Energy Saving in the Optimization of the Planning of Fixed WiMAX with Relays in Hilly Terrains: Impact of Sleep Modes and Cell zooming

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***Abstract*— For financial and environmental reasons, energy efficiency is a key consideration in the development and deployment of future mobile systems. Layered and cooperative elements such as femto-cells and relays can improve performance or energy efficiency in mobile networks; however, they consume energy per se and their durations in operational state must therefore be minimised. This paper investigates the use of relays in WiMAX network deployments and concentrates on the performance and energy efficiency trade-off in such cases. Specifically, it 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 requirements. It does this for scenarios based on pioneering propagation measurements in the hilly area of Covilhã, Portugal. Results show that through the maximal use of power saving by relays at low traffic times, considerable energy savings in the relays' power consumption are achievable, typically 47.6 %. These savings are shown to map to a financial saving for the operator of 10% in the operation and maintenance cost. However, it is also demonstrated that such solutions have to be used cautiously so as to maintain coverage requirements and not decrease the profit in challenging propagation scenarios such as investigated in this paper.**

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

I. INTRODUCTION

In the optimization of cellular planning for fixed WiMAX, the use of Relay Stations (RSs) reduces the necessary extent of wire-line backhaul, improving coverage significantly whilst achieving competitive values for 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 relays going into sleep mode. However, the comparison between WiMAX topologies with the presence and absence of relays from [1] did not consider the resulting loss in the coverage, with no relays being in real-world terrains. Such terrains may lead to increased loss to Subscriber Stations (SSs) and significant shadowing, which may result in coverage holes, whose impact must be further analyzed.

In this work, we compare the analytical results for the carrier-to-noise-plus-interference ratio (CNIR) versus distance and the maximum supported throughput with the results from cellular planning exercises performed using Winprop^{TM} (by considering the dominant path propagation model) for WiMAX deployments with relays in the zone of Covilhã, Beira Interior, Portugal, a very hilly region. Different modulation and coding schemes (MCSs) have been considered. RS backhauling is supported by using specific sub-frames within the radio channel created for that purpose. Besides base station (BS)-to-SS communications, BS-to-RS and RS-to-SS communications need also to be guaranteed. As there usually is less traffic load in the UL direction, wireless MM communications are generally asymmetric. This leads 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-sectored 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 discuss the pros and cons of using relays in practical terms.

By switching-off RSs during either the night period or the weekends [3], when the traffic load is low [4], energy saving occurs. In these periods, although the value for the transmitter power is kept the same the central coverage zone 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 working at the sleep mode, the air-conditioner and other energy consuming equipment can be switched-off. In this case, the coverage zones of the RSs in the sleep mode zooms in to 0 [3] and the central BS coverage zone zooms out to guarantee the coverage of the cell. In [1], it was shown that this special form of cell zooming may be explored to benefit from the lowest traffic demand and save power. The energy trade-offs arising from this process need therefore to be analyzed under simple assumptions for the energy consumption of each element of BSs/RSs. Cost/revenue optimization of the WiMAX network planning is also a goal.

The remaining of the paper is organized as follows. Section II discusses the assumptions for cellular topologies with relays and sub-frame format. Results for the supported throughput are analysed in Section III. Section IV discusses the coverage limitations from the topologies with no relays in practical terms. The economic performance and energy efficiency trade-off is discussed in Section V. Finally, Section VI presents the conclusions and suggestion for further work.

II. ASSUMPTIONS FOR THE ANALYSIS OF SYSTEM CAPACITY

To guarantee WiMAX communications with no coverage gaps near the cell edge, the CNIR must be higher than 3.3 dB throughout the cell [1], [2], to be able to use BPSK ½ MCS. The radio frequency bandwidth, noise figure, and frequency are b_{rf}=3.5 MHz, NF=3dB, and f=3.5 GHz [1], respectively. The modified Friis propagation model is assumed. The values of different parameters are considered as P_t=-2dBW, γ=2.55 in suburban areas (this value was obtained from field trials where instead of roaming the city at vehicular speed not exceeding 40 km/h [5], we have periodically stopped the car while acquiring the channel power several times, accounting for the cart for the repeatability/error as a function of the number of samples), G_t=10 dBi, and G_r=9dBi for BS-to-SS and SS-to-BS [1], and P_t=-2dBW, γ=3, G_t=17 dBi (RS-to-SS), while G_t=10 dBi and G_r=28dBi 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 28dBi directional antenna in the RS [1], pointing directly towards the central BS.

In the considered multihop context, a cell is composed by the central coverage area, served by the BS, and three 240º sector coverage areas, served by individual RSs (RS_1, RS_2 and RS_3), as shown in Figure 1. While the BS antenna may be either omnidirectional or sectored (120º sectors) RS antennas for communication with BS are considered to be directional, to reduce the received interference from BSs and facilitate non-overlapping coverage with the central zone of cell. The duration of each sub-frame is 5 ms [1]. Our proposal on frames is inspired in the sub-frame structure from [6] 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 [7], 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.

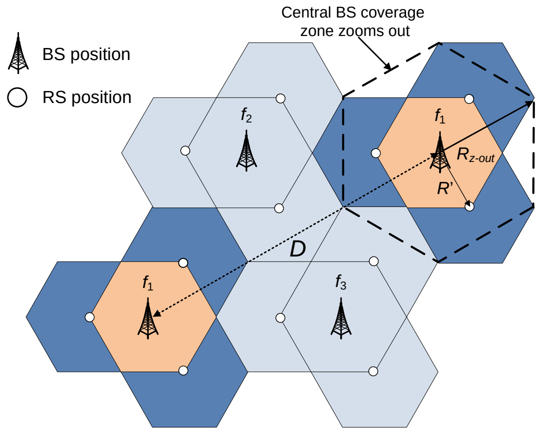

Figure 1. BS, RS and respective “hexagonal” coverage areas (central coverage zone zooms out when RSs sleep)

This type of relay is of lower complexity, and only operates in a centralized scheduling mode and for topology up to two hops. 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 RS in one frame, and the same data can be forwarded from the RS to 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 2 (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.

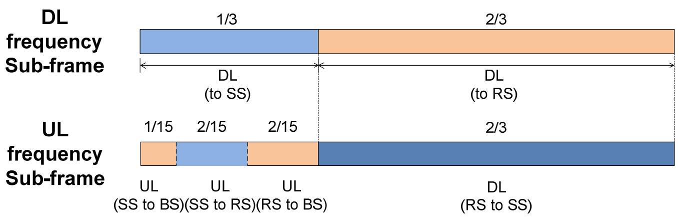

Figure 2. Structure for UL and DL sub-frames with deployed relays (tri-sectored BS)

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.

III. 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 $\left(3\sqrt{3}/2\right)\cdot R'^2$ is therefore given by (R' is the coverage distance for the BS/RS "hexagonal" coverage zones):

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

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.

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 $CNIR_{min}$, 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 3 for the DL, K=3 and the absence/presence of relays. 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 1. 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 ½ MCS, $CNIR \geq 3.3$ dB. In this case, the curves for the cell throughput reach 0 Mbps for distances lower than the coverage distance, e.g., the non-covered zone is ~7% for $R_{z\text{-}out}$=2000 m.

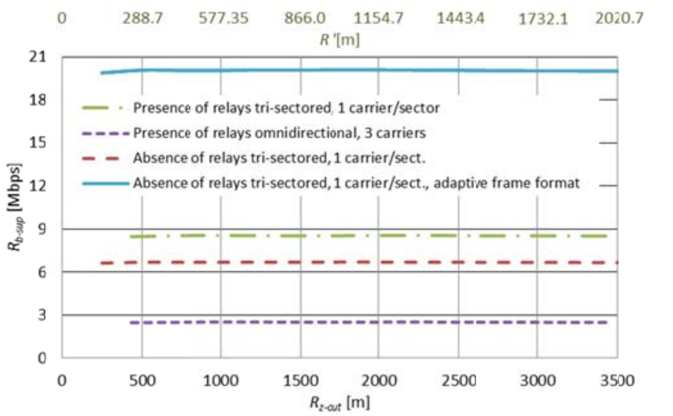

Figure 3. Comparison of the equivalent supported throughput between the cells with relays and the zoomed-out cells, K=3

As coverage distances are short, the decaying behaviour of $R_{b\text{-}sup}$ (from, e.g., Figure 8 from [1]) is not observed. 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.

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 ~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.

IV. CELLU

Covilhã is located on a very hilly terrain ~~at the bottom of~~ challenging cellular planning. In the Winprop™ simulations (by considering he dominant path propagation model), ~~W~~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 120º 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 μBS. 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 1~~2~~), as shown in Figure 4, t~~5~~, tri-sectored ~~omnidirectional~~ BSs, with

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

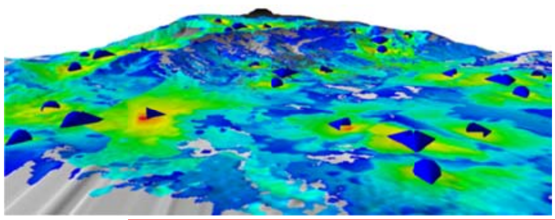

Figure 4. CNIR __CNIR in the central cell with omnidirectional BS and

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 *CNIR*<3.3 dB. The area of the cell with no coverage and the equivalent supported throughput are shown in Table I.

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 5.05 Mbps, a value much lower than the theoretical 6.7 Mbps (besides, if adaptive frame format was possible the supported throughput would be 15.15 Mbps, and not ~20Mbps). Figure 5 presents results for the cell/sector throughput in the central cell with tri-sectored antennas and the presence of RSs. The reuse topology is the same as in Figure 4 (with six "first tier" interferers).

TABLE I. SUMMARY OF THE CELLULAR PLANNING RESULTS

	Area not covered		$R_{b\text{-}sup}$ **[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

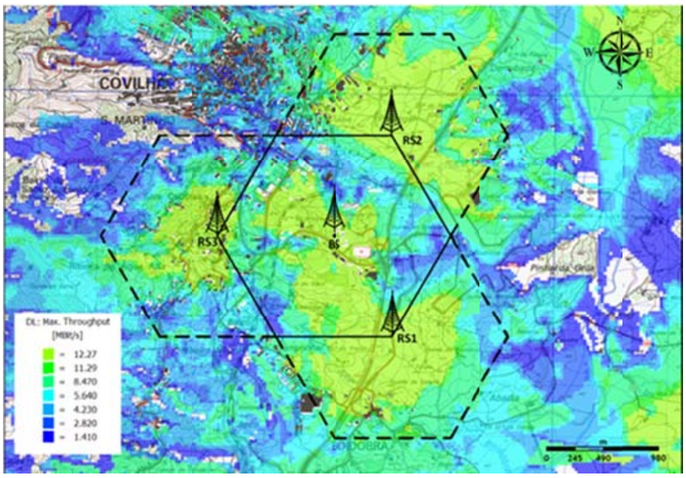

Figure 5. Spatial variation of the throughput with tri-sectored BS antenna and the presence of relays

V. ECONOMIC AND ENERGY EFFICIENCY TRADE-OFF

The cost/revenue analysis provides a means of combining several contributing factors in WiMAX cellular planning [1], [2]: determination of the reuse pattern, coverage distance, and the resulting supported physical throughput. It 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 II have been considered for K=3, with three carriers in the omnidirectional case and one carrier per sector in the tri-sectored case. C_{fi} is the fixed term of the costs, 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-sectored 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]. The revenue per MB is considered to be 0.005 €/MB. Extra details on the cost/revenue parameters are presented in [1].

Energy efficiency must be taken into account in the design of future mobile and wireless systems. Indeed, on-going expectations for increases in required data capacities point to significant increases in energy consumption of systems, especially as they get closer to the Shannon limit. According to [1], the total power consumption values for the stations are the following ones: $P_{BS\text{-}tri}$=680W, $P_{BS\text{-}omni}$=600 W and P_{RS}=180 W. 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. For example, 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 $R_{z\text{-}out}=\sqrt{3}R'$, 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+3·180=1220 W or 600+3·180=1140 W, 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 24·365·540=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 for eight hours overnight during the working days, and for the whole weekend (48 hours) then the total period when the energy is saved is 5·8+2·24=88 hours, i.e., full operation lasts only for 80/168=47.6% of the week time.

Therefore, by switching-off the three RSs of each cell 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 operation costs of the "equivalent BS" of 247.17/3=82.62 €/year (approximately 10% of the operation and maintenance cost).

TABLE II. 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

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 the one presented in the first three curves from Figure 6 (for a revenue per MB of 0.005€/MB), which does not consider the case of omnidirectional BS antennas in the absence of relays (see Section IV). Note that the ~83 €/year reduction in the operation and maintenance costs are reflected in the computations for the zoomed out central BS coverage zone cell (in the no RSs case).

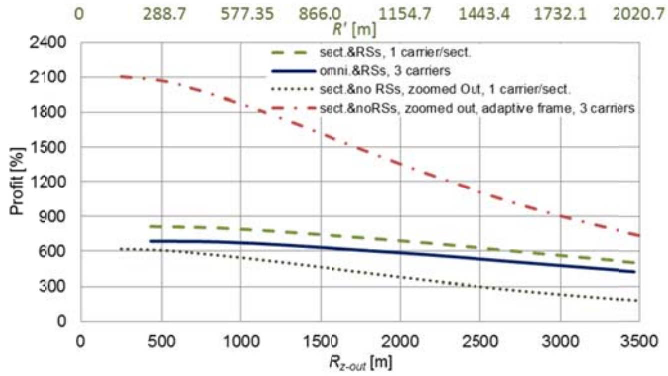

Figure 6. Comparison of the economic performance between omnidirectional (3 carriers) and tri-sectored (one carrier/sector) BSs in the presence of relays and with the central BS coverage zone zoomed out (while RSs coverage zoom in to zero) under the same total BW, in the DL and K=3

If the frames are not adaptively adapted, as the throughput is lower with no relays (see results in Figure 3) the economic performance is lower compared to the cases with the presence of relays. For $R_{z\text{-}out}$ =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 %. 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.

By putting the RSs into the sleeping mode during the night period and weekends, with tri-sectored BS antennas, there is an increase of the area of the cell with no coverage to 19.44 % (which is not adequate), leading to a still reasonable economic performance. The use of omnidirectional BS antennas is not a viable option at all 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 BS zooms out, the economic performance would reach, in theoretical terms, 1871.6%.However, this is not credible, the non-covered area is 19.44 %, and the throughput does not reach the theoretical 20 Mbps (from Figure 3) but only 15.15 Mbps.

VI. Conclusion

This paper has investigated the use of relays in WiMAX network deployments, particularly looking at energy efficiency aspects and economic implications under the assumption that power saving modes can be used for relays in conjunction with cell zooming. It has shown that, in the presence of relays, as the coverage is adequate, the practical results obtained from cellular planning exercises are similar to the theoretical results. In the absence of relays, the supported throughput is lower in practice, as the coverage is not 100% guaranteed. It was also concluded that, in this case, with omnidirectional BS antennas, the cell zone with no coverage reaches 38.77 %.

Under cell zooming in conjunction with relay power saving modes, if we assume the downlink sub-frame format cannot be changed to a more favourable one at times when the relays (RSs) are switched-off, the economic performance is better with RSs. If there are no relays, the economic performance is reduced as throughput decreases. However, it is important to highlight that, differently from the omnidirectional case (where coverage is extremely weak with no relays), in the tri-sectored case if RSs go into sleep mode (and their cooling system is switched-off), although there is an increase of the area of the cell with no coverage to 19.44 %, 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 almost 40 %.

This paper shows that through the use of power saving by RSs at low traffic times, energy savings at relays (excluding BSs) of some 47.6 % can be achieved. Result operational saving 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

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