Fixed WiMAX Profit Maximisation with Energy Saving through Relay Sleep Modes and Cell Zooming

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***Abstract*— In Fixed WiMAX, the cost/revenue optimisation function for radio and network planning incorporates the cost of building and maintaining the infrastructure and the impact of the available resources on revenues. Supported throughput typically decreases with larger cells due to the implied greater average distance of users from the base station, although the use of subchannelisation can keep throughput steady with a larger cell radius. The use of sectored base stations facilitates selection of higher order modulation and coding schemes in the cell and can improve throughput; however, sectored equipment is more expensive. Fortuitously, using Relay Stations (RSs) can reduce the deployment cost of such systems. In such a context, if RSs are put into sleep mode during the night and at weekends when they are not necessary, important energy savings can be achieved. With relays, only the consideration of tri-sectored Base Station (BS) antennas with *K*=3 (at the cost of extra channels, where 9 channels corresponds to a bandwidth of 31.5MHz) obtains values of system throughput comparable to those without using relays. This is due to the more favourable frame format that is employed under the use of tri-sectored BS antennas.**

This paper shows that the application of cell zooming in conjunction with relays going into sleep mode at times of low load achieves a notable power saving, corresponding to 10% saving in operation and maintenance cost on average. Moreover, as it is assumed that the DL sub-frame format cannot be changed to a more favourable one, economic performance is better when RSs are deployed. It is however important to highlight that in the absence of RSs, economic performance is still reasonable (for tri-sectored and omnidirectional BSs, 700-800% and 400-450% profit, respectively), compared with the case where RSs are deployed (~1000% and ~900% profit, respectively).

***Index Terms*— Broadband communication, WiMAX, planning, economics, relays, green communications, cell zooming.**

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I. Introduction

To complement landline services, the demand for multimedia (MM) service delivery through broadband wireless access (BWA) is gaining momentum from both subscribers and service providers. This next step in wireless communications provides ubiquitous Internet and large bandwidth. In order to create conditions for an efficient technology, addressing interoperability and competition in this promising market, a standardization effort has been led by the Institute of Electrical and Electronic Engineers (IEEE). The first released standard was the IEEE 802.16, which addresses a wide range of frequencies, and defines the main principles for the series of the IEEE 802.16 fixed wireless and mobile standards published afterwards [1], [2]. The advanced air interface of IEEE 802.16m will enable multi-hop relay architectures, roaming and seamless connectivity across IMT-advanced and IMT-2000 systems through the use of appropriate interworking functions.

Worldwide interoperability for Microwave Access (WiMAX) is the commercial name for IEEE 802.16. WiMAX is a BWA technology capable of delivering voice, video, data and MM over the microwave RF spectrum to stationary or moving users.

In the optimization of cellular planning for fixed WiMAX, the use of Relay Stations (RSs) makes unnecessary a wire-line backhaul, improving significantly coverage whilst achieving competitive values for the system capacity (although slightly lower throughput is achieved). RSs have much lower hardware complexity and using them may significantly reduce the deployment cost of the system as well as its energy consumption: these reasons justify the need for optimization of fixed WiMAX networks with relays. The motivation to carry out this research work was to optimize the method to obtaining curves for carrier-to-noise-plus-interference, CNIR, vs. distance and the maximum supported throughput by considering different modulation and coding schemes (MCSs) for all possible frequency reuse patterns, e.g. *K*=1, 3 and 7. A modelling approach is followed by the computation of CNIR and supported throughput. By weighting the physical throughput achieved in each concentric cell coverage ring by the size of the ring, 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 throughput, through an inversion procedure.

A comparison of the different values of achieved throughput is performed between the RSs, Base Stations (BSs) and Subscriber Stations (SSs). In the presence of relays, the frames need to guarantee resources for BS-to-SS communications but also for BS-to-RS and RS-to-SS communications. As there usually is less traffic load in the UL direction, wireless MM communications are generally asymmetric. These requirements lead to a 1/5 asymmetry factor between the UL and DL in the omnidirectional and tri-sectored BS antennas. The main improvement of tri-sectored frame corresponds to increase the throughput in the central cell, by a factor of N_{sec}. This N_{sec} increase occurs both in DL and UL, due to the use of a more favourable frame format.

Nevertheless, as resources are still needed for the 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 difficulties, topologies with no relays would consequently still have a higher throughput performance.

An additional challenge has been to optimize the energy saving when RSs are switched-off during either the night period or the weekends [3], when the traffic load is low [4]. 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. 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 analysed under simple assumptions for the energy consumption of each element of the BSs and RSs.

Cost/Revenue optimization of the cellular planning was also a goal. Formulations have been proposed to take into account the interference in cellular coverage and reuse geometries, without and with the use of relays, in the Frequency Division Duplexing (FDD) mode. Optimisation of the cost/revenue trade-off provides a means of combining several contributing factors in cellular planning, including the determination of the reuse pattern, coverage distance, and the resulting supported throughput, following the vision proposed in [5]. This paper explores new methodologies to the optimization of the fixed WiMAX network planning, finding efficient ways to reduce interference between co-channel cells, redesigning the structure of the frames, and optimizing the system capacity and coverage.

The remaining of the paper is organized as follows. Section II addresses the impact of interference and MCSs into the planning process. The sub-frame structure is presented in Section III, which also highlights its relation and differences in comparison to the IEEE 802.16j one. Section IV presents aspects of the determination of the system capacity, including a brief description of the adopted formulation and results for the supported throughput. Green engineering aspects are discussed in Section V, where a solution coping with cell zooming is proposed, where the coverage zone from the central BS is zoomed out while the coverage zone from the RSs is zoomed in to zero. Section VI describes the cost/revenue model and discusses the optimisation results. A comparison is performed between the cases of absence and presence of cell zooming (with RSs switch-off during low traffic periods/empty hours). Finally, Section VII presents the conclusions.

II. Impact of Interference and MCSs

In Fixed WiMAX, the supported physical user throughput is a function of the supported MCS, which in turn depends on the achievable CNIR compared with the minimum CNIR, $CNIR_{min}$ for each MCS, as shown in Table I (where *Auxfactor(d)* allows for computing the supported throughput as a function of d and the maximum supported throughput in the cell $R_b(0)$).

TABLE I
Auxiliar factor for the contribution of the different MCS in the communication between the RS and SSs.

ID	*MCS*	$CNIR_{min}$ [dB]	*Physical thr.* [Mbps]	*AuxFactor*(*d*)
1	BPSK ½	3.3	1.41	1.41/5.64
2	BPSK ¼	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	-
7	64-QAM 2/3	19.8	11.29	-
8	64-QAM ¾	21.0	12.27	-

It is therefore important to analyse the evolution of the CNIR against choices of several system parameters as well as the chosen co-channel reuse factor. To guarantee Fixed WiMAX with no coverage gaps near cell edges, the CNIR must be higher than 3.3dB throughout the cell.

This value corresponds to the $CNIR_{min}$ in order to use BPSK½ MCS. As FDD is used, analytical modelling of coverage and frequency reuse problems can only be carried out in Fixed WiMAX [6]. The approach accounts for carrier-to-noise and carrier-to-interference constraints [7]. The situation presents the distance associated with coverage and interference for a 2D geometry with six interferers at the first tier, when the mobile user is at a distance d from its serving BS [6].

The modified Friis propagation model is assumed at 3.5 GHz and the values of different parameters are considered as P_t=-2dBW, γ=3, in urban areas (no shadowing), G_t=17dBi, and G_r=9dBi for BS to SS and SS to BS [8], and P_t=-2dBW, γ=3,

G_t=17dBi (for RS/SS communication), and G_r=28dBi for the RS (BS to RS and RS to BS). The difference between receiver gains for RS/BS communication and RS/SS (or BS/SS) communication is because, in the RS, we assume we may use a directional antenna, pointing directly towards the central BS; this antenna has a gain of ~28dBi [9].

The radio frequency bandwidth, noise figure, and frequency are b_{rf}=3.5 MHz, N_f=3 dB, and f=3.5 GHz [8], respectively. The worst-case interference scenario is considered, when the mobile unit is in the cell edge, where 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 subscriber station (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 co-cells. Note that, if D is the reuse distance, there are tiers of interference at distances D, 2D, etc. However, if a high value for the propagation decay exponent is set, it is a valid approximation to only consider the first tier of interference [8]. For the UL, the worst-case scenario occurs when the SS is transmitting to the BS from the cell edge, while interfering mobiles are on the boundary between interfering cells' edges and the serving cell of the SS. When a sectored BS antenna is considered the number of interfering cell is decreased, and system capacity increases. Details are given in [10], [11].

III. Sub-frame Structure and IEEE 802.16j

A comparison of the correspondence between the throughput and the CNIR is performed for the RSs, BSs and SSs. 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 (e.g., 120º sectored or narrower beamwidth ones), to reduce the received interference from BSs and facilitate non-overlapping coverage with the central zone of cell.

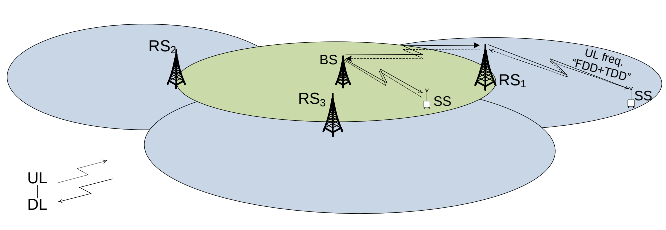

Fig. 1. BS, RS and respective "hexagonal" coverage areas.

While the BS backhaul is assured in the usual terms for mobile communications (e.g., cable or micro-wave radio link), RS backhauling is supported by using special specific sub-frames within the radius channel created for that purpose [12].

Our proposal on frames is inspired in the sub-frame structure from [13] and explores the inclusion of RS DL traffic/communications from RS to SS into the UL frequency sub-frame, differently from the proposal for IEEE 802.16j [14]. Another main difference between this proposal and IEEE 802.16j consists of only considering single-hop communications among the BS and RSs, while 802.16j allows for multihop communications [15].

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, as shown in Figure 1. Besides, the proposal for DL and UL frequency sub-frames from Figure 2 (omnidirectional BS antenna case) assumes an asymmetry factor of 1:5 between the UL and DL.

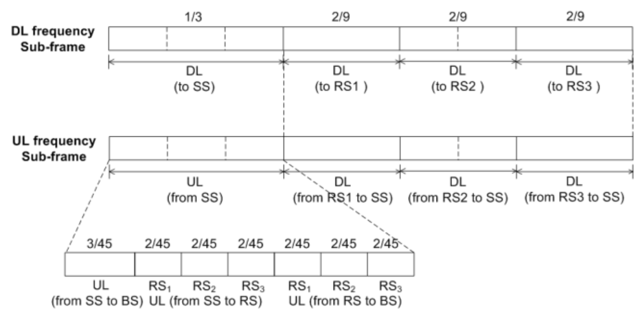

Fig. 2. Structure of DL and UL frequency sub-frames.

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. The advantage of using relays arises from the fact the co-channel interference now comes from cells at a larger distance [11], [16].

The duration of each sub-frame may be 5 ms; this information is given by 'Alvarion', the manufacturer of the communications equipment that has been used during this research [17], [18]. Note, however, that there may be some similarities between the sub-frame structure proposed in this work and the frame with transparent relaying in the 802.16j standard. With transparent relaying, the RSs do not forward framing information; hence do not increase the coverage area of the wireless access system; the main use of this mode is to facilitate capacity increases within the BS coverage area. 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 the RS in one frame, and the same data can be forwarded from the RS to the SS in the subsequent frame. For the cells with relays, the frame structure in the case of tri-sectored BS is different from the previous one, as proposed in [10], [11]. The main improvement of this tri-sectored frame 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.

IV. System Capacity

A. Formulation for the Physical and Supported Throughput

The formulation for the throughput is the one from [5], [16]. However, a formulation, proposed in [11], and adapted to topologies with RSs, is followed here. As presented in the previous Section, the frames need to guarantee enough resources for BS-to-SS communications but also for BS-to-RS and RS-to-SS communications. Worst-case situations between the BS-to-RS and RS-to-SS communications are considered. These formulations are based on the dependence of the physical throughput on CNIR for different MCSs and are proposed in [10], as well as the algorithm for the computation of the throughput (implemented in MATLAB).

Different topologies may be considered to calculate 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 cells. Results were presented in [10] for DL and UL geometries, using omnidirectional and tri-sectored BS antenna (applying also sub-channelization). From these CNIR experimental results, one may conclude that for the communication between BS and RS for the DL (RS-to-BS for UL) one obtains the highest values for CNIR, followed by the communication between BS and SS for DL (SS-to-BS for UL), and the communication between RS and SS for DL (SS-to-RS for UL). The higher the reuse pattern, *K*, is the higher CNIR is.

There is a correspondence between the values of CNIR and the physical throughput, $R_{b[Mb/s]}$. An example is presented in Figure 3 for a configuration with relays. The right hand side curves show the correspondence between the curves of CNIR and the throughput. The stepwise behaviour comes from the correspondence between CNIR, in dB, and the physical throughput for each MCS.

B. Results in the Absence and Presence of Relays

By considering the formulation for the supported throughput from [5], [16], the curves for the supported throughput versus distance may be obtained for different values of *K*. Results for the cell/sector supported throughput are shown in Figure 4 for *K*=3 and the absence of relays, and in Figure 5 for the case of the DL and presence of relays.

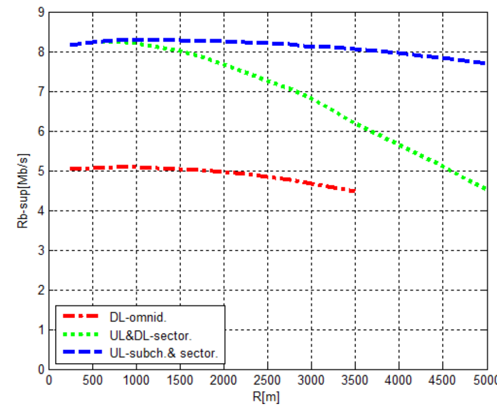

Fig. 4. Supported cell/sector throughput vs. for *K*=3 (no relays).

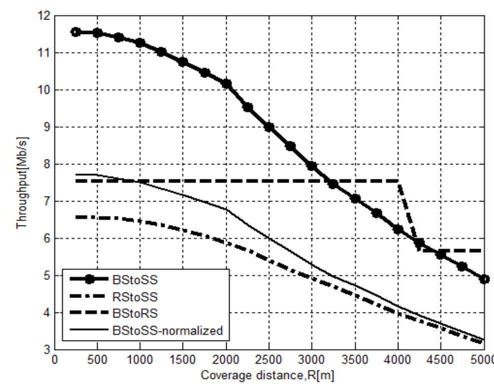

Fig. 5. Throughput as a function of the coverage distance with relays and sectored cells in the DL, *K*=3.

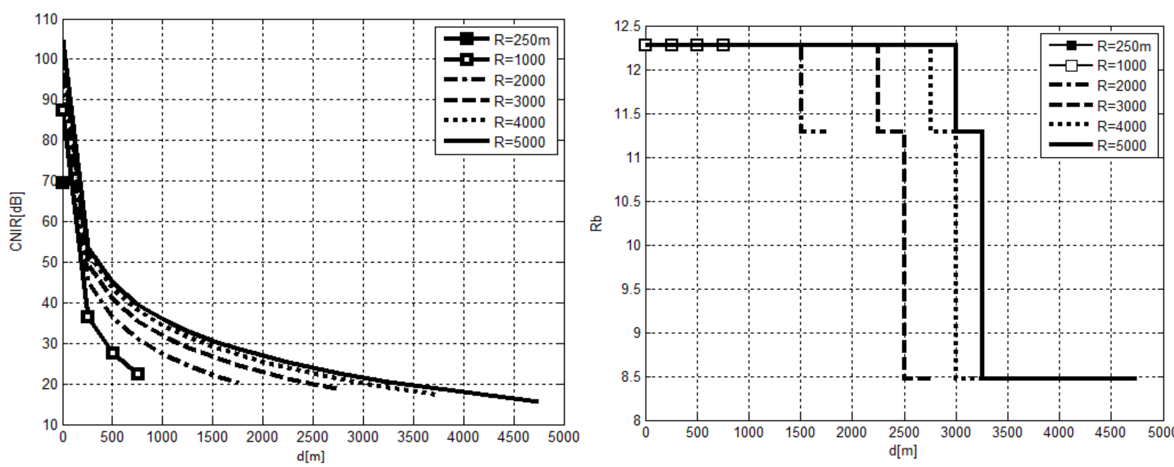

Fig. 3. Correspondence in UL between CNIR and throughput for tri-sectored BS antennas and subchannelisation for K=3.

For the former, different cellular configurations, with omnidirectional or tri-sectored BS antennas, are considered, and the use of subchannelisation may be considered in the UL.

Some of the curves with no subchannelisation are either impossible to obtain at all or after a given R because the physical throughput near the cell edge reaches 0 Mb/s, and full cell coverage may not be guaranteed. Achievable results for the supported throughput (with tri-sectored BS antennas and K=1) are of the order of 4.5 Mb/s, as shown in [5]. For the latter case (presence of relays), a tri-sectored BS antenna is considered and the case of the DL with K=3 is analysed in Figure 5. Owing to the availability of three times of the resources of the BS, we may conclude that using a tri-sectored BS antenna is clearly advantageous, compared with the omnidirectional case (where achievable values for the supported throughput are of the order of 2 Mb/s [10] against 6.5-7.5 Mb/s with tri-sectored cells). Although the curves are not presented here, for K=1, the supported throughput is of the order of 1.1 Mb/s for omnidirectional cells against 3.6 Mb/s with tri-sectored cells [10]. In the omnidirectional case, only if three transceivers are made available in the omnidirectional BS the results for the throughput become similar.

C. Equivalent Supported Throughput

With the proposed frame format presented, 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:

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

where $R_{b\text{-tot}}$ is the total throughput in the multihop cell (formed by the central zone plus RS zones). The use of sectored cells corresponds to an N_{sec} increase in both DL and UL traffic from/to the BS, due to the use of a more favourable frame format, as proposed in [10].

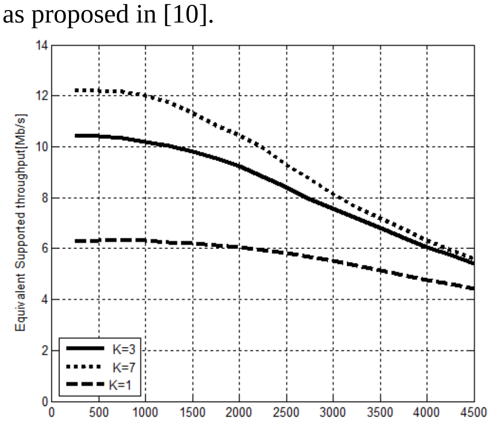

Fig. 6. Equivalent supported throughput fot tri-sectored cells in the DL with relays.

Curves shows the average throughput for K=1, 3 and 7. Figure 6 shows the equivalent supported throughput for the DL communication using tri-sectored BS antennas.

The equivalent supported throughput is used in Section 6 to calculate the costs, revenues and profits.

V. Cell Zooming with Relay Stations Switch-off

According to Niu et al. [3], when a BS/RS is working in the sleep mode, the air conditioning devices and other energy consuming equipment may be switched-off. BS/RS sleeping may significantly reduce the energy consumption of the WiMAX cellular network. In the solution we propose in this paper the three RS coverage zone working in the sleep mode zooms in to 0 while its central BS coverage zone zoom out to guarantee the coverage, as shown in Figure 7. The coverage radius for the zoomed out cell is given by $R_{z\text{-out}}=\sqrt{3}R'$, where R' is the radius for the BS/RS "hexagonal" coverage zones from the cell with relays.

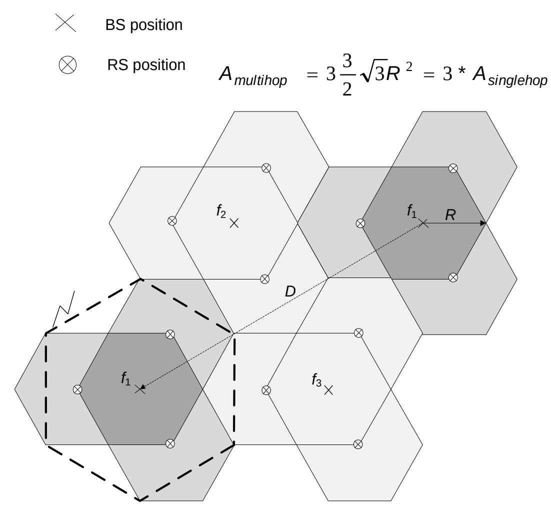

Fig. 7. When RSs go to the sleep mode the central coverage zone zooms out.

It is nevertheless worthwhile to note that, in comparison with this "zoomed out" central coverage zone, the topology with RSs enables us (i) to achieve a more regular coverage whilst guaranteeing almost regular physical layer throughput along wider zones of the cell (both central BS and RSs coverage zones) and (ii) to guarantee Line-of-Sight (LoS) coverage zones throughout the whole area, as shadowing is more efficiently avoided through the use of four stations (one BS and three RSs).

Results for the supported throughput are presented in Figure 8. When the RSs are switched-off, if the frame format needs to be kept there will be a partial loss of capacity (the part of the sub-frame dedicated to the communication with the 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 [11], yielding to an overall multiplying factor of 1. Note that, in Figure 8, there are different horizontal axis for the cells with relays (*R'* varies from 0 to 2886.8 m in this case) and for the ones with zoomed-out central coverage zone and no relays (*Rz*-out varies from 0 to 5000 m).

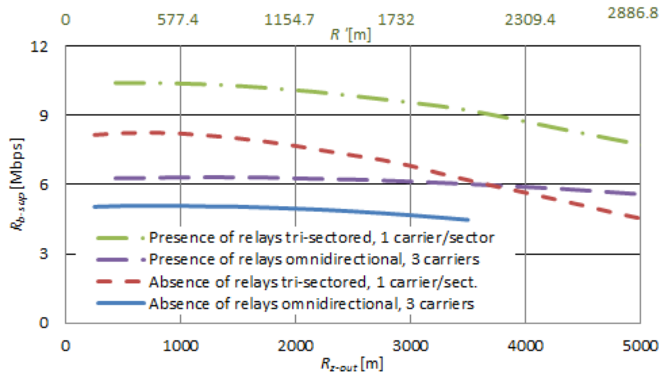

Fig. 8. Comparison of the equivalent supported throughput between the cells with relays and the zoomed-out cells (if the frame format is not adaptively adapted in the absence of relays) and the cells with relays.

Figure 9 presents the results for the throughput in the case the frame format can be adaptively adapted; hence, the factor 1/3 is not applied anymore in the absence of relays. Note however that, in [11, Section V.E.], the comparison between the tri-sectored BS for the topology with the presence and the absence of relays assumes one carrier per sector but erroneously fails to multiply the sector throughput by the number of sectors, N_{sec}, in the absence of relays. Hence, the economic performance in the tri-sectored case and absence of relays should be approximately three times higher than the erroneously represented in [11, Figure 18], instead the true behaviour in line with the one discussed in Section 6.A. This improvement leads to an advantage for the topologies with no relays that may possibly compensate the better (and more regular) coverage achieved in topologies with relays.

However, it is not reflected in the results for cell zooming from this paper yet, as we assume it is not possible, in practice, to adaptively change the frame format during the empty hours by now (as the mobile terminals that support communication with relays are not flexible enough to allow for sub-frame format changes).

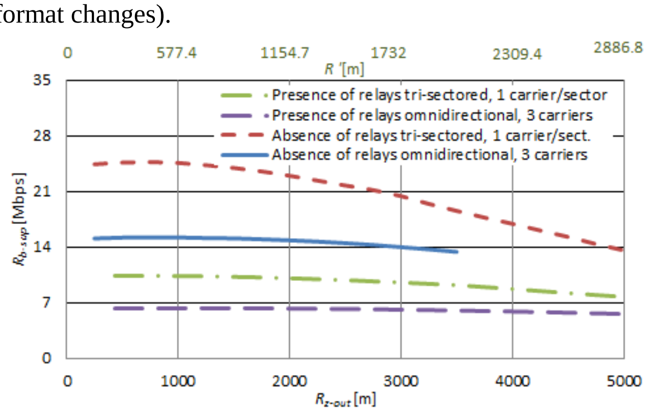

Fig. 9. Equivalent supported throughput for the cells with relays and the zoomed-out cells (if the frame format may be adaptively adapted in the absence of relays).

VI. Cost/Revenue Optimization

A. *Comparison between the Absence and Presence of Relay Stations*

The optimization of the cost/revenue trade-off 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 takes into account the cost of building and maintaining the fixed WiMAX infrastructure, and the way the number of channels available in each cell affects operators' and service providers' revenues. Fixed costs for licensing and spectrum bandwidth auctions should also be taken into account. The economic analysis is referred as a cost/revenue performance analysis. Although considers project duration of five years as a working hypothesis in radio and network planning, it is decided to analyze costs and revenues on an annual basis. The analysis is under the assumption of a null discount rate. By no means is it intended to perform a complete economic study in this paper, e.g., via the computation of the net present value; the aim is simply to present initial contributions that facilitate the incorporation of the main cellular planning optimisation aspects into the economic analysis. Appropriate refinements would be needed to perform a complete economic analysis based on discounted cash flows, e.g., to compute the net present value. Furthermore, the aim is to apply the optimization model from [10], [11] to facilitate WiMAX cellular planning. A similar investigation was followed in [19] for hierarchical WiMAX-WiFi networks but it is not followed here. Instead, the approach from [5] is followed here.

The cost per unit area is given by [8]:

$$C_{\left(€/km^2\right)} = C_{fi\left(€/km^2\right)} + C_b . N_{hex/km^2} \tag{2}$$

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. In the multi-hop case, with relays the number of hexagonal coverage zones per unit area is given by:

$$N_{hex/km^2} = \frac{2}{3.\sqrt{3}R'^2} \tag{3}$$

and the cost per BS is given by:

$$C_b = \frac{C_{BS} + C_{bh} + C_{ins}}{N_{year}} + C_{M\&O} \tag{4}$$

where N_{year} is the project's lifetime (assumed 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 [10].

In our formulation, as the supported throughput was obtained for an hexagon-shaped coverage zone (whose area is $\left(3\sqrt{3}/2\right)\cdot R'^2$), we maintain the formulation from [5] replacing cells by hexagon-shaped coverage zones, and $N_{hex/km^2}=N_{cell/km^2}\cdot 3$. Note that the three RS coverage zones exactly correspond to an area of two hexagons. Besides, note that the value for C_{BS} is such that the cost of the BS and the RSs (1/5 of the cost of the BS) are averaged in a way it enables to obtain the value for the cost of an "equivalent BS" for each of the three coverage zones, i.e., $C_{BS\text{-}equiv.}=(C_{BS}+3\cdot C_{RS})/3$. As only the central BS needs a fixed backhaul, C_{bh} is one third of the value for a normal BS. Besides, as one needs to install one BS and three RSs, the installation cost (for this "equivalent BS") is 4/3 the cost of a normal BS. It is assumed that the operation and maintenance (M&O) costs of the RSs are half the value of the ones for the BS, such that $C_{M\&O\text{-}equiv.BS}=(C_{M\&O\text{-}BS}+3/2\cdot C_{M\&O\text{-}BS})/3$.

The revenue in a hexagonal-shaped coverage zone per year, $(R_v)_{cov\_zone}$, can be obtained as a function of the equivalent supported throughput per coverage zone, $R_{b\text{-}sup[kbps]}$, and the revenue of a channel with a data rate $R_{b[kbps]}$, $R_{b[€/min]}$, by:

$$(R_v)_{cov\_zone} = \frac{N_{hex/km^2} R_{(b-\sup)_{equiv}} . T_{bh} . R_{R_b}[€/MB]}{R_{b-ch}[kbps]} \qquad (5)$$

where $R_{(b\text{-}sup)equiv}$ is fixed by the equation (4.1). 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-sectored case, one assumes that each sector has one different transceiver. Furthermore, there is a separate frequency channel available for each sector.

The revenue per unit length or area per year, $R_{v[€/km^2]}$, is obtained by multiplying the revenue per cell by the number of cells per unit length or area. The profit, in absolute and percentage terms, was defined according to [5].

According to the assumptions with relays from [10], [11], the cost parameters from Table II were considered for K=1. The value of the fixed cost is "per carrier". For different values of K, the fixed cost, C_{fi}, increases proportionally to K while the values for the other parameters keep being the same [10]. For example, for K=3, it becomes $C_{fi}=3\cdot 3\cdot 15.63=140.68$ €/km^2 (with three carriers) in the omnidirectional case, and $C_{fi} = 3\cdot 47.14=140.68$ €/km^2 in the tri-sectored case.

TABLE II
COSTS WITH RELAYS WITH DIFFERENT ANTENNAS AND K=1 (ONE CARRIER PER CELL/SECTOR); FOR DIFFERENT VALUES OF K AND DIFFERENT NUMBER OF CARRIERS THE VALUE OF C_{FI} NEEDS TO BE CHANGED ACCORDINGLY WHILE THE VALUES FOR THE OTHER PARAMETERS REMAINS THE SAME.

Costs	*Omnidirectional*	*Tri-sectored*
C_{fi} [€/km2]	15.63	47.14
C_{BS} [€]	7680	6800
C_{Inst} [€]	1333.33	2000
C_{bh} [€]	833.33	833.33
$C_{M\&O}$ [€/year]	833.33	833.33

As a bandwidth of 31.5 MHz may be available for an operator, it is worthwhile to compare the case of tri-sectored cells (or central coverage zones, if the topology is with relays) and K=3, with the case K=3 with omnidirectional BS antenna getting three carriers, and the situation without RSs in both tri-sectored an omnidirectional antenna cases from [5]. In this situation, as in the K=1 situation, the number of carriers and the supported throughput are multiplied by three.

It should be noted that, with sectored cells, the cost of the frequency carriers licence (C_{fi}) with K=3 is three times the cost for the licence with omnidirectional BS antenna and K=3, as $K\cdot N_{sec}$=9 carriers need to be available. Besides, when more than one frequency carrier is considered per cell, extra channel equipment (transceivers) needs to be added to the BS (or RS) rack [20]. We assume a 60% increase on the cost of BS and RS equipment if tri-sectored antennas and RF equipment (including the outdoor units, ODUs) are considered. This means we assume that the channel equipment costs are 30% of the BS (or RS); hence, with tri-sectored equipment, two times 30% needs to be added to the cost. For K=3, with 3 frequency carriers and omnidirectional BS antennas, although C_{BS}, C_{inst}, C_{bh} and $C_{M\&O}$ keep being the same, as one considers $C_{BS\text{-}omni}$=14400€ and C_{RS}=2880€ then one obtains $C_{BS\text{-}equivalent}$=7680€. For the tri-sectored case, one considers $C_{BS\text{-}tri}$=15000€ and C_{RS}=1800€ (one assumes the RS is cheaper because it is simpler), yielding $C_{BS\text{-}equivalent}$ =6800€.

In Figure 10 we represent the coverage distances for the coverage zones with RSs by R' while $R=\sqrt{3}R'$ is the coverage distance for a cell with no RS whose area is the same (compared with the area of the cell with a central coverage zone plus three RS coverage zones). With no RSs and tri-sectored central coverage zone (sect.&no RSs) the economic performance would be weak (see Figure 10, example for R_b=0.005€/MB) if only one carrier may be used (as erroneously presented in Section V.E from [11]).

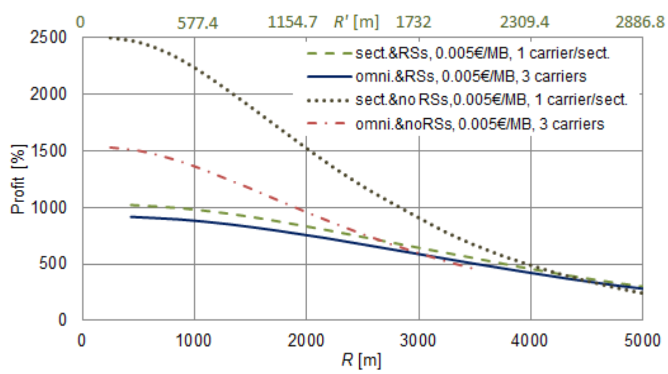

Fig.10. Comparison of the economic performance between omnidirectional (3 carriers) and tri-sectored (one carrier/sector) BSs in the presence and absence of relays under the same total BW for price R144= 0.005 €/MB, in the DL and K=3.

In this paper, owing to the proper accounting of the contribution from the three sectors (see results for the supported throughput in Figure 9), the profit in percentage with tri-sectored BS and no RSs achieves values ~2000-2500% for R up to 1400 m, an important change compared with [11, Figure 18]. With omnidirectional BS antenna, the profit in percentage is ~1400-1500% up to 1400 m. With tri-sectored BS and RSs the profit is also higher than the one obtained for the omnidirectional case (~ 900-1000% for R' up to 800m). Note that the costs of the BS and the three RSs are accounted for all together.

With omnidirectional BSs and no RSs (omni.&no RSs), under the same total bandwidth, three carriers may be used and the profit in percentage varies between ~1500 and 1200% for coverage distances (*R*) lower than 1400m, Figure 10. With RSs and omnidirectional antennas in the BS, profits of the order of 800-900% are achievable for *R'* up to 1000m [11].

B. Economic and Environmental Impact of Cell Zooming

We assume the values from Table III for the power of the BS and RS equipment, whose reference values are partially extracted from [21]. The values for the power consumption of the BS were chosen based on the powers for the Alvarion BS equipment while the values for the power consumption of the RS equipment refer to the powers of the micro-BS Alvarion equipment (the comparison is done because, as the RS, it can also be connected to two ODUs). Each BS sector has a different ODU, whose power consumption is 40W each. The RSs will have an ODU for the communication with the RS and a different one for the communication with the SSs (40+40=80W total).

TABLE III
POWER CONSUMPTION PARAMETERS FOR THE BSS AND RSS

Station	BS		*RS*
	Tri-sectored	*Omni.*	
Power for the full chassis [W]	420		80
Number of sectors	3	1	-
Power of the outdoor unit(s) [W]	120	40	80
Total power of the BS/RS	540	460	160
Power consumption for the router/switch [W]	100		-
Power consumption for the ventilator [W]	40		20
Total power consumption for the stations [W]	680	600	180
Annual energy consumption [kW•h]	6000	5250	1750

The power consumption for the fan of the cooler ventilation system is assumed to be 40 W for the BS equipment and 20W for the RS equipment. Besides, we assume the power consumption for the switch/router at the BS is 100W (and there is no such switch/router at the RS shelter). As a consequence, the total power consumption values for the stations are the following ones: $P_{\text{BS-tri}}$=540+100+40=680 W, $P_{\text{BS-omni}}$=460+100+40=600W and P_{RS}=160+20=180W. From this analysis, one may conclude that, by itself, the use of RSs instead of full functionality BSs 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 zero 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 600W, for tri-sectored and omnidirectional BSs, respectively). In the full functionality cell with RSs the total power is 680+3·180=1220W or 600+3·180=1140W, respectively. This is approximately twice the power of the zoomed out cell. The 540W reduction on the power corresponds to a given reduction in operations costs, proportional to the time period the RSs remain switched-off.

During the whole year, the total energy waste in RSs is 24·365·540=4730.4kW·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 while weekend (48 hours) then the total period when the energy is saved is 5·8+2·24=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 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).

As 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 Figure 11 (example for R_b=0.005€/MB). 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).

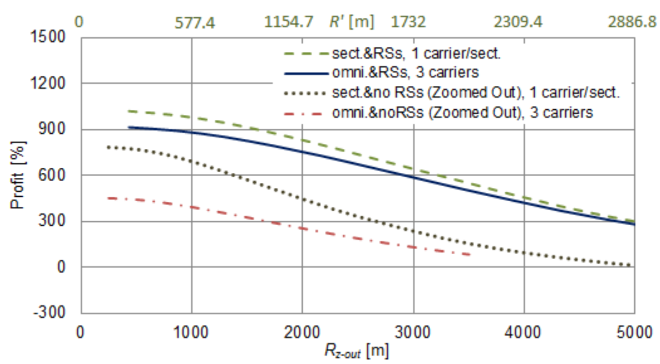

Fig.11. Comparison of the economic performance between omnidirectional (3 carriers) and tri-sectored (one carrier/sector) BSs in the presence of relays and with the central BS coverage zone zoomed out (while RSs coverage zoom in to zero) under the same total BW for price R144= 0.005 €/MB, in the DL and K=3.

As the throughput decreases with no RSs (see results in Figure 8) the economic performance is lower. However, it is important to highlight that in the absence of RSs, in the case of the zoomed out central BS coverage zone (with these RSs in the sleeping mode and its cooling system switched-off) the economic performance is reasonable (700-800% and 400-450% profit up to *R*=1km with tri-sectored and omnidirectional BSs, respectively) compared with the case of the full cell functionality (~1000% and ~900% profit, respectively). Besides, the switch-off of the RSs as the clear advantage of the power saving, and yields an important economic impact.

If adaptive radio is possible in WiMAX and the frame format can be changed when RSs are switched-off, the economic performance will be closer to the one presented in Figure 10 (although the reduction in the maintenance and operation cost arising from it were not fully incorporated in the analysis in this Figure).

Further work is needed to analyze the trade-offs between the clear economic advantage (as well as the advantage in the supported throughput) and the resulting loss in the coverage. With only one central BS the “illumination” throughout the zoomed out cell may not be as complete as the one with one from the central BS plus three RSs. From this point of view, omnidirectional cells should be avoided as they will only support the lowest order MCS near the cell edge (both in topologies with the presence and absence of RSs). The use of tri-sectored antennas is therefore preferable. For example, with tri-sectored BS antennas, the lowest order MCS is:

- QPSK½ (*ID*=3 and $(C/N)_{min}$=5.5 dB) with no RS ($R_{z\text{-}out}=\sqrt{3}\cdot 1750$=3031 m);
- QPSK¾ (*ID*=4 and $(C/N)_{min}$=8.9 dB) with RSs (for *R'*=1750 m).

As $(C/N)_{min}$=3.3 dB for the lowest order MCS in Fixed WiMAX (BPSK 1/2), in the absence of relays, there is a difference of only 2.2dB between the actual threshold for the MCS at the cell edge and the threshold enabling a non-null throughput (against a difference of 5.6 dB with relays). These difficulties need to be properly addressed in the future.

VII. Conclusion

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 optimisation have been discussed.

For a given coverage area, throughput is a stepwise function that decreases as distance from the base station increases. Its value depends on the supported MCS for each coverage ring. In this paper, the supported throughput has been computed for cellular WiMAX topologies, with deployed relays, by weighting the available throughput at each coverage ring with the area (or size) of the coverage area ring. Throughput typically decreases as the cell radius increases, although through the use of subchannelisation it is possible to keep its value steady at least up to a cell radius of 5000m. With the use of sectored cells, the supported throughput is higher, corresponding to the selection of the highest order MCSs. However, as tri-sectored equipment is more expensive and there is a need for three times more bandwidth to be provided to the BS in this case, costs are also higher.

Cellular deployment with relays can be cheaper than using BS alone. Because the use of relays (and a structure was proposed for the sub-frames to guarantee resources for BS-to-SS communication as well as BS-to-RS and RS-to-SS communication) to help on improving coverage while mitigating interference, may lead to lower costs, it is worthwhile to analyse the impact of using them on costs and revenues. WiMAX cost-benefit optimization has been explored in this paper for the case where relays are used. Although the reuse distance is augmented by a factor of $\sqrt{3}$, it was first shown that, with omnidirectional BSs, the use of relays corresponds to lower values of the supported throughput for *K*=3. It was also verified that the presence of subchannelization in the UL only improves the results for the highest values of *R*. Only the consideration of tri-sectored BS antennas with *K*=3 (at the cost of extra channels, where 9 channels corresponds to a bandwidth of 31.5MHz) obtains values of system throughput comparable (although lower) to the those without using relays. This is due to the more favourable frame format that is employed under the use of tri-sectored BS antennas.

With no RSs and omnidirectional BSs (“omni.&no RSs”) with *K*=3, under the same total bandwidth, three carriers may be used. The profit in percentage terms varies between ~400 and 300% for coverage distances lower than 1400m (one assume a price per MB of 0.005€/MB). However, with tri-sectored BSs (“sect.&noRSs”), as the throughput is multiplied by N_{sec}=3, it achieves values of ~2000-2500% for *R* up to 1400 m. With RSs, the use of tri-sectored BSs (sect.&RSs) is not advantageous relatively to the “no RS” case, as the profit decreases down to ~900-1000% (for *R* up to 1000m).

To save energy during empty traffic periods, cell zooming may be applied in conjunction with relays going into sleep mode at times of low load. As 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 better with RSs. With no RSs, as the throughput decreases, the economic performance is lower. However, it is important to highlight that, if RSs go into sleep mode (and their cooling system is switched-off), the economic performance of the zoomed out cell is still reasonable (for tri-sectored and omnidirectional BSs, 700-800% and 400-450%, respectively, profit up to *R*=1 km) compared with the case where RSs are deployed (~1000% and ~900% profit, respectively).

If adaptive radio is possible in WiMAX and the frame format can be changed when RSs are switched-off, the economic performance will be superior. However, the resulting loss in the coverage with no relays has not been properly addressed yet. With only one central BS the “illumination” throughout the zoomed out cell may not be as complete as the one with one from the central BS plus three RSs.

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