Cost/Revenue Tradeoff in the Optimization of Fixed WiMAX Deployment With Relays

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***Abstract*—In fixed Worldwide Interoperability for Microwave Access (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, multihop cells are formed by a central coverage zone and three outer coverage zones, which are served by cheaper low-complexity relays. Although the reuse distance in this case is augmented by a factor of $\sqrt{3}$, we show that, with the use of relays in frequency-division duplexing (FDD) mode with an adapted time-division duplexing (TDD) uplink (UL) subframe structure to accommodate communication from/to the relay station (RS) to/from subscriber station (SS), only the consideration of trisectored base stations (BSs) with a reuse pattern of $K = 3$ enables attainment of values for the cell per sector throughput that is comparable with cases without the use of relays. Cost/revenue optimization results show that trisectored 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 $R \sim 500$ m, we show that it is preferable to consider $K = 1$ with three carriers per sector instead of $K = 3$ with one carrier per sector, whereby the profit in this case is increased from ∼1000% to ∼1450%. Furthermore, if the price [in (€/MB)] is increased from 0.0025 to 0.005, the achievable profit more than doubles.**

***Index Terms*—Broadband communication, economics, planning, relays, Worldwide Interoperability for Microwave Access (WiMAX).**

Nomenclature

A_{multihop}	Area for the multihop cell (with relays).
$A_{\text{singlehop}}$	Area for the singlehop cell (with no relays).
$\text{Auxfactor}(d)$	Auxiliar factor to compute the physical throughput at a distance d.
b_{rf}	RF bandwidth.
C	Cost per unit area.
$C/(N+I)$	CNIR.
C/I	Carrier-to-interference ratio.
C_b	Cost per BS.
C_{bh}	Cost for the normal backhaul (in singlehop cells).
$C_{\text{bh-equiv}}$	Equivalent cost for the normal backhaul for a hexagonal-shaped coverage zone (in multihop cells).
C_{BS}	Cost of the BS.
$C_{\text{BS-omni}}$	Cost for an omnidirectional BS.
$C_{\text{BS-trisect}}$	Cost for a trisectored BS.
C_{fi}	Fixed term of the costs.
C_{inst}	Installation cost (in singlehop cells).
$C_{\text{inst-equiv}}$	Installation cost for a hexagonal-shaped coverage zone (in multihop cells).
$C_{\text{M\&O}}$	Maintenance and operational costs.
$C_{\text{M\&O-equiv}}$	Equivalent maintenance and operational costs.
$\text{CNIR}_{\min}$	Minimum CNIR.
C_{RS}	Cost for an 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 the 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.
$N_{\text{hexagon/km}^2}$	Number of hexagons (i.e., hexagonal-shaped coverage zones) per square kilometer.
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.

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$R_b(R)$	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 multihop cell, representing two thirds of its area and throughput.
$R_{b-\text{ch}}$	Bit rate for the basic "channel."
$R_{b-\max}$	Maximum throughput in the RS coverage zone.
$R_{b-\text{RS}-\text{zone}}$	Supported throughput at the RS zone of the multihop cell.
$R_{b-\sup}$	Supported throughput.
$(R_{b-\sup})_{\text{equiv}}$	Equivalent supported throughput.
$(R_{b-\text{sup}})_{\text{fromSS}}$	Supported throughput from the SS to the RS.
$(R_{b-\text{sup}})_{\text{RS}}$	Supported throughput at the RS coverage zone.
$(R_v)_{\text{cov\_zone}}$	Revenue in a coverage zone per year.
r_{cc}	Cochannel reuse factor.
R_{Rb}	Revenue for a channel with throughput R_b.
T_{bh}	Equivalent duration of busy hours per day.

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 the downlink (DL) in WiMAX, techniques such as subchannelization may be applied to reduce the impact of noise on link performance. However, only mobile WiMAX allows for subchannelization in both the UL and the 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 subchannelization 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). To more effectively use the RF spectrum, it is important to choose a frequency reuse scheme that leads to a coverage guarantee and improved system capacity while minimizing interference. Broadband wireless access (BWA), enabling the operation of multihop relay stations (RSs), aims to enhance not only the coverage but also the 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 wireline backhaul and have much lower hardware complexity and, hence, can significantly reduce the deployment cost of the system. The main objective is to achieve the highest values for the CNIR, i.e., $C/(N+I)$, and, in return, the maximum supported throughput, by using relays for a given frequency reuse pattern (e.g., $K=3$).

In this paper, 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 trisectored 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 per 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 optimization can be achieved by appropriately parameterizing a merit function, accounting for costs and revenues. Optimization of the cost/revenue tradeoff provides a means of combining several contributing factors in cellular planning, including the determination of the reuse pattern, the 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 optimization (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 analyze 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 optimization 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 the 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 trisectorization and relays. Section V investigates the cost and revenue optimization of these WiMAX deployments. Finally, Section VI concludes this paper.

II. Carrier-to-Noise Plus Interference Ratio 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, which is served by the BS, and three 240° sectored coverage

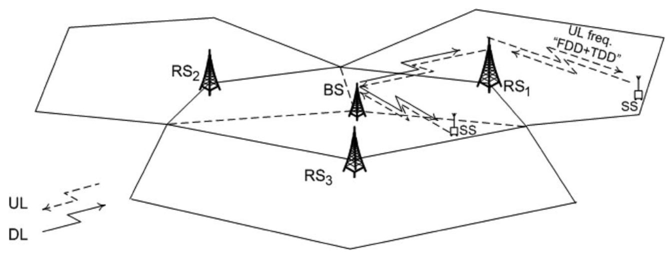

Fig. 1. BS, RS, and respective "hexagonal" coverage areas.

areas, which are served by individual RSs, i.e., RS_1, RS_2, and RS_3 (see Fig. 1). While the BS antenna may be either omnidirectional or sectored, the 240° sectored RS antennas facilitate nonoverlapping 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 subframes within the radio channel, which is created for that purpose [2]. With trisectored 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 subframes are allocated to the communication to/from relays, Fig. 2 shows the fixed WiMAX FDD mode frame structure assumed in this paper.

The WiMAX frame is divided into DL and UL subframes, which, in turn, include subdivisions with the following purposes (see Fig. 2):

1) BS-to-SS communication;
2) SS-to-BS communication;
3) BS-to-RS communication;
4) RS-to-BS communication;
5) RS-to-SS communication;
6) 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 subframe structure from [3] and explores the inclusion of RS DL traffic/communications from the RS to the SS into the UL frequency subframe, differently from the proposal for IEEE 802.16j [4]. Although the version of fixed WiMAX we consider here originally used FDD, this proposal implies that time-division duplexing (TDD) needs to be additionally supported (over the FDD frame structure) for RS-to-SS communications, as shown in Fig. 1. Hence, the proposal for DL and UL frequency subframes from Fig. 2 assumes an asymmetry factor of 1 : 5 between the UL and the DL and makes extra resources available to DL RS-to-SS communications by using the UL subframe, via TDD, as shown in Fig. 1. This type of RS is not standardized or available; however, this structure for frequency subframes 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 subframe.

The advantage of using relays arises from the fact that cochannel interference now is from cells at a larger distance, because the reuse distance is $\sqrt{3}$ times more than with no relays. This reuse distance D is given by (see [5] and [6])

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

where K is the reuse pattern, which is 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 Fig. 3. The cell is formed by a central coverage zone, with a hexagonal shape, and three hexagonal outer coverage areas with 240° sectored antennas, as shown in Fig. 3, each occupying two thirds 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]

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

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

B. Assumptions

A set of assumptions is considered in this paper 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 Fig. 3.

For the DL, the objective is to maximize the supported throughput. The optimization process is twofold [2].

1) 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 a distance R, i.e., $R_b(R)$, needs to be as high as possible.
2) 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 (to cope with RS communications, see Fig. 2), the DL supported throughput in the central coverage area is approximately one third of the total throughput.
   b) *Maximization of $(R_{b-\text{sup}})_{\text{RS}}$ in SSs in the three relay coverage zones:* The maximum throughput in the RS coverage area is $R_{b-\max} = \min\{R_b(R), (R_{b-\text{sup}})_{\text{RS}}\}$ multiplied by two ninths, i.e., $(2/9) \cdot R_{b-\max}$, 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 $(R_{b-\text{sup}})_{\text{RS}}$ 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 the communication with the BS are considered to be directional BSs, 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

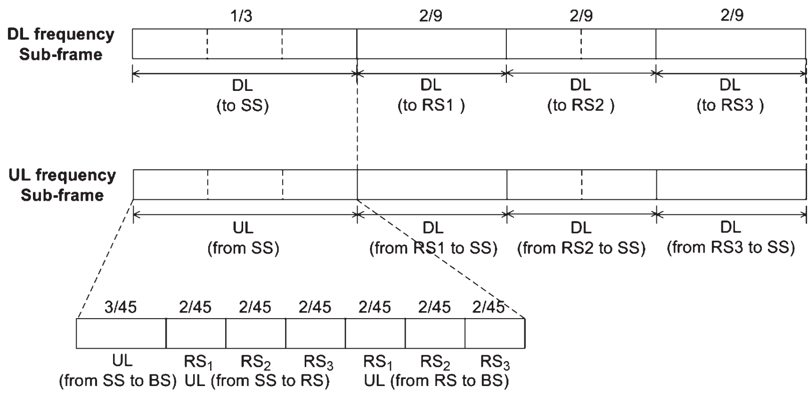

Fig. 2. Structure of DL and UL subframes supporting the deployment of relays (omnidirectional BSs).

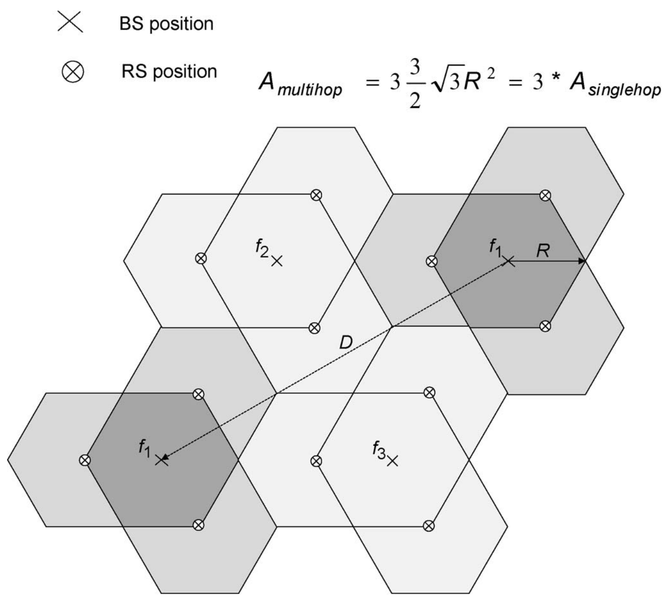

Fig. 3. Cell with the RS at the edge of the central coverage area.

$(2/9) \cdot R_{b-\max}$ 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, i.e., $R_b(d)$, depends on the supported MCS, which is given by [2]

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

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 us assume that the 16-QAM 1/2 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 $C/(N+I)(d)$ from the RS coverage area is within the range 1–8. The 16-QAM 1/2 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 that supported in the BS-to-RS link (16-QAM 1/2 in this example), the throughput for RS will be $(2/9) \cdot R_b(R)$; otherwise, the throughput will be $(2/9) \cdot (R_{b-\sup})_{\text{RS}}$.

TABLE I
AuxFactor FOR DIFFERENT VALUES OF THE MCS ID FOR THE COMMUNICATIONS TO THE SSs AT THE RS COVERAGE AREA

ID	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 the supported throughput R_{b-sup} is also twofold [2].

1) 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 $(2/45) \cdot R_{b-\sup}$.
2) 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 $(3/45) \cdot R_{b-\sup}$).
   b) Maximization of the offered throughput from SSs to RSs at the three RS coverage areas (the maximum here is $(2/45) \cdot (R_{b-\sup})_{\text{fromSS}}$).
3) Since the RS antennas are directional, the BS only receives interference from two BSs at a distance $D + R$. At the RS, it is only possible to achieve $(2/45) \cdot (R_{b-\sup})_{\text{fromSS}}$, where $(R_{b-\sup})_{\text{fromSS}}$ refers to the supported throughput from the SS to the 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 individually analyzed.

1) *BS to SS:* BS-to-SS communication is the simple case from Fig. 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.

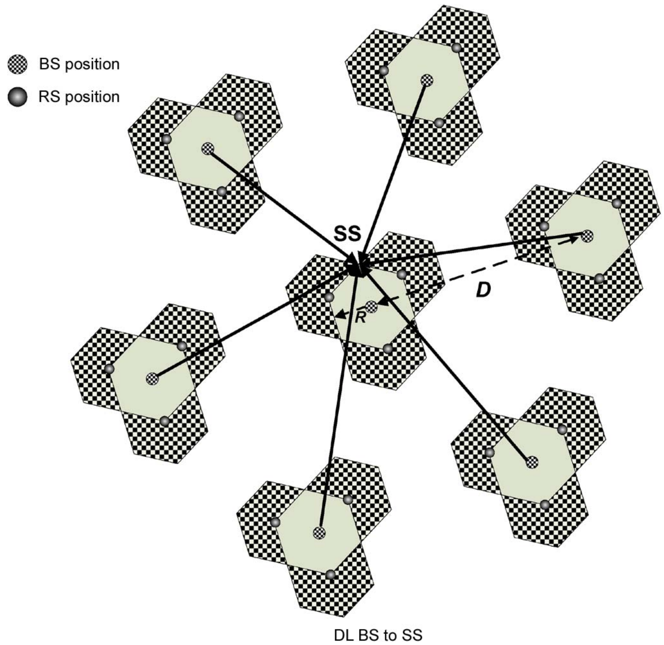

Fig. 4. DL scenario: distances from the BS interferers to the SS.

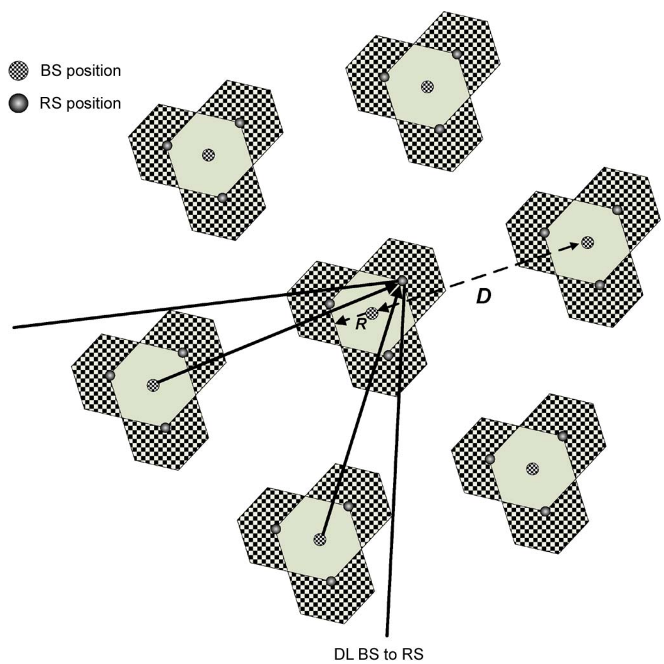

Fig. 5. DL scenario with 120° RS sectored antennas for the communication with the BS (and 240° sector RS coverage area).

2) *BS to RS:* In the case of BS-to-RS communication, one assumes that RSs are using 120° directional antennas and only receive interference from two BSs, as depicted in Fig. 5. This significantly enhances C/I, as will be highlighted in later discussion. Therefore, $(D+\alpha R)^{-\gamma}/R^{-\gamma} = (r_{\mathrm{cc}}+\alpha)^{-\gamma}$ has a coefficient of 2 while $\alpha = 1$, and C/I is given by

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

Note that the cochannel reuse factor r_{cc} is given by $r_{\mathrm{cc}} = D/R$.

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

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

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

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

There are two RSs 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 in (9), shown at the bottom of the page [2].

D. UL Scenarios

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

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

$$C/I = \frac{(r_{\mathrm{cc}} - 0.866)^{\gamma}}{6}. \tag{10}$$

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

$$C/I = \frac{(r_{\mathrm{cc}} + 1)^{\gamma}}{2}. \tag{11}$$

3) *SS to RS:* In this case, the RS receives interference from four SSs in neighboring cells. By using the same procedure

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

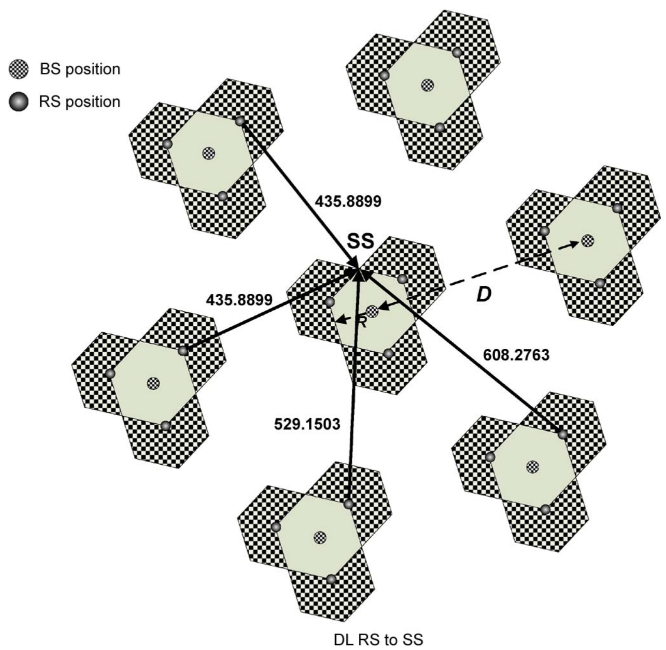

Fig. 6. Distances from the RS interferers to the SS.

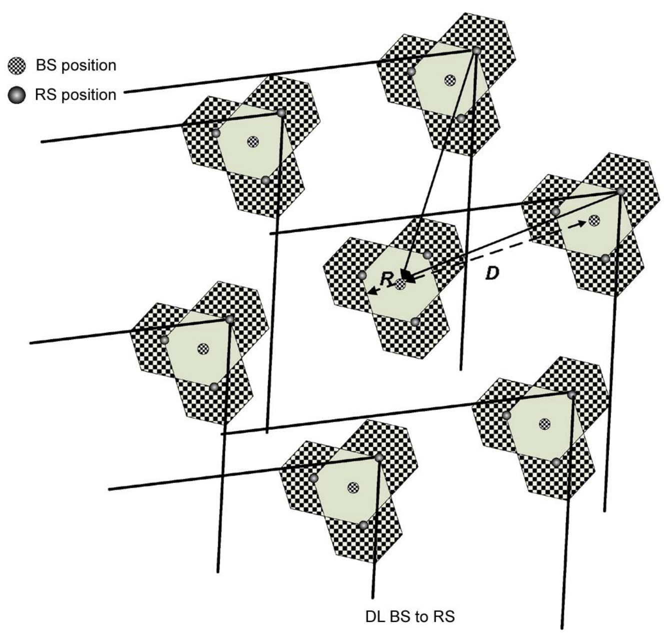

Fig. 7. Decrease of the cochannel interference by using directional antennas at the RS.

to measure the distances between the cell centers RS and SS, the following values are obtained for α: -0.8761, -0.082776, -0.80762, and -0.8761. *C/I* is therefore given in (12), shown at the bottom of the page.

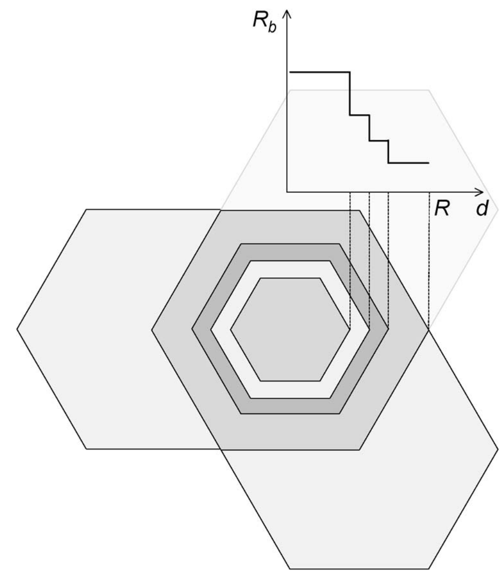

Fig. 8. Approximated cell coverage areas where the given values of the physical throughput are supported.

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 to use the binary phase-shift keying 1/2 MCS (see Table I).

The assessment of the supported cell per 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 center of the cell (see Fig. 8). As for cellular planning purposes, throughput is not constant over the whole coverage area (where R is the cell radius), and the supported throughput is obtained by computing the average supported throughput in each coverage zone. As previously stated, in contrast to [7] and [8], worst-case scenarios for interference geometry are considered here.

Assume that there are J different coverage rings in each coverage zone, each supporting a different MCS (for instance, $J = 4$ in Fig. 8). 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 by MCS_j. The number of different coverage rings is given by

$$J = \text{MCS}_{1^{\text{st}}} - \text{MCS}_{\text{last}} + 1 \tag{13}$$

where $\text{MCS}_{1^{\text{st}}}$ and MCS_{last} represent the MCSs for the first and last coverage rings, respectively.

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

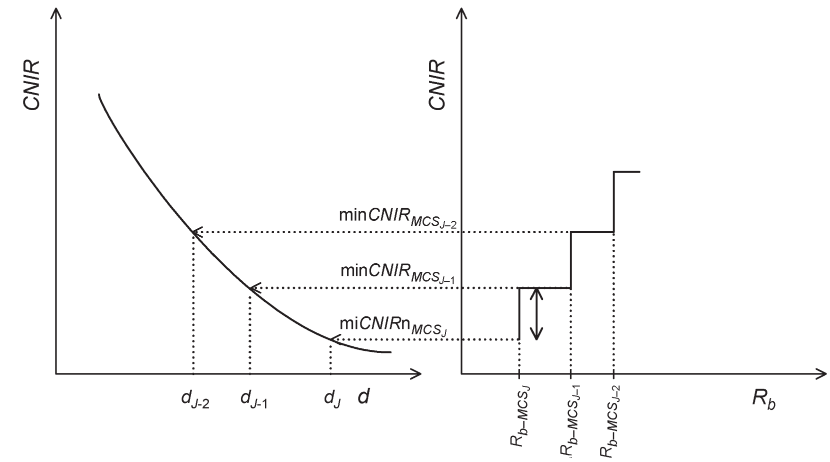

Fig. 9. Correspondence between the physical throughput for rings $J, J-1, J-2, \ldots$ and the minimum CNIRs of consecutive MCSs that map to step distances $d_J, d_{J-1}, d_{J-2}, \ldots$.

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

$$R_{b-\sup} = \frac{\iint\limits_{\mathrm{O}} R_b(d,R,K)dx\,dy}{\frac{3\sqrt{3}}{2}\cdot R^2} = \frac{\sum\limits_{j=1}^{J}\left(\frac{3\sqrt{3}}{2}\cdot\left(d_j^2 - d_{j-1}^2\right)\cdot (R_b)_{\mathrm{MCS}_{1^{\mathrm{st}}}+1-j}\right)}{\frac{3\sqrt{3}}{2}\cdot R^2} \tag{14}$$

where the 2-D 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.

$\mathrm{MCS}_{1^{\mathrm{st}}}, \mathrm{MCS}_{2^{\mathrm{nd}}}, \ldots, \mathrm{MCS}_{J^{\mathrm{th}}}$ depend on the CNIR value as defined in [9], vary from 0 to 8, and can be obtained from Table I, where the corresponding values for the physical throughput are also given. $\mathrm{MCS}_j = 0$ 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., $\mathrm{CNIR}_{\min}$, which supports a throughput R_b. Hence, $d_0 = 0$, and

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

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

for $p = 1$ to $p_{\max}$
{
$R = p \cdot R_{\mathrm{step}}$;
$N_{\max} = trunc(R/d_{\mathrm{step}})$;
$J = 0$;
$d[0] = 0$;
for $n = 1$ to $N_{\max}$
{
$C/(N+I) = C(n \cdot d_{\mathrm{step}})/\{I(n \cdot d_{\mathrm{step}}, R, r_{\mathrm{cc}}) + N\}$;
$R_{b\_n} = R_b[\mathrm{MCS}(C/(N+I))]$;
If $(n > 1)$ then
{
If $(R_{b\_n} - R_{b\_n-1} <> 0)$ then
{
$d[J] = d_{\mathrm{step}} \cdot (n-1)$;
$R_b[J] = R_{b\_n}$;
$R_{b\_n-1} = R_{b\_n}$;
}
else
{
$R_{b\_n-1} = R_{b\_n}$;
}
}
$R_{b-\sup}[p] = 0$;
for $j = 1$ to J
{
$R_{b-\sup}[p] = R_{b-\sup}[p] + (d[j]^2 - d[j-1]^2)\ Rb[j]$;
$R_{b-\sup}[p] = R_{b-\sup}[p]/R^2$;
}
}

Fig. 9 presents the correspondence between the CNIR versus propagation distance curve and the stepwise function that represents the $\mathrm{CNIR}_{\min}$ threshold for each MCS versus R_b. This figure illustrates how the mapping between the CNIR and the supported physical throughput relates to step distances between consecutive MCSs, i.e., $d_J, d_{J-1}, d_{J-2}, \ldots$. 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 [10].

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

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

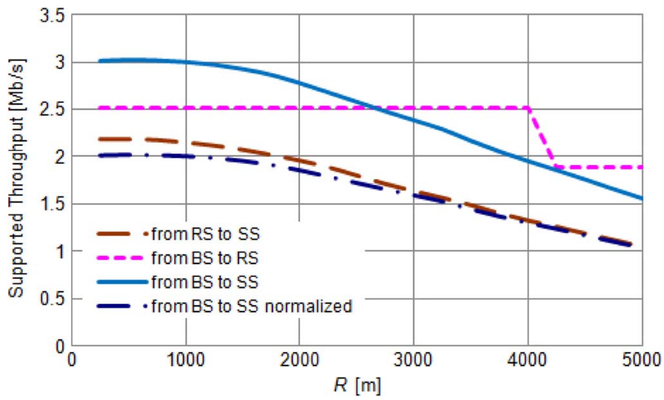

Fig. 10. Supported throughput as a function of R in the DL with deployed relays ($K = 3$, omnidirectional BSs).

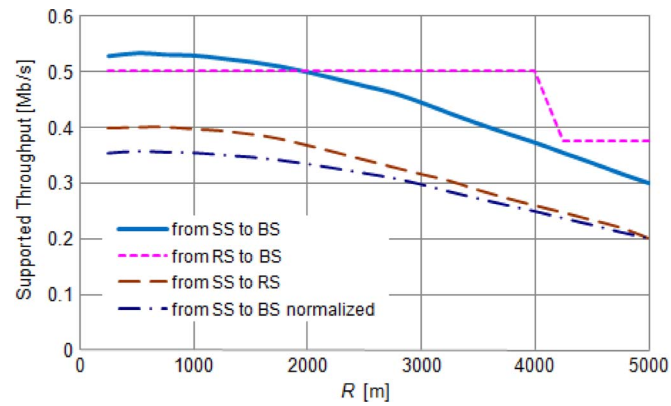

Fig. 11. Supported throughput as function of R in the UL in the absence of subchannelization ($K = 3$, omnidirectional BSs).

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

B. DL With Relays

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

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

2) *From the BS to the RS:* The throughput from the BS to the RS remains high (at a constant level) until the distance of 4 km is reached and then sharply decreases. This throughput is obtained by considering directional antennas at the RS, which greatly decreases cochannel interference (see Fig. 7). Only two RSs 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.e.,

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

3) *From the RS to the SS:* The throughput from the RS to the SS is almost of the same value as that from the BS to the SS. In our assumptions, two ninths of the overall frame structure is assigned to this hop in the DL; thus, the DL throughput is obtained by multiplying this factor of two ninths by the total obtained throughput.

C. UL With Relays

Fig. 11 shows the throughput result for different UL transmission hops $(K = 3)$.

1) *From the SS to the BS:* The throughput from the SS to the BS resembles the previous case for the DL. The 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; thus, the UL throughput for this hop is obtained by multiplying this factor of 3/45 by the total obtained throughput. If we want to compare this value with the throughput in the RS coverage zone, as they only cover two thirds of the coverage area, a normalized throughput should be needed that is obtained by multiplying the throughput by two thirds.

2) *From the RS to the BS:* The throughput from the RS to the BS remains high at a constant level until a distance of 4 km is reached and then sharply decreases. This throughput is obtained by the use of directional antennas at the RS, which greatly decreases the cochannel interference (see Fig. 7).

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

D. Use of Subchannelization

The IEEE 802.16-2004 standard is only able to support subchannelization in the UL. Therefore, to obtain a sufficient level of throughput for the UL, subchannelization is used. Although the curves are not presented here, the main difference from Fig. 11 is that the throughput from the RS to the BS now remains constant, even for the longest distances as the cell

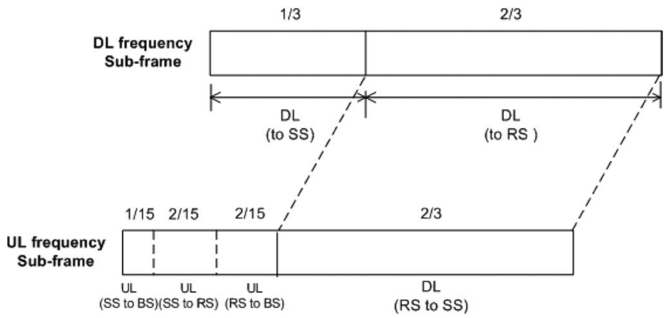

Fig. 12. Frame structure for UL and DL subframes with deployed relays (trisectored BSs).

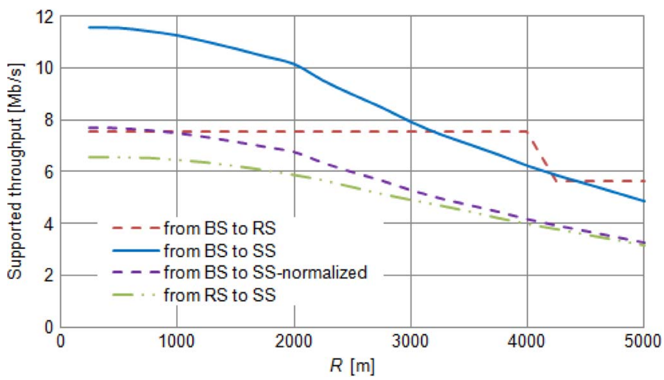

Fig. 13. Supported throughput as a function of R in the DL with relays ($K = 3$, trisectored BSs).

coverage distance varies [9]. There are no notable differences in other curves.

IV. Throughput With Sectorization and Relays

Constraints due to limited subframe system capacity support motivate us to consider trisectored 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 the UL, respectively) but, now, with $D = 3\sqrt{k}R$:

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

The formulation for the communication between RSs and SSs is the same, as is that for the communication between RSs and BSs. By considering trisectored 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 Fig. 12 for the DL and UL frequency subframes. The asymmetry factor between the UL and the DL is 1 : 5 in this case. One can define the sector throughput for only one third of the cell, meaning that only 1) one sector is covered by one frequency carrier and that 2) only one RS coverage area is considered for each sector to determine the cell throughput, against three in the omnidirectional case.

Figs. 13 and 14 give the results for supported throughput for the DL and the UL, respectively ($K = 3$). With trisectored BS antennas, on the one hand, the DL supported throughput is twice the omnidirectional case throughput. On the other hand,

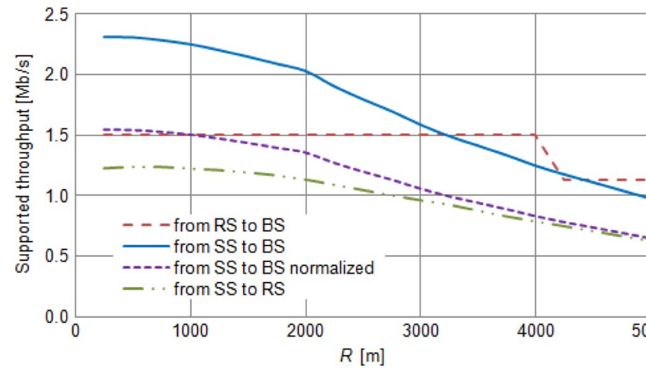

Fig. 14. Supported throughput as function of R in the UL, with relays ($K = 3$, trisectored BSs).

the UL supported throughput is more than four times higher. Apart from the gain arising from interference mitigation owing to trisectorization, this is mainly due to the most favorable frame format (note that N_{sec} is the number of sectors, and it may take values of 1 or 3 in this paper).

- $N_{\text{sec}}/3$ against one third subframe space in the DL (BS to SS), as $N_{\text{sec}} = 3$ frequency carriers are available to the central coverage zone;
- two thirds against two ninths subframe space in the DL (BS to RS);
- two thirds against two ninths subframe space in the DL (RS to SS);
- $N_{\text{sec}}/15$ against 3/45 subframe space in the UL (SS to BS);
- 2/15 against 2/45 subframe space in the UL (RS to BS), as $N_{\text{sec}} = 3$ frequency carriers are available to the central coverage zone;
- 2/15 against 2/45 subframe space in the UL (SS to RS).

With this frame format, communications using a given frequency carrier are only from/to a sector and an 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 $(3\sqrt{3}/2) \cdot R^2$ is therefore given by

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

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

This corresponds to an N_{sec} increase in both the DL and the UL traffic from/to the BS, due to the use of a more favorable frame format.

In the future, we also may analyze the presence of subchannelization in the UL with $K = 3$, as well as its impact for the longest coverage distances when trisectored 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]–[13]. In this paper, although it is possible 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's/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 the 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 2-D system that is 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 subchannels), 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 paper, i.e., it is assumed, as a simplification, that one carrier will be sufficient per cell per sector.

System cost has two major parts: 1) capital costs (normal backhaul, cell site planning, and installation) and 2) operating expenses (operation, administration, and maintenance) [14], [15].

The capital cost is taken to consist of the following:

1) a fixed part (e.g., licensing and spectrum auctions or fees);
2) a part proportional to the number of BSs per kilometer or square kilometer (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);
3) a part proportional to the total number of transceivers per kilometer or square kilometer (e.g., the cost of the transceivers).

It is assumed that the cost of the connection between BSs and the switching center, i.e., the fixed part of the network (e.g., the cost of laying fiber), 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 the following:

1) a part proportional to the number of BSs per kilometer or square kilometer;
2) a part proportional to the number of transceivers per kilometer or square kilometer.

These costs will be incurred on an annual basis. A similar approach was followed in [16] for hierarchical WiMAX–wireless fidelity (WiFi) networks; however, here, we follow the approach from [9].

The cost per unit area is given by

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

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

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

and the cost per BS is given by [9]

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

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

In our formulation, as the supported throughput was obtained for a hexagon-shaped coverage zone (whose area is $(3\sqrt{3}/2) \cdot R^2$), we maintain the formulation from [9] by replacing "cells" by "hexagon-shaped coverage zones," and $N_{\mathrm{hexagon/km}^2} = N_{\mathrm{cell/km}^2} \cdot 3$. Note that the three RS coverage zones exactly correspond to an area of two hexagons.

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

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

where N_{sec} is the number of sectors (one or three), T_{bh} is the equivalent duration of busy hours per day, and $R_{b-\mathrm{ch}}$ is the bit rate for the basic "channel." In the trisectored 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, i.e., $R_{v[€/\mathrm{km}^2]}$, is obtained by multiplying the revenue per coverage zone by the number of hexagon-shaped coverage zones per unit area, i.e.,

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

The (absolute) profit is given by

$$P_{[€/\mathrm{km}^2]} = R_v - C \tag{25}$$

from which the profit in percentage terms is given by

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

B. Hypothesis and Assumptions With Relays

If a topology with the deployment of relays is considered, the assumptions for costs with relays are given in the list that follows.

1) *Cost for the BS and RSs:*
   - $C_{\text{BS-omni}} = 9000$ €;
   - $C_{\text{RS}} = 9000/5 = 1800$ €;
   - $C_{\text{BS-trisect}} = 15\,000$ €.

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

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

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

$$C_{\text{bh-equiv}} = 1/3C_{\text{bh}} \quad (28)$$

   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).
3) *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), i.e., C_{inst}, but we need to multiply C_{inst} by one third to obtain the installation cost for each hexagonal coverage zone. This is given by

$$C_{\text{inst-equiv}} = 4/3C_{\text{inst}}. \quad (29)$$

4) *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 maintenance and operational costs for the three RSs are one half of those of the BS. This is given by

$$C_{\text{M\&O-equivalent}} = \frac{(C_{\text{M\&O}} + (3/2)C_{\text{M\&O}})}{3}. \quad (30)$$

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

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

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

For the trisectored BS antennas, the parameters are the following (see Table II; note that the costs for the normal backhaul and the maintenance and operation are the same):

1) $C_{\text{BS-trisect}} = 15\,000$ €, $C_{\text{RS}} = 1800$ € (i.e., $C_{\text{BS-equiv}} = 6800$ €);
2) $C_{\text{inst}} = 1500$ € (i.e., $C_{\text{inst-equiv}} = 2000$ €);
3) $C_{\text{bh}} = 2500$ € (i.e., $C_{\text{bh-equiv}} = 833.33$ €);
4) $C_{\text{M\&O}} = 1000$ € (i.e., $C_{\text{M\&O-equiv}} = 833.33$ €).

TABLE II
COSTS WITH RELAYS FOR OMNIDIRECTIONAL AND TRISECTORED 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

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

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

It should be noted that, with trisectorization, the cost for the frequency carriers license with $K = 3$ is three times the cost for the license with omnidirectional BS antennas and $K = 3$, as $K \cdot N_{\text{sec}} = 9$ carriers need to be available. In addition, 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, Tab. 18.8]. When trisectored antennas and RF equipment (including the outdoor units) are considered, we assume a 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, Ch. 18]; hence, with trisectored 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., $3 \cdot K \cdot N_{\text{sec}} = 9$. In this case, the fixed costs for the license are three times higher, as well as the channel equipment at the BSs and RSs, while computing the throughput by using (19).

With trisectorization, 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 subframe format), a gain of $(N_{\text{sec}}/3)/(1/3) = N_{\text{sec}}$ occurs, which compensated the lowest value of the frame throughput.

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

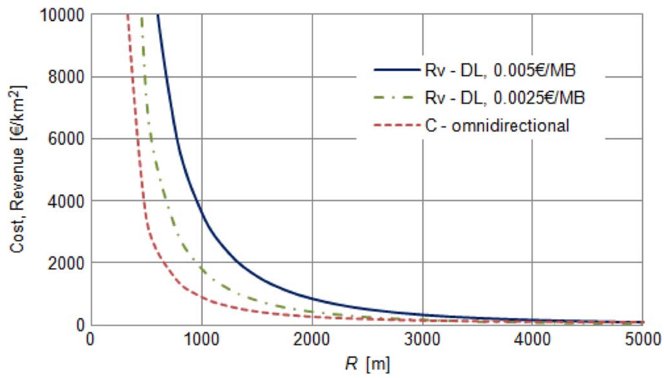

Fig. 15. Cost and revenues with relays ($K = 3$, omnidirectional BS antennas) for prices per MB $R_{144} = 0.0025$ and 0.005 €/MB in the DL.

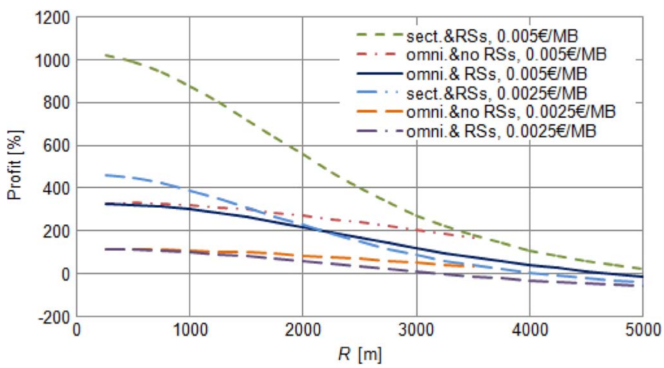

Fig. 16. Profit in percentage for prices per MB $R_{144} = 0.0025$ and 0.005 €/MB in the DL and $K = 3$, without and with RSs (omnidirectional and trisectored BS antennas for the latter).

C. Optimization and Profit With Relays

In seeking profit optimization, revenues should be maximized with respect to costs. By using Table II (and Table III), as well as 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 antennas), in €/km^2, are depicted in Fig. 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 $144 \cdot 60/8 = 1080 \sim 1$ MB; hence, hereafter, one will use €/MB instead of €/min as the unit for price.

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 Fig. 15, a certain level of profit may correspond to different values of cost. For example, cost is higher for trisectored 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/service provider's goal is to optimize this profit in percentage.

Results are obtained with RSs and $K = 3$ (trisectored BS antennas, identified by "sect.&RSs") and $K = 3$ (omnidirectional BS antennas, identified by "with RSs") in the DL case. Fig. 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 also presented for $K = 3$) enables us to achieve a higher profit. The optimum (maximum) values occur for coverage distances up to 1000 m.

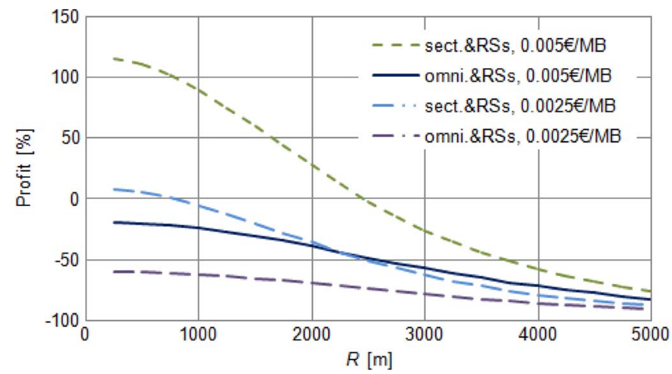

Fig. 17. Profit in percentage for prices per MB $R_{144} = 0.0025$ and 0.005 €/MB in the UL and $K = 3$, with RSs (omnidirectional and trisectored BS antennas for the latter).

D. UL Analysis With $K = 3$

We have also performed analysis for the UL with $K = 3$. By using the values from Table II (and Table III), as well as 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 antennas) were also analyzed for $R_{144} = 0.0025$ and 0.005 €/MB. In Fig. 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 the 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 trisectored (identified by "sect.&RSs") and omnidirectional (identified by "omni.&RSs") BS antennas.

In the UL, with relays, i.e., $R_{144} = 0.005$ €/MB, only the use of trisectored BS antennas (an example is presented for $K = 3$ in Fig. 17) enables us to achieve a 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, a positive profit is achievable only up to $R \sim 700$ m. No subchannelization is considered in these curves. Results with no RSs are not included for such $K = 3$ because, with omnidirectional antennas, as the CNIR is very low, it was impossible to obtain results for the supported throughput [9].

E. Comparison of Trisectored and Omnidirectional Cells With Different K's and Number of Carriers

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

1) *omnidirectional cells:* 3.5 MHz for $K = 1$ and 10.5 MHz for $K = 3$;

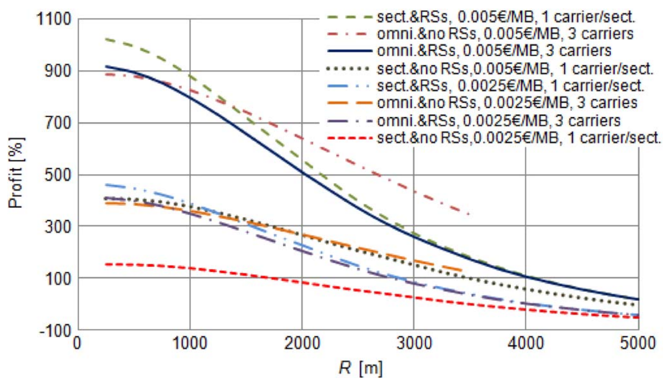

Fig. 18. Comparison between omnidirectional (three carriers) and trisectored (one carrier per sector) BSs under the same total bandwidth for prices per MB $R_{144} = 0.0025$ and 0.005 €/MB in the DL and $K = 3$.

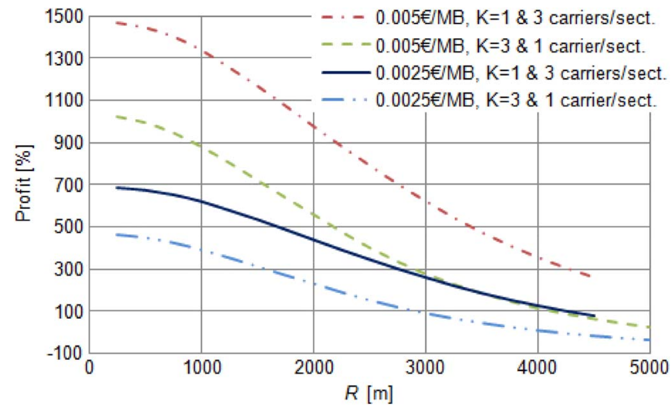

Fig. 19. Comparison between $K = 1$ and $K = 3$ under the same total bandwidth for prices per MB $R_{144} = 0.0025$ and 0.005 €/MB in the DL, with RSs and trisectored BS antennas.

2) *trisectored cells:* $3 \cdot 3.5 = 10.5$ MHz for $K = 1$ and $3 \cdot 10.5 = 31.5$ 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 trisectored 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).

1) *Comparison with omnidirectional BSs and* $K = 3$ *(three carriers per sector):* With no RSs and sectorization ("sect.&no RSs"), the economic performance is weak (see Fig. 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 Fig. 18. With RSs, with omnidirectional central coverage zone antennas, higher profits are only achievable for R's up to ∼700 m.

However, with trisectored BSs and RSs ("sect.&RSs"), there is a clear advantage up to $R \sim 1300$ m. This is very clear in Fig. 18 (mainly in the example for $R_b = 0.005$ €/MB).

2) *Comparison with trisectored BSs and* $K = 1$ *(three carriers per sector):* Fig. 19 addresses the case with trisectored antennas and RSs ("sect.&RSs") and shows a comparison between the curves for $K = 3$ (one carrier per sector), as also shown in Fig. 18, and the case $K = 1$ (three carriers per sector).

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

VI. Conclusion

In this paper, 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 2-D geometries that are commonly used in rural and suburban environments, and the basic limits for system capacity and cost/revenue optimization have been obtained under simple assumptions. It has been assumed that the line-of-sight propagation to the BSs 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 Geographic Information System cellular planning tools.

For a given coverage area, throughput is a stepwise function that decreases as the distance from the BS 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 subchannelization, 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 trisectorized 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 subframe for RS-to-SS communication. Frames need to guarantee resources for BS-to-SS communication, as well as for BS-to-RS and RS-to-SS communications. A $1:5$ asymmetry factor between the UL and the 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 subchannelization in the UL only improves the results for the highest values of R. Only the consideration of trisectored BS antennas with $K = 3$ (at the cost of extra channels, where nine channels correspond to a bandwidth of 31.5 MHz) enables attainment of values of throughput comparable with those without relays (see [9, Fig. 10]). This is due to the more favorable frame format.

Deployment with relays can be cheaper than using the BS alone. Because the use of relays, through helping improve coverage while mitigating interference, may lead to lower costs, it is worthwhile to analyze 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 trisectored BS antennas, it is shown that with RSs and with coverage distances up to $\sim$1300 m, the achievable profit is only clearly higher with the use of trisectored BSs. Results also show that, under the same fixed bandwidth and for the example where the coverage distance is set at $R \sim 500$ m, it is preferable to consider $K = 1$ with three carriers per sector instead of $K = 3$ with one carrier per sector, whereby the profit in this case is increased by more than 45% from $\sim$1000% to $\sim$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 trisectored BSs (or central coverage zone antennas). With trisectored BSs, given that one third of the DL frequency subframe is used for each sector (i.e., the three sectors give user access to $N_{\mathrm{sec}}/3 = 1\ (= 100\%)$ of one DL subframe), 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.

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