Microcellular Design and System Capacity Determination for Outdoors Urban Mobile Broadband Communication Systems in the Millimetrewave Bands

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ABSTRACT

This paper addresses the cellular design of mobile microcellular communications systems operating in the millimetrewave bands in outdoor urban environments. In such systems and environments the shape of cells and the interference among them are highly dependent on the geometry of the surrounding obstacles (e.g., buildings) and the classical regular geometry based approaches to frequency reuse and capacity evaluation cannot be used. In the paper is described an approach to frequency reuse and system capacity evaluation where conclusions are drawn from cellular layouts obtained, via an interactive computer graphical tool, for specific urban environments. Numerical examples are presented for coverage in the 40 and 60 GHz bands showing that, depending on the cell size, reuse factors in the range 5–11 are achievable. It is also concluded that, in interference limited scenarios, if cells with similar coverage length are used, equal values are obtained for the reuse factor and system capacity in both bands.

I. INTRODUCTION

Future personal and mobile communications systems will provide to their users a flexible mix of services (e.g., interactive data, file transfer, voice, video) at high data rates. In the framework of the European Union research programs on mobile communications, one such system, designated Mobile Broadband System (MBS) [1], has been considered, aiming at providing individual user bit rates up to the order of tens of Mbit/s. We consider in this paper the cellular design of such type of systems in urban outdoor environments, and in particular the determination of achievable frequency reuse and system capacity.

Broadband mobile systems will operate in the millimetrewave frequencies, prospective radio allocation having been made in Europe in the 40 GHz and 60 GHz bands. The high desired capacity and high operating frequency of these systems lead to microcellular architectures, employing a large number of cells, with base stations deployed at relatively low heights above street level (around 5 m, e.g., in lamp posts). The shape of cells and the interference between them are strongly determined by the propagation characteristics of the millimetrewave bands, in particular the facts that propagation occurs essentially in line-of-sight, with negligible diffraction, and that building materials are almost totally opaque [2]. Thus, in an outdoor urban environment, the cell shapes are determined, to a large extent, by the disposition of the surrounding objects, in particular buildings. The spatial arrangement of buildings also determines the existence of line-of-sight, and hence interference, between cells. Given the irregularity of typical urban environments, it is not easy to draw general conclusions on cellular design on the basis of the study of regular cell structures, as is done, for example, for lower frequency systems, or for millimetrewave systems with linear structure, e.g., deployed along a highway [3].

In this paper is presented an approach where generic conclusions on the quantities of interest related to cellular design, such as achievable frequency reuse and system capacity, are obtained from example cellular layouts for specific (but, as much as possible, typical) environments. Under this approach, a choice of placement of base stations and the definition of the associated coverage areas, or cells, so as to satisfy given system capacity and signal quality requirements, is first made. After a cellular layout is obtained, the achievable system capacity is determined. For this purpose an estimate of the achievable frequency reuse is obtained by determining the number of frequency groups required for system operation under static frequency assignment policies, and hence what is the bandwidth available per cell[1].

Signal quality is determined essentially by the

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[1] Even if dynamic resource allocation is used during the system operation, the minimum number of frequency groups required under a static assignment policy will provide an upper bound on the frequency reuse achievable.

relationship between the carrier power, the thermal noise power, and the cochannel interference power at the receivers throughout the cells. Since, normally, the thermal noise power is a characteristic of the equipment used, only the other two variables are under control of the system designer. The controlling variables are the cell dimensions, which determines the minimum received signal power throughout the cell, and the distance at which frequencies are reused, which determines the received cochannel interference power. Although straightforward, in an environment with irregular geometry the determination of these quantities is computationally heavy. In order to partially automate the computations, an interactive computer graphical tool was developed that allows the placement of base stations over a 2-D representation of an area to be covered, computes the associated coverage and the interference between cells, and inputs these results into frequency assignment algorithms to determine achievable values of frequency reuse and system capacity. The tool includes suitable propagation and channel model information. Generic considerations about the number of frequency groups needed, and hence system capacity, are then obtained via case studies.

Of special interest is the comparison between the system capacity achievable in the 40 and 60 GHz bands. The latter have been proposed as desirable for microcellular systems because of the higher oxygen absorption than in the 40 GHz band, which reportly should lead to higher frequency reuse. However, it will be seen that this is not the case in the examples considered.

In Section 2 of this paper the tool functionality, and the input and output data are briefly presented. In Section 3 are presented the models for the computation of the cell coverage length and for the cochannel interference evaluation, as set by the carrier-to-noise/interference constraints. In Section 4 microcellular design results are given for systems operating at the 40 and 60 GHz bands. The frequency assignment algorithm used is described, and results for the urban coverage, frequency reuse, and system capacity achieved are given.

II. MICROCELLULAR DESIGN TOOL

A. Functionality

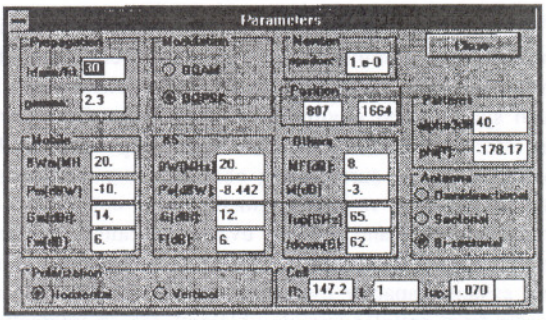
For the problem being dealt with, a two-dimensional representation of the operating environment is appropriate. The microcellular design interactive tool developed provides the capability to position base stations over a city map, and to compute their coverage area and the interference between cells. These results can be input to either off-line or on-line frequency assignment algorithms. The tool also allows the creation and editing of arbitrary urban configurations via a map editor.

Given a propagation model, the map of the area to be covered, and the quality requirements associated with digital signal transmission, one is able to perform, for each base station, the following sequence of steps:

(i) to position a new base station over a non-covered area;
(ii) to choose the communication parameters associated with the new base station;
(iii) to compute the coverage of the new cell;
(iv) to compute the cochannel interference between the new cell and the existing cells, taking into account the path obstructions due to buildings and the directivity patterns of the base station antennas;
(v) in association with a frequency assignment algorithm, to choose the frequency channel(s) for the new cell taking into account cochannel interference constraints.

B. Input Data

The input data consists of the map of the area under consideration and the system parameters (Fig. 1).



30
2.3
1.e-0
807
1664
alpha3dB 40.
phi[°] -178.17
BW[MHz] 20.
Pt[dBW] -10.
G[dBi] 14.
F[dB] 6.
BW[MHz] 20.
Pt[dBW] -8.442
G[dBi] 12.
F[dB] 6.
NF[dB] 8.
M[dB] -3.
fup[GHz] 65.
fdown[GHz] 62.
R: 147.2
1
fup: 1.070

Fig. 1 - Window with cellular design parameters

The map is input as a set of coordinates of non overlapping polygons, each of which representing a city building or city block. The system parameters are grouped into two categories: (i) system-wide and (ii) cell-specific. The former are common to all cells, whereas the latter can be tailored to individual cells. The list of system parameters is the following.

System-wide parameters

i. Propagation

α - power law propagation exponent
γ_o - oxygen excess absorption coefficient
γ_r - rain excess absorption coefficient

ii. Base station

BW_B - bandwidth of the base station receiver
F_B - noise figure of the base station receiver

iii. Mobile unit

BW_M - bandwidth of the mobile station receiver
$(P_t)_M$ - transmitted power at the mobile station
G_M - gain of the mobile station antenna
F_M - noise figure of the mobile station receiver

iv. Additional

Modulation method
$(C/N)_0$ - minimum required ratio between the received power of the carrier C and the power of the thermal noise N in the absence of cochannel interference

f_{up}, f_{down} - operating frequencies

BER_{max} - maximum allowed bit error rate

M - I/N ratio at the cell boundary

MF - fade margin

Cell-specific parameters

$(P_t)_B$ - transmitted power at the base station

Directivity pattern of base station antenna

G_B - gain of the base station antenna

α_{3dB} - 3 dB sector beamwidth (if applicable)

Φ - angle between antenna sectors (if applicable)

Three kinds of horizontal directivity patterns (omnidirectional, sector, and bi-sector) have been considered in the tool.

C. Output Data

The tool output data can be presented in graphical and numerical form and includes

(i) the characteristics of the base stations and associated cells covering the area of interest;

(ii) the number of frequency groups necessary.

For each base station, the following results are presented:

(i) the coordinates of the base station;

(ii) the coverage length;

(iii) the cochannel interference power at the base station receiver;

(iv) the frequency group used.

D. Tool Implementation

The tool has to perform both numerical processing, for the determination of cell dimensions (*coverage length*) and cochannel interference power, and geometrical processing, for the determination of the cell shapes and the visibility between cells. The former is based on appropriate propagation and transmission models, and the latter consists mostly of geometrical operations on polygons, implemented by standard computational geometry algorithms for polygon intersection, difference, and visibility. The tool implementation is described in more detail in [4].

III. MODELS FOR COVERAGE LENGTH AND COCHANNEL INTERFERENCE

A. Coverage Length

The cell dimension in the absence of obstruction (coverage length) is chosen so as to guarantee a desired minimum signal quality throughout the cell, with signal quality being measures in terms of, e.g., raw bit error rate (BER), and being determined by the thermal noise, desired signal, and cochannel interference at the system receivers. In general, the most stringent conditions in terms of bit errors occur when the mobile is at the cell boundary. For a given system BER requirement and thermal noise level N, several distinct pairs of values for the received desired carrier power C and cochannel interference power I are possible, as described by an interference/noise model BER=$f(C/N, C/I)$. Thus, several choices are available for the coverage length. The approach followed, described in more detail in [3], consists of parametrizing the allowable signal and cochannel interference levels by the ratio $M=I/N$ of the cochannel interference power I to the thermal noise power N. In this way, a more or less uniform cell size is obtained in the design.

Under this approach, with a noise model where BER=$f(C/(N+\alpha_c I))$, the coverage length is determined, after fixing the value of M, via the equation

$$C/N = (C/N)_0(1+\alpha_c M) \qquad (3.1)$$

which gives the target desired carrier power level at the cell boundary. Here $(C/N)_0$ is as defined in Section 2.2 (iv) and $\alpha_c=(C/I)_0/(C/N)_0$, where $(C/I)_0$ is the minimum required carrier-to-interference ratio [3]. The coverage length is then obtained via a suitable propagation model [5]. This model includes, in addition to the free-space propagation loss, the excess appropriate absorption losses due to atmospheric oxygen or rain.

B. Co-channel Interference

In a mobile system using FDD (Frequency Division Duplexing), with separate bands for the uplink and downlink directions, the worst case interference situation occurs when a base station receives desired signal from a mobile at its cell boundary and cochannel interference from mobiles in cochannel cells placed at the boundary of those cells closest to that base station (Figure 2). Thus, the uplink is considered for design purposes.

The maximum allowed cochannel interference power at a base station is given by $I=N\cdot M$. After a cellular layout is obtained via Eq. (3.1), the maximum allowed cochannel interference can be used in frequency assignment algorithms as a constraint on the total interference power coming from cochannel cells. Such interference power depends not only on the distance between cells but also on the visibility between the boundary of cochannel cells and the desired base station. Such situation are checked automatically by the planning tool [4].

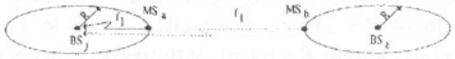


Fig. 2 - Cochannel interference at a base station

IV. RESULTS

In this Section is presented a case study of cellular layout and capacity determination for a Mobile Broadband System operating either at the 40 or at the 60 GHz band in an urban environment. In this particular case, a part of the city of Lisbon [6] was considered for coverage. Cellular layouts were produced for various cell sizes, as defined by the parameter M according to the approach described in Section 3.1. An estimate of feasible reuse factors was obtained by producing frequency assignments based on an appropriate algorithm. From this an estimate for the system capacity was then obtained.

A. Frequency Assignment Algorithms

The problem of frequency assignment with channel reuse constraints has been recognized as being closely related to the NP-complete problem of graph coloring [7]. For practical applications, a number of sub-optimal heuristic algorithms has been proposed [8]. In the example considered, a variant of the *frequency exhaustive* insertion algorithm known as the *uniform assignment* algorithm [9] was used. Under this algorithm, cells are considered in a given (arbitrary) order, and for each cell is attempted the assignment of the least used frequency among those used up to the moment. If this assignment violates the interference constraints, the next least used frequency is attempted, and so on. If no assigned frequency can be used, a new frequency is brought into use. This algorithm was implemented in the tool to be used on-line, i.e., assignments are made to new cells as soon as they are created.

B. Reuse and Capacity Results

A city area of approximately 2.54 km^2 was considered for coverage, of which about 16%, or .406 km^2, corresponds to "net" street area effectively covered. Several cases were worked out both at the 40 and 60 GHz bands using a common set of system-wide parameters, shown in Fig. 1, except for the parameter $M = I/N$. This parameter provides a uniform mechanism to control the cell size and system capacity, whereby an increase in M yields smaller cells and therefore higher capacity. Figure 3 shows an example layout.

Tables 1 and 2 show the number of cells N, reuse factor k, and coverage length R for the different values of M considered. A wide range of values for the reuse factor is obtained, ranging from $k = 11$, for a coverage length of $R = 219$ m at 40 GHz, down to $k = 5$, for a coverage length $R = 84$ m. Intuitively, this decrease can be related to the fact that larger coverage lengths lead to cells spanning a larger number of street intersections, thus being exposed to interference from a larger number of cells and consequently requiring the use of a higher number of frequency groups.

For the shorter coverage distances, corresponding to system configurations clearly limited by interference, the reuse factors obtained for the 40 and 60 GHz bands are the same in situations with similar coverage length. This is because in urban environments the cochannel interference between cells will not depend much on the specific attenuation of atmospheric elements [10], but mostly on the urban geometry, mainly the relative dimensions and shapes between blocks of buildings and cells which will determine the existence of line-of-sight between cells.

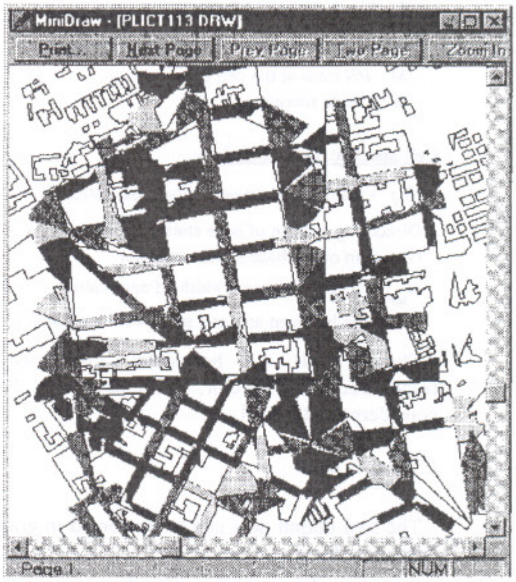


Fig. 3 - Example cell layout and frequency assignment (40 GHz, $M = 11.3$ dB)

Table 1 - Coverage and frequency reuse results (60 GHz)

M [dB]	N	k	$R_{12\,\text{dBi}}$ (m)
-3	70	9	147
0	79	9	136
3	85	7	121
6	86	6	103
9	114	5	84

Table 2 - Coverage and frequency reuse results (40 GHz)

M [dB]	N	k	$R_{12\,\text{dBi}}$ (m)
-3	61	11	219
0	64	9	203
3	66	8	179
6	70	7	152
9	83	7	124
11.3	94	6	103
13.8	117	5	84

C. Available One-way Bandwidth Density

Tables 3 and 4 show the available one-way (i.e., either uplink or downlink) bandwidth per cell, B_c, and the one-way available bandwidth density, B_d, given by $B_c = B_t / (2k)$ and $B_d = N B_t / (2k A_t)$, where B_t is the total bandwidth assigned to the system, N the total number of cells, k the reuse factor (i.e., number of frequency groups required), and A_t the "net" street area covered by the system. As expected, higher bandwidth densities are obtained with the decrease in cell size. Further increases not due to the reduction of cell size alone are obtained as M increases above 0 dB because of the decrease in the reuse factor. It should be noted that the actual data rates supported depend on further system parameters, such as the spectral efficiency of the modulation scheme, and the FEC coding rates. Similar values are obtained for B_c and B_d for both bands for systems using cells with similar dimensions since the resulting values of k are equal.

Table 3 - Available one-way bandwidth (60 GHz band)

M [dB]	k	$B_{c\,[\mathrm{MHz}]}$	$B_{d\,[\mathrm{GHz/km^2}]}$
-3	9	111	19.2
0	9	111	21.6
3	7	142.9	29.91
6	6	166.7	35.3
9	5	200.0	56.2

Table 4 - Available one-way bandwidth (40 GHz band)

M [dB]	k	$B_{c\,[\mathrm{MHz}]}$	$B_{d\,[\mathrm{GHz/km^2}]}$
-3	11	90.9	13.7
0	9	111	17.5
3	8	125	20.3
6	7	142.9	24.6
9	7	142.9	29.2
11.3	6	166.7	38.6
13.8	5	200	57.6

V. CONCLUSIONS

In this paper was presented an approach to frequency reuse and system capacity evaluation of millimetrewave mobile communication systems operating in urban outdoor environments, where conclusions are obtained from cellular layouts for specific environments. An interactive computer graphical tool for assisting the layout process is described, and results are given on the frequency reuse and capacity achievable in such systems. The tool allows the interactive placement of base stations over a map of an area to be covered, and determines the coverage area for each cell and the interference among cells. These results can be fed to frequency assignment algorithms for the determination of the reuse factor and the system capacity. An application was made to the coverage of part of a city by millimetrewave microcellular systems operating at the 40 and 60 GHz bands. Reuse factors in the range 5–11 were obtained, with the smaller values corresponding to smaller cell sizes, and vice-versa. For interference limited scenarios, using cells with similar dimensions, equal feasible values of the reuse factor and similar values for the total number of cells were achieved for both bands, yielding to similar values for the system capacity.

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