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Optimisation of Mobile Broadband Multi-Service Systems Based in Economics Aspects

FERNANDO J. VELEZ *
University of Beira Interior, Department of Electromechanical Engineering, Calçada Fonte do Lameiro, 6201-001 Covilhã, Portugal and Instituto de Telecomunicações, Instituto Superior Técnico, Technical University of Lisbon, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

LUIS M. CORREIA
Instituto de Telecomunicações, Instituto Superior Técnico, Technical University of Lisbon, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

Abstract. Multi-service traffic engineering has a strong impact in Mobile Broadband Systems (MBS) revenues, allowing one to obtain merit functions for optimisation purposes, a key aspect in cellular planning. A net cost model is presented for the design trade-offs between re-use pattern, K, coverage distance, R, and spectral efficiency, $S_{\text{ef}}(R)$. It allows for the determination of the revenue per basic channel, R_{384}, that achieves a given value for the annual profit per kilometre. Fast terminal mobility has an important impact in handover failure probability, hence, in system capacity. While in the business city centre and other urban scenarios mobility has no significant effect, it strongly affects the supported traffic in main roads. Comparing the urban with the roads scenarios, a reduction up to 54% may come as a consequence, from $(S_{\text{ef}})_{\text{TOT}} = 32.2$ to 15.2%, for $R = 100$ m and $K = 2$; R_{384} has to be 0.005 and 0.045 €/min, respectively, i.e., the prices in the roads scenario have to be around one order of magnitude higher than in the urban one. As time goes by, and the use of MBS evolves, the operator will be able to choose different cell coverage distances, in order to support a different number of users, whilst maximising profit. In a medium term scenario, while the number of foreseen users is less than 70% of the number of users in the mature phase, cells with $R = 200$ m will be used.

Keywords: mobile broadband system, multi-service, mobility, cost and revenues, deployment scenarios

1. Introduction

In the next years, a large demand is foreseen for mobile multimedia services, limitations on achievable data rates and system capacity leading to the use of mobile broadband communication systems operating at millimetre wavebands, e.g., MBS (Mobile Broadband Systems [4]). MBS will be deployed mainly in urban areas, to cover hotspots in the centre of large cities, main roads, and highways, where the highest demand will occur; moreover, MBS will be multi-service systems, i.e., they will support several services simultaneously over the same platform, for different, or even the same, user(s). Owing to their high transmission data rate, and due to the saturation of the spectrum at lower frequency bands, MBS are intended to operate at the millimetre waveband (e.g., the 40 or 60 GHz bands), offering improved performance in system capacity [4]. Although it is not necessary that future MBS will be based on ATM technology, the work from RACE-MBS [4] and ACTS-SAMBA [11] projects considered so, this being the approach one follows here. In ATM networks the available resources are shared in a way that allows multiplexing of different traffic sources, enabling a gain from this statistical multiplexing [13].

MBS deployment optimisation can be achieved by seeking optimum values of a merit function taking into account both costs and revenues. The optimisation of costs and revenues provides a mean of joining together the several contributions from cellular planning: the determination of the re-use pattern and the coverage distance [21], plus the aspects of multi-service traffic engineering. In practice, frequency reuse constraints impose the cost component, through the values of the coverage distance and the achieved re-use pattern, while multi-service traffic engineering [2] determines the revenues, together with the frequency re-use aspects. The latter allows for the determination of the number of available channels in each cell, and is determined by the characteristics of the combination of applications that make use of it, through data and video service components, and by the traffic from mobility [16]. The supported load (i.e., the sum of the supported kb/s) is a measure of the supported traffic (resulting from multi-service), and depends on the blocking and handover failure probability thresholds.

A cost/revenue function has to be developed, taking into account the cost of building and maintaining the infrastructure, and the way the number of channels available in each cell affects operators' revenues. Fixed costs for licensing and bandwidth auctions (or beauty contests) should also be taken into account [3]. The economic analysis is referred as a cost revenue performance analysis, because optimising costs do not necessarily mean optimising net revenues.

Although one considers a project duration of five years as a working hypothesis, one will analyse costs and revenues on an annual basis. Furthermore, the analysis is made under the assumption of null discount rate. By no means is it intended to perform a complete economic study, but only to present

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* Corresponding author.

initial contributions. Appropriate changes would be needed to perform a complete economic analysis based on discounted cash flows (e.g., to compute the net present value).

This paper is organised as follows. In section 2, one starts by presenting details of the MBS concept, namely the ones related to teletraffic. In section 3, the components of the model for cost/revenue optimisation are presented and a function for the net cost is proposed. In section 4, the values for the parameters are presented, and some assumptions are described. In section 5, results for the supported fraction of active users and the spectral efficiency are presented, and a comparison is made between the cases of presence and absence of mobility. Then, results for the cluster revenue-to-cost ratio, the net cost and the revenue associated with each basic channel are presented, and a comparison is made between the urban and roads scenarios. Finally, based in results for profit, MBS deployment strategies are discussed, for medium- and long-term operation. Conclusions are drawn at the end.

2. MBS concept

Although OFDM (Orthogonal Frequency Division Multiplexing) can be a solution for MBS, in this work one is still assuming TDMA/FDMA (Time/Frequency Division Multiple Access), following the approach from RACE-MBS (Research in Advanced Communications in Europe – Mobile Broadband System) and ACTS-SAMBA (Advanced Communications Technologies and Services – System for Advanced Mobile Broadband Applications) European Commission projects [11].

Because the MBS concept is not yet completely defined, it is important to clarify the boundaries in data rates, operation scenarios, and mobility. Under RACE initiatives in mobile communication systems, a first definition of MBS and related systems was presented, assuming that, in terms of terminal mobility and supported data rates, MBS operation will just begin where UMTS ends. At that time, it was assumed that UMTS would support data rates up to 2 Mb/s in every mobility scenario [4]. However, with the standardisation of UMTS, this concept evolved, and, although one is aware that enhanced versions of UMTS will arise, the current MBS/UMTS boundary is the following: 144 kb/s for fast mobile, 384 kb/s for slow mobile and 2 Mb/s for movable applications [17].

In order to model multi-services in MBS, one needs first to model the air interface access, as well as the slot arrival process. Because traffic can be generated from different mixtures of voice, data and video sources, it is important to obtain performance measures for resource usage, making use of the characteristics of the frame structures [11] and of the MAC (Medium Access Control) protocol, the DSA++ (dynamic slot allocation) one. The DSA++ protocol has an important characteristic: it allows one to consider connection-oriented communications [9]. By allocating a so-called container, formed by a number of slots, a Base Station (BS) defines channels like in circuit-switched connections. Thus, the methodologies for circuit-switched network analysis supporting heterogeneous traffic can be applied, while the MAC protocol guarantees that the maximum delay is kept under values that do not affect the performance of applications [1], namely real-time ones. According to this approach, one assumes that a minimum data rate is guaranteed by the system for non-real time applications, e.g., in ABR (Available Bit Rate) ones, and only this minimum is considered in tele-traffic computations. The access to supplementary resources (if needed) is only possible if they are available, but it has not to be taken into account in the computations of the blocking probability, because it does not correspond to the worst-case situation.

The different types of information (audio, video and data) are organised into a set of service components to which applications have access to. For each deployment scenario [18], a complete classification of MBS services and applications is needed, as well as their characterisation parameters [17]. An appropriate model is used for the superimposition of a number of independent resources, which results from the correspondence between service components and applications. One adopted the Markov-modulated Poisson process to model multi-service traffic, assuming the use of a MAC protocol that extends ATM (Asynchronous Transfer Mode) to the air interface [13]. In particular, considering that IPP (Interrupted Poisson Process) models voice, data and video sources, one used the Bernoulli case of the BPP (Bernoulli–Poisson–Pascal) model [2].

Because of terminal mobility, and the resulting handovers, the network planner has also to account for handover failure probability (the probability that a user will not succeed in transferring his connection from a cell to another). The resulting connection-dropping probability is the probability of forced termination of the connection during its duration. When a single service is considered, and if one does not use guard channels for handover, the handover failure probability is equal to the blocking probability [8]. For multi-service traffic purposes, one considers here a generalisation of this approach [19].

The high capacity desired for MBS, and the high operating frequency, lead to micro-cellular configurations, hence, requiring a large number of BSs to be deployed. For cost efficiency, these BSs should be inexpensive to manufacture and install; in particular, a small number of types should exist, and their installation should not require extensive adjustments. In [5], the MODAL (Microwave Optical Duplex Antenna Link) project concept is proposed to provide an alternative technique for the generation of millimetre waves by using optical technology, offering the perspective of reduced installation and maintenance costs when compared to more conventional solutions.

3. Cost/revenue model

3.1. Cost/revenue components

Some useful cost/revenue models were already developed in [3] and [6], in a simpler context: a single service system

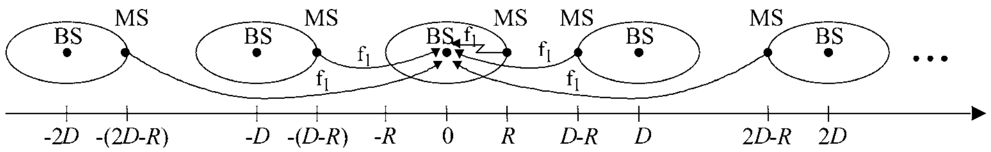

Figure 1. Linear coverage geometry.

is considered in the former case, while some simplifications (not considering the multi-service traffic analysis) were assumed in the latter one. The economics of cellular systems can be viewed from the points of view of different entities: the subscribers, the network operators, the service providers, the regulator, and the equipment vendors [6]. In this work, although one is aware that in future mobile multimedia systems the network operator and the service providers could be different entities, one is not distinguishing them. Thus, one is considering the operator/service provider's point of view.

In the cellular planning process, the objective of the operator is to determine an optimal operation point that maximises its expected revenues. Examples of major decisions include the type of technology to be used, the size of the cell, and the number of channels to use in each cell.

In this section, the main components of system cost and revenues are identified, in particular those that bear a direct relationship to either the maximum cell coverage distance or the number of frequency groups. One will consider the cost per unit length (or unit area) of (i) linear-coverage and (ii) Manhattan grid urban geometries [21] incurred during a year of operation. It must be kept in mind that the system is considered to have a transmission structure formed by a set of frequency carriers, each supporting a TDMA frame structure, meaning that each BS comprises a number of transceivers equal to the number of carriers assigned to it.

System cost has two major parts: (i) capital costs (cell site planning and installation), and (ii) operating expenses (operation, administration and maintenance) [12,14]. 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 the BSs, and the cost of hardware common to all); and
- a part proportional to the total number of transceivers per kilometre, or square kilometre (e.g., the cost of the transceivers).

One is assuming 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, one considers that it is proportional to the number of BSs, which can be true if, e.g., the mobile operator contracts this service from a fixed network operator. The operating cost during system lifetime is taken to contain:

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

These costs (and revenues) will be taken on an annual basis. One will start by considering the linear coverage geometry, figure 1. Let T be the number of carriers available, for each transmission link, up-/down- link, and N_{op} the number of operators. For a linear geometry one then has:

- the maximum cell coverage distance is R;
- the number of BSs per kilometre is $1/(2R_{[\mathrm{km}]})$;
- the number of different frequency groups required is K (the re-use pattern);
- the number of carriers per cell is $T/(N_{\mathrm{op}}K)$;
- the number of carriers per kilometre is $T/[KN_{\mathrm{op}}(2R_{[\mathrm{km}]})]$.

Therefore, the system cost will contain a fixed term C_{fi}, and terms proportional to the number of BSs and to the number of transceivers. Letting C_{fb} and C_{ft} denote the corresponding coefficients, the overall cost per unit length per year is

$$C_{0[\text{€/km}]} = C_{\mathrm{fi}[\text{€/km}]} + C_{\mathrm{fb}[\text{€}]}\frac{1}{2R_{[\mathrm{km}]}} + C_{\mathrm{ft}[\text{€}]}\frac{T}{KN_{\mathrm{op}}(2R_{[\mathrm{km}]})}. \tag{1}$$

System capacity is usually defined with reference to QoS (quality-of-service) constraints, such as blocking probability (for real time applications) or packet delay (for non-real time ones). Their calculation involves the multi-service traffic analysis. The load supported by the system, in kb/s, is proportional to the supported fraction of active users, f, which is a measure of system capacity. However, revenue is proportional to the spectral efficiency. Hence, results from [19] are fed into the net cost function defined in this work via the total spectral efficiency, $(S_{\mathrm{ef}}(R))_{\mathrm{TOT}}$, which copes with the simultaneous contribution of up- and downlinks, and depends on the maximum cell coverage distance. The revenue per cell per year, $(R_{\mathrm{v}})_{\mathrm{cell}}$, depends on the revenue per transceiver per year, R_{vt}, and is given by

$$(R_{\mathrm{v}})_{\mathrm{cell}[\text{€}]} = \frac{TS_{\mathrm{ef}}R_{\mathrm{vt}[\text{€}]}}{KN_{\mathrm{op}}}. \tag{2}$$

The revenue per kilometre per year, R_{v}, apart from a constant that depends on the number of slots per frame (each frame, in turn, corresponding to a carrier) and on the number of busy hours per year, does depend on S_{ef}, K and R. It is obtained by multiplying the revenue per cell per year by the number of cells per kilometre, which, for the linear geometry, is given by $N_{\mathrm{c/km}[\mathrm{km}^{-1}]} = 1/(2R_{[\mathrm{km}]})$, yielding

$$R_{\mathrm{v}[\text{€/km}]} = \frac{(R_{\mathrm{v}})_{\mathrm{cell}[\text{€}]}}{2R_{[\mathrm{km}]}} = \frac{TS_{\mathrm{ef}}R_{\mathrm{vt}[\text{€}]}}{KN_{\mathrm{op}}(2R_{[\mathrm{km}]})}. \tag{3}$$

Both the overall cost and the revenue per kilometre will be fed into the net cost function.

3.2. Net cost

A net cost function (in €/km/year) results from (1) and (3)

$$C_{\mathrm{n}[€/\mathrm{km}]} = C_{\mathrm{fi}[€/\mathrm{km}]} + \frac{C_{\mathrm{fb}[€]}}{2R_{[\mathrm{km}]}} + \frac{T}{K N_{\mathrm{op}}(2R_{[\mathrm{km}]})}(C_{\mathrm{ft}[€]} - R_{\mathrm{vt}[€]}S_{\mathrm{ef}}), \quad (4)$$

which can be simplified by considering $C_{\mathrm{fi}} = 0$. The analysis of the cases with $C_{\mathrm{fi}} \neq 0$ can then be done by comparing the net cost obtained for $C_{\mathrm{fi}} = 0$ with the fixed cost threshold, $(-C_{\mathrm{fi}})$. If C_{n} is lower than $(-C_{\mathrm{fi}})$ the system becomes profitable.

In the linear geometry, the number of cells per kilometre is given by $1/(2R_{[\mathrm{km}]})$, while the net cost per cell is given by the third term in (4), which allows defining the cluster revenue-to-cost ratio

$$r_{\mathrm{c}} = \frac{T}{N_{\mathrm{op}}} \frac{R_{\mathrm{vt}[€]}S_{\mathrm{ef}} - C_{\mathrm{ft}[€]}}{C_{\mathrm{fb}[€]}}. \quad (5)$$

It provides the number of times the net revenue per cluster is higher than the cost associated with the installation and maintenance of a BS, and its associated equipment and infrastructures.

In the *Manhattan grid* geometry [21], however, the cell *net street area* is $2l(2R - l/2)$, thus, the number of cells by net square kilometre is $1/[2l_{[\mathrm{km}]}(2R_{[\mathrm{km}]} - l_{[\mathrm{km}]}/2)]$, yielding the following net cost cost function for $C_{\mathrm{fi}} = 0$, in €/km^2/year,

$$C_{\mathrm{n}[€/\mathrm{km}^2]} = \frac{1}{2l_{[\mathrm{km}]}(2R_{[\mathrm{km}]} - l_{[\mathrm{km}]}/2)} C_{\mathrm{fb}[€]}\left(1 - \frac{r_{\mathrm{c}}}{K}\right). \quad (6)$$

Analysing the net cost function for $C_{\mathrm{fi}} = 0$, one concludes that r_{c} should be higher than the re-use pattern (i.e., the cluster size), in order to obtain a profitable system. For a two-dimensional system, it is rather natural to define a cost function, in €/km^2/year. Nevertheless, in order to have a quantitative comparison with the linear coverage geometry, one can consider that cells are formed by two orthogonal street portions forming a cross(ing), each with equivalent length $(2R - l/2)$ and width l. As a consequence, for each of the street segments composing the cell, one can consider a *linearised net cost* function, as follows:

$$(C_{\mathrm{n}})_{\mathrm{lin}[€/\mathrm{km}]} = \frac{1}{(2R_{[\mathrm{km}]} - l_{[\mathrm{km}]}/2)} C_{\mathrm{fb}[€]}\left(1 - \frac{r_{\mathrm{c}}}{K}\right), \quad (7)$$

This linearised net cost function can be very useful for comparison purposes, and can consequently simplify the analysis. Thus, one can directly compare the linear and the Manhattan grid geometries, the difference between them coming from the possibility of having different values of K, and from a slight difference in the number of cells per kilometre, as $1/(2R_{[\mathrm{km}]})$ is slightly different from $1/(2R_{[\mathrm{km}]} - l_{[\mathrm{km}]}/2)$ for low values of R.

4. Economic analysis

4.1. Cost parameters

In order to understand the trade-offs involved in the economic analysis, values for the model parameters have to be introduced for hypothetical scenarios. This is due to the dependence of the cluster revenue-to-cost ratio on R, which would make the analysis with a normalised cost function difficult. The goal is to grasp the impact of the choice of R and related frequency re-use parameters (e.g., the re-use pattern) on the MBS economic analysis. The net cost function, C_{n}, has several parameters, namely R, K, N_{op}, S_{ef}, C_{fb}, R_{vt} and C_{ft}. Besides, one is considering coverage distances up to 500 m.

The re-use pattern depends on the frequency band, and on the coverage and re-use geometries. Values taken from the analysis in [21] are considered:

- $K = 2$ in the [62, 63] GHz sub-band of the 60 GHz band for $R \geqslant 66$ m, in the linear geometry;
- $K = 2$ in the [62.0, 62.5] GHz sub-band of the 60 GHz band for $R \geqslant 175$ m, in the Manhattan grid geometry (lower R being, however, allowed for frequencies near 62 GHz);
- $K = 3$ in the remaining 60 GHz band (because oxygen attenuation imposes a different attenuation along the band) and in the 40 GHz one, for both linear and "Manhattan" geometries.

One considered four operators per band, i.e., $N_{\mathrm{op}} = 4$, each using a 0.5 GHz bandwidth, from a total of 2 GHz.

As a hypothesis, one uses data extracted from [6,7] for costs. One has also assumed that MBS will only be viable when the cost of deploying and operating the system will decrease to the order of magnitude of the costs associated with today's systems: a little bit higher in an initial phase, and decreasing down to values comparable to the GSM ones in the following years. One is also expecting that, although the available average data rates increase from generation to generation by a factor near $10\sqrt{2}$ (from circa 10 kb/s in GSM to 144 kb/s in UMTS, and to 2 Mb/s in MBS; in what follows, 1920 kb/s will be considered as an hypothesis), users will not be willing to spend much more per minute during a call (or equivalent). It is worthwhile to note that in MBS the referred 1920 kb/s is faced as the net user load, i.e., the "silent" periods of each application can be explored in order to allow for the use of the shared resources by other applications, hence, they are not taxed.

One assumes that the average load is 1920 kb/s; one also assumes that a unidirectional 1920 kb/s MBS connection will cost approximately as much as a today's GSM call. Thus, e.g., a 8064 kb/s unidirectional connection will cost 4.2 times more, whereas a 384 kb/s connection (thus, using a basic channel) will cost a fifth. Consequently, it is also natural to consider that the cost associated with the usage of the corresponding *fraction* of the transceiver infrastructure (supporting 1920 kb/s, unidirectionally) will cost as much as a second generation system channel. As each frame has 48 slots [19],

Table 1
Assumptions for $K = 3$ (288 channel/cell) in the URB scenario (in the presence of mobility).

C_{fb} [€/year]	C_{1920} [€/year]	R_{384} [€/min]							
		A	B	C	D	E	F	G	H
6500	300	0.00125	0.0025	0.00375	0.005	0.00625	0.0075	0.00875	0.01

there are 48 basic units of 384 kb/s associated to the carrier, and there are $48/5 = 9.6$ times 1920 kb/s available; consequently, under these assumptions, the cost of an MBS transceiver will be 9.6 times the cost of a today's second generation channel (note, however, that a GSM carrier has eight channels, instead of 9.6).

As only micro-cells are used in MBS, one only considers the case of cell ranges up to 300 m [6]. In this case, the setup cost is $C_{\text{BS-tower}} = 20$ k€, the channel cost is $C_{1920} = 300$ €/year (1920 kb/s corresponds to five basic channels of 384 kb/s) and the maintenance and operation costs are $C_{\text{mnt\&op}} = 2.5$ k€/year. Consequently, the cost of a basic channel is $C_{384} = 60$ €/year. These costs are presented in Euros (€), differently from the ones in [6], assuming parity between US Dollar and Euro. One also assumes that the estimated BS tower life is five years [6], and that the duration of the project is five years, $N_{\mathrm{year}} = 5$.

Finally, $C_{\text{BS-tower}}/N_{\mathrm{year}}$ represents the annual cost of a BS equipment and infrastructure, which is true in the approximation of a null discount rate, if the calculations were made in real terms, i.e., in constant Euros [10]. Such is the approach followed here. A complete economic analysis based on discounted cash flows (e.g., to compute the net present value) will need the appropriate adaptations.

As a consequence, in the model from (1) one has

$$C_{\mathrm{fb}} = C_{\text{BS-tower}}/N_{\mathrm{year}} + C_{\text{mnt\&op}}, \tag{8}$$

and

$$C_{\mathrm{ft}} = 9.6 C_{1920}. \tag{9}$$

Furthermore, there is a fixed cost of licensing and frequency auctions (or *beauty contests*) to be taken into account. In a country like Portugal, if a 0.5 GHz license costs 200 M€ (twice the price of an UMTS one), under the simple assumptions of null rate of interest, one obtains an annual fixed cost of 40 M€. Dividing this value by the number of kilometres covered by the MBS network in a medium phase of operation (e.g., 2000 km if only three or four main cities, main roads and highways were considered), one obtains an annual fixed cost per kilometre $C_{\mathrm{fi}}(N_{\mathrm{op}} = 4) = 40000000/2000 = 20$ k€/km/year. One will further consider, as a hypothesis, an operator's target net revenue per kilometre per year of 130 ± 15 k€/km.

4.2. Assumptions for revenues

Taking costs and revenues on an annual basis, one follows the approach of considering six busy hours per day, 240 busy days per year [6] and a 384 kb/s basic channel revenue $R_{384[€/\mathrm{min}]}$. Note that considering a number of equivalent busy hours per day is an approximation, and will need validation. The revenues are then proportional to the load supported by the system, in kb/s, which is reflected in the analysis via the spectral efficiency. It is, in turn, the minimum S_{ef} obtained from the blocking and handover failure probabilities constraints, since traffic from mobility has a strong impact. The revenue per cell per year is then obtained by

$$(R_{\mathrm{v}})_{\mathrm{cell}[€]} = \frac{6 \cdot 240 \cdot 60 \cdot S_{\mathrm{ef}} \cdot T \cdot 48 \cdot R_{384[€/\mathrm{min}]}}{K N_{\mathrm{op}}}, \tag{10}$$

where $T 48/N_{\mathrm{op}}$ gives the number of 384 kb/s channels available in the cell. Note that 48 denotes the number of slots per frame, numerically corresponding to the number of basic channels (of 384 kb/s) per carrier, i.e.,

$$R_{\mathrm{vt}} = 48 R_{384}. \tag{11}$$

Thus, the revenue per transceiver is

$$R_{\mathrm{vt}[€]} = 86400 \cdot 48 \cdot R_{384[€/\mathrm{min}]}. \tag{12}$$

Replacing the cost per carrier/transceiver C_{ft} by $48C_{1920}/5 = 9.6C_{1920}$, where C_{1920} is the cost associated with a 1920 kb/s set of channels, and further considering $T = 72$ and $C_{\mathrm{fi}} = 0$, one obtains

$$C_{\mathrm{n}[€/\mathrm{km}]} = \frac{1}{2R_{[\mathrm{km}]}}\left[C_{\mathrm{fb}[€]} - \frac{3456}{K N_{\mathrm{op}}}\left(86400 S_{\mathrm{ef}} R_{384[€/\mathrm{min}]} - \frac{C_{1920[€]}}{5}\right)\right] \tag{13}$$

for the linear coverage geometry, with the restriction that $3456/(K N_{\mathrm{op}})$ should be multiple of 48 (the number of slots per frame). Note that $T \cdot 48 = 3456$ represents the sum of slots from of all carriers (each carrier contributing with one frame).

In table 1, besides the values of C_{fb} and C_{1920}, one presents eight different cases (A, B, C, ..., H) which correspond to different values of R_{384}, i.e., these labels will distinguish the values of the revenue per basic channel of 384 kb/s in the plots with results. The values in this table correspond to the urban (URB) scenario and $K = 3$ (in the presence of mobility). For instance, $R_{384} = 0.0075$ €/min corresponds to the case F for the urban, URB, scenario, represented by a grey cell background in the table.

Results are being presented for (i) $K = 3$ – URB scenario (288 channel/cell), and (ii) $K = 2$ – ROA (roads) scenario.

Table 2
List of applications and their abbreviations.

Abbreviation	Application
HVT	HD Video-telephony
IVC	ISDN-Videoconference
MVS	Mobile Video Surveillance
HOB	HDTV Outside Broadcast
WLI	Wireless LAN Interconnection
FTP	Data File Transfer (FTP)
PIM	Professional Images
DMM	Desktop Multimedia
MES	Mobile Emergency Service
MRA	Mobile Repair Assistance
MTW	Mobile Tele-working
FFM	Freight & Fleet Management
EMB	E-mailbox Serv. for Multimedia
ECO	E-commerce
MML	Multimedia Library
TIN	Tourist Information
RPC	Remote Procedure Call
UGD	Urban Guidance
ATR	Assistance in Travel
TVD	TV Programme Distribution
ENP	E-newspaper

5. Results

5.1. Supported traffic

One considers the set of 21 applications defined in [18], table 2, operating in the BCC (business city centre), URB and ROA scenarios; a proposal for their usage was defined in [19] (knowing the average duration, burstiness and asymmetry factors of applications [17]). The characteristics of bearer service components are also extracted from [19], as well as their correspondence with applications. These data and video components have different data rates; the basic bit rate is 384 kb/s. The list of the applications is presented in table 2.

One considers the assumptions for available channels from [19,20]. The total amount of channels in each cell is a fraction of the total number of channels, depending on the number of operators and on the re-use factor, K [11]. In this paper, one considers the cases of 432 and 288 channel/cell. The former corresponds to 4 operators and $K = 2$, while the latter corresponds either to 4 operators and $K = 3$ or 3 operators and $K = 4$.

The starting point of MBS optimisation consists in obtaining the variation of the spectral efficiency (a measure of the supported traffic) with the coverage distance. In order to have a balance of the supported traffic between the links, table 3, one considered the results from [20], where the computations from [19] were redone, in order to have also a set of results for different values of R, say, $10 \leqslant R \leqslant 500$ m. While in [19] one has considered a total potential number of user per cell of $M = 250$, 100 and 100 (for $R = 100$, 100 and 150 m), in the BCC, URB and ROA scenarios, respectively, in [20] it is considered that M is directly proportional to R. It is computed by $M = 2.5R$, $M = R$ and $M = 0.67R$, respectively.

Results for the supported fraction of active users, f, as a function of R, are presented in figure 2 (the example is also for the ROA scenario), while the variation of the spectral efficiency with R is presented in figure 3 (example for the URB scenario). As our approach consists of considering an equivalent number of busy hours per day, to use the supported traffic is appropriate since system operation near the saturation is properly modelled.

Table 3
Distribution of channel between the links.

c_{Link}	Link	288 channel/cell	432 channel/cell
BCC	uplink	66	99
	downlink	222	333
URB	uplink	90	110
	downlink	198	322
ROA	uplink	63	99
	downlink	225	333

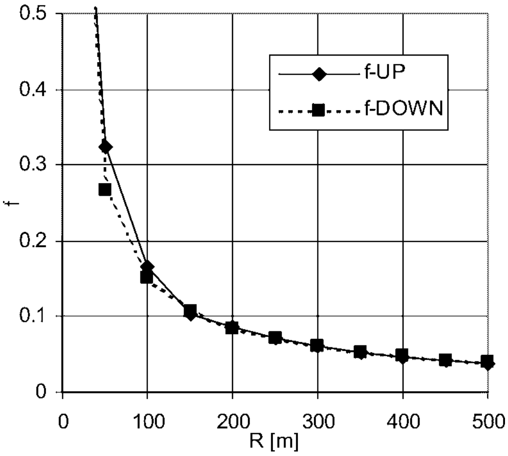

Figure 2. Supported f as a function of R, for the ROA scenario, and presence of mobility, $K = 2$.

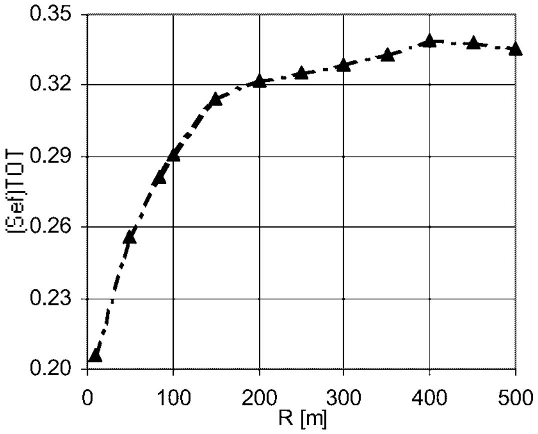

Figure 3. Total spectral efficiency for the URB scenario ($K = 3$).

The variation with R of the supported number of user/km was also studied in the presence of mobility (although detailed results are not presented here [15]). It allows one to choose $K = 3$ for the URB scenario, whereas $K = 2$ is needed in the BCC and ROA scenarios (note that according to RACE-MBS forecasts, the initial objective was to obtain, at least, 200, 58 and 39 users per kilometre in the BCC, URB,

Table 4
Summary of the results for $R = 100$ m.

Scenario	K	Limiting link	f [%]	R [m]	Supported no. user/km	$(S_{\mathrm{ef}})_{\mathrm{TOT}}$ [%]
BCC	2	downlink	10.4	100	130	39.5
URB	3	downlink	14.1	100	74	29.1
ROA	2	downlink	15.1	100	50	15.2
			10.3	150	34	16.3

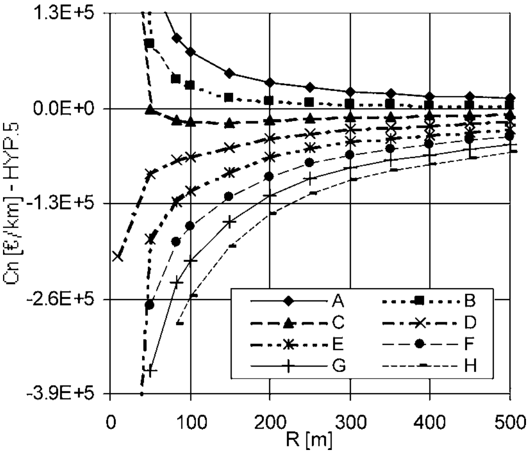

Figure 4. Net cost for the URB scenario ($K = 3$).

and ROA scenarios, respectively), table 4. Whereas in the URB and ROA scenarios the initial objective is overcome, in the BCC scenario the goal of supporting 200 user/km cannot be achieved only with a single operator. Besides, it is worthwhile to note that, whereas $K = 3$ corresponds to using the 40 GHz band and/or the upper 1 GHz sub-band of the 60 GHz band, $K = 2$ corresponds to the lower 1 GHz sub-band of the 60 GHz band [15].

The spectral efficiency is lower for the ROA scenario, because of the high terminal mobility, which strongly degrades system performance [20].

5.2. Net cost/revenue

From the total spectral efficiency, one has obtained the net cost for the URB and ROA scenarios (the linearised net cost is considered for the latter). Results for $C_{\mathrm{n}}(R)$ are presented in figure 4 for the URB scenario, where the values of R_{384} are labelled with A, B, …, G and H. For cases D–H, the net revenue increases when R decreases (corresponding to a decrease of the net cost). However, as the initial investment associated with a system with smaller cells is much higher (and it will not be immediately compensated with revenues), deployment strategies for MBS have to be analysed in detail (next section).

It is important to analyse the values obtained for r_{c}, C_{n}, and R_{384}, so that the operator achieves a net revenue of 150 ± 15 k€/km/year (not considering C_{fi}), while the annual payment of the fixed cost associated with licensing is $C_{\mathrm{fi}} = 20$ k€/km/year, table 5. One has considered $K = 2$ and 3, cells with $R = 100$ m and the presence of mobility (corresponding to a potential number of users in a cell $M = 100$ and 66, in the URB and ROA scenarios, respectively). Results are included for the supported number of user/km. Values are also included for $K = 2$ in the URB scenario for comparison purposes.

Table 5
Results for r_{c}, C_{n} and R_{384} as a function of K and the scenario ($R = 100$ m).

Scenario	K	M_{T}	r_{c}	C_{n} [€/km]	R_{384} [€/min]	Supported no. user/km
URB	2	100	10.49	−146021	0.005	117
	3		17.07	−161302	0.0075	74
ROA	2	66	11.68	−166495	0.045	50

Table 6
Total cost and revenues, in €/km/year, for $R = 100$ and 200 m.

Scenario	R [m]	R_{ev} [€/km]	$C_{[€/\mathrm{km}]}$	$C_{\mathrm{n}[€/\mathrm{km}]}$	P_{ft} [%]
URB	100	287122	125820	161302	128.2
$K = 3$	200	154462	61131	93331	152.7
ROA	100	338029	171534	166495	97.0
$K = 2$	200	184849	83342	101597	121.8

To achieve an annual net revenue (or profit) of 130 k€/km, R_{384} should be higher for the deployment scenarios with lower associated spectral efficiency (for a given value of K). Whereas the spectral efficiency takes values $(S_{\mathrm{ef}})_{\mathrm{TOT}} = 32.2\%$ and 15.2% for the URB and ROA scenarios, the revenue from each basic channel has to be at least $R_{384} = 0.005$ and 0.045 €/min, respectively, i.e., the prices in the ROA scenarios have to be one order of magnitude higher than in the URB scenario. From these results for R_{384}, price lists can be obtained. The differentiation between scenarios will be possible if prices can be distinguished according to the BS users are accessing to. Billing is done on a "per min" basis, and not by volume of information. However, the volume of information is reflected in the price per minute of each service component, as it is proportional to the service component data rate (it is obtained by an weighted sum of the service components activity duration, where the weights are the respective data rates). As a consequence of this approach, ABR applications will only be billed by the application minimum guaranteed data rate.

5.3. Deployment strategies

Because, for the value of the net revenue one is assuming as a goal, the net cost function does not have a mathematical minimum in the zone of interest ($50 \leqslant R \leqslant 350$ m), it is important to explore different criteria to optimise MBS design. Different deployment strategies can then be adopted in different phases of MBS deployment, namely the medium term phase and mature operation.

In table 6, one presents the achieved values for the total cost and revenues for $R = 100$ m and $R = 200$ m, as well as

Table 7
Comparison of the number of supported users per kilometre.

Scenario	Foreseen no. of user/km	No. of supported user/km		Ratio of no. of user/km between	Ratio supported/ foreseen no. of user/km	
		$R = 100$ m	$R = 200$ m	$R = 200$ and 100 m	$R = 100$ m	$R = 200$ m
URB	58	74	41	0.554	1.276	0.707
ROA	39	50	28	0.560	1.282	0.718

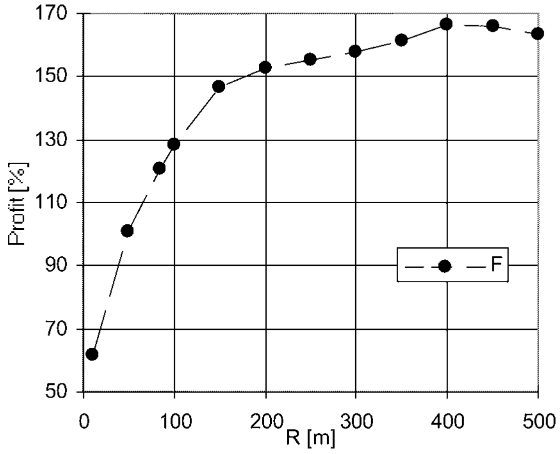

Figure 5. Profit as a function of R, URB scenario ($K = 3$).

the respective profit, P_{ft}, defined as the ratio between the net revenue and the cost,

$$P_{\mathrm{ft}} = \frac{R_{\mathrm{ev.tot}} - C_{\mathrm{tot}}}{C_{\mathrm{tot}}}. \tag{14}$$

In the urban and roads scenarios, the profit strongly decreases with the decrease of R. In table 7, one presents the comparison of the number of supported users per kilometre between the cases of $R = 100$ m and $R = 200$ m, as well as the comparison between the foreseen and the actually supported number of users per kilometre.

The dependence of the profit (in percentage) with R is presented in figure 5 for the ROA scenario (corresponding to the values presented in table 6 for $R = 100$ and 200 m). The shape of the curves is equal to the shape of the curves of $r_c(R)$, thus, the associated increasing behaviour is a consequence of the increasing behaviour of $S_{\mathrm{ef}}(R)$. In these scenarios, the foreseen number of users for mature MBS can only be achieved with cells with $R = 100$ m, table 7. However, during the initial phase, while 70% of the foreseen mature MBS users were not achieved, one can use cells with $R = 200$ m.

As a consequence, in a medium term scenario, assuming that the number of foreseen users will be less than 70% of the number of users in mature MBS, they will be supported using cells with $R = 200$ m in the URB ($K = 3$ is used in the range of feasible R) and ROA (in the linear coverage geometry $K = 2$ is only allowed for $R \geqslant 66$ m [21]) scenarios. This solution has the advantage of corresponding to a higher profit (e.g., 121.8% against 97.0% in the ROA scenario, or 152.7% against 128.2% in the URB scenario). It is important to note that, although beginning with cells with $R = 200$ m (changing it later to $R = 100$ m) is very easy to implement in the ROA scenario, it will be more difficult in the URB scenario. As the ROA scenario has a linear geometry, the system can be designed in the beginning using cells with $R = 200$ m, it being very easy to introduce cells with $R = 100$ m in between, in a later phase. In the URB scenario, which has a Manhattan grid geometry, these changes will be much more complex to achieve, or even unlikely.

6. Conclusions

A net cost model is presented for the design trade-offs between re-use pattern, K, the coverage distance, R, and the spectral efficiency, $S_{\mathrm{ef}}(R)$, which allows for optimising the cellular planning in linear and regular urban geometries. This model allows for the determination of the revenue per channel that achieves a given value for the annual profit per kilometre. The existence of profitable cell configurations for the system was seen to depend critically on the relation between the re-use pattern and the cluster revenue-to-cost ratio.

Data from the supported fraction of active users and the spectral efficiency was fed into the MBS economic analysis for system optimisation purposes. Results were achieved for the cluster revenue-to-cost ratio and for the net cost for the cases URB scenario – $K = 3$ (and $K = 2$, for comparison purposes) and ROA scenario – $K = 2$. In order to achieve an annual net revenue of 150 k€/km, the revenue per basic channel should be higher for the scenario with lower associated spectral efficiency. For example, comparing the URB and ROA scenarios for $R = 100$ m and $K = 2$, whereas the spectral efficiency takes values $(S_{\mathrm{ef}})_{\mathrm{TOT}} = 32.2\%$ and 15.2%, the revenue from each basic channel has to be $R_{384} = 0.005$ and 0.045 €/min, respectively, i.e., the prices in the ROA scenario have to be around one order of magnitude higher than in the URB scenario.

In a medium term scenario, if one assumes that the number of foreseen users will be less than 70% of the mature MBS number of users, one concludes that they can be supported using cells with $R = 200$ m in the URB and ROA scenarios. However, the foreseen number of users for mature MBS can only be achieved with cells with $R = 100$ m; using larger cells has the advantage of corresponding to a higher profit (e.g., 121.8% against 97.0% in the ROA scenario, or 152.7% against 128.2% in the URB scenario).

As time passes, and the use of MBS evolves, the operator is able to choose different cell coverage distances, in order to support a different number of users, whilst maximising profit. Profit (in percentage) is higher for higher coverage distances, because few cells are used, and costs are lower. Hence, the stringent design requirements associated with cost/revenue analysis show that it is important to have accurate forecasts for user demand in each phase of MBS evolution, in order to avoid over-dimensioning, and thus not making unnecessary high investments (without immediate return) in an early phase.

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Fernando J. Velez was born in Benguela, Angola, on February 1970. He 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. He made or makes part of the teams of RACE/MBS, ACTS/SAMBA, COST 259, COST 273 and IST/SEACORN European projects, and he has authored more than twenty papers and communications in international journals and conferences. His main research areas are cellular planning tools, traffic from mobility, multi-service traffic and cost/revenue performance of advanced mobile communication systems.
E-mail: fjv@ubi.pt

Luis M. Correia was born in Portimão, Portugal, on October 1958. He received the Ph.D. in electrical and computer engineering from IST (Technical University of Lisbon) in 1991, where he is currently a Professor in Telecommunications, with his work focused in Wireless/Mobile Communications in the areas of propagation, channel characterisation, traffic, services and cellular planning. He has acted as a consultant for Portuguese GSM operators and for the telecommunications regulator. Besides being responsible for research projects at the national level, he was or is part of various ones within European frameworks (RACE, ACTS, IST and COST). He participated in and was co-editor of the Final Report for COST 231, Chairman, and editor of the Final Report for COST 259, and he is currently the Chairman of COST 273. He was and is responsible for the supervision of students at both the M.Sc. and Ph.D. levels. He has authored papers and communications in international journals and conferences, for which he has served also as a reviewer, and has been a co-editor of a special issue of a journal on *Wireless Broadband Systems*. He has served as evaluator and auditor in ACTS, ESPRIT and IST frameworks. He was the Chairman of the Technical Programme Committee of PIMRC'2002.
E-mail: luis.correia@lx.it.pt