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BASIC LIMITS FOR SYSTEM CAPACITY AND COST/REVENUE OPTIMISATION: A FORMULATION FOR FIXED WIMAX

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ABSTRACT

In Fixed WiMAX, the cost/revenue radio and network planning optimisation function incorporates the cost of building and maintaining the infrastructure and the effect 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 it steady up to a larger cell radius. Sectorization facilitates the use higher order modulation and coding schemes in the cell and may improve the throughput; however, sectorization equipment is more expensive, and there is the need for three times more spectrum bandwidth, increasing costs. In turn, the use of Relay Stations (RSs) may significantly reduce the deployment cost of the system. 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 31.5 MHz) enables to obtain values of throughput comparable to the ones without using relays. This is due to the more favourable frame format. With no RSs and sectorization with K=3 the economic performance is weak, as only one carrier may be used. However, with omnidirectional BSs with K=3, under the same total bandwidth, three carriers may be used and the profit in percentage varies between ~900 and 800% for coverage distances lower than 1000 m. With RSs, the use of tri-sectored BSs corresponds to a clear advantage relatively to the "no RS" case up to R~1300 m. When the price per MB, R_{144}, increases from 0.0025 to 0.005 €/MB the profit in percentage increases more than 100%.

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 and also system capacity. RSs have much lower hardware complexity and using them may significantly reduce the deployment cost of the system: 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.

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 [3]. 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. Section V describes the cost/revenue model and discusses the optimisation results. Finally, Section VI 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 1. 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 3.3 dB throughout the cell. This value corresponds to the $CNIR_{min}$ in order to use BPSK ½ MCS.

As FDD is used, analytical modelling of coverage and frequency reuse problems can only be carried out in Fixed WiMAX [4]. The approach accounts for carrier-to-noise and carrier-to-interference constraints [5]. 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 [4].

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=17 dBi, and G_r=9dBi for BS to SS and SS to BS [6], and P_t=-2dBW, γ=3, G_t=17 dBi (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 ~28dBi [7]. The radio frequency bandwidth, noise figure, and frequency are b_{rf}=3.5 MHz, NF=3dB, and f=3.5 GHz [SVCR09], respectively.

Table 1: 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	1
7	64-QAM 2/3	19.8	11.29	1
8	64-QAM ¾	21.0	12.27	1

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 [6]. 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 sectorized BS antenna is considered the number of interfering cell is decreased, and system capacity increases. Details are given in [8], [9].

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 sectorial (120º sectors) RS antennas for communication with BS are considered to be directional (e.g., 120º sectorial or narrower beamwidth ones), to reduce the received interference from BSs and facilitate non-overlapping coverage with the central zone of cell.

While the 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 [10].

Our proposal on frames is inspired in the sub-frame structure from [11] 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 [12]. Another main difference between this proposal and IEEE 802.16j consists of only considering single-hop communications among the BS and SSs, while 802.16j allows for multihop communications [13].

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. 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 [9], [14].

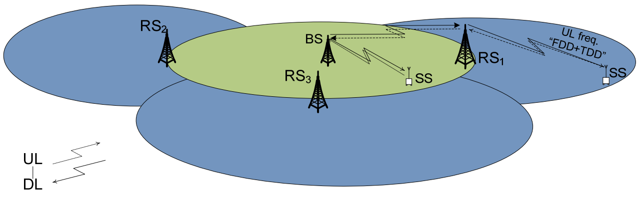

Figure 1: BS, RS and respective “hexagonal” coverage areas.

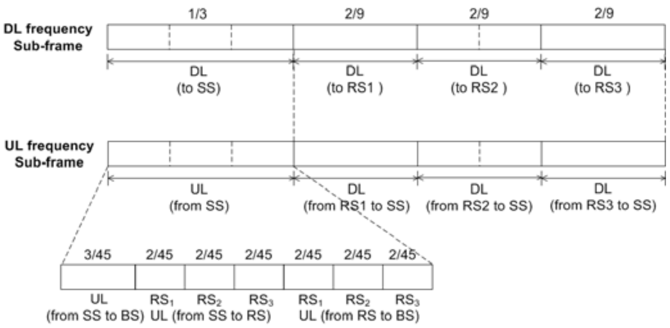

Figure 2: Structure of DL and UL frequency sub-frames.

The duration of each sub-frame may be 5 ms; this information is given by ‘Alvarion’, the manufacturer of the material that has been used during this research [15], [16]. 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.

The main improvement of 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 proposed in [8], [9]. 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 formulations one uses for the throughput are the ones from [3], [14]. However, a formulation, proposed in [9], 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 [8], 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 [8] 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, $R_{b[\mathrm{Mb/s}]}$. 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 $CNIR_{min}$, in dB, and the physical throughput for each MCS.

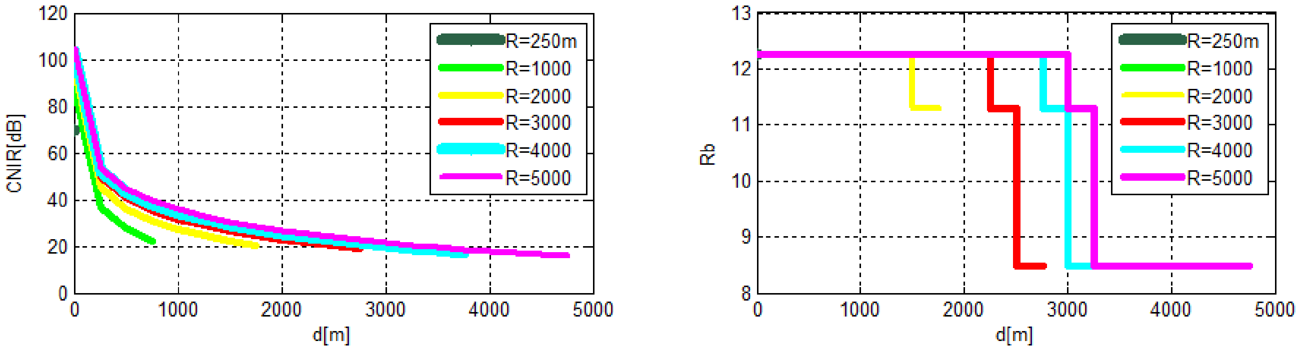

Figure 3: Correspondence in UL between CNIR and throughput tri-sectored BS antennas and subchannelisation for K=3.

B. *Results in the Absence and Presence of Relays*

By considering the formulation for the supported throughput from [3], [14], 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 absence of relays, and in Figure 5 for the case of the presence of relays.

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 on the outer coverage ring of the cell 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 [3]. For the latter case (presence of relays), a tri-sectored BS antenna is considered and the case of the DL with *K*=3 is analyzed. 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 [8] against 6.5 Mb/s with tri-sectored cells). Although he 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 [8].

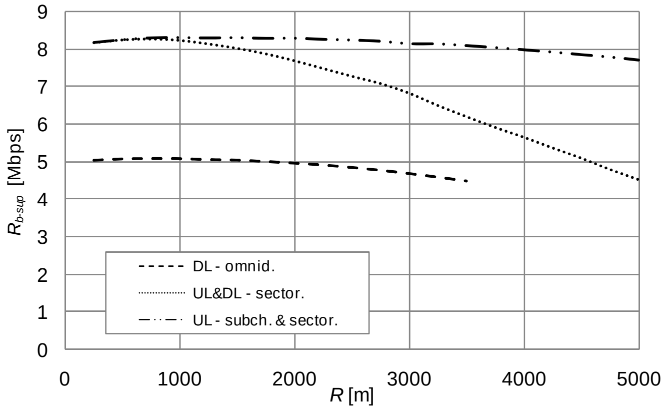

Figure 4: Supported throughput vs. *R* for *K*=3 (no relays).

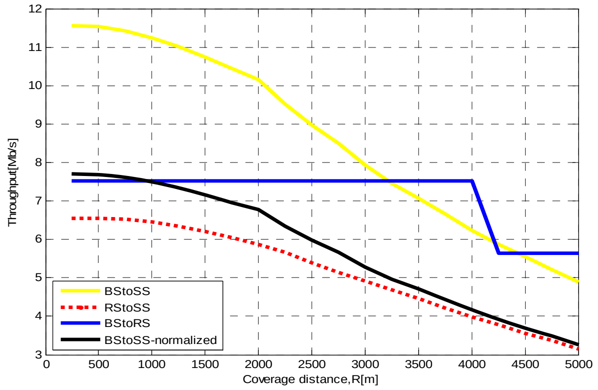

Figure 5: Throughput with relays and sectorization, *K*=3 / DL.

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 with an area of $\left(3\sqrt{3}/2\right)\cdot R^2$ is therefore given by:

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

where $R_{b\text{-}tot}$ is the total throughput in the multihop cell (formed by the central zone plus RS zones). The use of sectorization 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 [8]. 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.

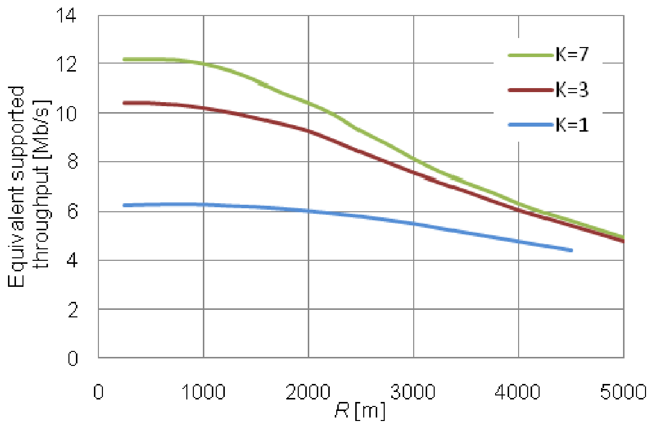

Figure 6: Equivalent supported throughput for tri-sectored cells in the DL with relays.

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

V. COST/REVENUE OPTIMIZATION

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 [8], [9] to facilitate WiMAX cellular planning. A similar investigation was followed in [17] for hierarchical WiMAX-WiFi networks. However here, the approach from [3] is followed.

The cost per unit area is given by [6]:

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

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 [6].

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 [3] 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.

The revenue in a hexagonal-shaped coverage zone per year, $(R_v)_{\text{cov\_zone}}$, 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:

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

where $R_{(b\text{-}sup)equiv}$ is fixed by the equation (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, 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 [3].

According to the assumptions with relays from [8], [9], the cost parameters from Table 2 were considered for K=1. For a different K, the fixed cost increases proportionally to K while the other parameters keep being the same [8].

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 [3]. 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 sectorization, the cost of the frequency carriers licence 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 [18]. We assume a 60% increase on the cost of BS and RS equipment if tri-sectored antennas and RF equipment (including the outdoor units) 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 $C_{BS\text{-}omni}$=14400€ and C_{RS}=2880€ then $C_{BS\text{-}equivalent}$ =7680€.

With no RSs and sectorization (sect.&no RSs) the economic performance is weak (see Figure 7), as only one carrier may be used. However, with omnidirectional BSs (omni.&no RSs), under the same total bandwidth, three carriers may be used and the profit in percentage varies between ~900 and 800% for coverage distances lower than 1000 m, Figure 7.

Table 2: Costs with relays with different antennas and K=1.

Costs	Omnidirect.	Tri-sectored
C_{fi}[€/km^2]	15.63	47.14
C_{BS}[€]	4800	6800
C_{Inst}[€]	1333.33	2000
C_{bh}[€]	833.33	833.33
$C_{M\&O}$[€/year]	833.33	833.33

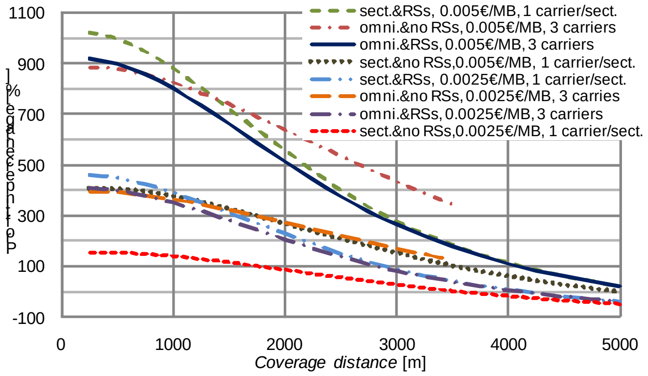

Figure 7: Comparison between omnidirect. (3 carriers) and tri-sectored (one carrier/sector) BSs under the same total BW for prices R_{144}=0.0025 and 0.005 €/MB, in the DL and K=3.

With RSs, with omnidirectional antennas higher profits are only achievable for *R*s up to ~700m [9]. However, with tri-sectored BS and RSs ("sect.&RSs") there is a clearly advantage up to *R*~1300 m. This is very clear in Figure 7 (mainly in the example for R_b=0.005€/MB).

VI. CONCLUSIONS

Frequency reuse topologies have been explored for 2D broadband wireless access geometries in the absence and presence of relays, and the basic limits for system capacity and cost/revenue optimisation have been obtained.

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 sub-channelization it is possible to keep its value steady at least up to a cell radius of 5000 m. With the use of sectorization, the supported throughput is higher, corresponding to the use of the highest order MCSs. However, as tri-sectorized 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.

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 31.5 MHz) enables to obtain values of throughput comparable to the ones without using relays. This is due to the more favourable frame format.

With no RSs and sectorization (sect.&no RSs) with *K*=3 the economic performance is weak, as only one carrier may be used. However, with omnidirectional BSs ("omni.&no RSs") with *K*=3, under the same total bandwidth, three carriers may be used and the profit in percentage varies between ~900 and 800% for coverage distances lower than 1000 m. With RSs, the use of tri-sectored BSs (sect.&RSs) corresponds to a clear advantage relatively to the "no RS" case up to *R*~1300 m. When the price per MB, R_{144}, increases from 0.0025 to 0.005 €/MB the profit in percentage is twice.

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