Cost/Revenue Trade-off in the Optimization of Fixed WiMAX Deployment with Relays

Fernando J. Velez, *Senior Member, IEEE*, M. Kashif Nazir, A. Hamid Aghvami, *Fellow, IEEE*, Oliver Holland, *Member, IEEE*, and Daniel Robalo

***Abstract*—In Fixed WiMAX, the contribution from each transmission mode can be incorporated into an implicit formulation to obtain the supported throughput as a function of the carrier-to-interference ratio. This is done by weighting the physical throughput in each concentric coverage ring by the size of the ring. In this paper, multi-hop cells are formed by a central coverage zone and three outer coverage zones, served by cheaper low-complexity relays. Although the reuse distance in this case is augmented by a factor $\sqrt{3}$, we show that with the use of relays in FDD mode with an adapted TDD UL sub-frame structure to accommodate communication from/to the relay station (RS) to/from subscriber station (SS), only the consideration of tri-sectored BSs with reuse pattern *K*=3 enables attainment of values for the cell/sector throughput comparable to cases without the use of relays. Cost/revenue optimization results show that tri-sectored base stations (BSs) in topologies with relays enable us to achieve more profitable reuse configurations than with omnidirectional BSs and no relays. Under the same total bandwidth and with the coverage distance set at *R*~500 m, we show that it is preferable to consider *K*=1 with three carriers/sector, instead of *K*=3 with one carrier per sector, whereby profit in this case is increased from ~1000% to ~1450%. Further, if the price (€/MB) is increased from 0.0025 to 0.005, the achievable profit more than doubles.**

***Index Terms*— Broadband communication, WiMAX, planning, economics, relays**

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Fernando J. Velez is with the Centre for Telecommunications Research, King’s College London, Strand, London WC2R 2LS, UK, on leave from the Instituto de Telecomunicações, Universidade da Beira Interior, Covilhã, Portugal (phone: +351 275329953; fax: +351 275329972; e-mail: fjv@ubi.pt).

M. Kashif Nazir, A. Hamid Aghvami, and Oliver Holland are with the Centre for Telecommunications Research, King’s College London, Strand, London WC2R 2LS, UK (e-mail: kashifspacian@hotmail.com, hamid.aghvami@kcl.ac.uk, oliver.holland@kcl.ac.uk).

Daniel Robalo is with the the Instituto de Telecomunicações, Universidade da Beira Interior, Covilhã, Portugal (e-mail: drobalo@lx.it.pt).

I. Introduction

In Worldwide Interoperability for Microwave Access (WiMAX) radio and network 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-channelization may be applied to reduce the impact of noise on link performance. However, only Mobile WiMAX allows for sub-channelization in both the UL and DL; fixed WiMAX only allows for it in the UL and, owing mainly to the extra noise caused by the large spectrum bandwidth in fixed WiMAX, this absence of sub-channelization in the DL may be a cause of performance degradation. For cellular planning purposes, the UL and DL CNIRs from/at the wireless Subscriber Station (SS) are very significant parameters.

Using 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 a coverage guarantee and improved system capacity, whilst minimising interference. Broadband wireless access (BWA), enabling the operation of multi-hop relay stations (RSs), aims not only to enhance the coverage but also system capacity, as interference is mitigated owing to the lower transmitter power associated with the short-range RSs. Compared with base stations (BSs), RSs do not need a wire-line backhaul, and have much lower hardware complexity, hence can significantly reduce the deployment cost of the system. The main objective is to achieve the highest values for the carrier-to-noise-plus-interference ratio (or CNIR), $C/(N+I)$, and, in return, the maximum supported throughput, by using relays for a given frequency reuse pattern (e.g., *K*=3).

In this work, a comparison of the different values of achieved throughput is performed between the RSs, BSs and SSs, in topologies where relays are present. Topologies with omnidirectional and tri-sectored BS antennas are compared in cases where RSs may or may not be used. Under the same total bandwidth, different number of carriers per cell/sector are considered for different values of the reuse pattern. 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 physical throughput, through an inversion procedure.

WiMAX deployment optimisation can be achieved by appropriately parameterizing a merit function, accounting for costs and revenues. 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. The cost/revenue function takes 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") are also taken into account, and an economic analysis, accounting for all these factors, is referred to as a cost/revenue performance analysis, because the optimisation (i.e., minimization) of cost does not necessarily mean the optimization of net revenues.

Although, typically, the duration of five years is considered as a working hypothesis in radio and network planning, it is decided in this paper to analyse costs and revenues on an annual basis following the visions proposed in [1]. Furthermore, our analysis assumes a null discount rate. By no means is it intended to perform a complete economic study in this paper via, e.g., computation of the net present value; the aim is simply to present initial contributions that facilitate incorporation of the main cellular planning optimisation aspects into the economic analysis. Appropriate refinements would be needed (e.g., the inclusion of business aspects) to perform a complete economic analysis based on discounted cash flows, such as to compute the net present value.

The remainder of this paper is organized as follows. Section II presents formulations and assumptions for the CNIR analysis in the DL and UL for Fixed WiMAX multihop configurations (with relays). The supported physical throughput, in cellular topologies with no sectorization, is analyzed in Section III. Section IV in turn addresses the use of tri-sectorization and relays. Section V investigates the cost and revenue optimization of these WiMAX deployments. Finally Section VI concludes the paper.

II. *CNIR* VERSUS PHYSICAL THROUGHPUT WITH RELAYS

A. *Formulation*

In the considered context where cellular topologies are supported by relays, a cell is composed of the central coverage area, served by the BS, and three 240º sectored coverage areas, served by individual RSs: RS_1, RS_2 and RS_3 (see Figure 1). While the BS antenna may be either omnidirectional or sectorial, the 240º sectored RS antennas facilitates non-overlapping coverage with the central zone of the cell. While the BS backhaul is assured through the usual means for mobile communications (e.g., cable, or dedicated microwave radio link), RS backhauling is guaranteed through dedicated sub-frames within the radio channel, created for that purpose [2]. With tri-sectored BS antennas, if Frequency Division Duplexing (FDD) is considered more channels are needed, which in turn allows for extra resources to be made available to the RSs (as separate frequency channels are made available at each sector).

Given that dedicated UL/DL frequency sub-frames are allocated to communication to/from relays, Figure 2 shows the fixed WiMAX FDD mode frame structure assumed in this work.

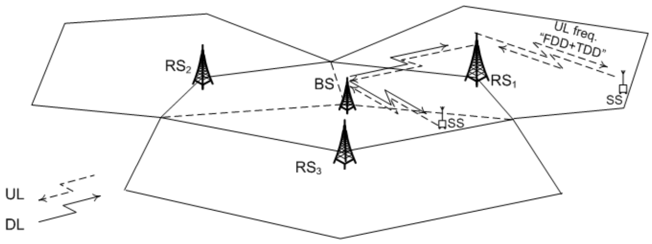

Fig. 1. BS, RS and respective "hexagonal" coverage areas.

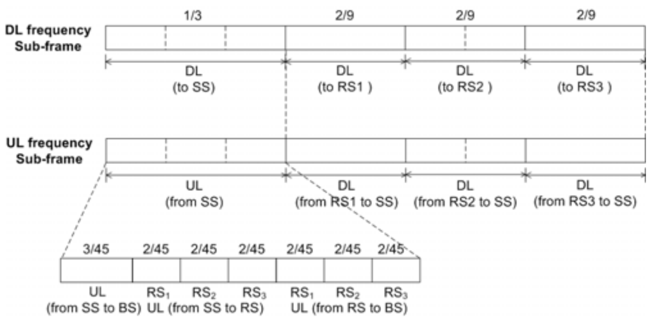

Fig. 2. Structure of DL and UL sub-frames supporting the deployment of relays (omnidirectional BS).

The WiMAX frame is divided into DL and UL sub-frames which, in turn, include sub-divisions with the following purposes (refer to Figure 2):

- BS to SS communication;
- SS to BS communication;
- BS to RS communication;
- RS to BS communication;
- RS to SS communication;
- SS to RS communication.

Given that there is less traffic load usually in the UL direction, wireless multimedia communications is generally asymmetric. Our proposal on frames is inspired in the sub-frame structure from [3], 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 [4]. Although the version of fixed WiMAX we consider here

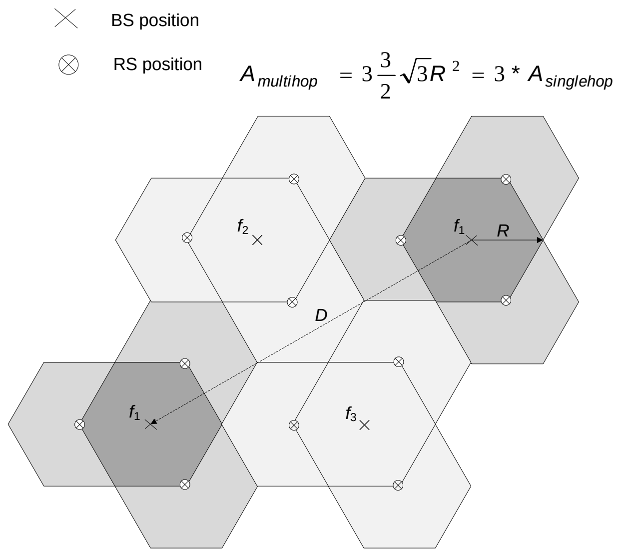

Fig. 3. Cell with RS at the edge of the central coverage area.

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. Hence, the proposal for DL and UL frequency sub-frames from Figure 2 assumes an asymmetry factor of 1:5 between the UL and DL, and makes extra resources available to DL RS to SS communications by using the UL sub-frame, via TDD, as shown in Figure 1. This type of RS is not standardized or available, yet this structure for frequency sub-frames will certainly be 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 that co-channel interference now is from cells at a larger distance, because reuse distance is $\sqrt{3}$ times more than with no relays. This reuse distance, D, is given by (see [5], [6]):

$$D = 3\sqrt{K}\,R \tag{1}$$

where K is the reuse pattern, the number of different frequency groups needed in the reuse scheme, and R is the coverage distance.

Assuming the presence of such fixed relays, the corresponding cell geometry is presented in Figure 3. The cell is formed by a central coverage zone, with a hexagonal shape, and three hexagonal outer coverage areas with 240º sectored antennas, as shown in Figure 3, each occupying 2/3 of the area relative to the central coverage zone. This different approach corresponds to considering three times the coverage area for the cell, i.e., [7], [8]:

$$A_{multihop} = 3.A_{singlehop} \tag{2}$$

Different cases for the DL and UL, for the communication to and from RS and BS, are discussed in this paper.

B. Assumptions

A set of assumptions is considered in this research on frequency reuse for fixed WiMAX with relays, with a frequency reuse pattern (or cluster size) of K=3. Every coverage zone of the cell uses the same frequency group as the central zone, e.g., f_1, f_2 or f_3, as shown in Figure 3.

For the DL, the objective is to maximize supported throughput. The optimization process is two-fold [2]:

- The offered throughput from the BS to the RS needs to be maximized, i.e., for a hexagonal coverage zone with radius R the physical throughput at distance R is $R_b(R)$ needs to be as high as possible;
- The offered throughput to SSs needs to be maximized. This objective is further divided into two points:
  a) **Maximization of $R_{b\text{-}sup}$ at the SSs in the central coverage zone**: By considering our assumptions for the DL and UL frames (in order to cope with RS communications, see Figure 2) the DL supported throughput in the central coverage area is approximately 1/3 of the total throughput;
  b) **Maximization of $(R_{b\text{-}sup})_{RS}$ in SSs in the three relay coverage zones:** The maximum throughput in the RS coverage area is $R_{b\text{-}max}=min\{R_b(R),\ (R_{b\text{-}sup})_{RS}\}$ multiplied by 2/9, i.e, $2/9\cdot R_{b\text{-}max}$, where $R_b(R)$ is the maximum throughput at the edge of the central coverage zone where the distance is R from the BS, and $(R_{b\text{-}sup})_{RS}$ is the total throughput that may be supported in the RS coverage zone if the RS backhaul can support it (also considering the total frame duration).

RS antennas for communication with the BS are considered to be directional ones, so that they only cause interference to two BSs, as it will be shown in the formulation.

For the communication at the relay, using our assumptions for the frame structure, it is only possible to achieve $2/9\cdot R_{b\text{-}max}$ supported throughput in the whole RS coverage zone. However, this is only if the BS to RS link supported throughput is larger enough. In practice, the throughput at a distance d from the RS, $R_b(d)$ depends on the supported MCS, given by [2]:

$$R_b(d) = \frac{2}{9} R_b(R) \times AuxFactor\ (d) \tag{3}$$

where d is the distance to the RS, $R_b(R)$ is the maximum throughput at the edge of the central cell, at a distance R from the BS and $AuxFactor(d)$ allows for computing the physical throughput, R_b, at a distance d and is given in Table I.

As an example, let's assume that the 16-QAM ½ MCS is supported in the central coverage area. Table I shows the values for $AuxFactor(d)$ if the MCS ID that may be guaranteed for the $C/(N+I)(d)$ from the RS coverage area is within the range 1..8. The 16-QAM ½ MCS is shown in bold in Table I.

In practice if the MCS supported at a distance d from the RS is higher than or equal to the one supported in the BS-to-RS link (16-QAM ½ in this example) the throughput for RS will be $2/9 \cdot R_b(R)$; otherwise, the throughput will be $2/9 \cdot (R_{b\text{-}sup})_{RS}$.

TABLE I
AUXFACTOR FOR DIFFERENT VALUES OF THE MCS ID FOR THE COMMUNICATIONS TO THE SSS AT RS COVERAGE AREA

ID=l	MCS	$CNIR_{min}$ [dB]	*Physical thr* [Mbps]	*AuxFactor*(*d*)
1	BPSK ½	3.3	1.41	1.41/5.64
2	BPSK ¾	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 ⅔	19.8	11.29	1
8	64-QAM ¾	21.0	12.27	1

For the UL, the maximization objective of supported throughput, $R_{b\text{-}sup}$, is also two-fold [2]:

- The supported throughput from the RS to the BS needs to be maximized. At the BS, from the RS it is only possible to achieve $2/45 \cdot R_{b\text{-}sup}$;
- The supported UL throughput needs to be maximized. This objective is further divided into two parts:
  a) Maximization of the supported UL throughput at the RS (from the SS) in the central coverage area (the achievable throughput here is $3/45 \cdot R_{b\text{-}sup}$);
  b) Maximization of the offered throughput from SSs to RSs at the three RS coverage areas (the maximum here is $2/45 \cdot (R_{b\text{-}sup})_{fromSS}$).

Since the RS antennas are directional, the BS only receives interference from two BS at distance $D+R$. At the RS it is only possible to achieve $2/45 \cdot (R_{b\text{-}sup})_{fromSS}$, where $(R_{b\text{-}sup})_{fromSS}$ refers to the supported throughput from the SS to RS. This traffic will only reach the BS if the RS to BS radio link supports such a value for the throughput.

C. DL Scenarios

In the DL, there are three different possible transmission cases that need to be analyzed individually:

i) BS to SS: BS to SS communication is the simple case from Figure 4. The same formula for the carrier-to-interference ratio, *C/I*, is used as in the absence of relays [9] but now with the reuse distance $\sqrt{3}$ larger.

ii) BS to RS: In the case of BS to RS communication, one assumes that RSs are using 1200 directional antennas, and only receive interference from two BSs, as depicted in Figure 5. This enhances C/I significantly, as will be highlighted in later discussion. Therefore, $(D+\alpha R)^{-\gamma}/R^{-\gamma} = (r_{cc}+\alpha)^{-\gamma}$ has a coefficient 2 while $\alpha = 1$, and the *C/I* is given by:

$$\frac{C}{I} = \left(\frac{1}{2(r_{cc}+1)^{-\gamma}} \right) \tag{4}$$

Note that the co-channel reuse factor, r_{cc}, is given by $r_{cc}=D/R$.

iii) RS to SS: In the case of RS to SS transmission, the SS receives interference from four neighbouring RSs, as in Figure 6. The distances between cell centres, RS and SS are shown in Figure 4, for a worst-case situation. On the basis of measured distances from Figure 6, the coefficients of R in $(D+\alpha R)^{-\gamma}$, are calculated as [2] (for R=100 m):

$$D = 3R\sqrt{3} = 519.615242 \ m \tag{5}$$

There are two RS at 435.8899 m from the envisaged SS, giving the coefficient:

$$\frac{435.89 - 519.62}{100} = -0.8373 \tag{6}$$

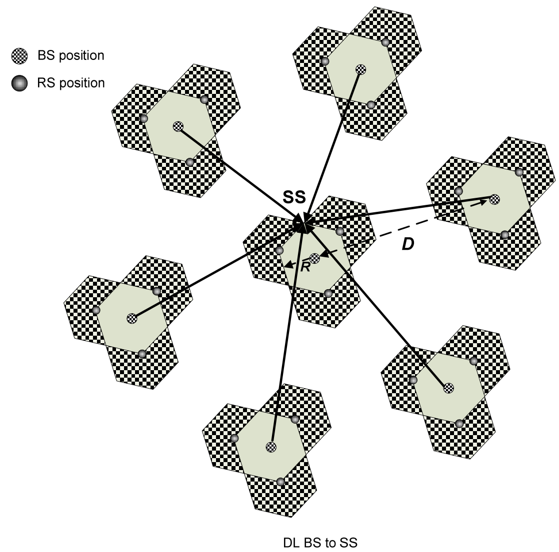

Fig. 4. DL Scenario: distances from the BS interferers to SS.

There are two RS at 435.8899 m from the envisaged SS, and two at a distance 608.2763 m, giving the coefficients:

$$\frac{529.15 - 519.62}{100} = 0.0953 \tag{7}$$

$$\frac{608.28 - 519.62}{100} = 0.8866 \tag{8}$$

Hence, *C/I* is given by [2]:

$$\frac{C}{I} = \frac{R^{-\gamma}}{2(D - 0.8373R)^{-\gamma} + (D + 0.0953R)^{-\gamma} + (D + 0.8866R)^{-\gamma}} \tag{9}$$

D. UL Scenarios

For the UL, there are three different transmission cases that need to be analyzed individually:

i) SS to BS: Interference in the BS comes from six surrounding SS. Thus *C/I* is given by:

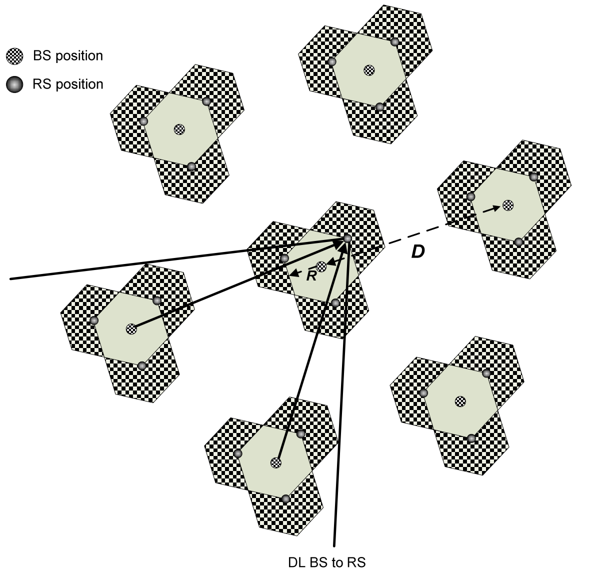

Fig. 5. DL scenario with 120º RS sectored antennas for the communication with the BS (and 240^0 sector RS coverage area).

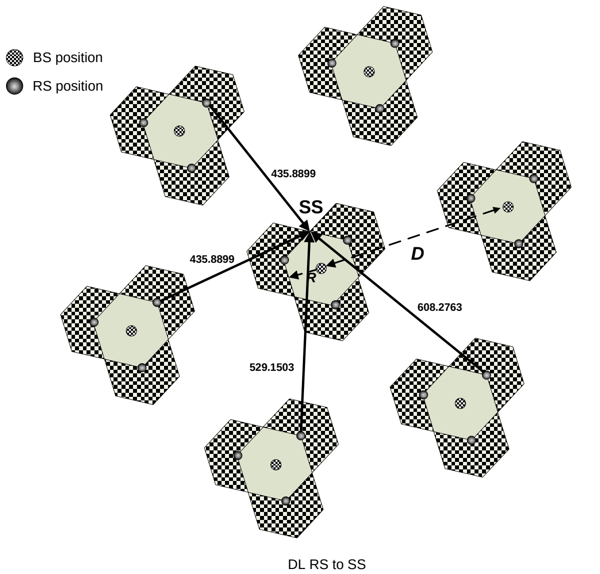

Fig. 6. Distances from the RS interferers to the SS.

$$\frac{C}{I} = \frac{\left(r_{cc} - 0.866\right)^{\gamma}}{6} \tag{10}$$

ii) RS to BS: In this case, we have assumed that RS antennas are 120^0 sectored. Thus, the BS at the central cell only receives interference from two RS, at distance *D+R* (see Figure 7). The carrier-to-interference ratio is therefore given by:

$$\frac{C}{I} = \frac{\left(r_{cc} + 1\right)^{\gamma}}{2} \tag{11}$$

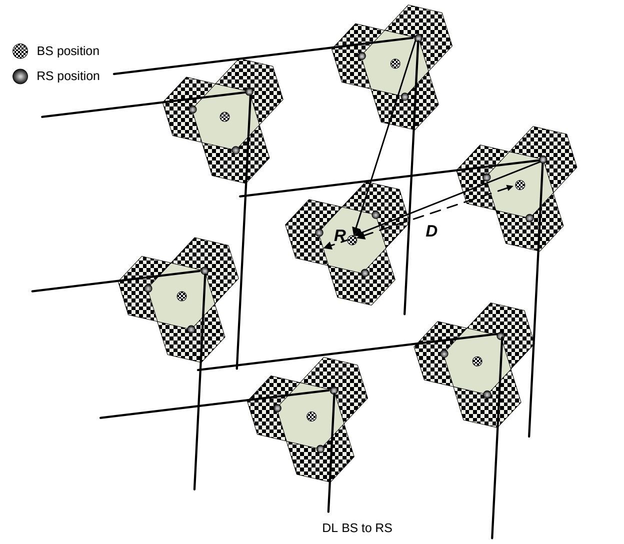

Fig. 7. The decrease of the co-channel interference by using directional antennas at RS.

iii) SS to RS: In this case the RS receives interference from four SSs in neighbouring cells. By using the same procedure to measure the distances between the cell centres, RS and SS, the following values are obtained for α: -0.8761, -0.082776, -0.80762, and -0.8761. C/I is therefore given by:

$$\frac{C}{I} = \frac{R^{-\gamma}}{2(D - 0.8761\,R)^{-\gamma} + (D - 0.082776\;R)^{-\gamma} + (D - 0.80762\;R)^{-\gamma}} \tag{12}$$

III. Supported Physical Throughput

A. Implicit function formulation

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 ½ MCS (see Table I).

The assessment of the supported cell/sector physical throughput (per transceiver), R_b, as a function of distance, d, produces a staircase-shaped curve indicating that higher maximum achievable throughputs are supported near the centre of the cell (see Figure 8). As, for cellular planning purposes, throughput is not constant over the whole coverage area (where *R* is the cell radius), the supported throughput is obtained by computing the average supported throughput in each coverage zone. As stated previously, in contrast to [7], [8], worst-case scenarios for interference geometry are considered here.

Assume there are *J* different coverage rings in each coverage zone, each supporting a different MCS (for instance, *J* = 4 in Figure 8). The distances that correspond to the steps between consecutive MCS are represented by d_j, j = 1, 2, …, *J*. Here we denote the order of the MCS as MCS_j. The number of different coverage rings is given by:

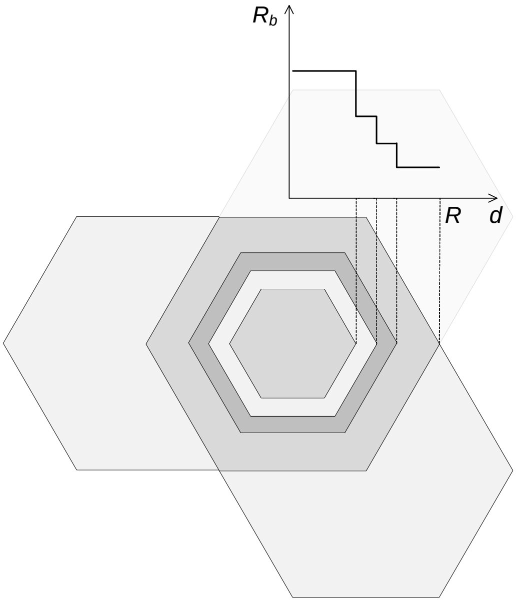

Fig. 8. Approximated cell coverage areas where given values of physical throughput are supported.

$$J = MCS_{1^{st}} - MCS_{last} + 1 \tag{13}$$

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

If only one frequency channel is considered per cell, the supported throughput is obtained as [1], [9]:

$$R_{b-\sup} = \frac{\iint_{O} R_b(d, R, K)dxdy}{\frac{3\sqrt{3}}{2} \cdot R^2} = \frac{\sum_{j=1}^{J} \left(\frac{3\sqrt{3}}{2} \cdot \left(d_j^2 - d_{j-1}^2\right) \cdot (R_b)_{MCS_{1^{st}}+1-j} \right)}{\frac{3\sqrt{3}}{2} \cdot R^2} \tag{14}$$

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.

MCS_1^{st}, MCS_2^{nd}, …, MCS_J^{th} depend on the CNIR value as defined in [9], varies from 0 to 8 and can be obtained from Table I, where the corresponding values for the physical throughput are also given. MCS_j=0 means that there is not enough coverage in that part of the cell (or coverage ring) in which case the system will not be viable. $C/(N+I)(R_b)$ is not a bijective function. Therefore, the value of CNIR that corresponds to a given R_b is the minimum value of CNIR, i.e., $CNIR_{min}$, which supports a throughput R_b. Hence $d_0 = 0$, and:

$$d_j = cnir^{-1}\left(\min\left(CNIR\left((R_b)_{MCS_{1^{st}}+1-j} \right)\right)\right),\ j = 1,\ldots, J. \tag{15}$$

$R_{b\text{-}sup}(p \cdot R_{step\,[\mathrm{m}]})$ is given by the following algorithm, in the range p = 1 to p_{max} (in the computations, R_{step} = 250 m and d_{step} = 5 m were considered):

```
for p = 1 to p_max
  {
   R = p·R_step;
   N_max = trunc(R/d_step);
   J = 0;
   d[0] = 0;
   for n = 1 to N_max
    {
      C/(N+I) = C(n·d_step)/{I(n·d_step,R, r_cc)+N};
      R_b_n=R_b[MCS(C/(N+I))];
      If (n > 1) then
        {
         If (R_b_n-R_b_n-1 <> 0) then
           {
            d[J]=d_step·(n-1);
            R_b[J]=R_b_n;
            R_b_n-1=R_b_n;
           }
         else
           {
            R_b_n-1 = R_b_n;
           }
      }
   R_b-sup[p] = 0;
   for j = 1 to J
    {
      R_b-sup[p] = R_b-sup[p] + (d[j]^2 - d[j-1]^2) Rb[j];
      R_b-sup[p] = R_b-sup[p]/R^2;
    }
  }
```

Figure 9 presents the correspondence between the CNIR vs. propagation distance curve and the stepwise function that represents the $CNIR_{min}$ threshold for each MCS versus R_b. This Figure illustrates how the mapping between CNIR and supported physical throughput relates to step distances between consecutive MCS, d_J, $d_{J\text{-}1}$, $d_{J\text{-}2}$, … 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 [10].

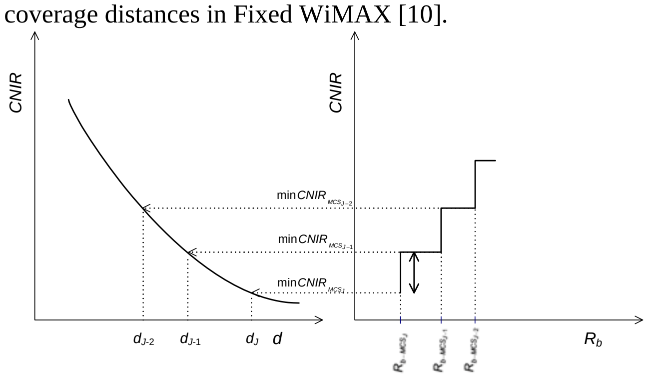

Fig. 9. Correspondence between the physical throughput for rings J, J-1, J-2, …, and the minimum CNIR*s* of consecutive MCS that map to step distances d_J, $d_{J\text{-}1}$, $d_{J\text{-}2}$, ….

According to the modified Friis equation, the received power (at a distance d) is given by:

$$p_r(d) = \frac{p_t \cdot g_t \cdot g_r \cdot \lambda^2}{(4\pi)^2 d^\gamma} \quad (16)$$

where $0 \le d \le R$, λ is the wavelength, P_t, G_t and G_r are the alternatives to p_t, g_t and g_r in dB (the transmitter power, and the transmitter and receiver gains), and γ is the propagation distance-loss exponent. The values for the transmitter power, and transmitter and receiver antenna gains are set at P_t = -2 dBW, G_t = 17 dBi (for the communication with SSs), and G_r = 9 dBi, respectively. The antenna for the communication between the RS and BS is however directional (120º sectored) and its gain is G_{RS} = 28 dBi (note that the RS also has an antenna with gain G_t, for the communication to/from SSs). The radio frequency bandwidth, noise figure, and frequency are b_{rf} = 3.5 MHz, N_f = 3 dB, and f = 3.5 GHz, respectively.

B. *DL with relays*

Figure 10 shows the throughputs of the different transmission hops for the DL (K=3). There are three transmission cases that also need to be analyzed individually:

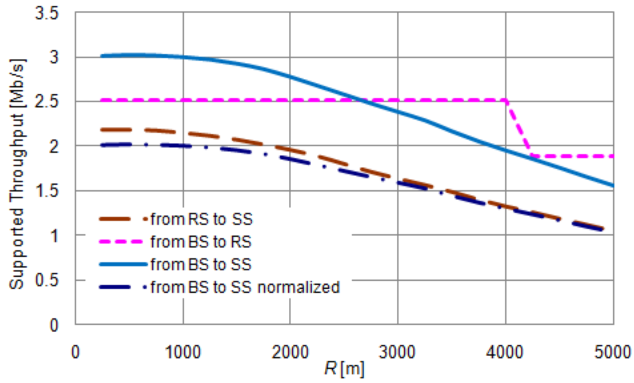

Fig. 10. Supported throughput as a function of R in the DL with deployed relays (K=3, omnidirectional BS).

i) **From BS to SS:** Throughput from BS to SS is sufficiently high, and gradually decreases as the cell coverage distance R increases. In our assumptions, 1/3 of the frame structure is assigned to the DL, so the DL throughput is obtained by multiplying this factor of 1/3 by the total obtained throughput. If we want to compare this value with the throughput in the RS coverage area, as they only have 2/3 of the coverage area, a normalized value $R_{b\text{-}central\text{-}norm}$ (representing 66.6% of the central coverage zone) is needed, obtained by multiplying the central coverage zone throughput of the multihop cell by 2/3.

ii) **From BS to RS:** The throughput from the BS to RS remains high (at a constant level) until the distance of four kilometres is reached, and then sharply decreases. This throughput is obtained by considering directional antennas at the RS, which greatly decreases co-channel interference (see Figure 7). Only two RS receive/cause interference from/to the central cell BS (note that the signal of interest for the RS comes from its own cell BS). The interference from each BS (into the RS) is computed as the received power from an interferer at a distance D+d:

$$i(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2}(D+d)^{-\gamma} \quad (17)$$

iii) **From RS to SS**: The throughput from the RS to SS is almost of same value as from the BS to SS. In our assumptions, 2/9 of the overall frame structure is assigned to this hop in the DL, so the DL throughput is obtained by multiplying this factor of 2/9 by the total obtained throughput.

C. *UL with relays*

Figure 11 show the throughput result for different UL transmission hops (K=3).

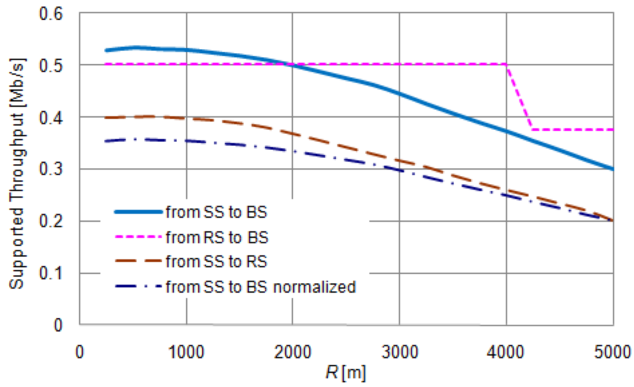

Fig. 11. Supported throughput as function of R in the UL, in the absence of sub-channelization (K=3, omnidirectional BS).

i) **From SS to BS:** Throughput from the SS to BS resembles the previous case for the DL. Throughput decreases with increasing cell coverage distance R. In our assumptions, 3/45 of the overall frame structure is assigned to the SS to BS UL hop, so the UL throughput for this hop is obtained by multiplying this factor of 3/45 by the total obtained throughput. If you want to compare this value with the throughput in the RS coverage zone, as they only cover 2/3 of the coverage area, a normalized throughput should be needed that is obtained by multiplying the throughput by 2/3.

ii) **From RS to BS:** The throughput from RS to BS remains high at constant level until a distance of four kilometres is reached, then sharply decreases. This throughput is obtained by the use of directional antennas at RS, which greatly decreases the co-channel interference (see Figure 7).

iii) **From SS to RS:** Throughput from the SS to RS is almost of same value as SS to BS. In our assumptions, communications from the SS to RS are allocated 2/45 of the overall frame structure, so this factor influences the throughput computation.

D. Use of Sub-channelization

The IEEE 802.16-2004 standard is only able to support sub-channelization in the UL. Therefore, to obtain a sufficient level of throughput for the UL, sub-channelization is used. Although the curves are not presented here, the main difference from Figure 11 is that the throughput from the RS to BS now remains constant even for the longest distances as the cell coverage distance varies [9]. There are no notable differences in other curves.

IV. Throughput with Sectorization and Relays

Constraints due to limited sub-frame system capacity support motivate us to consider tri-sectored antennas at the BS of the central coverage area. Here we have used the following equation to compute *C/I* from/to the BS at the central cell (for the DL and UL, respectively) but now with $D = 3\sqrt{k}R$:

$$C/I = \frac{d^{-\gamma}}{(r_{cc} \cdot R + 0.7 \cdot d)^{-\gamma} + (r_{cc} \cdot R - 0.22 \cdot d)^{-\gamma}} \qquad (18)$$

The formulation for communication between RSs and SSs is the same, as well as the one for communication between RSs and BSs. By considering tri-sectored antennas, we need to have one different channel (i.e., frequency carrier) for each sector. This way, more resources are made available to the RSs, and we can consider the assumptions from Figure 12 for the DL and UL frequencies sub-frames. The asymmetry factor between the UL and DL is 1:5 in this case. One can define the sector throughput for only 1/3 of the cell, meaning that (i) only one sector is covered by one frequency carrier, and (ii) only one RS coverage area is considered for each sector to determine the cell throughput, against three in the omnidirectional case.

Figures 13 and 14 give results for supported throughput for the DL and UL respectively (K=3). With tri-sectored BS antennas, on the one hand, the DL supported throughput is twice the omnidirectional case throughput. On the other hand, the UL supported throughput is more than four times higher. Apart from the gain arising from interference mitigation owing to tri-sectorization this is mainly due to the most favourable frame format (note that N_{sec} is the number of sectors, and it may take values of 1 or 3 in this paper):

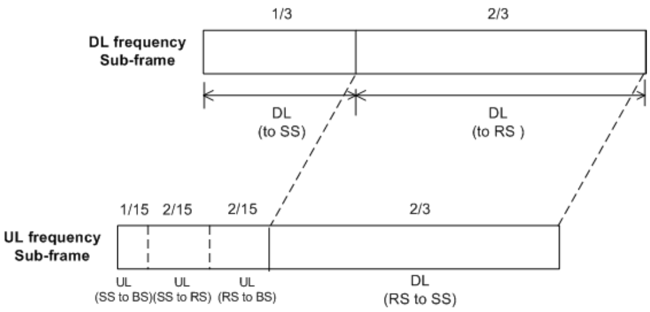

Fig. 12. Frame structure for UL and DL sub-frames with deployed relays (tri-sectored BS).

- N_{sec}/3 against 1/3 sub-frame space in the DL (BS to SS), as N_{sec} =3 frequency carriers are available to the central coverage zone;
- 2/3 against 2/9 sub-frame space in the DL (BS to RS);
- 2/3 against 2/9 sub-frame space in the DL (RS to SS);
- N_{sec} /15 against 3/45 sub-frame space in the UL (SS to BS);
- 2/15 against 2/45 sub-frame space in the UL (RS to BS), as N_{sec} =3 frequency carriers are available to the central coverage zone;
- 2/15 against 2/45 sub-frame space in the UL (SS to RS).

With this frame format, communications using a given frequency carrier are only from/to a sector and a RS. Hence, to obtain the supported throughput, the contribution from the central cell results from multiplying the sector 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:

$$\begin{aligned}(R_{b-\sup})_{equiv} &= R_{b-tot} = \frac{N_{\sec} \cdot R_{b-central} + 3 \cdot R_{b-RS-zone}}{3} = \\ &= \frac{1}{2} \cdot N_{\sec} \cdot R_{b-central-norm} + R_{b-RS-zone}\end{aligned} \qquad (19)$$

where $R_{b\text{-}tot}$ is the total throughput in the multihop cell (formed by the central zone plus RS zones).

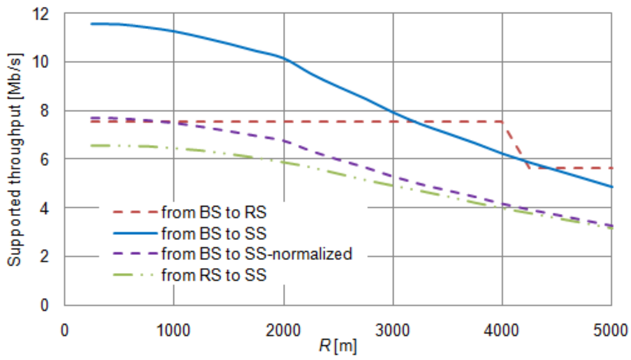

Fig. 13. Supported throughput as a function of R in the DL, with relays (K=3, tri-sectored BS).

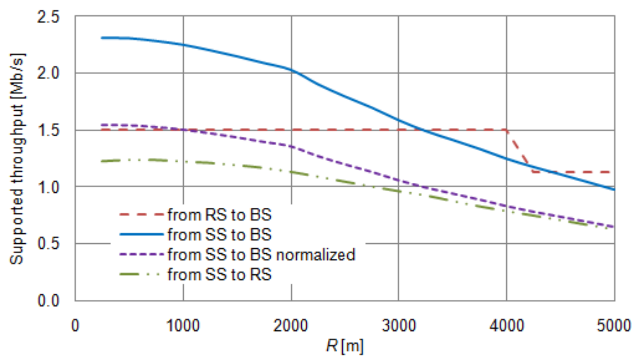

Fig. 14. Supported throughput as function of R in the UL, with relays (K=3, tri-sectored BS).

This 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.

In the future, we also may analyse the presence of sub-channelization in the UL with K=3, as well as its impact for the longest coverage distances when tri-sectored antennas are considered in the central coverage zone.

V. Cost/Revenue Optimization

A. Models

The economics of cellular systems can be viewed from the points of view of the different entities: subscribers, network operators, service providers, the regulator, and equipment vendors [11], [12], [13]. In this paper, although it is possible that in mobile multimedia networks for the network operator and service providers to be different entities, we do not distinguish between them. Thus we are considering the operator/service provider's point of view, whose primary bottom line is to make money from his business.

From a cellular planning perspective, the objective of the operator is to determine an optimal operating point that maximizes expected revenue. 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 costs 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 base station 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, i.e., 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) [14], [15].

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);
- 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, i.e., 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, e.g., 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,
- 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 [16] for hierarchical WiMAX-WiFi networks, however, here we follow the approach from [9].

The cost per unit area is given by:

$$C_{[\text{€/km}^2]} = C_{fi[\text{€/km}^2]} + C_b \cdot N_{hexagon\ /\ km^2} \tag{20}$$

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. If no relays were used the number of hexagons (i.e., hexagonal-shaped coverage zones) per unit area is given by:

$$N_{hexagon\ /\ km^2} = \frac{2}{3 \cdot \sqrt{3} \cdot R^2} \tag{21}$$

and the cost per BS is given by [9]:

$$C_b = \frac{C_{BS} + C_{bh} + C_{Inst}}{N_{year}} + C_{M\&O} \tag{22}$$

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.

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 [9] replacing "cells" by "hexagon-shaped coverage zones", and $N_{hexagon/km^2}$=$N_{cell/km^2}\cdot 3$. Note that the three RS coverage zones exactly correspond to an area of two hexagons.

The revenue in a coverage zone per year, $(R_v)_{cov\_zone}$, can be obtained as a function of the equivalent supported throughput per BS or sector (in the omnidirectional and tri-sectored cases, respectively), $(R_{b\text{-}sup})_{equiv}$, and the revenue of a channel with throughput R_b, R_{Rb}, by:

$$(R_v)_{cov\_zone} = \frac{\left(R_{b-\sup}\right)_{equiv\,[\text{kb/s}]} \cdot T_{bh} \cdot R_{R_b\,[\text{€/min}]}}{R_{b-ch\,[\text{kb/s}]}} \tag{23}$$

where N_{sec} is the number of sectors (one or three) T_{bh} is the equivalent duration of busy hours per day, and $R_{b\text{-}ch}$ is the bit rate for the basic "channel". In the tri-sectored case, as one assumes that each sector has one different transceiver, there is a separate frequency channel available for each sector.

The revenue per unit area per year, $R_{v[\text{€/km}^2]}$, is obtained by multiplying the revenue per coverage zone by the number of hexagon-shaped coverage zones per unit area:

$$R_{v[€/km^2]} = N_{hexagon\ /km^2} \cdot (R_v)_{cov\_zone} = \\ = N_{hexagon\ /km^2} \cdot \frac{(R_{b-\sup})_{equiv\,[\text{kb/s}]} \cdot T_{bh} \cdot R_{R_b\,[€/\min]}}{R_{b-ch\,[\text{kbps}]}} \tag{24}$$

The (absolute) profit is given by

$$P_{[€/km^2]} = R_v - C, \tag{25}$$

from which, the profit in percentage terms is given by:

$$P_{[\%]} = \frac{R_v - C}{C} \cdot 100\,. \tag{26}$$

A. Hypothesis and assumptions with relays

If a topology with the deployment of relays is considered, the assumptions for costs with relays are the following:

i) Cost for BS and RSs

- $C_{BS\text{-}omni}$=9000€;
- C_{RS} =9000/5 =1800€;
- $C_{BS\text{-}trisect}$=15000€.

In these cells there are three RS coverage areas, with an area equal to the central coverage zone. The BS plus three RS need to guarantee the coverage for the whole area of cell. The equivalent cost for the cell base/relay station infrastructure, denoted by $C_{BS\text{-}equiv}$, represents an average cost per hexagonal coverage zone between the BS and RS, and is given by:

$$C_{BS-equiv} = \frac{(C_{BS} + 3C_{RS})}{3}. \tag{27}$$

ii) Cost for backhaul

The cost for the normal backhaul is the same as in case without relays for RSs and BS, i.e., the equivalent cost for the normal backhaul for a hexagonal-shaped coverage zone (in multihop cells) is given by:

$$C_{bh-equiv} = {}^{1}\!/_{3}\, C_{bh} \tag{28}$$

for each hexagonal coverage area. This is because backhaul is only needed for the central zone of the cell (i.e., the coverage area of the BS).

iii) Installation cost

The cost for installation is the same for every BS and RS. In a cell, it is four times the installation cost of a BS (as, with this relay configuration, there are three RS besides the BS), C_{inst}, but we need to multiply C_{inst} by 1/3 to obtain the installation cost for each hexagonal coverage zone. This is given by:

$$C_{inst-equiv} = {}^{4}\!/_{3}\, C_{inst} \tag{29}$$

iv) Maintenance and operational costs

In comparison with the case without relays, we assume that the maintenance and operational costs for the BS are the same but the ones for the three RS are one half of the BS ones. This is given by

$$C_{M\&O-equivalent} = \frac{\left(C_{M\&O} + {}^{3}\!/_{2}\, C_{M\&O}\right)}{3} \tag{30}$$

These equations may be applied to the topology with relays and omnidirectional BSs. In this case the following parameters were used (see Table II):

- $C_{BS\text{-}omni}$=9000€, C_{RS}=1800€ (i.e., $C_{BS\text{-}equiv}$ =4800€);
- C_{inst}=1000€ (i.e., $C_{inst\text{-}equiv}$ = 1333.33€);
- C_{bh}=2500 (i.e., $C_{bh\text{-}equiv}$ =833.33€);
- $C_{M\&O}$=1000€ (i.e., $C_{M\&O\text{-}equiv}$=833.33€).

These values are partly based on those from [5, chap. 18], [9].

For the tri-sectored BS antennas the parameters are the following, Table II (note that the costs for the normal backhaul, and maintenance and operation are the same):

- $C_{BS\text{-}tri\text{-}sect}$=15000€, C_{RS}=1800€ (i.e., $C_{BS\text{-}equiv}$ =6800€);
- C_{inst}=1500€ (i.e., $C_{inst\text{-}equiv}$ = 2000€);
- C_{bh}=2500 (i.e., $C_{bh\text{-}equiv}$ =833.33€);
- $C_{M\&O}$=1000€ (i.e., $C_{M\&O\text{-}equiv}$=833.33€).

The value for the fixed cost C_{fi} is obtained by multiplying C_{fi}=110 €/km^2 (from equation (21) from [9]) by the ratio between the reuse patterns 3/7. Note that C_{fi}=110 €/km^2 corresponds to K=7 (corresponding to an annual cost of a license of 10 000 000 €).

TABLE II
COSTS WITH RELAYS FOR OMNIDIRECTIONALAND TRI-SECTORED BS ANTENNAS (K=3)

Cost	Omnidirectional K=3	Tri-sectored K=1
C_{fi}[€/km^2]	47.14	141.43
C_{BS}[€]	4800	6800
C_{Inst}[€]	1333.33	2000
C_{bh}[€]	833.33	833.33
$C_{M\&O}$[€/year]	833.33	833.33

It should be noted that with tri-sectorization the cost for 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 [5, Table 18.8]. When tri-sectored antennas and RF equipment (including the outdoor units) are considered, we assume 60% increase on the cost of BS and RS equipment. This means we assume that the channel equipment costs 30% of the BS (or RS) [5, chap. 18]; hence, with tri-sectored equipment, two times 30% needs to be added to the cost. For comparison purposes, one is also considering three frequency carriers per sector with K=1, i.e., $3{\cdot}K{\cdot}N_{sec}$ =9. In this case the fixed costs for the license are three times higher, as well as the channel equipment at the BSs and RSs, whilst computing the throughput by using (19).

With tri-sectorization some other costs are also higher (e.g., BS and its installation). However, higher costs are compensated with the higher revenues. Because throughput is higher (mainly due to the difference on the sub-frame format), a gain of $\frac{N_{\text{sec}}/3}{1/3} = N_{\text{sec}}$ occurs, which compensated the lowest value of the frame throughput.

Besides, it is worthwhile to note that with relays the UL traffic is ~1/5 times the DL traffic (both with omnidirectional and tri-sectored BSs); hence UL revenues are lower than in DL.

B. Optimisation and profit with relays

In seeking profit optimisation, revenues should be maximised with respect to costs. By using Table II (but also Table III), and the results for the supported throughput, the curves for costs, revenues and profit in percentage were obtained. The costs and revenues with relays (K=3, omnidirectional BS antenna), in €/km^2, are depicted in Figure 15, for R_{144}=0.0025 and 0.005 €/min. Note that the volume of information transferred during 60 s (1 min) at 144 kb/s is 144·60/8=1080~1 MB; hence, from now one will use €/MB instead of €/min as the unit for the price.

In order to optimize the BWA network, the profit per unit area is of fundamental importance. However, it is not sufficient to compute the absolute profit because, as is shown in Figure 15, a certain level of profit may correspond to different values of cost. For example, cost is higher for tri-sectored cells; hence, revenue needs to be higher to obtain the same profit. This justifies the need to represent the profit in percentage, as defined by (26). The operator's/services provider's goal is to optimise this profit in percentage.

Results are obtained with RSs and K=3 (tri-sectored BS antennas, identified by "sect.&RSs") and K=3 (omnidirectional BS antennas, identified by "with RSs") in the DL case. Figure 16 presents the results for the profit in percentage for R_{144}=0.0025 and 0.005 €/MB. The case without relays (with K=3) is also presented for comparison purposes (extracted from the analysis in [9]), and is identified by "no RSs". It is clear that the use of relays with no sectorization in the BS leads to a lower profit (K=3). Only the use of sectorization (an example is presented for K=3, too) enables to achieve higher profit. The optimum (maximum) values occur for coverage distances up to 1000m.

TABLE III
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

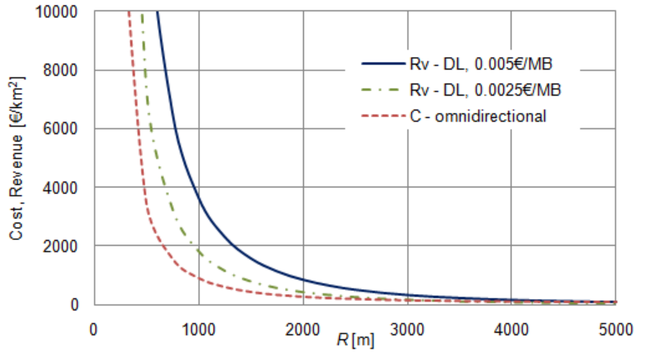

Fig. 15. Cost and revenues with relays (K=3, omnidirectional BS antenna) for prices per MB R_{144}=0.0025 and 0.005 €/MB, in the DL.

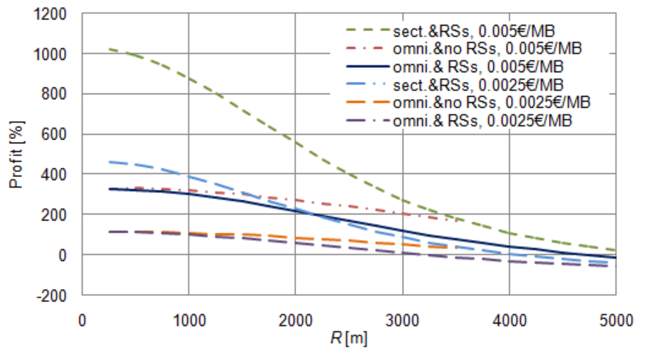

Fig. 16. Profit in percentage for a price per MB R_{144}=0.0025 and 0.005 €/MB, in the DL and K=3, without and with RSs (omnidirectional and tri-sectored BS antennas for the latter).

C. UL analysis with K=3

We have also performed analysis for UL with K =3. By using the values from Table II (but also Table III), and the results for the supported throughput from Sections III and IV, the curves for the costs, revenues and profit in percentage have been obtained.

The costs and revenues with relays (K=3, omnidirectional BS antenna), were also analyzed, for R_{144}=0.0025 and 0.005 €/MB. In Figure 17, it is shown that, in the UL, for K=3 and omnidirectional BS antennas there is no profit, i.e., revenues are always lower than costs. The profit in percentage is defined as in (25), and prices per MB of R_{144}=0.0025 and 0.005 €/MB are considered for K=3 in the UL case. Results are shown with relays with tri-sectored (identified by "sect.&RSs") and omnidirectional (identified by "omni.&RSs") BS antennas.

In the UL, with relays, R_{144}=0.005 €/MB, only the use of tri-sectored BS antenna (an example is presented for K=3 in Figure 17) enables to achieve positive profit, in percentage. As verified for the DL, the maximum values also occur for coverage distances up to 700-1000 m. With R_{144}=0.0025 €/MB, positive profit is achievable only up to R~700 m. No sub-channelisation is considered in these curves. Results with no RSs are not included for such K = 3 because, with omnidirectional antennas, as the CNIR is so low, it was impossible to obtain results for the supported throughput [9].

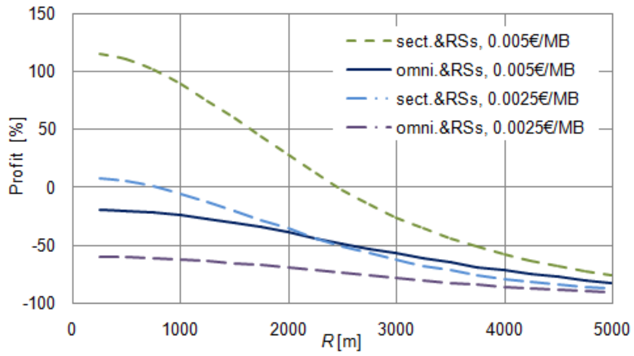

Fig. 17. Profit in percentage for prices per MB R_{144}=0.0025 and 0.005 €/MB, in the UL and K=3, with RSs (omnidirectional and tri-sectored BS antennas for the latter).

D. Comparison of tri-sectored and omnidirectional cells with different Ks and number of carriers

Until now, it is assumed that only one carrier was used per cell/sector, i.e., the total bandwidth in each communication direction is as follows:

- **Omnidirectional cells:** 3.5 MHz for K = 1 and 10.5 MHz for K = 3;
- **Tri-sectored cells:** 3·3.5 = 10.5 MHz for K=1 and 3·10.5 = 31.5 MHz for K = 3.

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 following cases (with a total bandwidth of 31.5 MHz):

i) Comparison with omnidirectional BSs and *K*=3 (three carriers/sector)

With no RSs and sectorization ("sect.&no RSs") the economic performance is weak (see Figure 18), 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, as shown in Figure 18. With RSs, with omnidirectional central coverage zone antennas higher profits are only achievable for Rs up to ~700m.

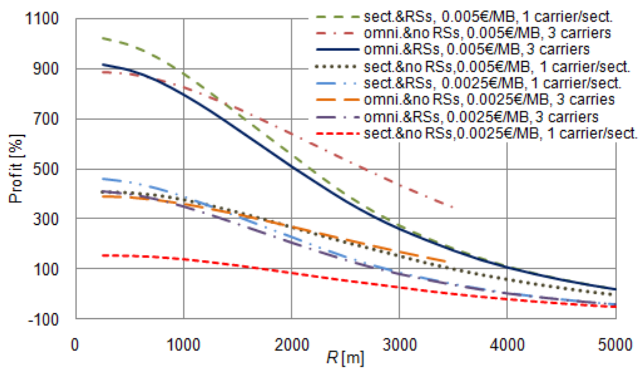

Fig. 18. Comparison between omnidirectional (3 carriers) and tri-sectored (one carrier/sector) BSs under the same total bandwidth for prices per MB R_{144}=0.0025 and 0.005 €/MB, in the DL and K=3.

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 18 (mainly in the example for R_b=0.005€/MB).

ii) Comparison with tri-sectored BSs and *K*=1 (3 carriers per sector)

Figure 19 addresses the case with tri-sectored antennas and RSs ("sect.&RSs"), and shows a comparison between the curves for K=3 (one carrier/sector), also shown in Figure 18, and the case K=1 (three carriers/sector).

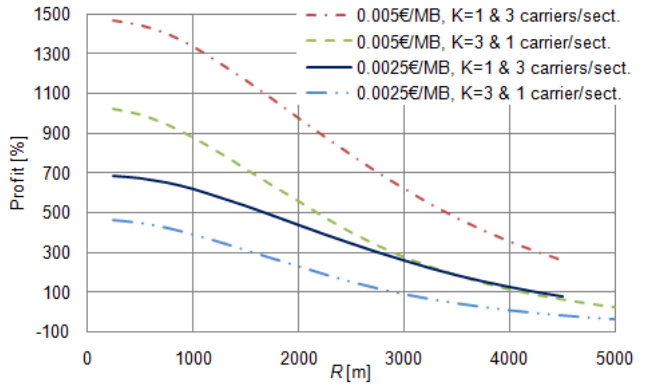

Fig. 19. Comparison between K = 1 and K = 3 under the same total bandwidth for prices per MB R_{144}=0.0025 and 0.005 €/MB, in the DL, with RSs and tri-sectored BS antennas.

From the curves, it is clear that, under the same total bandwidth, it is preferable to consider K=1 and three carrier/sector instead of K=3 and one carrier per sector, as the profit in percentage increases from ~1000% to ~1450% (example for R~500 m).

VI. Conclusion

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

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 of the coverage ring. Throughput typically decreases as the cell radius increases; however, 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 BSs are 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.

In our proposal, under the deployment of relays, FDD mode is considered although TDD is additionally supported over the FDD UL sub-frame for RS/SS communications. Frames need to guarantee resources for BS to SS communication, as well as BS to RS and RS to SS communication. A 1:5 asymmetry factor between the UL and DL is considered.

Although the reuse distance is augmented by a factor of $\sqrt{3}$, we have first shown that, with omnidirectional BSs, the use of relays corresponds to lower values of the supported throughput for K=3. It has also been verified that the presence of sub-channelization 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 attainment of values of throughput comparable to the ones without using relays (see Figure 10 in [9]). This is due to the more favourable frame format.

Deployment with relays can be cheaper than using the BS alone. Because the use of relays, through helping to improve 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.

Under a fixed total bandwidth, by comparing the topologies with omnidirectional and tri-sectored BS antennas, it is shown that with RSs and with coverage distances up to ~1300m the achievable profit is only clearly higher with the use of tri-sectored BSs. Results also show that under the same fixed bandwidth and for the example where the coverage distance is set at R~500 m, it is preferable to consider K=1 with three carriers per sector instead of K=3 with one carrier per sector, whereby profit in this case is increased by more than 45% from ~1000% to ~1450%. Moreover, if the price per MB is increased from 0.0025 to 0.005 €/MB, the achievable profit more than doubles under the aforementioned improved configuration.

Our proposal for the frame structure accounts for wireless communications traffic asymmetry. It is shown that this proposed frame structure is mainly advantageous with tri-sectored BSs (or central coverage zone antennas). With tri-sectored BSs, given that 1/3 of the DL frequency sub-frame is used for each sector (i.e., the three sectors give user access to N_{sec}/3=1 (=100%) of one DL sub-frame), there is no loss of capacity for the DL containers compared with the case where no RSs are deployed.

One possibility for future work on the optimization of cellular configurations with relays is to explore different assumptions for the prices of relays, and to jointly achieve profit curves considering the UL and DL contributions to supported traffic. Another possibility is to consider different assumptions for costs which change with time.

LIST OF SYMBOLS

$A_{multihop}$ - area for the multihop cell (with relays)
$A_{singlehop}$ - area for the singlehop cell (with no relays)
$Auxfactor(d)$ - auxiliar factor to compute the physical throughput at a distance d
b_{rf} - radio frequency bandwidth
C - cost per unit area
$C/(N+I)$ - carrier-to-noise-plus-interference ratio
C/I - carrier-to-interference ratio
C_b - cost per BS
C_{bh} - cost for the normal backhaul (in singlehop cells)
$C_{bh\text{-}equiv}$ - equivalent cost for the normal backhaul for a hexagonal-shaped coverage zone (in multihop cells)
C_{BS} - cost of the BS
$C_{BS\text{-}omni}$ - cost for an omnidirectional BS
$C_{BS\text{-}trisect}$ - cost for tri-sectored BS
C_{fi} - fixed term of the costs
C_{inst} - installation cost (in singlehop cells)
$C_{inst\text{-}equiv}$ - installation cost for a hexagonal-shaped coverage zone (in multihop cells)
$C_{M\&O}$ - maintenance and operational costs
$C_{M\&O\text{-}equiv}$ - equivalent maintenance and operational costs
$CNIR_{min}$ - minimum carrier-to-noise-plus-interference ratio
C_{RS} - cost for a RS
D - reuse distance
d_j - step distances between consecutive MCSs
f - frequency
G_r - receiver gain
G_{RS} - antenna gain for the communication between the RS and BS
G_t - transmitter gain
J - number of different coverage rings in a cell or hexagonal coverage zone
K - reuse pattern
MCS_j - order of the MCS at the coverage ring j
N_f - noise figure
$N_{hexagon/km^2}$ - number of hexagons (i.e., hexagonal-shaped coverage zones) per km^2
N_{year} - project's lifetime
P - absolute profit
$P_{[\%]}$ - profit in percentage terms
$p_r(d)$ - received power at a distance d
P_t - transmitter power
R - coverage distance
R_b - physical throughput
$R_b(d)$ - physical throughput at a distance d
$R_b(R)$ - physical throughput at the edge of the central coverage zone at a distance R
$R_{b\text{-}central}$ - supported throughput at the central zone of the multihop cell
$R_{b\text{-}central\text{-}norm}$ - normalized supported throughput at the central coverage zone for a multi-hop cell, representing 2/3 of its area and throughput
$R_{b\text{-}ch}$ - bit rate for the basic "channel"
$R_{b\text{-}max}$ - maximum throughput in the RS coverage zone
$R_{b\text{-}RS\text{-}zone}$ - supported throughput at the RS zone of the multihop cell
$R_{b\text{-}sup}$ - supported throughput
$(R_{b\text{-}sup})_{equiv}$ - equivalent supported throughput
$(R_{b\text{-}sup})_{fromSS}$ - supported throughput from the SS to RS
$(R_{b\text{-}sup})_{RS}$ - supported throughput at the RS coverage zone

$(R_v)_{cov\_zone}$ - revenue in a coverage zone per year
r_{cc} - co-channel reuse factor
R_{Rb} - revenue for a channel with throughput R_b
T_{bh} - equivalent duration of busy hours per day

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Fernando J. Velez (M’93–SM’ 05) received the Licenciado, M.Sc. and Ph.D. degrees in Electrical and Computer Engineering from Instituto Superior Técnico, Technical University of Lisbon in 1993, 1996 and 2001, respectively. Since 1995 he has been with the Department of Electromechanical Engineering of University of Beira Interior, Covilhã, Portugal, where he is Assistant Professor. He is also researcher at Instituto de Telecomunicações, Lisbon, and was a Research Fellow in King’s College London in 2008/09. He made or makes part of the teams of RACE/MBS, ACTS/SAMBA, COST 259, COST 273, COST 290, ISTSEACORN, IST-UNITE, PLANOPTI, COST 2100, COST IC0902 and COST IC 0905 (TERRA) European projects, he participated in SEMENTE, SMART-CLOTHING and UBIQUIMESH Portuguese projects, and he was or is the coordinator of five Portuguese projects: SAMURAI, MULTIPLAN, CROSSNET, MobileMAN and OPPORTUNISTIC-CR. He is the coordinator of the WG2 (on Cognitive Radio/Software Defined Radio Co-existence Studies) of COST IC0905 “TERRA”. Prof. Velez has authored two books, several book chapters, around 80 papers and communications in international journals and conferences, plus 25 in national conferences, and is a senior member of IEEE and Ordem dos Engenheiros (EUREL), and a member of IET and IAENG. His main research areas are cellular planning tools, traffic from mobility, cross-layer design, spectrum sharing/aggregation, and cost/revenue performance of advanced mobile communication systems.

Muhamad Kashif Nazir concluded his MSc in Space Science at the University of Punjab Lahore in 2002 and his MSc in Signal Processing for Communications at King's College London in 2010. His research is on Fixed WiMAX with multi-hop relays and its cost/ revenue analysis.

A. Hamid Aghvami (M’87–SM’91–F’05) received the M.Sc. and Ph.D. degrees from the University of London, London, U.K., in 1978 and 1981, respectively. In 1984, he joined the academic staff of King’s College London, where he was promoted to Reader in 1989, became a Professor of telecommunications engineering in 1993, and is currently the Director of the Centre for Telecommunications Research. He carries out consulting work on digital radio communications systems for both British and international companies. He is the author of more than 500 technical papers and has given invited talks on various aspects of personal and mobile radio communications and courses on the subject worldwide. Prof. Aghvami is a Fellow of the Royal Academy of Engineering and the Institution of Electrical Engineers. From 2001 to 2003, he was a Member of the Board of Governors of the IEEE Communications Society. He is a distinguished Lecturer of the IEEE Communications Society and has been a Member, Chairman, and Vice Chairman of the technical program and organizing committees of several international conferences. He is also the Founder of the International Conference on Personal, Indoor, and Mobile Radio Communications.

Oliver Holland ((M’02) obtained his BSc degree with First Class Honours from Cardiff University, and his PhD from King's College London. Oliver is currently working on dynamic spectrum usage optimisation for green mobile communications. Among his other activities, Oliver is presently a member of the IEEE 1900.6 standardisation effort, and in the past has been the Designated Representative for King's College London within IEEE 1900.4 and was one of the technical editors of the IEEE 1900.4 standard. He is a voting member of IEEE Standards Coordinating Committee 41 (“Dynamic Spectrum Access Networks”), and acts as an Officer (Treasurer) for that committee. He is a member of the Management Committee representing the UK for two prestigious European Science Foundation managed collaborative "COST" efforts, COST IC0902 and COST IC0905 “TERRA”, and acts in a management position within an EU “Network of Excellence” on Cognitive Radio and related topics. He serves on the Technical Programme Committee of a number of major conferences, including IEEE Globecom, IEEE CCNC, IEEE PIMRC, IEEE VTC, IEEE INFOCOM, and IEEE ICC, and frequently serves as a reviewer and organiser/editor for various prestigious international Conferences and Journals. Dr. Holland is a guest editor of the special issue "Achievements and the Road Ahead: The First Decade of Cognitive Radio," published in IEEE Transactions on Vehicular Technology, is a Specialist Editor of the SAIEE Africa Research Journal, and is co-chair of the "Cognitive Radio and Cooperative Communications" track of IEEE VTC 2010 Fall. He has chaired technical sessions on a variety of topics in various prestigious international conferences, and has been invited to give international tutorials on Cognitive Radio and other topics.

Daniel Robalo received the Licenciado and MSc degrees in Electrical Engineering from University of Beira Interior, Covilhã, Portugal, in 2005 and 2008, respectively. He is currently a PhD student and a researcher in Instituto de Telecomunicações, where he has been participating in MobileMAN, a project on WiMAX deployment. Mr. Robalo’s research interest is in the field of design and implementation of Broadband Wireless Access networks. Besides conference papers, he published journal papers and book chapters.