

# Cost/Revenue Optimization of WiMAX Networks with Relay Power Saving Modes: Measurement-Based Scenario in a Hilly Region

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**Abstract**—This paper investigates cell zooming and relaying in conjunction with the use of opportunistic sleep modes to save energy at times of low load in WiMAX network deployments. It performs extensive propagation measurements in a hilly area of Covilhã, Portugal, in order to present a realistic and topographically challenging scenario in which to perform dynamic optimizations. It describes these measurements and their methodology in detail. Based on this scenario, it then investigates the performance achievable by networks that are deployed in various sectorization configurations with and without relays, and matches this to varying traffic loads at different times of the day to maximise the use of sleep modes, where possible, by relays, also in consideration of coverage constraints. Results demonstrate that savings typically of 47.6% in relays' average power consumption can be achieved. These savings are shown to map to a financial saving for the operator of 10% in operation and maintenance cost combined. It is also demonstrated that such solutions have to be used cautiously in such hilly regions due to challenges in maintaining coverage.

**Keywords**- *Broadband communication, WiMAX, cellular planning, economics, relays, green communications, cell zooming.*

## I. 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. Relays are also amenable to opportunistic utilisation of power-saving modes. In [1], it has been shown that to save energy during low traffic periods, cell zooming may be applied in conjunction with relay sleep modes. 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, with no consideration of real-world terrains. Such terrains may lead to

increased loss to Subscriber Stations (SSs) and significant shadowing, which 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 ray tracing is considered in the cellular planning tool simulations as opposed to the use of the dominant path model. We obtain analytical results for the carrier-to-noise-plus-interference ratio (CNIR) versus distance and maximum supported throughput, with the results from cellular planning exercises being achieved using Winprop™ for WiMAX deployments, with and without relays, in the zone of Covilhã, Portugal, a very hilly region. Different modulation and coding schemes (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 being appropriate.

Despite the above, as considerable resources are needed for BS-to-RS communication, some configurations with no relays, e.g., with tri-sectorised BSs, may still lead to better efficiency in theoretical terms. If there were 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 in to 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 time. 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 the frame structure.

This paper is organized as follows. Section II addresses the empirical modified Friis propagation model for the performed spectrum measurements. Section III discusses the assumptions in terms of cellular topologies with relays and the sub-frame format. Results in terms of supported throughput are analysed in Section IV. Section V investigates coverage limitations for the topologies with no relays present. The economic performance and energy efficiency trade-off is discussed in Section VI. Finally, Section VII concludes the paper.

## II. MODELLING OF THE PROPAGATION ENVIRONMENT

### A. 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 ( $\mu$ BS). During these experiments, this 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. For the  $\mu$ BS, we have considered a 10 dBi omnidirectional antenna, installed at the top of a 7 m pole on the rooftop of the Health Science Faculty (HSF) of the University of Beira Interior. This places the antenna 28 m above ground level.

A Rohde & Schwarz FSH8 portable spectrum analyser was used during the trials. This measured channel power from the WiMAX transmitter in the considered band using the “channel power measurement” option. The frequency range of the spectrum analyser covered 9 kHz to 8 GHz, with a sensitivity of -160 dBm. The sweep time can be configured between 200  $\mu$ s and 100 s. Another 10 dBi omnidirectional antenna was installed on the rooftop of a car, approximately 2.3 m above ground level. Geo-referencing was provided by a GPS receiver.

In order to improve our acquisition methodology, instead of roaming the city at vehicular speed not exceeding 40 km/h [6], we stopped the car approximately every 30-50 m to acquire the channel power several times. Aside from improvements in spectrum measurement accuracy, this method provides an increased confidence to the geo-referring process. GPS receivers have a margin of error of usually a few meters; this margin is increased whenever the receiver is in movement. Further to spectrum measurement accuracy, the number of channel power measurements is defined by the value of the sweep time. From the chart of the repeatability/error as a function of the number of samples, extracted from [7], one achieves the values for the sweep time and acquisition parameters as given in Table I.

TABLE I. SPECTRUM ANALYZER 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]	$\pm 0.45$	$\pm 1.00$

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 of lower than -90 dBm. The repeatability for a given number of samples is also presented in Table I [7]. For example, a repeatability of  $\pm 0.45$  dB means that the measured value lies within a range of  $\pm 0.45$  dB from the true value, with a confidence level of 99% [7]. Further to this, we have verified that the histogram of the 80 measurements taken in a single location follows a Gaussian distribution with a confidence interval of 95%, with expectation  $\mu = -73.08$  dBm (location of the peak) and standard deviation  $\sigma = 0.711$  dB.

### B. Measurement results and curve fitting approach

During the autumn 2011 measurements, we achieved an adequate fit to the SUI-C model for distances of up to 900 m with a lower density of trees (and other foliage). In spring 2012 we observed a substantial increase of the foliage and even the existence of additional vegetation (as the trees had grown). Then, 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. For larger distances (up to 1670 m), the influence of the foliage near the HSF was negligible. Figure 1 shows the variation of the measured and the modified Friis path loss the distance ( $\sim 1.30$ -1.67 km) in this case.

By comparing the results with known models through least-square (LS) regression, we achieved a fit to the modified Friis m with a propagation exponent,  $\gamma$ , varying from 2.416, in the case shown in Figure 1, to 2.55, in other field trials.

## III. ASSUMPTIONS FOR THE ANALYSIS OF SYSTEM CAPACITY

To guarantee WiMAX communications with no coverage gaps near the cell edge (i.e., to achieve BPSK with  $\frac{1}{2}$  MCS), the CNIR must be higher than 3.3 dB throughout the cell [1], [2]. Here, the radio frequency bandwidth, noise figure, and frequency are  $b_r = 3.5$  MHz,  $NF = 3$  dB, and  $f = 3.5$  GHz [1].

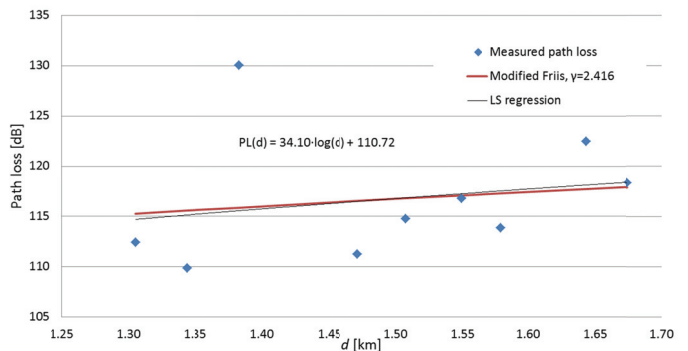


Figure 1. Measured and modified Friis ( $\gamma=2.416$ ) path loss curves

In line with the performed measurements, the modified Friis propagation model is assumed. Values of different parameters are chosen as  $P_t = -2\text{dBW}$ ,  $\gamma = 2.55$  in suburban areas  $G_r = 10\text{ dBi}$ , and  $G_t = 9\text{dBi}$  for BS-to-SS and SS-to-BS [1], and  $P_t = -2\text{dBW}$ ,  $\gamma = 3$ ,  $G_r = 17\text{ dBi}$  (RS-to-SS), while  $G_r = 10\text{ dBi}$  and  $G_t = 28\text{dBi}$  for the BS-to-RS and RS-to-BS communications. The difference between receiver gains for RS/BS communication and RS/SS (or BS/SS) communication is justified by the use of a directional antenna in the RS, pointing directly towards the central BS; this antenna has a gain of  $\sim 28\text{dBi}$  [1]. The worst-case interference scenario is considered, where the mobile is at the cell edge and co-channel interference is higher. This worst-case DL scenario occurs when the BS of the serving cell transmits to the most distant possible location of the SS it is serving, 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. For the UL, the worst-case scenario occurs when the SS is transmitting to the BS from the cell edge, and interfering SSs are on the boundary between interfering cells and the serving cell.

In the considered multihop context, a cell is composed of the central coverage area, served by the BS, and three  $240^\circ$  sector coverage areas, served by individual RSs ( $RS_1$ ,  $RS_2$  and  $RS_3$ ), as shown in Figure 2. While the BS antenna may be either omnidirectional or sectored ( $120^\circ$  sectors) RS antennas for communication with BS are considered to be directional (e.g.,  $120^\circ$  sectored or narrower beamwidth ones), to reduce the received interference from BSs and facilitate non-overlapping coverage with the central zone of cell.

Although BS backhaul is assured in the usual terms for mobile communications (e.g., cable or micro-wave radius link), RS backhauling is supported by using special specific sub-frames within the radius channel created for that purpose. The duration of each sub-frame is 5 ms [1]. Our proposal on frames is inspired in the sub-frame structure from [8] 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, differently from the proposal for IEEE 802.16j from [9], which enables multihop. Note, however, that there may be some similarities between the sub-frame structure proposed here and the frame 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. This type of relay is of lower complexity, and only operates in a centralized scheduling mode and for topology up to two hops.

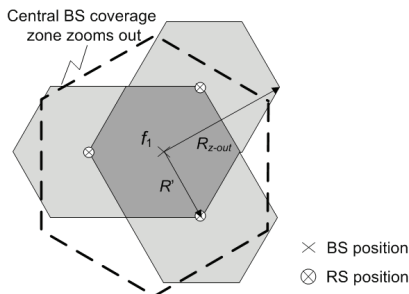


Figure 2. BS, RS and respective “hexagonal” coverage areas (central coverage zone zooms out when RSs sleep)

This 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 for the frame are also inspired in the IEEE 802.16-2004 frames, which consists of two sub-frame, operate in FDD, DL and UL transmitted at simultaneously. Although the version of fixed WiMAX we consider here originally used FDD, this 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 Figure 3 (the case of 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 this tri-sectored frame, relatively to the frame for the omnidirectional cells proposed in [1], [2], corresponds to the increase of the throughput in the central cell by a factor of the number of sectors,  $N_{sec}$ , as there is a carrier assigned to each sector. This  $N_{sec}$  increase takes place both in DL and UL, due to the use of a more favourable frame format.

This 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.

#### IV. SUPPORTED CELL/SECTOR THROUGHPUT

With the proposed frame format, communications using a given frequency carrier are only from/to a sector and a RS. Hence, to obtain the supported throughput, the contribution from the central cell results from multiplying the sector supported throughput by  $N_{sec}$ . The equivalent supported throughput in a hexagonal coverage zone (or cell) with an area of  $(3\sqrt{3}/2) \cdot R'^2$  is therefore given by ( $R'$  is the coverage distance for the BS/RS “hexagonal” coverage zones):

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

where  $R_{b-tot}$  is the total throughput in the multihop cell (formed by the central plus RS zones). The use of sectored cells corresponds to  $N_{sec}$  increase in both DL and UL traffic from/to the BS, due to the use of a more favourable frame format.

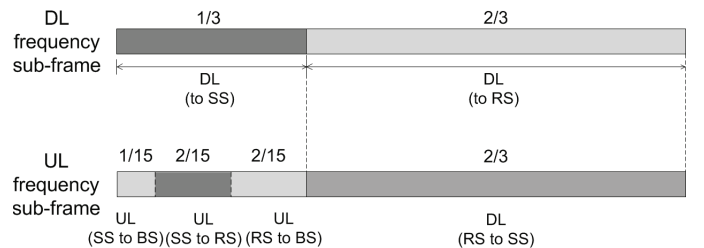


Figure 3. Structure for UL and DL sub-frames with deployed relays (tri-sectored BS)

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, yielding a stepwise behavior that comes from the correspondence between  $\text{CNIR}_{\min}$ , in dB, and the physical throughput for each MCS. When a sectored BS antenna is considered the number of interfering cell is decreased, and system capacity increases.

Results for the equivalent supported throughput as a function of  $R'$  and  $R_{z\text{-out}}$  are shown in Figure 4 for the DL,  $K=3$  and the absence/presence of relays, where two different horizontal axis are represented. While  $R'$  is the coverage distance for the central and RS coverage zones,  $R_{z\text{-out}}=\sqrt{3}R'$  is the radius for the zoomed out cell, as shown in Figure 2. We have considered BSs with omnidirectional and tri-sectored antennas whilst first assuming that the frame format is not adaptively adapted in the absence of relays. For omnidirectional BS antenna, 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  $\frac{1}{2}$  MCS, corresponding to  $\text{CNIR}\geq 3.3$  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).

As a consequence, although the total throughput is obtained by multiplying the cell/sector throughput by three, because there are three available carriers, in the omnidirectional case, and three sectors in the ‘‘zoomed out’’ cell with one carrier each, in the tri-sectored case), one still needs to consider the effect of the DL sub-frame format in the resulting supported throughput, i.e., a factor of 1/3 in both cases [2], yielding to an overall multiplying factor of 1.

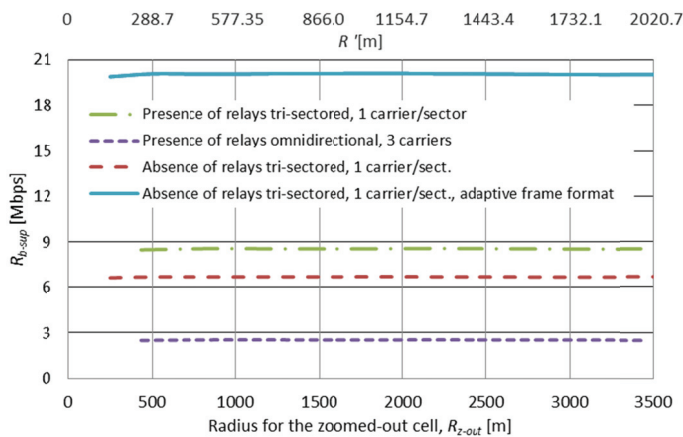


Figure 4. Comparison of the equivalent supported throughput between the cells with relays and the zoomed-out cells,  $K=3$

For tri-sectored BS antennas, we have also additionally considered the possibility of adaptively adapt the frame format when 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 Section VI to calculate the costs, revenues and profits.

## V. CELLULAR PLANNING IN ACTUAL ENVIRONMENTS

Covilhã is located on a very hilly terrain at the bottom of Serra da Estrela, a 2000 m mountain, leading to very challenging cellular planning. In the Winprop<sup>TM</sup> simulations (by considering ray tracing, RT, with several reflections while neglecting diffraction), we have considered BS, SS and RS parameters similar to the ones considered in the field trials and in [1] with only slight changes, namely the SS is considered to be at 2 m height, and the gain from 120° tri-sectored antenna form 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  $\mu$ BS. 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:

- Zoomed-out cells with no relays, covering the same area as the cells with relays, with  $R_{z\text{-out}}=\sqrt{3}R'=1732$  m;
- Cells with relays (shape from Figure 2), as shown in Figure 5, 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 adequate in the central cell, the only that suffers interference from six co-cells.

By considering the co-channel interference and noise, one has been able to obtain results for the coverage and determine if there are some zones of the cell with no coverage guarantee, i.e., where  $\text{CNIR}<3.3$  dB. The area of the cell with no coverage and the equivalent supported throughput are shown in Table II.

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 19.44 % 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 in [3] with the dominant path model instead of RT (besides, if adaptive frame format was possible the supported throughput would be 15.58 Mbps, and not  $\sim 20$  Mbps).

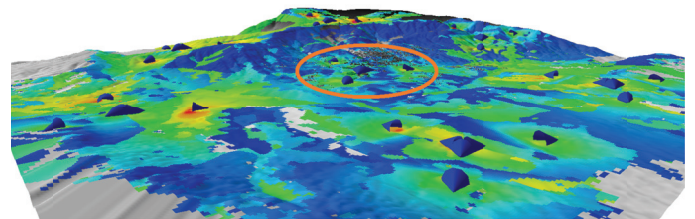


Figure 5. CNIR in the central cell (marked with the orange circle) comprising tri-sectored BS and three relays

TABLE II. SUMMARY OF THE CELLULAR PLANNING RESULTS

Type of cell	Area not covered		$(R_{b-sup})_{equiv}$ [Mbps]	
	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

Figure 6 presents results for the cell/sector throughput in the central cell with tri-sector antennas and the presence of RSs. The reuse topology is the same as in Figure 5 (where six “first tier” interferers are considered). In configurations with RSs, the results for the supported throughput obtained from Winprop<sup>TM</sup>, are clearly better in the tri-sector case (8.616 Mbps compared to 2.67 Mbps in the omnidirectional case) but slightly better than the ones obtained in [3] with ray tracing.

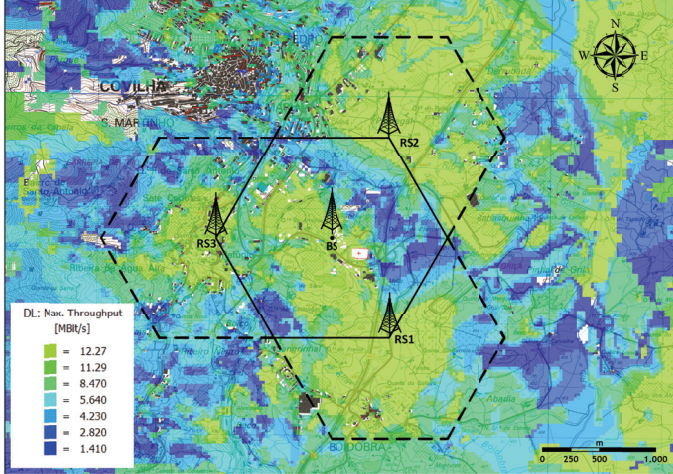


Figure 6. Spatial variation of the throughput with tri-sector BS antenna and the presence of relays

## VI. ECONOMIC AND ENERGY EFFICIENCY TRADE-OFF

The cost/revenue analysis provides a means of combining several contributing factors in WiMAX cellular planning: determination of the reuse pattern, coverage distance, and the resulting supported physical throughput. The cost/revenue function proposed in [1], [2] accounts for the cost of building and maintaining the fixed WiMAX infrastructure, and 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 project duration of five years as an assumption, it is decided to analyze costs and revenues on an annual basis. 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 III have been considered for  $K=3$ , with three carriers in the omnidirectional case and one carrier per sector in the tri-sector case.  $C_f$  is the fixed term of the costs,

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

Costs	Omnidirectional	Tri-sector
$C_f$ [€/km <sup>2</sup> ]	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

$C_{BS}$  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 [1]. As a bandwidth of 31.5 MHz may be available for an operator, with  $K=3$ , it is worthwhile to compare the case of tri-sector cells (or central coverage zones, if the topology is with relays), with the case with omnidirectional BS antenna getting three carriers of 3.5 MHz each, and the situation without RSs in both tri-sectored an omnidirectional antenna cases from [2]. Extra details on the cost/revenue parameters are presented in [1].

According to [1], the total power consumption values for the stations are the following ones:  $P_{BS-tri}=680W$ ,  $P_{BS-omni}=600W$  and  $P_{RS}=180W$ . Hence, the use of RSs instead of full functionality BSs per se lead to circa 70% reduction in the power consumption for their coverage zones. These RSs can be switched-off in periods when the traffic exchange is low. In a scenario where RSs are zoomed in to 0 during the night periods and weekends, by switching the RS equipment off, and the central BS coverage zone is zoomed out, leading to a coverage distance of  $R_{z-out}=\sqrt{3}R'$ , the total power becomes now simply the power of the central BS, either 680 or 600 W, for tri-sectored and omnidirectional BSs, respectively [1]. In the full functionality cell with RSs the total power is  $680+3\cdot 180=1220W$  or  $600+3\cdot 180=1140W$ , respectively. This is approximately twice the power of the zoomed out cell. The 540 W decrease on the power corresponds to a given reduction in operation costs, proportional to the time the RSs remain switched-off.

During the whole year, the total energy waste in RSs is  $24\cdot 365\cdot 540=4730.4$  kW·h. If the price of the 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 hours) then the total period when the energy is saved is  $5\cdot 8+2\cdot 24=88$  hours (against 80 hours 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  $473.04_{[€]}\cdot 0.476=225.17$  €/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 operation costs of the “equivalent BS” of  $247.17/3=82.62$  €/year ( $\sim 10\%$  of  $C_{M\&O}$ ).

If we assume the DL sub-frame format cannot be changed to a more favorable one when the RSs are switched-off, the economic performance is the one presented in the first three curves from Figure 7. This is an example for a revenue per MB of 0.005€ [1], and does not consider the case of omnidirectional BS antennas in the absence of relays (see Section IV). Note that the  $\sim 83$  €/year reduction in the operation and maintenance cost is reflecting the case for the zoomed out central BS coverage zone with no RSs.

If the frames are not adaptively changed, as the throughput is lower with no relays (see results in Figure 4) the economic performance is lower compared to the cases with the presence of relays. For  $R_{z-out}=1732$  m, in the case of the zoomed out central BS coverage zone (with the RSs in the sleeping mode and its cooling system switched-off) and tri-sectored BS antenna, the profit in percentage terms [2] achieves 544.5 %.

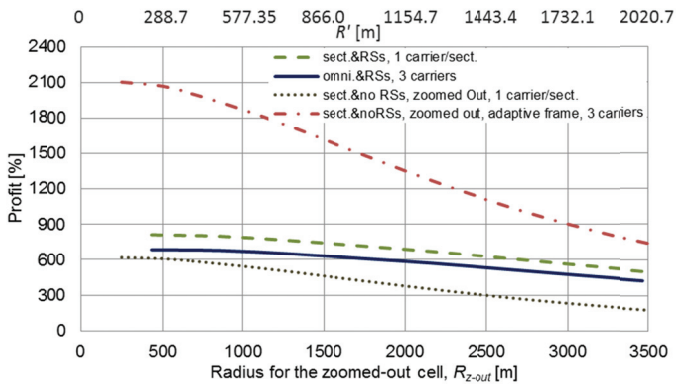


Figure 7. Comparison of the economic performance between omnidirectional (3 carriers) and tri-sectored (one carrier/sector) BSs in the presence of relays and with the central BS coverage zone zoomed out (while RSs coverage zoom in to zero) under the same total BW, in the DL and  $K=3$

However, 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 (3 carriers) and tri-sectored (1 carrier/sector) cases, an increase of 12.1 and 32 %, respectively. As the coverage is adequate with relays (more than 93.92 % of the cell is covered), we show that the use of relays leads 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, with tri-sectored BS antennas, there is an increase of the area of the cell with no coverage to 18.10 %. This coverage is not adequate, but this situation still leads to a reasonable economic performance. The use of omnidirectional BS antennas is not a viable option, as the area with no coverage is almost 40%.

If the frames could be adaptively adjusted when the RSs go into the 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 non-covered area is 18.10 % and the throughput does not reach the theoretical 20 Mbps (from Figure 4), but only 15.58 Mbps.

## VII. CONCLUSION

This paper has investigated the use of relays (RSs) in WiMAX networks, particularly looking at energy efficiency and economic implications under the assumption that power saving modes can be used for 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 on 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. Moreover, through ray tracing, it has been shown that without RSs the supported throughput is lower in practice, as coverage is not 100%. If omnidirectional bases station (BS) antennas are used without RSs, the proportion of the cell with no coverage reaches 41.68 %.

Under cell zooming in conjunction with RS power saving modes, if we assume the downlink sub-frame format cannot be

changed to a more favourable one at times when the RSs are not present, the economic performance is better with the presence of RSs. If there are no RSs, economic performance is reduced because 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 and their cooling systems are switched-off, although there is an increase of the area of the cell with no coverage to 18.10 % 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 more than 40%.

This paper shows that through the use of power saving by RSs at low traffic times, average energy savings at 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 operation and maintenance cost. It is also demonstrated that in challenging propagation scenarios such as investigated in this paper, such solutions must be used cautiously.

## ACKNOWLEDGMENT

This work was supported by "PEst-OE/EEI/LA0008/2011, ICT-ACROPOLIS, UbiquiMesh, OPPORTUNISTIC-CR, PROENERGY-WSN, PTDC/EEA-TEL/120666/2010, COST IC 0905 "TERRA", IC 0902 and IC 1004, and by PLANOPTI. Authors acknowledge contributions from Maria del Camino Noguera and from VIATEL.

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