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Basic limits for fixed worldwide interoperability for microwave access optimisation based in economic aspects

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Abstract: In fixed worldwide interoperability for microwave access (WiMAX), radio and network planning can be optimised by tuning a cost/revenue function which 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 because of the implied greater average distance of users from the base station, although the use of sub-channelisation can keep throughput steady up to a larger radius. Sectorisation can improve the throughput of the cell by facilitating the use of higher order modulation and coding schemes; besides, sectorisation equipment is more expensive, and there is the need for three times more spectrum bandwidth, increasing costs while increasing system capacity by a factor of 3. On a multi-cell level, system capacity is determined by the chosen frequency reuse pattern, K. In this study, under the assumption of a revenue per Mbyte of information transfer somewhere between 0.0025 € and 0.010 €, the choice of $K = 3$ or 4 with sectorial cells is preferable to the use of omnidirectional cells with $K = 7$. This study also concludes that a cell radius in the range 1000–1500 m is preferable, corresponding to profit in percentage terms of near the achievable maximum, while keeping costs acceptable.

1 Introduction

To complement landline services, multimedia service delivery through broadband wireless access (BWA) is gaining interest from both subscribers and service providers points of view. To this end, worldwide interoperability for microwave access (WiMAX) is the topic of this study. WiMAX is a BWA technology capable of delivering voice, video, data and multimedia over the microwave radio frequency (RF) spectrum to stationary or moving users. It is the commercial name for IEEE 802.16, which incorporates two versions: fixed and mobile WiMAX [1–3].

Fixed WiMAX is standardised in IEEE 802.16-2004 (or IEEE 802.16d), and is optimised for fixed and nomadic application, designed to serve as a wireless digital subscriber line replacement technology for voice and broadband access. Fixed WiMAX is also a viable solution for wireless backhaul for wireless fidelity (WiFi) access points, and potentially as well for cellular networks. Mobile WiMAX is standardised in IEEE 802.16e, and primarily aims at portable and mobile applications, although it can also provide fixed and nomadic access.

In the context of WiMAX planning, research on the variation of the carrier-to-noise-plus-interference ratio (CNIR), against different system parameters, is of fundamental importance. As there are challenges in both the uplink (UL) and downlink (DL) in WiMAX, techniques such as sub-channelisation may be applied to reduce the impact of noise on link performance. However, only mobile WiMAX allows for sub-channelisation in both the UL and DL; fixed WiMAX only allows for it in the UL – this absence of sub-channelisation in the DL for fixed WiMAX may be a cause of performance degradation (mainly owing to the extra noise caused by the larger spectrum bandwidth). For cellular planning purposes, the UL and DL

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CNIRs from/at the wireless subscriber station (SS) are very significant parameters. From a detailed analysis of CNIR variation for different coverage and reuse distances, an evaluation of the achievable reuse patterns can be performed for different modulation and coding schemes (MCSs). In order to more effectively use radio frequency spectrum, it is important to choose a frequency reuse scheme that leads to coverage guarantee and improved system capacity, while minimising interference.

WiMAX deployment optimisation can be achieved by appropriately parameterising a merit function, taking costs and revenues into account. The optimisation of the cost/revenue tradeoff provides a means of combining several contributing factors in cellular planning: determination of the reuse pattern, coverage distance and the resulting supported physical throughput.

Given the current state of national frequency spectrum assignments throughout Europe, the fixed WiMAX achievable frequency reuse pattern, K, determines the reduction in the initial fixed cost if the required spectrum bandwidth is reduced to values comparable to the ones for wideband code division multiple access systems. In turn, the supported throughput will determine the achievable revenue, which has interdependencies with the use (or not) of sub-channelisation and/or sectorisation. The optimisation of the cost/revenue tradeoff for different topologies is thus of fundamental importance, and can be achieved by varying system parameters and implied coverage and reuse distances.

A cost/revenue function has to be developed by taking into account the cost of building and maintaining the 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 (often known as 'beauty contests') should also be taken into account. Although a project duration of 5 years is assumed, it is decided in this paper to analyse costs and revenues on an annual basis. Furthermore, our 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, the aim is simply to present initial contributions that facilitate cellular planning optimisation. Appropriate refinements would be needed to perform a complete economic analysis based on discounted cash flows (e.g. to compute the net present value).

The main contributions from this work are two-fold:

- By weighting the physical throughput in each concentric cell coverage ring by its size, 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 the correspondence between minimum values at the CNIR curves (for a given MCS) and the supported physical throughput through an inversion procedure (via the consideration of each MCS stepwise threshold);
- By considering these fundamental limits for the supported throughput, the cost of building and maintaining the fixed WiMAX infrastructure, and the way the capacity affects the system revenues, a function for cost–benefit optimisation is used to find the range of coverage distances and reuse patterns that maximise the 'profit' in percentage terms. A similar approach was used in [4] for hierarchical WiMAX–WiFi networks, where the design trade-offs between maximising the service provider profit and satisfying the end-user performance requirements was addressed.

The remaining of this paper is organised as follows. Section 2 discusses the geometries of interference in the UL and DL, investigates the variation of the CNIR for different co-channel reuse factors and coverage distances, and analyses variations in the supported physical throughput versus distance to the base station (BS). In Section 3, based in a model for cost/revenue optimisation, numerical results for the assessment of cost, profit per unit area and percentage profit are presented as a function of the coverage distance. The advantages of choosing certain ranges for the coverage distance are discussed for omnidirectional and tri-sectorial layouts with different reuse patterns. Finally, conclusions are given in Section 4.

2 CNIR against physical throughput

2.1 Effect of sectorisation and sub-channelisation

In order to achieve efficient spectrum use, the selection of an appropriate frequency reuse scheme is of fundamental importance. This chosen frequency reuse scheme must guarantee coverage and improved system capacity, while minimising interference. 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 (see Table 1). It is therefore important to analyse the

Table 1 Correspondence between MCSs, $CNIR_{min}$ for each MCS, and the physical throughput

ID	MCS	$CNIR_{min}$, dB	Physical throughput, Mb/s
1	BPSK 1/2	3.3	1.41
2	BPSK 3/4	5.5	2.12
3	QPSK 1/2	6.5	2.82
4	QPSK 3/4	8.9	4.23
5	16-QAM 1/2	12.2	5.64
6	16-QAM 3/4	15.0	8.47
7	64-QAM 2/3	19.8	11.29
8	64-QAM 3/4	21.0	12.27

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evolution of the CNIR against choices of several system parameters as well as the chosen co-channel reuse factor.

If frequency division duplexing (FDD) is used, analytical modelling of coverage and frequency reuse problems can only be carried out in fixed WiMAX. Our chosen approach simultaneously accounts for carrier-to-noise and carrier-to-interference constraints [5, 6].

Fig. 1 presents the distance associated with coverage and interference for a 2D geometry with six interferers, when the mobile user is at a distance d from its serving BS. The worst-case scenario in the DL occurs when the BS of the serving cell transmits to the most distant possible location of 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. If d is replaced by R, the cell coverage distance or radius ($0 \leq d \leq R$), this worst case is as depicted in Fig. 1. Note that if D is the reuse distance, there are tiers of interference at distances D, $2D$ and so on. 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, as shown in Fig. 1.

In 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 [7]. When sectorisation is considered, the number of interfering cells is decreased and system capacity increases. Such coverage

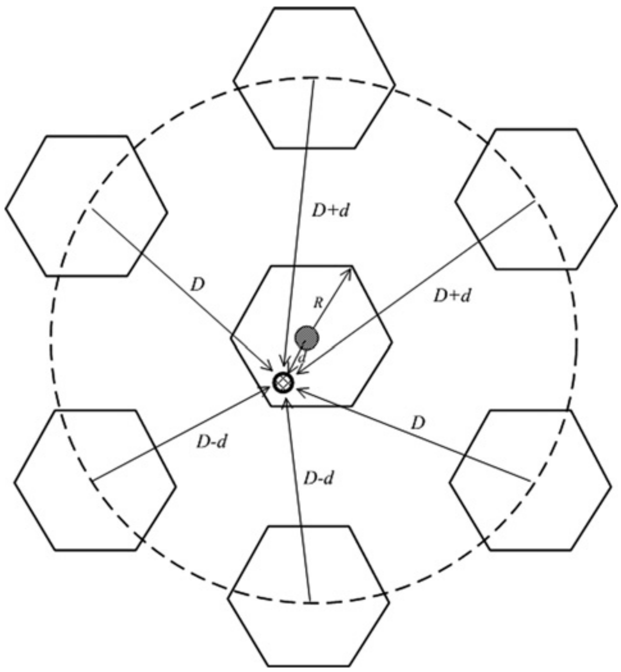

Figure 1 *Co-channel interference for the DL where the SS is at a distance d ($0 \leq d \leq R$) from the centre of the cell (D is the reuse distance)*

The worst-case occurs when $d = R$

and reuse geometries are commonly found in rural and suburban environments. In urban areas, owing to the obstruction of buildings and other urban obstacles, perfect circular/hexagonal cell coverage cannot be assumed anymore.

Here, for the sake of simplicity, we assume the use of the modified Friis propagation model [7] with different values for the propagation exponent ($\gamma = 3$ is considered in numerical examples, as it may be suggested from the experimental work from [8]). In the experimental fixed WiMAX demonstrator from [8] the values for the transmitter power, and transmitter and receiver antenna gains are set at $P_t = -2$ dBW, $G_t = 17$ dBi and $G_r = 9$ dBi, respectively. The radio frequency bandwidth, noise figure and frequency are $b_{rf} = 3.5$ MHz, $N_f = 3$ dB and $f = 3.5$ GHz.

In contrast with mobile WiMAX, a limitation of IEEE 802.16-2004 is that it does not support sub-channelisation on the DL [1]. On the UL, the use of sub-channelisation allows SS transmissions to only use 1/16 of the bandwidth assigned to transmissions from the BS, leading to a 12 dB link budget improvement [9]. The IEEE 802.16-2004 standard defines 16 sub-channels, where 1, 2, 4, 8 or all sub-channels can be assigned to a SS. Each user in each different sub-channel may use a different MCS in successive bursts as long as he/she is using a different sub-channel. Nevertheless, it is a worth noting that in the DL, because the MCS can be chosen at burst level, there is also the flexibility to in effect use different MCS by different users (even without sub-channelisation), as they may use consecutive bursts within a frame.

In snap-shot simulations, averaging the generated interference by just placing all SSs in the centre of the cell is not the correct procedure because of the non-linear influence of pathloss at different distances [10]. The contributions to interference from SSs equally distributed all over the cell surface area needs to be taken into account [10]. However, in this paper, in our chosen analytical approach for fixed WiMAX, we do not follow this methodology. Instead we consider the worst-case interference scenario, where the UL interferer is located at the edge of the neighbouring cell while considering that the user at the central cell can move between the centre and the edge of the cell.

With omnidirectional antennas, the worst case for interference geometry corresponds to the case where the SS in Fig. 1 is at the cell edge, hence $d = R$. The carrier-to-interference ratio in the DL is given by

$$\frac{C}{I} = \frac{1}{2(r_{cc}+1)^{-\gamma} + 2r_{cc}^{-\gamma} + 2(r_{cc}-1)^{-\gamma}} \simeq \frac{r_{cc}^{\gamma}}{6} \qquad (1)$$

where the co-channel reuse factor, r_{cc}, is the ratio of reuse distance D to R, that is, $r_{cc} = D/R$. With tri-sectored cells

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(120° sectors), (1) becomes [11]

$$\frac{C}{I} = \frac{1}{(r_{cc} + 0.7)^{-\gamma} + (r_{cc} - 0.22)^{-\gamma}} \quad (2)$$

which is valid for both links. Note that in the omnidirectional case, the equation for the carrier-to-interference ratio in the UL results from the respective reuse geometry, where interferers are all at a distance $D-0.866R$ from the central cell BS. This is given by

$$\frac{C}{I} = \frac{(r_{cc} - 0.866)^{\gamma}}{6} \quad (3)$$

If low values for the propagation exponent are considered, interference to at least the second tier needs also to be considered [6]. To satisfy this, for example, for (1), terms proportional to $2(2r_{cc}+1)^{-\gamma}$, $2r_{cc}^{-\gamma}$ and $2(2r_{cc}-1)^{-\gamma}$ need to be added to the denominator.

The differences caused by the presence of sub-channelisation and sectorisation can be interpreted by analysing the curves for CNIR as a function of the co-channel reuse factor, r_{cc}, with R as a parameter. To produce these curves, the power of the carrier is obtained by computing the power received by an SS at a distance R from the BS, while the computation of the interference depends on the UL and DL configuration, and also on the use of sectorisation. This can be computed for a fixed R by making the same considerations for frequency reuse as in (1)–(3). The noise power is computed by using the following equation

$$N_{[\mathrm{dBW}]} = -204 + 10\log(b_{\mathrm{rf[Hz]}}) \quad (4)$$

where b_{rf} is the channel radio frequency bandwidth. In the sub-channelisation case, b_{rf} should be divided by 16.

From these curves for the achievable CNIR as a function of r_{cc}, by considering the values of $\mathrm{CNIR}_{\min}$, it is straightforward to obtain the maximum supported physical throughput at the cell edge (distance R) in a simplified way, that is, by considering that users are uniformly distributed on the cell but not considering the exact details for the corresponding services and applications 'multiplexing' characteristics. For hexagonal-shaped cells, $K=1$, 3, 4 and 7 correspond to reuse factors $r_{cc}=1.732$, 3.000, 3.464 and 4.583. These are the values utilised here.

Fig. 2 presents the curves for CNIR(r_{cc}) with R as a parameter for the UL (with no sub-channelisation) whereas Fig. 3 presents the corresponding variation of the physical throughput with r_{cc} at the cell edge for each of the eight possible MCS (see Table 1) when a channel bandwidth of 3.5 MHz is considered.

It is clear that, in $K=7$ (corresponding to $r_{cc}=4.583$), the values for CNIR are always lower than 8.9 dB. For coverage distances higher than 2 km, they decrease drastically. As a consequence, for $r_{cc}=4.583$, the supported physical throughput is very low ($R_b = 2.82$ Mb/s maximum), compared with the maximum achievable one, that is, 12.27 Mb/s as shown in Fig. 3. The significant difference among curves for different values of the coverage distance shows that the system is noise limited.

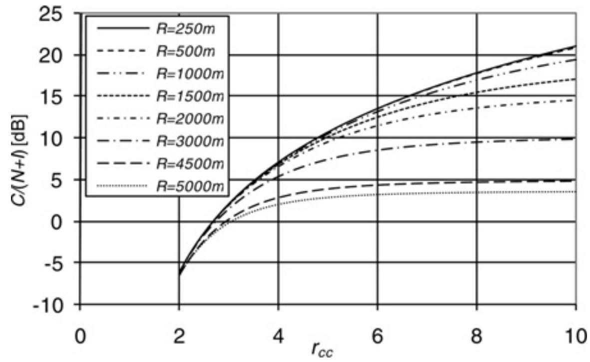

Figure 2 *CNIR as a function of r_{cc}, with R as a parameter, for the UL, in the omnidirectional case and no sub-channelisation*

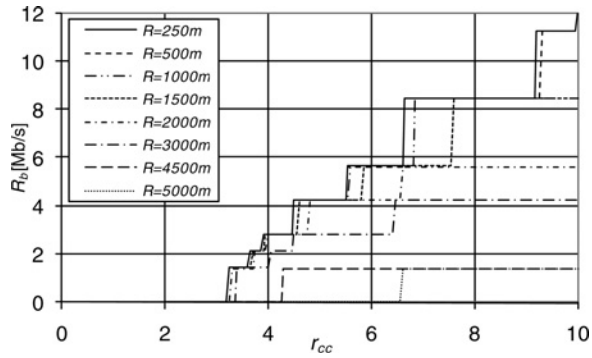

Figure 3 *Physical throughput as a function of r_{cc}, with R as a parameter, for the UL, in the omnidirectional case and no sub-channelisation*

If sectorisation is applied alone then the values of CNIR at $r_{cc}=4.583$ will be higher. However, only when both sectorisation and sub-channelisation are simultaneously applied in the UL, a considerable improvement is achieved for coverage distances of up to 3 km. For these values of r_{cc} and R, the values of CNIR exceed 15 dB, as shown in Fig. 4, while the physical throughput reaches 8.47 Mb/s. Here, mainly because of the presence of sub-channelisation, there is no strong variation among the various curves for CNIR for coverage distances up to 2–3 km, meaning that the cellular system is interference limited (not noise limited anymore).

These observations justify the need to explore the impacts of using both improvement techniques simultaneously.

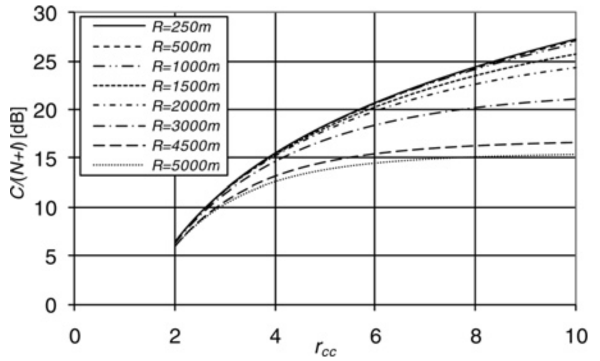

Figure 4 *CNIR as a function of r_{cc}, with R as a parameter, for the UL, with sub-channelisation and sectorisation*

2.2 Supported physical throughput in a cell

To guarantee fixed WiMAX coverage with no coverage gaps near cell edges, the CNIR must be higher than 3.3 dB throughout the cell. This value corresponds to the minimum CNIR in order to use the BPSK 1/2 MCS (see Table 1).

The assessment of the supported cell/sector physical throughput (per transceiver), R_b, as a function of the distance, d, produces a staircase-shaped curve indicating that higher maximum achievable throughputs are supported near the centre of the cell (see Fig. 5). As throughput is not constant over the whole coverage area for cellular planning proposes (where R is the cell radius), the

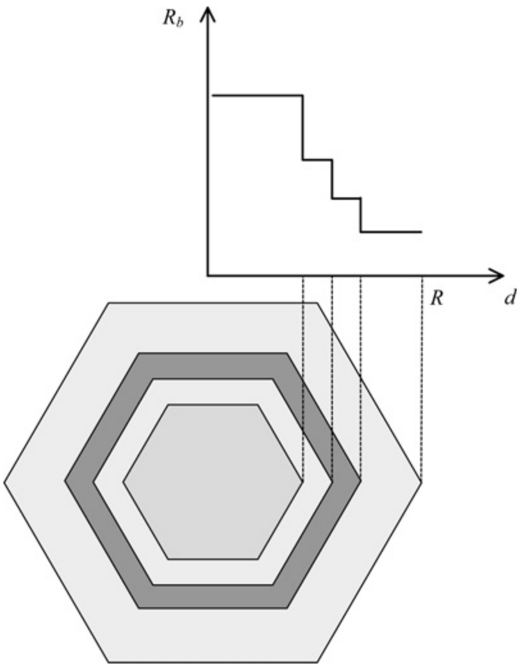

Figure 5 *Areas of the coverage rings where a given value of physical throughput is supported*

supported throughput is obtained by computing the average supported throughput in the cell. As stated previously, in contrast to [9, 10], worst-case scenarios for interference geometry are considered here.

There are J different coverage rings in a cell, each supporting a different MCS (for instance, $J = 4$ in Fig. 5). The distances that correspond to the steps between consecutive MCS are represented by d_j, $j = 1, 2, \ldots, J$. Here we denote the order of the MCS as MCS_j. The number of different coverage rings is given by

$$J = \text{MCS}_{\text{1st}} - \text{MCS}_{\text{last}} + 1 \tag{5}$$

where MCS_{1st} and MCS_{last} represent the MCS for the first and last coverage rings, respectively.

If only one frequency channel is considered per cell, the supported throughput is obtained as the average throughput over the cell area

$$\begin{aligned} R_{\text{b-sup}} &= \frac{\iint_{\text{O}} R_\text{b}(d, R, K)\text{d}x\,\text{d}y}{(3\sqrt{3}/2)R^2} \\ &= \frac{\sum_{j=1}^{J}\left((3\sqrt{3}/2)(d_j^2 - d_{j-1}^2)(R_\text{b})_{\text{MCS}_{\text{1st}}+1-j}\right)}{(3\sqrt{3}/2)R^2} \end{aligned} \tag{6}$$

where the 2D integral is performed over the hexagonal shape of the cell. It is computed by weighting the supported physical throughput in each concentric coverage ring by the size of the ring where that value is supported. The contribution of each of the transmission modes is thus considered.

$\text{MCS}_{\text{1st}}, \text{MCS}_{\text{2nd}}, \ldots, \text{MCS}_{J\text{th}}$ can be obtained in the following way

$$\text{MCS}_j(\text{CNIR}_{[\text{dB}]}) = \begin{cases} 0, & \text{CNIR} < 3.3 \\ 1, & 3.3 \le \text{CNIR} < 5.5 \\ 2, & 5.5 < \text{CNIR} < 6.5 \\ 3, & 6.5 < \text{CNIR} < 8.9 \\ 4, & 8.9 < \text{CNIR} < 12.2 \\ 5, & 12.2 < \text{CNIR} < 15.0 \\ 6, & 15.0 < \text{CNIR} < 19.8 \\ 7, & 19.8 < \text{CNIR} < 21.0 \\ 8, & \text{CNIR} > 21.0 \end{cases} \tag{7}$$

where j represents the coverage ring, $\text{CNIR}_{[\text{dB}]} = 10\log(\text{cnir})$, and $\text{MCS}_k = 0$ means that there is not enough coverage in that part of the cell (or coverage ring); in this case, the system will not be viable. Besides, if $l = \text{MCS}_j$, one can represent the physical throughput, in Mb/s,

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corresponding to each MCS, $l = 0, 1, \ldots, 8$, as

$$(R_b)_l = \begin{cases} 0, & l = 0 \\ 1.41, & l = 1 \\ 2.12, & l = 2 \\ 2.82, & l = 3 \\ 4.23, & l = 4 \\ 5.64, & l = 5 \\ 8.47, & l = 6 \\ 11.23, & l = 7 \\ 12.27, & l = 8 \end{cases} \tag{8}$$

$\text{CNIR}(R_b)$ is not a bijective function. Therefore the value of CNIR that corresponds to a given R_b is the minimum value of CNIR, that is, $\text{CNIR}_{\min}$, that supports a given throughput R_b. Hence $d_0 = 0$, and

$$d_j = \text{cnir}^{-1}(\min(\text{CNIR}((R_b)_{\text{MCS}_{1\text{st}}+1-j}))), \quad j = 1, \ldots, J \tag{9}$$

Fig. 6 presents the correspondence between the CNIR against propagation distance curve and the stepwise function that represents the $\text{CNIR}_{\min}$ threshold for each MCS against R_b. This figure illustrates how the mapping between CNIR and supported physical throughput relates to step distances between consecutive MCS $d_J, d_{J-1}, d_{J-2}, \ldots$.

In the context of the experimental work performed within our research group, results have fitted the modified Friis equation to some ranges of coverage distances in fixed WiMAX [8]. According to the modified Friis equation, the received power is given by

$$p_r(d) = \frac{p_t g_t g_r \lambda^2}{(4\pi)^2 d^\gamma} \tag{10}$$

where $0 \le d \le R$, λ is the wavelength, p_t, g_t and g_r are the linear quantities corresponding to P_t, G_t and G_r (the latter ones are in dB).

In the DL, for a given R, the reuse distance is given by $D = r_{cc}R$, and the interference at a distance d from the BS is computed by the following approximate equations

$$i(d, D, R) = \frac{p_t g_t g_r \lambda^2}{(4\pi)^2}\left(\frac{2}{(D-d)^\gamma} + \frac{2}{D^\gamma} + \frac{2}{(D+d)^\gamma}\right) \tag{11}$$

$$i(d, D, R) = \frac{p_t g_t g_r \lambda^2}{(4\pi)^2}\left(\frac{1}{(D-0.7d)^\gamma} + \frac{1}{(D-0.22d)^\gamma}\right) \tag{12}$$

Equation (11) is applied in the omnidirectional BS antenna case whereas (12) is applied in the tri-sectored case. Under sectorisation, only two interference sources need to be considered. Although these formulas are both valid for the DL, (12) is also valid for the UL. For the omnidirectional case on the UL, (3) for interference can still be applied as it does not depend on d, as the distances from the SS interferers to the cell BS are $D-0.866R$. Note that, as for (1)–(3), the second tier of interference would also need to be considered if lower values of the propagation exponent were used.

We are aware that in this paper we do not consider per sub-channel equivalent signal-to-noise-plus-interference ratio (SINR) (or CNIR) computations when sub-channelisation is used. These computations could be performed accounting either for exponential effective SINR mapping (EESM [12–14]), effective code rate map, or mean instantaneous capacity [9]. The consideration of these compression techniques may be needed in the presence of selective fading to adapt the curves to actual CNIRs in the UL.

In the following, five different cases are addressed:

- The DL in the absence of sub-channelisation and sectorisation (which we denote as the 'DL – omnid.' case).

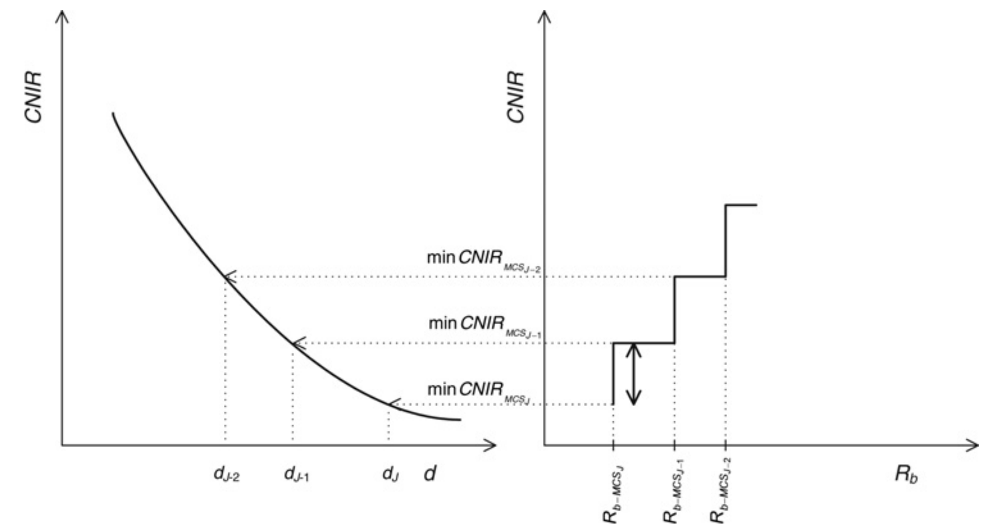

Figure 6 *Correspondence between the physical throughput for rings J, J − 1, J − 2, …, and the minimum CNIRs of consecutive MCS that map to step distances d_J, d_{J-1}, d_{J-2}, …*

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- The UL in the absence of sub-channelisation and sectorisation (the 'UL – omnid.' case).

- The UL in the presence of sub-channelisation and absence of sectorisation (the 'UL – sub-channel.' case).

- The UL and DL in the absence of sub-channelisation and the presence of sectorisation (the 'UL and DL – sector.' case).

- The UL in the presence of sub-channelisation and sectorisation (the 'UL – subch. and sector.' case).

Fig. 7 presents the curves for $R_b(d)$ for $K = 4$ with a coverage distance $R = 2500$ m. Without using sub-channelisation or sectorisation, the DL performance is clearly better than the UL one. However, when sectorisation is considered, higher physical throughputs are achievable. Besides, the better results are obtained when both sub-channelisation and sectorisation are used. In this case, the highest physical throughput reaches 12.27 Mb/s, which is achieved for distances up to $d \simeq 1500$ m.

As an example, Fig. 8 presents a comparison of the results for the cell physical throughput for different reuse patterns $K = 1$, 3, 4 and 7, for 'UL – subch. and sector.' and $R = 2500$ m.

If one carefully analyses the difference in the areas below the curves in these figures, the following conclusions can be extracted:

- Although the physical throughput clearly increases with the use of sectorisation only with the simultaneous use of sectorisation and sub-channelisation in the UL the highest order MCSs are possible near the cell edge.

- With no improvement technique the DL performs better than the UL.

- A value for the reuse pattern $K = 7$ only presents a slight advantage relatively to the consideration of $K = 4$ or 3, whose behaviour is very similar; this is mainly true in the 'DL' and 'UL and DL – sector.' cases, whose curves are not presented here. It should be noted here that $K = 1$ is not supported without the use of sectorisation.

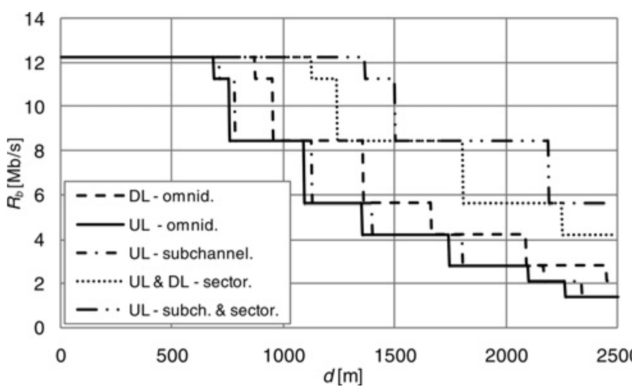

Figure 7 *Example of the variation of the physical throughput as a function of d for R = 2500 m and K = 4*

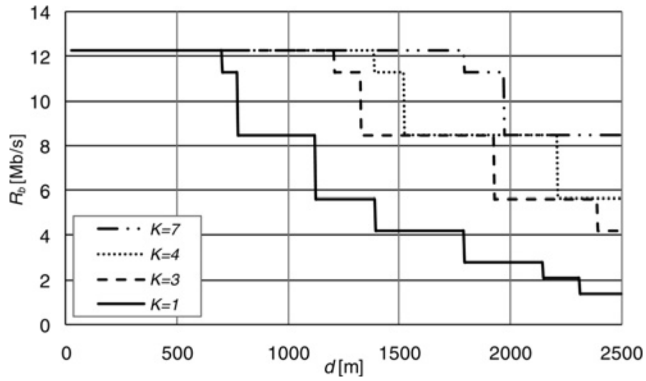

Figure 8 *Variation of the physical throughput in the 'UL – subch. and sector.' case against d, for R = 2500 m*

By applying (6) to the results for the cell physical throughput (as the ones from Figs. 7 and 8), one obtains the curves for the supported throughput as a function of R for $K = 1$, 3, 4 and 7 presented in Figs. 9–12, respectively. Some of the curves with no sub-channelisation are either impossible to obtain at all or after a given R, for example, for $K = 1$, 3 or 4. This is because the physical throughput on the outer coverage ring of the cell reaches 0 Mb/s and full cell coverage may not be guaranteed. The supported throughput results for $K = 4$ are slightly worst than the ones for $K = 7$ but they are still acceptable (where there is the advantage under $K = 4$ of using only 4/7 = 57 % of the spectrum bandwidth).

For $K = 3$, although the degradation compared to $K = 7$ seems high compared with $K = 4$, only 3/4 = 75% of the bandwidth is used. This reduction in spectrum bandwidth is, however, not as much as between $K = 7$ and 4. Using $K = 1$ is advantageous because only a small portion of spectrum is needed. If tri-sectorisation is used, as sub-channelisation is not supported in the DL, a fractional use of the WiMAX channels is not possible and three different channels are needed, one for each sector. In this case, the

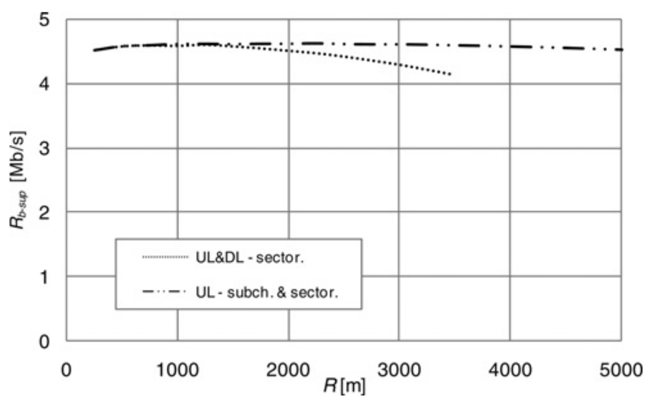

Figure 9 *Supported sector physical throughput against R for K = 1*

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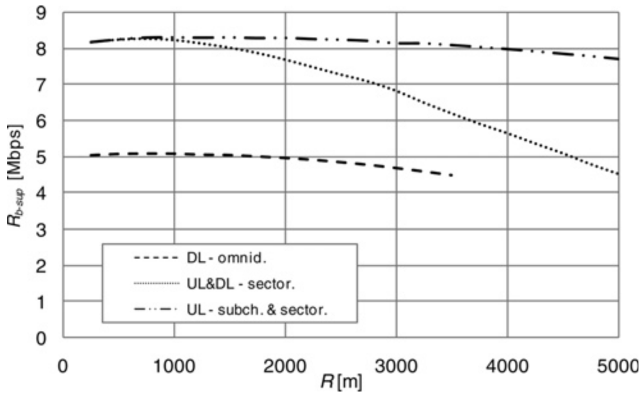

Figure 10 *Supported cell/sector physical throughput against R for K = 3*

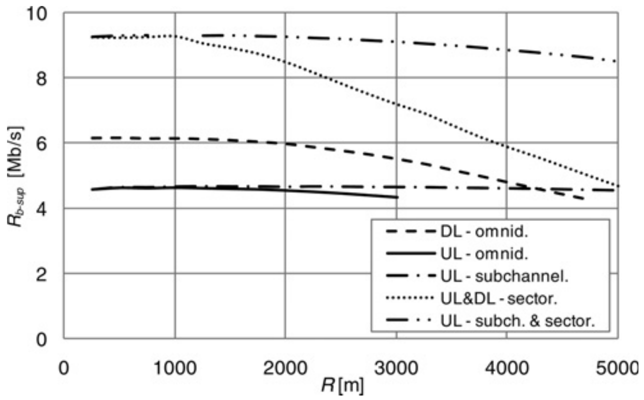

Figure 11 *Supported cell/sector physical throughput against R for K = 4*

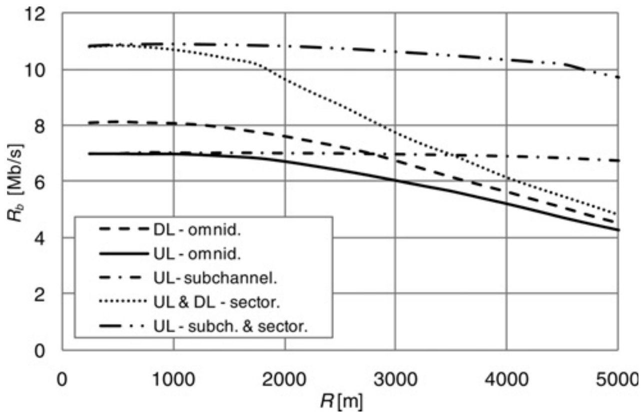

Figure 12 *Supported cell/sector physical throughput against R for K = 7*

total supported throughput is three times the sector average throughput. With 3.5 MHz channels, only 10.5 MHz are needed for each link direction.

It is however worthwhile to compare results for the supported throughput among different values of K by assuming, for the sake of simplicity, that only one single channel could be used (even with tri-sectorisation). For short coverage distances, that is, up to 1500–2500 m, depending on the cases (the highest R's occur with sub-channelisation), the average values of achievable supported throughput are presented in Table 2.

When K decreases, if sectorisation is not used the reduction in physical throughput is considerable, that is, high values of throughput are only achievable through the use of sectorisation. Moreover, for this range of coverage distances, the values of supported throughput are only ~1–2% lower without sub-channelisation compared with the case where both sub-channelisation and sectorisation are used.

The comparison between the 'UL – sector. and subch.' and 'DL – omnid.' cases shows a reduction in the supported throughput for the DL case of 38.7, 34.1 and 25.8%, for $K = 3$, 4 and 7, respectively (note that for $K = 1$, it is not possible to support users in the DL without sectorisation). While with omnidirectional antennas there is a clear asymmetry between UL and DL traffic (see Figs. 11 and 12) it is evident that the UL and DL can be balanced through the use of sectorisation.

These curves may be better interpreted by analysing the variation with R of the cell area, in percentage, corresponding to each supported data rate, that is, for each MCS (according to Table 1). Fig. 13 presents the corresponding curves for $K = 4$ in the 'UL – subch. and sector' case. From this, it can

Table 2 Average supported throughput for low coverage distances with different K's with simple assumptions

$\overline{R_{b-sup}}$, Mb/s	DL – omnid.	UL – omnid.	UL and DL – sector.	UL – sector. and subch.
$K = 1$	–	–	4.515	4.591
$K = 3$	5.051	–	8.160	8.241
$K = 4$	6.100	4.623	9.149	9.255
$K = 7$	8.024	6.985	10.689	10.813

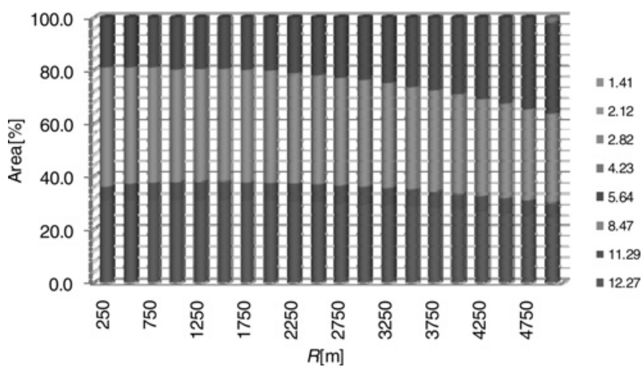

Figure 13 *Area covered by each MCS against R for K = 4, in the 'UL – subch. and sector' case*

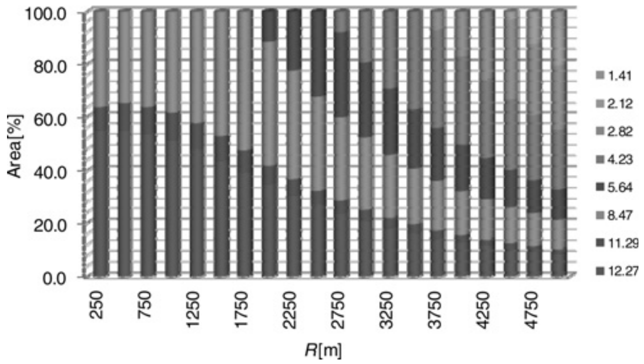

Figure 14 *Area covered by each MCS against R for K = 7, in the 'UL and DL – sector' case*

be observed that the highest values of the throughput are supported in the presence of sub-channelisation plus sectorisation, and correspond to the exclusive operation with the four highest order MCS for coverage distances of up to 4750 m.

Fig. 14 presents the variation of the coverage area, in percentage, against R, for each MCS, but this time for the case $K = 7$ and 'UL – subch. and sector', which is presented as an example.

By comparing these results with the ones for $K = 4$ one concludes that, for $K = 7$, the three highest order MCS are only supported up to $R = 1750$ m, whereas, for $K = 4$, four different MCS are needed. However, for $K = 7$ and coverage distances higher than 2500 m, the trend of enabling larger coverage distances while solely using the highest order MCS is not maintained anymore.

3 Cost/revenue optimisation

3.1 Models

Although the subscribers, regulator and equipment vendors' economic points of view could also be taken into account [15–17], in this paper we are considering the operator/service provider's perspective, whose primary bottom line is to improve his business. In the cellular planning process, the objective of the operator is to determine an optimal operating point that maximises expected revenues. Examples of major decisions affecting this include the type of technology to be used, the size of the cell and the number of radio resources in use in each cell. It is important to identify the main components of the system's cost and revenues, in particular those that bear a direct relationship to either the maximum cell coverage distance or the reuse pattern. Here we consider the cost per unit area of a 2D system incurred during the system lifetime. The system is considered to have a transmission structure formed by a set of frequency carriers or channels (or the corresponding WiMAX sub-channels), each supporting a TDM frame structure. Each BS comprises a number of transceivers equal to the number of carriers assigned to the BS (or to the BS sector), which is assumed to be one in this study, that is, it is assumed as a simplification that one carrier will be sufficient per cell/sector.

System cost has two major parts: (i) capital costs (normal backhaul, cell site planning and installation), and (ii) operating expenses (operation, administration and maintenance) [18, 19].

The capital cost is taken to consist of

- a fixed part (e.g. licensing and spectrum auctions or fees),
- a part proportional to the number of BSs per kilometre or square kilometre (e.g. the installation costs of BSs including the cost of obtaining cell sites, the normal backhaul and the cost of hardware and core equipment common to all) and
- a part proportional to the total number of transceivers per kilometre or square kilometre (e.g. the cost of the transceivers).

It is assumed that the cost of the connection between BSs and the switching centre, that is, the fixed part of the network (e.g. the cost of laying fibre), is not a fixed cost. Instead, we consider this to be proportional to the number of BSs, which can be true if, for example, the mobile operator's service is contracted from a fixed network operator.

The operating cost during a system's lifetime is taken to contain

- a part proportional to the number of BSs per kilometre or square kilometre, and
- a part proportional to the number of transceivers per kilometre or square kilometre.

These costs will be incurred on an annual basis. A similar approach was followed in [4] for hierarchical WiMAX–WiFi networks.

The cost per unit area is given by

$$C_{[€/\mathrm{km}]} = C_{\mathrm{fi}[€/\mathrm{km}]} + C_{\mathrm{b}} N_{\mathrm{cell/km}^2} \quad (13)$$

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 per sector. The number of cells per unit area is given by

$$N_{\mathrm{cell/km}^2} = \frac{2}{3\sqrt{3}R^2} \quad (14)$$

and the cost per BS is given by

$$C_{\mathrm{b}} = \frac{C_{\mathrm{BS}} + C_{\mathrm{bh}} + C_{\mathrm{Inst}}}{N_{\mathrm{year}}} + C_{\mathrm{M\&O}} \quad (15)$$

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

The revenue per cell per year, $(R_v)_{cell}$, can be obtained as a function of the supported throughput per BS or sector (in the omnidirectional and sectorial cases, respectively), $R_{b-sup[kB/s]}$, and the revenue of a channel with a data rate $R_{b[kbps]}$, $R_{Rb[€/min]}$, by

$$(R_v)_{cell} = \frac{N_{sec} R_{b-sup[kb/s]} T_{bh} R_{R_b[€/min]}}{R_{b-ch[kb/s]}} \tag{16}$$

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

The revenue per unit area per year, $R_{v[€/km2]}$, is obtained by multiplying the revenue per cell by the number of cells per unit area

$$\begin{aligned} R_{v[€/km^2]} &= N_{cell/km^2} (R_v)_{cell} \\ &= N_{cell/km^2} \frac{N_{sec} R_{b-sup[kbps]} T_{bh} R_{R_b[€/min]}}{R_{b-ch[kbps]}} \end{aligned} \tag{17}$$

The (absolute) profit is given by

$$P_{[€/km^2]} = R_v - C \tag{18}$$

from which, the profit in percentage terms is given by

$$P_{[\%]} = \frac{R_v - C}{C} \times 100 \tag{19}$$

3.2 Hypothesis

Here we assume that project duration is of 5 years and there is a null discount rate; costs and revenues are taken on an annual basis. We consider 6 busy hours per day, 240 busy days per year [20] and a revenue/price of a 144 kB/s 'channel' per minute (approximately corresponding to the price of one Mbyte, as $144 \times 60 = 8640$ kB $\simeq 1$ Mbyte), $R_{144[€/min]}$. The revenue per cell can be obtained as

$$(R_v)_{cell[€]} = \frac{N_{sec} R_{b-sup[kbps]} \times 60 \times 6 \times 240 \times R_{144[€/min]}}{144_{[kbps]}} \tag{20}$$

Several assumptions for the price of the 144 kB/s channel (or a Mbyte of information) are considered for each scenario.

Two hypotheses are made for cost, denoted as A and B (see Table 3). Hypothesis A is today's situation. In the future, equipment prices will get lower with mass production, and spectrum bandwidth prices will also reduce, thereby making fixed WiMAX systems more accessible. This future case is hypothesis B.

Table 3 Fixed WiMAX cost assumptions

Costs		Omnidirectional		Tri-sectored	
		A	*B*	*A*	*B*
C_{fi} [€/km²]	$K = 1$	15.71	15.71	47.14	47.14
	$K = 3$	47.14	47.14	141.43	141.43
	$K = 4$	62.86	62.86	188.57	188.57
	$K = 7$	110.00	110.00	330.00	330.00
C_{BS}, €		18 000	9000	30 000	15 000
C_{Inst}, €		10 000	1000	18 000	1500
C_{bh}, €		5000	2500	5000	2500
$C_{M\&O}$, €/year		4000	1000	6000	1500

Assuming that the annual cost of a license is 50 000 000 € for 2×24.5 MHz bandwidth (UL and DL, $K = 7$), considering a total area of 91 391.5 km^2 as the area of Portugal, for example, the fixed cost per unit area is

$$C_{fi[€/km^2]} = \frac{50\,000\,000}{91\,391.5} = 108.24 \simeq 110\,€/km^2 \tag{21}$$

If one considers that only one carrier will be allocated to each cell (or sector), if $K = 4$ or $K = 3$ then the available BW (and the respective cost) will be 4/7 or 3/7 of the value for $K = 7$, respectively.

Given that the total bandwidth, BW, is given by

$$BW_{omni[MHz]} = N_{sec} K \times 3.5 \tag{22}$$

The necessary spectrum bandwidths can be obtained as in Table 4.

Note that $N_{sec} = 1$ for omnidirectional cells and $N_{sec} = 3$ for sectorial cells.

Table 4 Required spectrum bandwidth for different cell configurations and reuse patterns

K	BW, MHz	
	Omnidirectional	Tri-sectored
1	3.5	10.5
3	10.5	31.5
4	14.0	42.0
7	24.5	73.5

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3.3 Optimisation and profit

In seeking profit optimisation, revenues should be maximised with respect to costs. Under hypothesis B, which corresponds to the lowest cost case, and for $K = 7$, the variation of the cost and revenue in €/km^2 with R is depicted in Figs. 15 and 16, for omnidirectional and tri-sectored cells, respectively. The revenue curves were obtained for $R_{144[€/\text{min}]} = 0.0025$ (which approximately corresponds to the price per Mbyte [16]).

Note that the UL curves for the cases with omnidirectional BS antennas and sub-channelisation and tri-sectorisation are superimposed for distances up to 3000 m. With tri-sectorial BS antennas, as there is three times more available resources the revenues increase significatively.

In order to optimise the BWA network, it is important to analyse the profit per unit area. However, it is not sufficient to compute the absolute profit because, as is shown in Figs. 15 and 16, a certain level of profit may correspond to different values of cost. For example, cost is higher for tri-sectorial cells; hence, revenue needs to be higher to obtain the same profit. It is worthwhile to note that, with tri-sectorial BS antennas, higher revenues are expectable not only because of the interference mitigation caused by the use of directional antennas but also because three channels are now available in the cell, one for each sector, leading to an higher supported throughput per km^2. The different behaviour of cost and revenues curves justifies the need to depict curves for profit in percentage, as defined by (19). The operator's/services provider's goal is to optimise this profit in percentage.

We have obtained results for the profit in percentage for two values of the price per Mbyte, $R_{144[€/\text{min}]} = 0.005$ and 0.010 in hypothesis A, corresponding to higher costs, in Figs. 17 and 18, respectively.

It is particularly evident that profit increases as the price per Mbyte increases; nevertheless, the curves keep the same shape and behaviour. For tri-sectorial cells, as there is three carriers available in the cell, the profit in percentage is almost three times higher than the the one for the case of

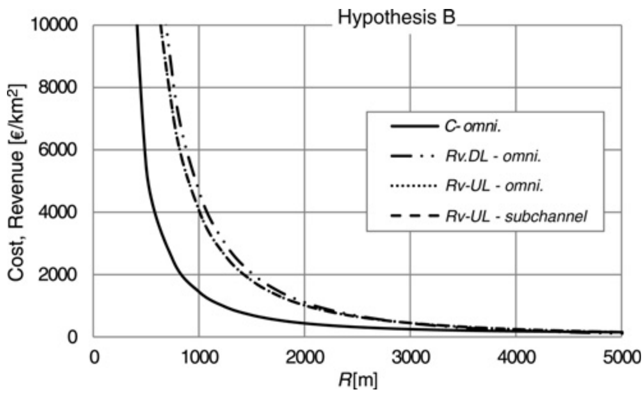

Figure 15 *Cost and revenues against R for $K = 7$ under hypothesis B, for the omnidirectional case*

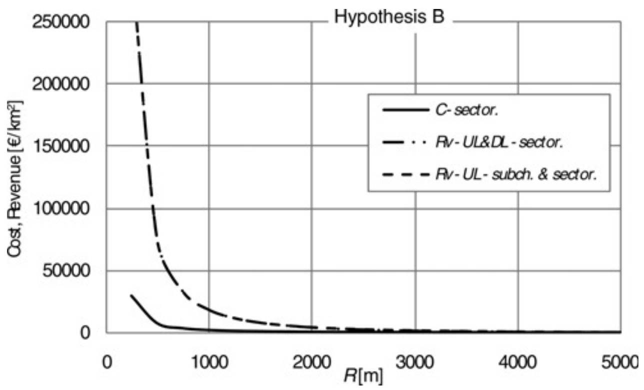

Figure 16 *Cost and revenues against R for $K = 7$ under hypothesis B, for the tri-sectored case*

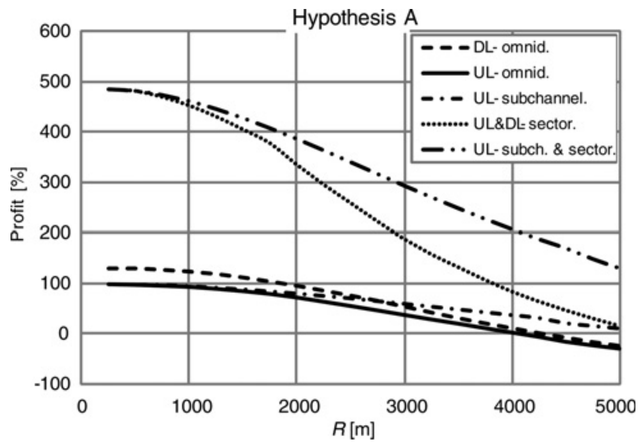

Figure 17 *Profit in percentage terms against R for $K = 7$ under hypothesis A, $R_{144[€/\text{min}]} = 0.005$*

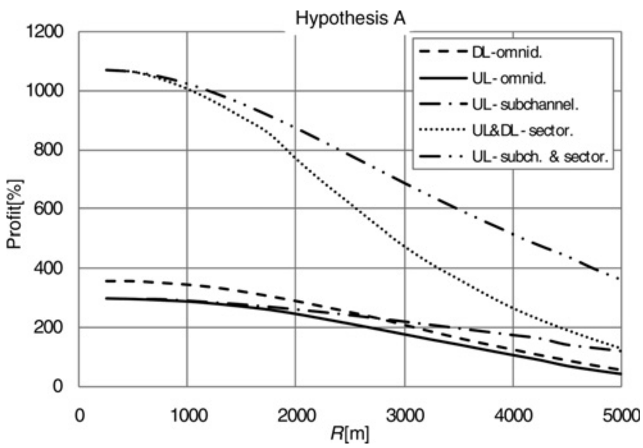

Figure 18 *Profit in percentage terms against R for $K = 7$ under hypothesis A, $R_{144[€/\text{min}]} = 0.010$*

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omnidirectional cells for a considerable range of coverage distances, typically lower than 1800 m, which only reaches ~375%. For coverage distances larger than this value, this relative difference is only kept if sub-channelisation is considered.

In hypothesis B (lower network cost), the advantage of using a tri-sectored configuration becomes even more evident for the shortest propagation distances of up to 1250–1500 m (see Fig. 19). Although the required bandwidth in each FDD link is three times higher, the profit in percentage terms is now more than three times higher than the one with omnidirectional cells. Fig. 19 presents an example for $R_{144[€/min]} = 0.005$ in hypothesis B, where it is clear that profit values are more than four times the values in Fig. 17. As costs are lower, even with a price per Mbyte of only $R_{144[€/min]} = 0.005$ the profit in percentage terms may exceed 1500%. Although the curves are not presented here, even for $R_{144[€/min]} = 0.0025$, the values of the profit are more than twice the ones from Fig. 17.

A comparison between $K = 7, 4, 3$ and 1 is presented in Fig. 20 (for tri-sectored cells in the UL and $R_{144[€/min]} = 0.005$). Sub-channelisation is considered, as it is specified on the UL.

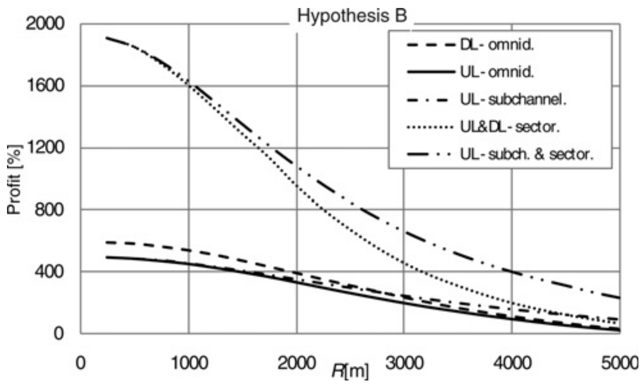

Figure 19 *Profit in percentage terms against R for K = 7 under hypothesis B, $R_{144[€/min]} = 0.005$*

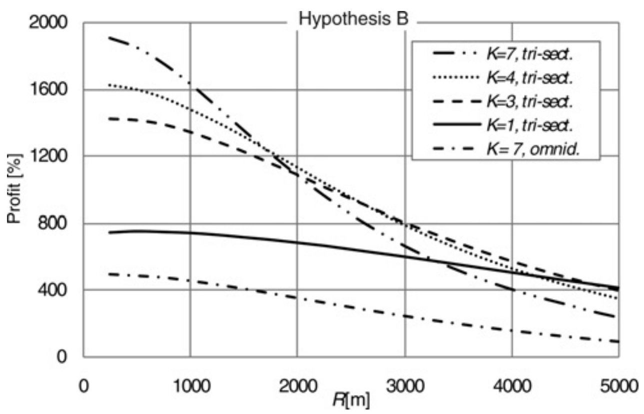

Figure 20 *Profit in percentage terms against R for different K's under hypothesis B, with tri-sectored cells for the UL where $R_{144[€/min]} = 0.005$*

Note that in the tri-sectorial case the required bandwidth in each FDD link is three times higher, for example, increasing from 10.5 to 31.5 MHz for the $K = 3$.

The consideration of a reuse pattern $K = 7$ is ideal in terms of interference mitigation, although $K = 1$, 3 and 4 may also be interesting possibilities for coverage distances between 1500 and 1800 m. Note, however, that, from the spectrum regulation point of view, to use $K = 7$ and tri-sectored cells seems to be infeasible, as a spectral bandwidth of 73.5 MHz is needed. With $K = 1$ and 3, the use of omnidirectional configurations cannot be supported as the throughput on the outer coverage ring of the cell reaches 0 Mb/s and full cell coverage is not guaranteed. Although the curve is not presented here, in the omnidirectional case, with $K = 4$, profits of 260–290% are achieved in the UL (and of 370–420% in the DL) for coverage distances up to 1500 m ($R_{144[€/min]} = 0.005$). Only with $K = 7$ higher profits are achieved with omnidirectional cells, of the order of 400–490% in the UL, as shown in Fig. 20 (where sub-cahnnelisation is considered), and 470–580% in the DL. However, this compares poorly with the values varying from 1400 to 1900% for $K = 3$, 4 and 7 with tri-sectored cells.

The cases $K = 1$, 3, 4 (all with tri-sectored cells) and $K = 7$ (with omnidirectional cells) correspond to a spectrum bandwidth of 10.5, 31.5, 42.0 and 24.5 MHz, respectively. $K = 4$ and 3 with tri-sectorial BS antennas seem to be the optimum choices, with an advantage for the choice of $K = 3$, as only 75% of the bandwidth is needed. With $K = 1$ and tri-sectored cells the profit in percentage terms is higher than with $K = 7$ and omnidirectional cells, with an additional advantage: only 43% of the bandwidth is needed. Besides, it is worthwhile to note that, for $K = 1$ and coverage distances longer than 4000 m, the values for the profit in percentage terms become comparable to ones with $K = 4$ and 3 (tri-sectored cells), that is, for sparse BS deployments in low density user environments $K = 1$ may be a solution.

If network costs are higher (hypothesis A), the relative behaviour is basically the same as in hypothesis B. Under the price per Mbyte of $R_{144[€/min]} = 0.010$, the profit may reach values of somewhere between 780 and 1060%. It seems that the relative disadvantage with $K = 7$ and omnidirectional cells becomes less evident, as shown in Fig. 21 under hypothesis A (in comparison to Fig. 20).

With $K = 1$ and tri-sectored cells, the profit in percentage terms is again higher than with $K = 7$ and omnidirectional cells. However, for the longest coverage distances, no advantage of using $K = 1$ can be found in comparison to $K = 3$ or 4 anymore.

In terms of the choice of optimum coverage distance, from analysis of the results in Figs. 15 and 16 it is evident that network cost strongly increases if the coverage distance decreases, particularly for the lowest coverage distances.

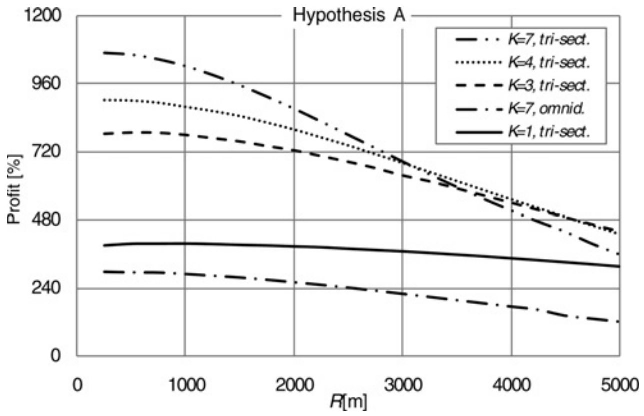

Figure 21 *Profit in percentage terms against R for different K's under hypothesis A, for the UL where* $R_{144[€/min]} = 0.010$

Investigating the profit in percentage terms, it can be observed that significant falls occur for coverage distances of higher than 1500 m. Hence coverage distances of around 1000 m might be chosen as optimum, as they maximise profit in percentage terms while keeping costs acceptable. A daily equivalent operation in saturated conditions over 6 h has been assumed, which is only valid if the offered traffic is high enough in this timespan. Otherwise, revenue will be lower, and low costs will definitively reduce the possibility of losses.

4 Conclusions

In this work, a model to compute the supported physical throughput as a function of the achievable CNIR has been proposed for fixed WiMAX. Frequency reuse topologies have been explored for 2D geometries that are commonly used in rural and suburban environments, and the basic limits for system capacity and cost/revenue optimisation have been obtained by considering simple assumptions. It is assumed that line of sight propagation to the BS is achieved in a high percentage of the cell, reducing the impact of selective fading, through allowing dimensioning to be done by GIS cellular planning tools.

For a given coverage area, throughput is a stepwise function that decreases as the distance to the BS increases. Its value depends on the supported MCS for each coverage ring. In this paper, the supported throughput has been computed by weighting the available throughput at each coverage ring with the area (or size) of the ring. Throughput typically decreases as the cell radius increases, although through the use of sub-channelisation it is possible to keep its value steady at least up to a cell radius of 5000 m. With the use of sectorisation, the supported throughput is higher, corresponding to the use of the highest order MCSs. However, as sectorised equipment is more expensive and there is a need for three times more bandwidth, costs are also higher.

From an undertaken cost–benefit analysis, one conclusion of this paper is that given today's hypothesis of price per Mbyte of information transfer of somewhere between 0.0025 € and 0.010 €, it is clear that the choice of reuse patterns 3 or 4 with sectorial cells is preferable to the use of omnidirectional cells with reuse pattern of 7, as three times more resources are made available in each cell. Besides, in nowadays networks, if there is a need for sparse BS deployments while reducing costs, $K = 1$ may be a solution, as it presents higher profit for the longest coverage distances. In future networks, when costs will be lower, the advantage of sectorisation is kept and will drive the deployment of tri-sectorisation forward. Nevertheless, in this case, $K = 1$ will not be advantageous with tri-sectorisation for the longest coverage distances anymore.

It has also been concluded in this paper, driven by our analysis as well as other observations, that cell radii in the range 1000–1500 m might be chosen. This range corresponds to a profit, in percentage terms, of near to the maximum achievable, while keeping costs acceptable.

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