular planning in this type of geographical location is a challenging engineering problem.

We have considered BS, SS and RS parameters similar to the ones considered in the field trials from [3] with only slight changes (see Table 5), namely the SS is considered to be at 2 m in height, and the gain from 120° tri-sectored antenna from the BS is 15.3 dBi, instead of 17 dBi, while the BS/RS and SS noise figures are 3 and 5 dB, respectively.

The OFDM parameters considered in the simulations are the ones from the Alvarion μBS, as shown in Table 6.

The cellular planning exercises assume $K = 3$ and topologies formed by a central cell and six first tier interferers using frequency f_1, for two different configurations, as follows:

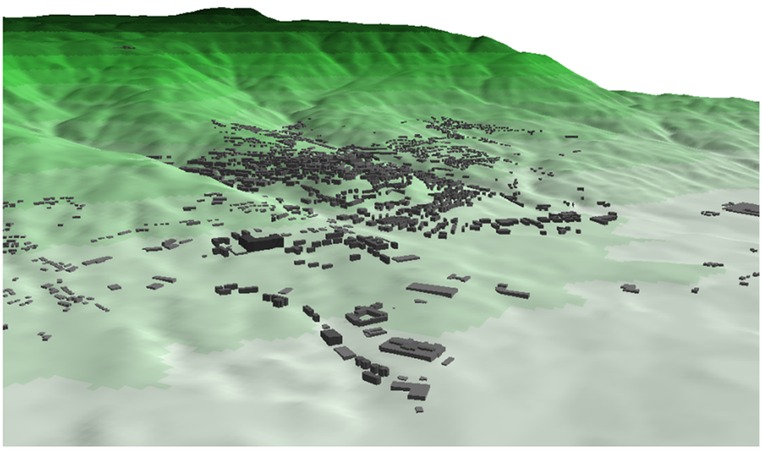

Fig. 7 Pixel database for the city of Covilhã terrain and buildings

Table 5 Cellular planning parameters considered for the sub-urban scenario within Winprop™

	System parameters
Operating frequency	3.5 GHz
Duplex mode	FDD/TDD or FDD
Channel bandwidth	3.5 MHz
BS height	20 m
SS height	2 m
SS antenna gain	9 dBi
BS/RS antenna gain	15 (OMNI), 15.3 (120° sectored), 17 (240° sectored)
BS/RS transmitter power	28 dBm
BS/RS noise figure	3 dB
SS noise figure	5 dB
Reuse pattern, K	3

Table 6 OFDM parameters

	OFDM parameters
FFT size	256
Subcarrier spacing (kHz)	15.625
Useful symbol time (μs)	64
Oversampling rate	8/7
No. of data subcarriers (DL)	192
No. of pilot subcarriers (DL)	8
No. of guard subcarriers (DL)	56

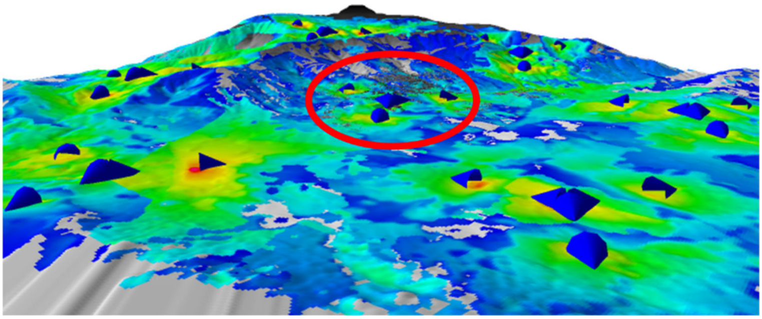

Fig. 8 CNIR in the central cell (marked with the *orange circle*) comprising tri-sectored BSs and three relays with RT

- Zoomed-out cells with no relays, covering the same area as the cells with relays, with $R_{z-out} = \sqrt{3}R' = 1732$ m;
- Cells with relays (see Fig. 4a), as shown in Fig. 8, tri-sectored BSs, with $R' = 1000$ m.

Note that the cells using f_2 and f_3 are not considered in the simulations and the results for CNIR are only valid in the central cell, as this is the only one that suffers interference from six co-channel cells in practice.

Table 7 Summary of the cellular planning results considering RT coverage in the simulations

	Area not covered		$(R_{b\text{-}sup})_{\text{equiv}}$ (Mbps)	
Type of cell	Omni.	Tri-sect.	Omni.	Tri-sect.
Zoomed-out cells, no relays	41.68 %	18.10 %	–	5.192
Cells with relays	4.35 %	4.25 %	2.67	8.616

By considering the co-channel interference and noise, it is possible to obtain results for the coverage and determine if there are some zones of the cell with no coverage guarantee, i.e., where $CNIR < 3.3$ dB. The area of the cell with no coverage and the equivalent supported throughput are shown in Tables 7 and 8 for the RT propagation functionality and DP model, respectively.

While in the presence of relays there is a reasonably adequate coverage, with “no relays” there are coverage gaps as the “illumination” is inadequate throughout the cell. For the latter topology, in the tri-sectored case, although the non-covered area reaches 18.10 %, if RT coverage is considered, we have nevertheless computed the supported throughput, which reaches 5.192 Mbps, a value lower than the theoretical 6.7 Mbps but higher than 5.05 Mbps obtained from Table 8 with the DP model instead of RT. Besides, if an adaptive frame format was possible, the supported throughput would be 15.58 Mbps, and not $\sim$20 Mbps).

Figure 9 presents results for the cell/sector throughput in the central cell with tri-sectored antennas and the presence of RSs with RT. The reuse topology is the same as in Fig. 8 (where six “first tier” interferers are considered). In configurations with RSs, the results for the supported throughput obtained from Winprop™ with RT are clearly better in the tri-sectored case (8.616 Mbps compared to 2.67 Mbps in the omnidirectional case) but slightly worse than the ones obtained with the DP model (8.67 and 2.76 Mbps, respectively).

6 Economic and Energy Efficiency Trade-Off

Cost/revenue analysis combines several technical factors in WiMAX cellular planning to produce a value for the expected overall financial gain (or loss). The cost/revenue function proposed in [1, 2] accounts for the cost of building and maintaining the fixed WiMAX infrastructure, as well as the way the cell capacity affects operators’ and service providers’ revenues.

Fixed costs for licensing and spectrum bandwidth auctions should also be taken into account. Although one considers a project duration of 5 years as an assumption, it is decided to analyse costs and revenues on an annual basis here. The analysis is under the assumption of a null discount rate. Furthermore, the aim is to apply the cost/revenue optimization model from [1, 2] to facilitate WiMAX cellular planning.

According to the assumptions with relays from [1, 2], the cost parameters from Table 9 have been considered for $K = 3$, with three carriers in the omnidirectional case and one carrier per sector in the tri-sectored case. The cost per unit area is given by [2]

$$C_{[€/\text{km}^2]} = C_{fi[€/\text{km}^2]} + C_b \cdot N_{hex/\text{km}^2}, \tag{3}$$

where C_{fi} is the fixed term of the costs, and C_b is the cost per BS assuming that only one transceiver is used per cell/sector. The number of hexagonal coverage zones per unit area (for which the equivalent supported throughput is computed) is given by

Table 8 Summary of the planning results considering the DP model

	Area not covered		$(R_{b\text{-}sup})_{\text{equiv}}$ (Mbps)	
Type of cell	Omni.	Tri-sect.	Omni.	Tri-sect.
Zoomed-out cells, no relays	38.77 %	19.44 %	–	5.05
Cells with relays	6.08 %	5.22 %	2.76	8.67

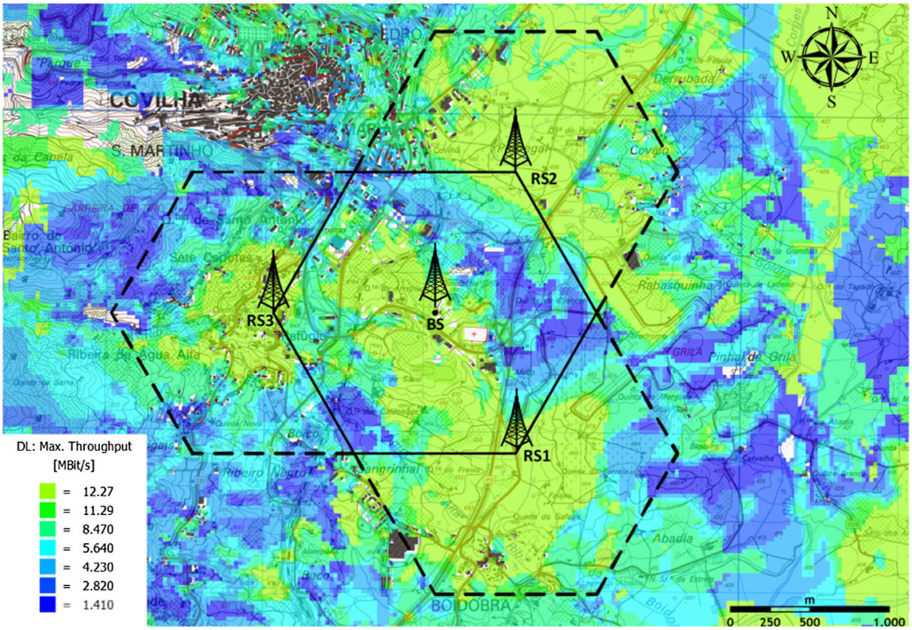

Fig. 9 Spatial variation of the throughput with tri-sectored BS antenna and the presence of relays with RT

Table 9 Costs with relays with different antennas and $K = 3$

Costs	Omnidirectional	Tri-sectored
C_{fi} [€/km2]	140.82	140.82
C_{BS} [€]	7680	6800
C_{Inst} [€]	1333.33	2000
C_{bh} [€]	833.33	833.33
$C_{M\&O}$ [€/year]	833.33	833.33

$$N_{hex/\text{km}^2} = \frac{2}{3 \cdot \sqrt{3} \cdot R^2}, \tag{4}$$

and the cost per BS is given by [2]

$$C_b = \frac{C_{BS} + C_{bh} + C_{Inst}}{N_{year}} + C_{M\&O}, \tag{5}$$

where N_{year} is the project's lifetime (assumed here to be $N_{year} = 5$), C_{BS} is the cost of the BS, C_{bh} is the cost for the normal backhaul, C_{Inst} is the cost of the installation of the BS, and $C_{M\&O}$ is the cost of operation and maintenance.

The revenue in a hexagonally-shaped coverage zone per year $(R_v)_{\text{cov\_zone}}$, can be obtained as a function of the supported throughput per BS or sector (in the omnidirectional and sectorial cases, respectively), $R_{b\text{-}sup[\text{kb/s}]}$, and the revenue of a channel with a data rate $R_{b[\text{kbps}]}$, $R_{Rb[€/\text{min}]}$. The resulting expression is

$$(R_v)_{\text{cov\_zone}} = \frac{N_{hex/\text{km}^2} R_{(b-\text{sup})_{equiv}} \cdot T_{bh} \cdot R_{R_b}[€/MB]}{R_{b-ch}[\text{kbps}]}, \tag{6}$$

where N_{sec} is the number of sectors (one or three) T_{bh} is the equivalent duration of busy hours per day, and $R_{b\text{-}ch}$ is the bit rate of the basic "channel". In the tri-sectorial case, given that one assumes that each sector has one different transceiver, there is a separate frequency channel available for it.

The revenue per unit area per year, $R^2_{v[€/\text{km}]}$, is obtained by multiplying the revenue per cell by the number of cells per unit area [2]:

$$\begin{aligned} R_{v[€/\text{km}^2]} &= N_{hex/\text{km}^2} \cdot (R_v)_{cell} \\ &= N_{hex/\text{km}^2} \cdot \frac{R_{b-\text{sup}[\text{kbps}]} \cdot T_{bh} \cdot R_{R_b[€/\text{min}]}}{R_{b-ch[\text{kbps}]}}. \end{aligned} \tag{7}$$

The (absolute) profit is given by

$$P_{[€/\text{km}^2]} = R_v - C, \tag{8}$$

from which, the profit in percentage terms is given by

$$P_{[\%]} = \frac{R_v - C}{C} \cdot 100. \tag{9}$$

As a bandwidth of 31.5 MHz may be available for an operator, under the case of $K = 3$ it is worthwhile to compare this tri-sectored cellular scenario (or the central coverage zones, if the topology is with RSs), with the case where the omnidirectional BS antenna has available three carriers of 3.5 MHz each. The scenario in both tri-sectored and omnidirectional antenna cases without RSs is considered in detail in [2]. Extra information on the cost/revenue parameters is presented in [1].

According to [1], the total power consumption values for the stations are: $P_{BS\text{-}tri} = 680$ W, $P_{BS\text{-}omni} = 600$ W and $P_{RS} = 180$ W. Hence, the use of RSs instead of BSs only leads to a circa 70 % reduction in the power consumption for the RS coverage zone. These RSs can be switched-off in periods when the traffic exchange is low. In a scenario where RS coverage zones are reduced to zero during the night and at weekends, by switching the RS equipment off and zooming out the central BS coverage zone leading to a coverage distance of $R_{z-out} = \sqrt{3}R'$, the total power consumption becomes simply the power consumption of the central BS. This is either 680 or 600 W, for tri-sectored and omnidirectional BSs respectively [1]. In the cell with RSs, the total power consumption is $680 + 3 \times 180 = 1220$ W for tri-sectored BS, or $600 + 3 \times 180 = 1140$ W for omnidirectional BSs. This is approximately twice the power of the zoomed out cell. The 540 W power decrease corresponds to a given reduction in operational cost, proportional to the time the RSs remain switched-off.

During the whole year, the total energy consumed by RSs is 24 × 365 × 540 = 4730.4 kW h. If the price of energy is 0.10 €/kW h the electricity cost is 473.04 €/year. If the RSs are switched-off overnight (for eight hours each night during the working days) and during the whole weekend (48 h) then the total period when the energy is saved is 5 × 8 + 2 × 24 = 88 h (against 80 h of full functionality cell operation), i.e., full operation lasts only for 80/168 = 47.6 % of the time. Therefore, by switching-off the RSs, the economic annual expenditure resulting from the power reduction in each cell is $473.04_{[€]}$ × 0.476 = 225.17 €/year per cell, corresponding to a reduction in the annual cost per cell of 247.17 €/year. The aforementioned reduction in the cost per cell corresponds to a reduction of the operational cost of the "equivalent BS" of 247.17/3 = 82.62 €/year (~10 % of $C_{M\&O}$).

If we assume the DL sub-frame format cannot be changed to a more favourable one when the RSs are switched-off, the economic performance is as presented in the first three curves from Fig. 10. These plots assume an example revenue per MB of 0.005 € [1], and do not consider the case of omnidirectional BS antennas in the absence of relays (see Sect. 4). Note that the ~83 €/year reduction in the operation and maintenance cost reflects the case for the zoomed out central BS coverage zone with no RSs. If the frames are not adaptively changed, given that the throughput is lower with no relays (see the results in Fig. 10) the economic performance is lower compared to the cases with the presence of relays. For $R_{z\text{-}out}$ = 1,732 m, in the case of the zoomed out central BS coverage zone (with the RSs in sleep mode and its cooling system switched-off) and a tri-sectored BS antenna, the profit in percentage terms achieves 544.5 % [2].

In the presence of relays, for R' = 1000 m (corresponding to the same equivalent area), the profit is 610.2 and 718.8 %, for the omnidirectional (three carriers) and tri-sectored (one carrier/sector) cases respectively, an increase of 12.1 and 32 %. As the coverage is adequate with relays (more than 95.65 % of the cell is covered under RT calculations, as

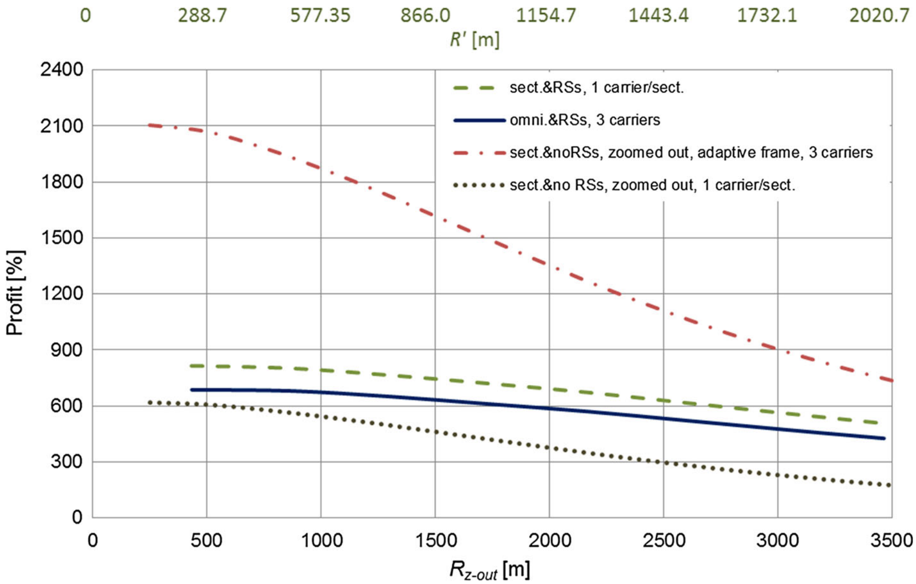

Fig. 10 Comparison of the economic performance between omnidirectional (three carriers) and tri-sectored (one carrier/sector) BSs in the presence of relays and with the central BS coverage zone zoomed out. RSs coverages are zoomed into zero. All plots are under the same total DL BW, and $K = 3$

shown in Table 7), we show that the use of relays lead to an actual increase of the economic performance whilst clearly increasing the cell coverage.

By putting the RSs into sleep mode during the night and at weekends, and with tri-sectored BS antennas, there is an increase of the area of the cell with no coverage to 18.10 %. This coverage situation is not adequate, but still leads to a reasonable economic performance. The use of omnidirectional BS antennas in this scenario is not a viable option, as the area with no coverage increases to almost 40 %.

If the frames could be adaptively adjusted when the RSs go into sleep mode and the BS zooms out, the economic performance would reach, in theoretical terms, 1871.6 %. However, this is not entirely credible, as the area without coverage would be 18.10 % and the throughput would not reach the theoretical 20 Mbps (from Fig. 6) but only 15.58 Mbps (i.e., 3×5.193).

7 Conclusion

This paper has investigated energy efficiency and economic implications in WiMAX deployments of the use of power saving modes for relays (RSs) in conjunction with cell zooming. The challenging case of a propagation measurement-based scenario in the hilly region of Covilhã, Portugal, has been chosen, whereby precise details of the measurement campaign have been outlined. Given that coverage is adequate in the presence of RSs, practical results from cellular planning exercises have been shown to be similar to theoretical results for a full-coverage scenario. Through RT and the application of the DP model, it has been shown that without RSs the supported throughput is lower in practice, as coverage is not 100 % (even with tri-sectored BSs). If omnidirectional BS antennas are used without RSs, the proportion of the cell with no coverage reaches 41.68 or 38.77 %, through RT and the application of the DP model, respectively.

Under the use of RS power saving modes in conjunction with cell zooming, if it is assumed that the downlink sub-frame format cannot be changed to a more favourable one at times when the RSs are sleeping, the economic performance is better in the presence of RSs. Therefore, if there are no RSs, economic performance is reduced because the supported throughput decreases. However, it is important to highlight that contrary to the omnidirectional case (where coverage is extremely weak with no RSs), in the tri-sectored case, if RSs go into sleep mode (thereby saving energy and money), although there is an increase of the area of the cell with no coverage from 4.25 to 18.10 % (RT coverage), there is still a reasonable economic performance. The use of omnidirectional BS antennas, however, is not a viable option as the area with no coverage is approximately 40 %.

This paper shows that through the use of power saving by RSs at low traffic times, average energy savings for RSs (excluding BSs) of some 47.6 % can be achieved. On a system-level, this translates to a financial saving for the operator of 10 % in the combined operation and maintenance cost. It is also demonstrated that in challenging propagation scenarios such as the ones investigated in this paper, such power saving solutions must be used cautiously.

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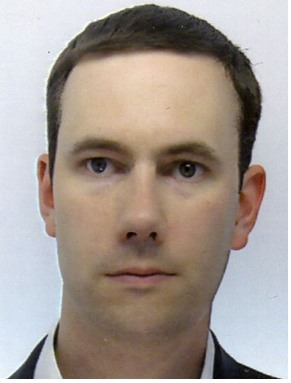

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