

Optimization Criteria for Cellular Planning of Mobile Broadband Systems in Linear and Urban Coverages

Fernando J. Velez¹, Luis M. Correia²

¹Universidade da Beira Interior, Covilhã, Portugal

²Instituto Superior Técnico*, Lisboa, Portugal
fjv@ubi.pt, luis.correia@lx.it.pt

Abstract: *This paper addresses the comparison of characteristics between the prospective allocated bands for MBS by the International Telecommunications Union, 40 and 60 GHz, and its consequences in the optimization criteria for the cellular design. The key difference between the two bands is the oxygen absorption attenuation which is negligible at 40 GHz, but presents high values at 60 GHz, larger than 10 dB for the typical reuse distance. At 60 GHz the carrier-to-interference ratio is larger, and depends on the coverage distance, while at 40 GHz this dependence does not exist. At 60 GHz lower values for the co-channel reuse factor are obtained and, as a consequence, a larger system capacity is achieved.*

1. Introduction

Mobile Broadband Systems, MBSs, will significantly extend to mobile users the access to broadband services, i.e., they will allow mobile communications to be fully integrated into Broadband-ISDN and to support new mobile-specific applications. Examples are the videotelephony, business communications (banking, insurance), multimedia library access, teleworking, emergency services support, repair assistance, city guidance, transport and travel information, industrial wireless LAN and TV outside broadcast [1]. Owing to its high transmission data rates (corresponding to large bandwidths) and due to the saturation of the spectrum at lower frequency bands, MBS is intended to operate in the millimetre waveband, offering improved performance in system transmission capacity. This usage of the millimetre waveband for the future MBS imposes that the attenuation of atmospheric elements, namely rain and oxygen, has to be taken into account in cellular design, which is not necessary at the UHF band. This paper addresses the comparison of characteristics between the prospective allocated bands for MBS by ITU (International Telecommunications Union), 40 and 60 GHz, and its consequences in the optimization criteria for the cellular design.

The following specific bands are being considered for the implementation of MBS: [39.5, 43.5] GHz and [62, 66] GHz, with an interval of 2 GHz in between 1 GHz bands. The propagation characteristics are not equal in these two bands, with oxygen and rain presenting different values for their attenuation coefficients; moreover, these coefficients are not uniform within each of the bands. Since a larger attenuation leads to the possibility of reusing frequencies at a closer distance for approximately the same coverage (the attenuation is not substantial for short distances like the ones involved in cell coverage), the usage of one or the other frequency bands has significant consequences on system capacity and on its cost/revenue performance. Thus, it is important to establish the correspondence between the maximum coverage and reuse distances, R and D , and the carrier-to-interference ratio, C/I , for both bands, and to analyze the resulting consequences, in order to decide under which conditions it is preferable to use one band or another. It is well known that the attempt to reuse each frequency to a maximum in close cells is limited by the interference between co-channel cells. As a minimum bounding value for the carrier-to-interference ratio is required to guarantee a

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given quality of service (maximum bit error rate), threshold values for co-channel reuse factor, $r_{cc} = D/R$, and system capacity are needed, depending on carrier-to-interference constraints. On the other hand, although it is not usual in cellular systems, limitations on maximum cell coverage can be imposed by noise rather than traffic, if for example low values are considered for the transmitter power or a very demanding modulation scheme is used. This suggests that a comparison between the two bands is in order, concerning not only interference but noise as well.

In the millimetre wavebands propagation occurs essentially in line-of-sight, LOS, thus the shape of the cells and the co-channel interference are determined by the surrounding scenario geometry. As a consequence, for cellular design purposes, an easy analytical treatment is only possible for coverage environments with regular structure as the linear and “Manhattan grid” geometries. The associated system capacity depends on the total number of base stations and on the number of carriers available per unit length (or unit area), whose equations can be obtained by simple geometrical considerations.

In Section 2 of this paper the propagation characteristics at 40 and 60 GHz are analyzed. Although free space path loss and rain attenuation are similar for both bands, oxygen attenuation shows a different behaviour. This fact originates a relevant difference in the attenuation between the two bands and different behaviours of the carrier-to-interference ratio. Taking into account the importance of this analysis, a comparison study of C/I in terms of r_{cc} is presented in Section 3; here, a model consisting of only two co-channel cells is first considered, and then the linear and “Manhattan grid” geometries are studied. The resulting co-channel reuse factors are also highlighted, and the influence of rain on the results is discussed. In Section 4, the influence of the noise threshold on the transmission quality is discussed, in order to distinguish under which conditions the system is interference limited or interference-plus-noise limited. The variation of the carrier-to-noise-interference ratio with distance is studied, and graphical representations for the co-channel reuse factor in terms of the maximum coverage distance are presented. Conclusion are drawn at the end.

2. Propagation Characteristics

The average power received at a distance d from a transmitter can be found by considering the free space received power, plus the attenuation due to oxygen and rain, and assuming that the average decay can be different from the one of free space [2]. Thus, the total received power is given by

$$P_{r[\text{dBm}]}(d) = -32.4 - 30 \cdot n + P_{t[\text{dBm}]} + G_{t[\text{dBi}]} + G_{r[\text{dBi}]} - 10 \cdot n \cdot \log(d_{[\text{km}]}) - \gamma_{r[\text{dB/km}]} \cdot d_{[\text{km}]} - \gamma_{o[\text{dB/km}]} \cdot d_{[\text{km}]} - 20 \cdot \log(f_{[\text{GHz}]}) \quad (1)$$

where: P_t is the transmitted power; G_t and G_r are the gains of the transmitting and receiving antennas, respectively; n is the average decay; γ_r is the rain absorption coefficient; γ_o is the oxygen attenuation coefficient; and f is the frequency. For an outdoor environment, a value of $n=2.3$ is used.

There is only a small difference for the free space path loss between both bands, $20 \cdot \log(60/40) = 3.52$ dB. Therefore, it is obvious that the difference between the two bands is not imposed by this parameter.

For the oxygen absorption the difference is relevant. Using the formulas of ITU-R [3] for $f < 57$ GHz and the formulas presented in [2] for $60 \leq f \leq 66$ GHz one obtains the curves presented in Fig. 1, where the frequency scale is normalized in order to superimpose the 40 and 60 GHz bands in the same graph (-2 GHz corresponds then to the lower limit of each band, 39.5 or 62 GHz respectively, and 2 GHz to the upper limit). In the 40 GHz band, γ_o is almost constant and negligible, less than 0.07 dB/km. However, in the 60 GHz band, the oxygen absorption has to be considered, decreasing from 14 dB/km (at 62 GHz) down to approximately 1 dB/km (at 66 GHz). In the case of the higher frequency band, the additional path loss caused by the oxygen absorption is negligible for short coverage distances, but it can present high values, larger than 10 dB, for typical reuse distances, which results in smaller values for r_{cc} and a larger system capacity.

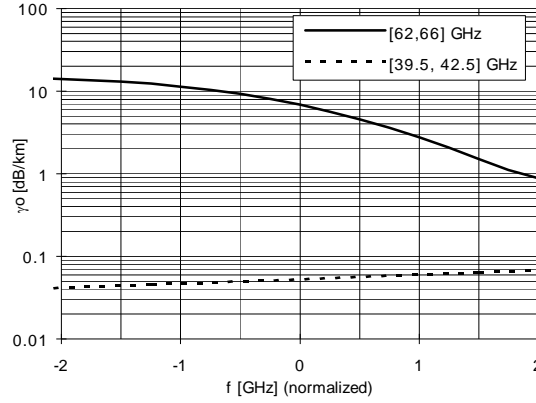


Fig. 1 - Oxygen attenuation coefficient as a function of normalized frequency for the 40 and 60 GHz bands (0 corresponds to the centre frequency of each band).

This is of course the added value of using the 60 GHz band instead of the 40 GHz one.

The rain attenuation has also to be considered. The model presented by ITU-R [4] has been used

$$\gamma_r [\text{dB/km}] (f[\text{GHz}], I_r[\text{mm/h}]) = k(f) I_r^{\alpha(f)} \quad (2)$$

where I_r is the rain intensity. For a rain intensity of $I_r = 30$ mm/h, which occurs in Europe with a probability less than 0.03%, the rain attenuation is approximately 8 dB/km at 40 GHz, and it is slightly increasing through the band. At the 60 GHz band, the behaviour is similar, with a value of the order of 12 dB/km. One may conclude that the presence of rain causes worst-case situations for the received power which should be considered in the cellular design. Nevertheless, the difference between the two bands is not as significant as the one concerning oxygen.

3. Analysis of the Carrier-to-Interference Ratio

The carrier-to-interference ratio has a direct influence on the co-channel reuse factor and on system capacity. Considering two co-cells with maximum coverage distance R and with their centres separated by a distance D , the minimum value for the carrier-to-interference ratio is given by

$$C/I_{[\text{dB}]} = \gamma \cdot (r_{cc} - 2) \cdot R + 10 \cdot n \cdot \log(r_{cc} - 1) \quad (3)$$

where γ represents the attenuation by atmospheric elements, $\gamma = \gamma_o + \gamma_r$; the usual assumptions for C/I analysis have been considered. In the absence of rain, Fig. 2, one concludes that, at the 40 GHz band (where the oxygen absorption is negligible), C/I does not depend on the value of R when r_{cc} varies, presenting a value of the order of 10 dB for $r_{cc} = 4$, which is a typical value for the UHF band (where a similar behaviour is found). However, at 60 GHz the behaviour is much different, because the values for the oxygen attenuation are not negligible. For the same value of r_{cc} and different values of R , different values for C/I exist, and the larger R is the larger C/I one gets, with values ranging from 12 dB up to 25 dB at $r_{cc} = 4$, when R varies one order of magnitude from 50 to 500 m.

In the presence of rain, a larger value for the attenuation coefficient is obtained, and basically the previous behaviour for the 60 GHz, without rain, is observed for the two bands. At the 60 GHz band, the main difference consists in a larger value for C/I ; at 40 GHz the previous behaviour changes, and different curves exist for different coverage distances, since the attenuation coefficient is not negligible.

At 40 GHz the values range from 12 dB up to 19 dB (at $r_{cc} = 4$), while at 60 GHz they range from 14 dB up to 37 dB. One can conclude that because the absence of rain is more favourable for propagation purposes, it determines a higher value for the interference power and a worst-case situation for the carrier-to-interference ratio.

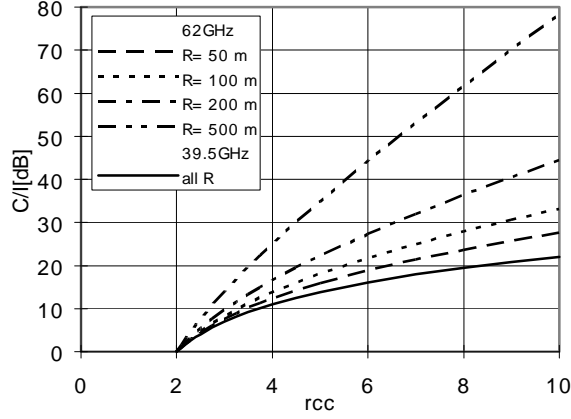


Fig. 2 - Carrier-to-interference ratio in terms of the co-channel reuse factor with R as a parameter, in the absence of rain.

The linear coverage geometry consists of cells with a total length of $2R$ and a reuse distance D , corresponding to the coverage of an indefinitely long street or highway. The worst case situation for the received carrier at a base station occurs when the transmitter mobile unit is at the boundary of the cell, at a distance R from the base station. There are interfering mobiles at both sides of the considered cells, whose interference, also in the worst case, comes from mobile units located at distances $mD-R$, $m=1, \dots, T$, where T is the number of relevant tiers of interference. The following equation results for C/I

$$\left(\frac{C}{I}\right)_{dB} = \gamma \cdot R \cdot [T(r_{cc}(T+1) - 2) - 1] + 10 \cdot n \cdot (2T - 1) \log(R) + 20 \cdot n \cdot \log\left(\prod_{m=1}^T (m \cdot r_{cc} - 1)\right) \quad (4)$$

Values approximately 3 dB below those of the previous case (only two cells) are obtained; in this situation, there are co-channel interference sources at both sides of the cell, which explains the degradation. A similar difference exists for the “Manhattan grid” geometry: a regular urban structure with streets perpendicular to each other. In this case, the cells, which form reuse patterns with an associated reuse distance D , also have a maximum coverage distance R , and four main lobes in the directions of orthogonal streets. The base stations are placed in the middle of each crossing, and there is a perfect tessellation between the cells and the urban grid. Due to the obstruction by blocks of buildings, interference occurs only in LOS, coming from the directions associated with each street (the West/East and South/North directions); as a consequence, C/I is 3 dB lower than the value corresponding to the the linear coverage case (and 6 dB below the value obtained for the pair of interfering cells).

4. Influence of Noise Threshold

Depending on the maximum coverage distance and on the co-channel reuse factor, the system operates either interference limited or interference-plus-noise limited. For a proper system operation, the carrier-to-noise ratio, C/N , should exceed its minimum value, which depends on the maximum bit error rate, BER, allowed and on the modulation type; this implies the consideration of the technologic parameters of the system in the analysis of its performance.

It is well known that the BER at a receiver is a function of the received carrier and co-channel interference powers as well as the thermal noise power. Using the parametrization of constant BER contours presented in [5], for a situation where the same equipment and data rates are used, an equation for the minimum carrier-to-noise-interference ratio can be obtained in terms of $\alpha_c = (C/I)_o / (C/N)_o$ which is specific of each modulation, $(C/N)_o$, $(C/I)_o$ being the minimum values for the carrier-to-noise and carrier-to-interference ratios. The calculation of the reuse and maximum coverage distances can be separated once the parameter $M=I/N$ is fixed. For a $BER_{max}=10^{-3}$, minimum

carrier-

-to-noise and carrier-to-interference ratios of 13 and 11 dB, respectively, were obtained for OQPSK modulation by simulation [6] leading to $\alpha_c = -2$ dB.

A typical configuration envisaged for a Mobile Broadband System is considered [5] using a vehicle-mounted antenna, and with the following design parameters: transmitted power of 100 mW, base station antenna gain of 20 dBi, mobile antenna gain of 14 dBi, receiver noise figure of 6 dB, and noise power of -125 dBW. The value of EIRP is kept constant in all the cases (two cells, linear and urban coverages), which implies a decrease of 3 dB from the two cells case to the linear coverage, and a similar situation from the linear coverage to the urban one.

The dependence of carrier-to-noise-interference ratio with distance, in the absence of rain was analyzed and a comparison between the consideration of first, second, third and fourth tiers of interference was done, Fig. 3. At the 60 GHz band ($f = 62$ GHz), for the "Manhattan grid" geometry maximum values were obtained for $R \sim 75$ -125 m. However, at 40 GHz ($f = 39.5$ GHz), the function is almost constant up to $R \sim 100$ m, showing afterwards a slightly decreasing behaviour. In the presence of rain, owing to the larger attenuation, at the 60 GHz band the carrier-to-noise-interference ratio will have higher local maxima, while at 40 GHz the function will have a similar behaviour as for the 60 GHz band without rain. Given a certain D/R , at 60 GHz there is an optimum value for R , where $C/(N+a_c I)$ has a maximum; this is no longer the case for 40 GHz. Again $C/(N+a_c I)$ has higher values for the upper frequency band. One can also conclude that while at the 60 GHz band it is enough to consider two tiers of interference, at the 40 GHz band the consideration of three tiers is needed, because there still is an important difference on the results between the consideration of the second and third tiers. This difference is only negligible between the third and fourth tiers of interference.

Given a value of R , the minimum reuse distance that can be achieved and the corresponding value of $M=I(R)/N$ can be obtained in the presence and absence of rain [5]. For the "Manhattan grid" geometry the curves for $r_{cc}(R)=D(R)/R$ are presented in Fig. 4 for both bands. At the 60 GHz band, lower coverage distances are obtained as a consequence of the larger oxygen absorption attenuation; thus, the minimum r_{cc} is 3.75. At 40 GHz one has the minimum r_{cc} of 5.8. There is however the need to use even values for the co-channel reuse factor, corresponding to an integer number of cells. So, a value of $r_{cc}=4$ is obtained for the OQPSK modulation at 60 GHz, corresponding to $D=640$ m ($R=160$ m) and

$M \sim 12$ dB. At 40 GHz one obtains $r_{cc}=6$, corresponding to $D=1860$ m ($R=310$ m) and $M \sim 12$ dB. So, both configurations are limited by the interference. For the linear geometry, one obtains slightly smaller minimum values, and equal feasible values for the co-channel reuse factors for both the bands.

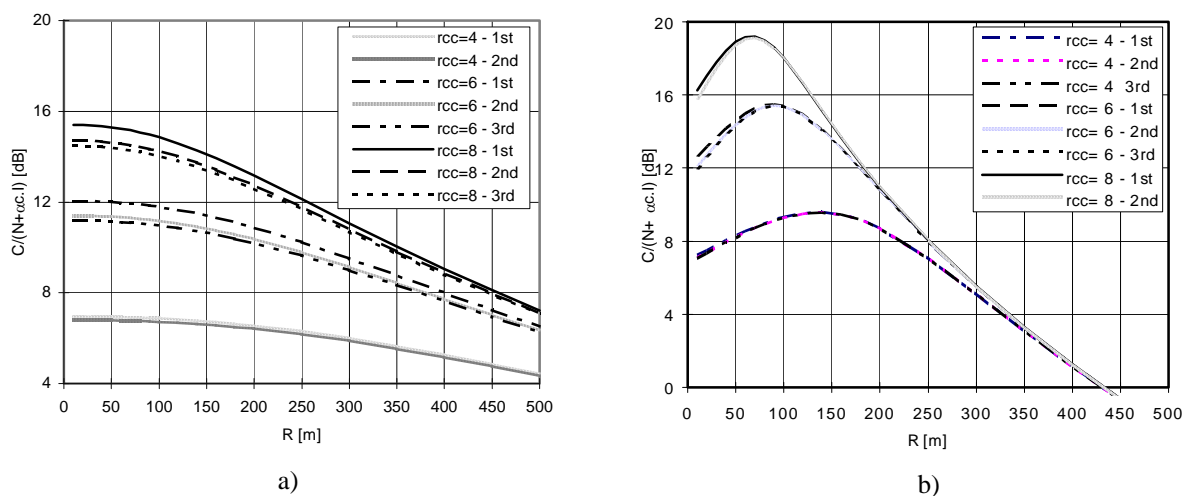


Fig. 3 - Carrier-to-noise-interference ratio as a function of the maximum coverage distance, with the co-channel reuse factor r_{cc} as a parameter, for the "Manhattan grid" geometry at a) the 40 GHz band, and b) the 60 GHz band.

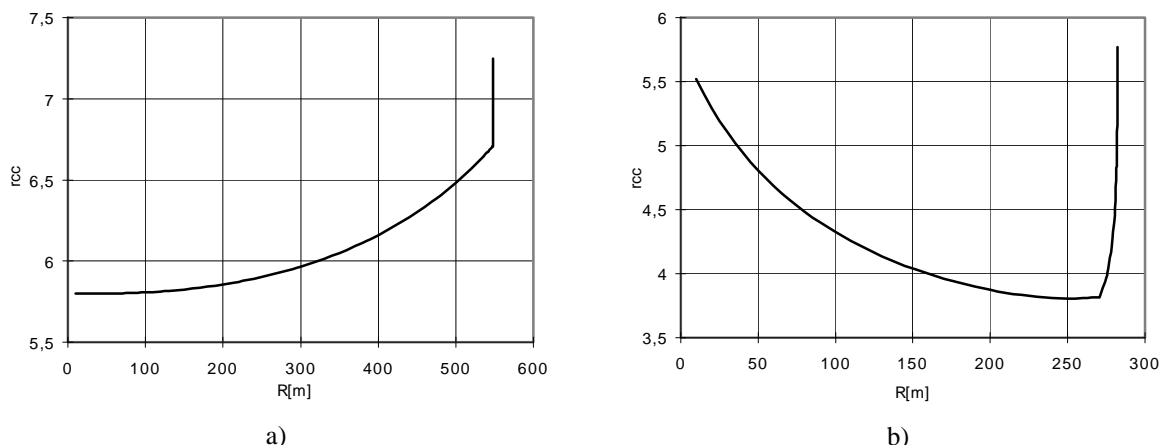


Fig. 4 - Co-channel reuse factor as a function of the maximum coverage distance for a "Manhattan grid" geometry at a) the 40 GHz band, and b) the 60 GHz band.

5. Conclusions

The fundamental difference between the two bands, 40 and 60 GHz, is the oxygen absorption attenuation. While, at 40 GHz, the attenuation is negligible, at 60 GHz, it has to be considered, decreasing from 14 dB/km (at 62 GHz) down to approximately 1 dB/km (at 66 GHz). At 40 GHz, one concludes that the carrier-to-interference ratio does not depend on the value of the maximum coverage distance, but only on the reuse distance, presenting a value of the order of 10 dB for $r_{cc}=4$. However, at 60 GHz the behaviour is much different because the values for the oxygen attenuation are not negligible. For different values of the maximum coverage distance, different values for the carrier-to-interference ratio exist, and the larger R is, the larger C/I one gets, with values ranging from 12 dB up to 25 dB (at $r_{cc}=4$) when R varies one order of magnitude, from 50 to 500 m. In the presence of rain, a larger value for the attenuation coefficient is obtained, and basically the previous behaviour for the 60 GHz band is observed for the two bands. There is no significant difference between the values of the co-channel reuse factor for the linear and "Manhattan grid" geometries because the presence of obstructions decrease considerably the degree of interference between cells. One obtains $r_{cc}=4$ at the 60 GHz band and $r_{cc}=6$ at the 40 GHz band, which means that the former leads to a higher capacity system.

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