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Cellular Planning in Urban Regular Structures with Application to Millimetre Wave Mobile Communications Systems

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Abstract

The main goal of this work is to develop a model for cellular planning for MBS (Mobile Broadband System) when a regular urban area is considered for coverage and when the main requirement is to have a low co-channel interference.

The first step has been to present a propagation model at the millimetre waveband as the one suitable for UHF cannot be adopted. Phenomena as oxygen absorption and rain attenuation that did not influence the propagation at the UHF, are very important at these frequencies. Also the scenario (urban structures, outdoor or indoor environment) and antenna patterns influence the received power. All these elements are summed up in the average received power formula.

A simple formula, depending on two parameters (ζ - power decay rate and - H –the power constant) is given, and theirs values are analyzed, for both 40 and 60 GHz bands in the presence and in the absence of rain in 3 distance ranges ([0,250] m, [250,1000] m, [1000,2000] m). Parabolic functions are presented for both parameters, thus enabling the use of the model for any frequency or distance in the range of interest.

With the use of developed propagation model the interference suffered from co-cells has been calculated. The carrier to interference ratio can take advantage of the oxygen absorption, thus presenting higher values at 60 GHz (where the attenuation rises up to 15 dB/m).

The cellular planning aims minimise interference. Three different shapes have been considered ("cigar", "L" and "cross" ones) as suitable to set a coverage in a "Manhattan grid" scenario. Following the basic rules of symmetry and repetition of patterns, cell clusterers have been developed and in some cases, taking advantage of obstruction by buildings, non perfectly symmetrical pattern, but with a high reuse factor, has been chosen.

Key words:

Propagation models, millimetre waveband, co-channel interference, cellular planning

.

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List of Acronyms

ATM: Asynchronous Transfer Mode.

BER: Bit Error Rate.

B-ISDN: Broad Integrated Services Digital Network.

BS: Base Station.

CPN: Costumer Permiser Network.

HIPERLAN: High Performance Radio Local Area Network.

IBC: Integrated Broadband Communications.

LOS: Line Of Sight.

MBS: Mobile Broadband System.

MS: Mobile Station.

UHF: Ultra High Frequency.

UMTS: Universal Mobile Telecommunication Systems.

Lyst of Symbols

d: Distance.

D: Reuse distance.

g: Rain rate.

G_r: Receiving antenna gain.

G_t: Transmitting antenna gain.

H: Power constant

h_r: Receiving antenna height.

h_t: Transmitting antenna height.

I: Interference.

K_r: Parameter depending on wave polarisation.

L_c: Cell length.

L_o: Oxygen attenuation.

L_r: Rain attenuation.

N: Noise power.

N_{ac}: Number of available carriers.

N_{cc}: Number of carrier per cell.

n_{cc}: Number of carriers por cell normalised to N_{ac}

N_{fg}: Number of frequency groups.

P_r: Received power.

P_t: Transmitted power.

R: Cell radius.

N_{ic}: Number of cells between cocells.

α_r: Parameter depending on the wave polarisation.

α: Parameter depending on scenario and antenna type.

ε: Avarage error in the linear approximation

ε_{max}: maximum error in the linear approximation

γ_r: Rain attenuation coefficient.

γ_o: Oxygen attenuation coefficient.

η_{cell}: Coverage efficiency.

λ: Wave length.

σ: Standard deviation in the linear approximation

ζ: Parameter accounting for rain and oxygen attenuations.

1.Introduction

MBS (Mobile Broadband System) [Fern95] is considered a fourth generation system since it will give mobile users access to broadband services which either already exist or will exist for fixed users, high quality video being expected to be one important component of these services. In addition, it will support new applications that will arise from the mobility offered by the system. The need to build this system comes from the fact that PC users are exchanging larger and larger quantities of information and are asking for higher and higher data rates. For instance, connection of Local Area Network or transmission of moving images with high resolution may require considerable high transmission rate, much higher than the basic or primary access offered by ISDN (Integrated Services Digital Network). B-ISDN enlarges the possibility of ISDN supporting switched semi-permanent, permanent, point-to-point and point-to-multi point connections. MBS has been defined to be a wireless extension to the B-ISDN, thus enabling the creation of IBCN (Integrated Broadband Communication Network), its implementation being based on ATM (Asynchronous Transfer Mode).

The two broadband systems that will be implemented, for wireless mobile networks, are the BWLANs and the MBSs. The former is foreseen to work mainly in indoor environments, while the latter is thought to work both in indoor and outdoor scenarios. Their architecture will be different as they are intended to support complementary services: a WLAN (Wireless Local Area Network) is mainly intended for communication between computers, nevertheless it can support real time voice and high definition images. MBS enlarge the perspectives and will allow more applications and higher mobility. It is even envisaged that the two MSs (Mobile Stations) will be able to transmit directly between them without the MSC (Mobile Switching Center) or any other central management structure.

Several mobile systems are already installed or will be introduced in the next year, such as the UMTS (Universal Mobile Telecommunication System) or HIPERLAN (High Performance Radio Local Area Network). UMTS has as a limiting factor an upper rate of 2 Mbit/s, which may impose severe restrictions especially if high definition is required. HIPERLAN, that enables short distance high speed radio links between computers, does not provide handover functions and the portable station will not be able to communicate while in motion at a speed higher than 36 km/h.

The main difference with other mobile systems is the maximum possible bit rate and the maximum velocity of the MS (it can get at 100 km/h), Fig.1.1. MBS will provide radio coverage restricted to small areas (e.g. sport arenas, factories, television studios) and will be based on a micro-cellular structure where cells are expected to have lengths of the order of a few hundreds of meter, ranging from 200 m up to 1 km, depending on the frequency. These restrictions are not imposed by the received power at the MS neither by thermal noise (since it is foreseen that in an imminent future 500 mW will be possible at the MS). As a consequence of the small area covered by each cell, the influence of the BSs (Base Stations) cost on the overall cost of the system infrastructures is high, since the number of BSs will be much greater from the usual one.

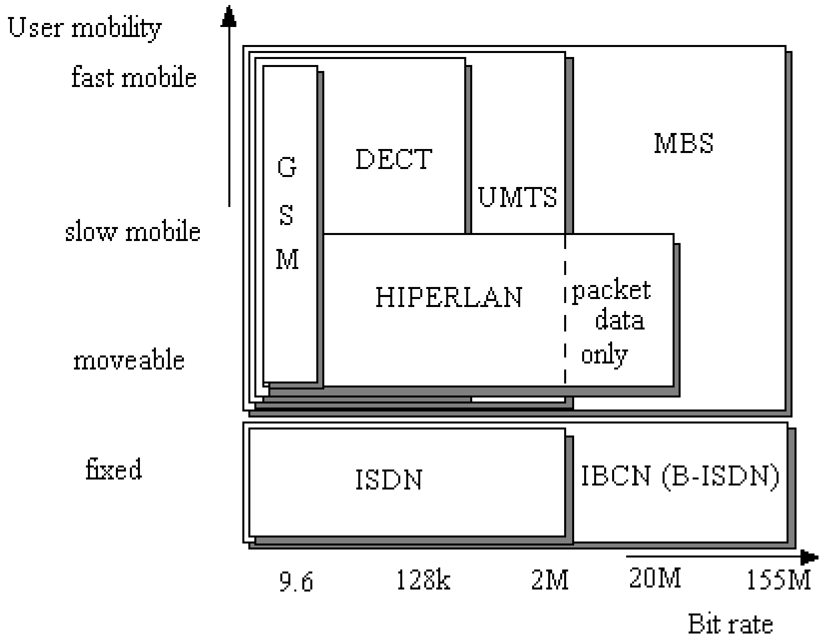


Fig.1.1--Comparison of MBS with other systems (extracted from [MBS98a]).

MBS will be installed as Customer Permiser Network*s* (CPNs), from which the need to link different CPNs in a city or industrial area will create the first MBS network. As a wireless CPN, MBS will offer access to LANs at a high bit rate, video conferencing with low delay video coding, and many other services for professional users, Fig.1.2.

The frequencies chosen for this system, in order to have high transmission data rates and to relief from frequency constraints, are allocated in the millimeter waveband; more specifically, bands are [39.5,43.5] GHz and [62,66] GHz with intervals of 2 GHz in between 1 GHz bands, Fig.1.3 [ITUR90], (the wavelength is of the order of 7 mm for the former and of 5 mm for the latter). At these frequencies it is not possible to use the propagation model suitable for the UHF band, phenomena as oxygen absorption and rain cannot be neglected anymore, which leads to a simple model, similar to the one for free space. The oxygen absorption in particular introduces a strong and selective attenuation at 60 GHz and this frequency will play an important role in the design of a system as far as the reuse distance is concerned [CoFr93]; moreover if one considers that usually BSs present space diversity while MSs do not, it can be helpful in the frequency characterization of the down link. A higher attenuation leads to the possibility of reusing frequency at a lower distance for a given coverage, thus increasing the capacity of the system, but the effort to reduce the reuse distance is limited by the carrier to interference ratio, as a threshold that guarantees a given quality of service is required. On the other hand the limitation on the coverage distance can be imposed by the noise. Thus, the final purpose is to find a compromise between a system with a high capacity and a high quality of service.

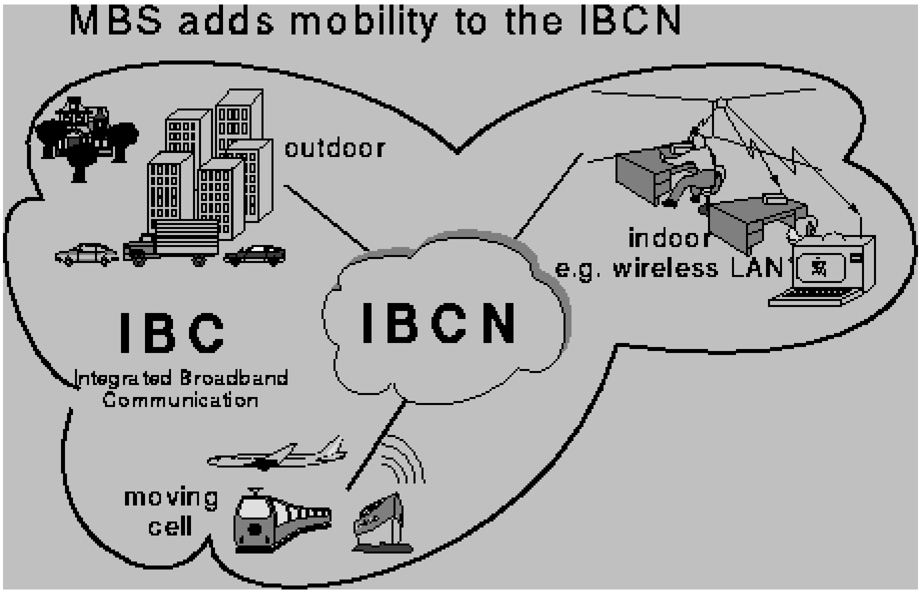


Fig.1.2--Integration of MBS into IBCN (extract from [MBS98b]).

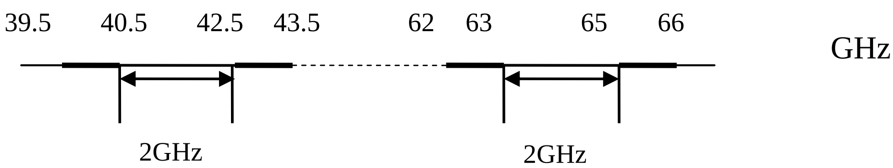


Fig.1.3--Range of frequencies in MBS.

The function that describes the average power, besides other parameters like frequency or antenna height, is important most of all for outdoor scenarios, since it is crucial for the evaluation of the co-channel interference. For indoor ones it is not so crucial since interference will be limited by walls and not by distance [CoFr95]. The average decay of power for outdoors is the one that will be considered. In this case the distance dependence factor for an outdoor environment ranges from 2.3 up to 2.8 or from 7.0 to 7.5, depending on the distance interval in which power is to be calculated.

Of course not only propagation and topology aspects are of importance when referring to MBS, although they are the ones discussed in this work. All the problems arising from the choice of antennas are not considered, antenna radiation patterns being neglected. One is aware that the role of the antennas radiation pattern is not negligible when discussing the performance of a system, since it influences the parameters associated with the propagation, but in a perspective of a global planning of the system, both for coverage and interference, this approach is acceptable.

The main goal of all the results that have been achieved with recent researches and works, such as the SAMBA project, is the improvement of spectral efficiency to give the user a good quality of service. The system is not expected to offer all the services at the same data rate, which means that it will be capable to work with "bandwidth on demand" and it will be the user or the system that will decide how much bandwidth it will be used, overcoming the problem of congestion.

A few years ago some of the characteristics of today's systems seemed to be unreachable, thus it is foreseen that in a near future the studies about the MBS will be enough to permit a standardization, as it is happening for the UMTS.

In this work it will be analyze mainly the aspect of propagation and its implications on cellular design. In Chapter 2 a propagation model will be developed for MBS, taking as a starting point the one for free space and referring the model suitable for UHF; a power decay law for MBS is shown, and propagation will be studied in the presence and the absence of rain. In Chapter 3 the cellular design will be considered as well as the limitations imposed by the interference in term of reuse distance and coverage length. And in Chapter 4 it will be shown an example of coverage for a particular city structure, with the help of a Visual Basic program that has been developed. Through out the report a comparison between the 40 GHz and the 60 GHz bands is done in order to show the opportunities that each one offers.

2.Propagation model

2.1.General propagation concepts

The propagation model for millimetre mobile communication cannot be derived directly from the one suitable for the UHF. One of the model used for the power decay with distance in the UHF band goes approximately like a fourth power law and depends on the environment type and on the break-point distance. The propagation phenomena at 60 GHz band is very different from the last one, since in the millimetre waveband waves propagate almost as light; as a consequence, GO (Geometrical Optic) can be adopted to describe the phenomena.

Taking the free space propagation model as a starting point and considering atmospheric influences, a good estimation of the average power can be given. If one considers propagation in free space, it is well known that the power decay with distance is [Pars92]:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 \tag{2.1}$$

where:

- P_r, P_t are the received and the transmitted power;

- G_r, G_t are the receiver and the transmitter antenna gains;

-d is the distance between receiver and the transmitter;

- λ is the wavelength;

which corresponds to, in logarithmic units:

$$P_r[dBm] = -32.4 + P_t[dBm] + G_t[dBi] + G_t[dBi] - 20\log(d[km]) - 20\log(f[GHz]) \tag{2.2}$$

Propagation in the UHF band, for LOS conditions, is based on the interference between the direct ray and the reflected one on a planar surface, and as a consequence the formulation differs from the one in free space [Pars92]:

$$P_r = 4\left(\frac{\lambda}{4\pi d} \right)^2 P_t G_t G_r \sin^2\left(\frac{2\pi h_t h_r}{\lambda d} \right) \tag{2.3}$$

where:

- h_t, h_r are the receiver and the transmitter antenna heights.

When the argument of the sine function is very small, one can approximate the sine by its argument, which leads to the fourth-power law:

$$P_r = \frac{(h_t h_r)^2}{d^4} P_t G_t G_r \tag{2.4}$$

or in dB:

$$P_r[dBm] = -120 + 20\log(h_t[m]) + 20\log(h_r[m]) - 40\log(d[km]) + P_t[dBm] + G_r[dBi] + G_t[dBi] \tag{2.5}$$

This approximation is valid when the path length difference is less than $\lambda/2$, defining the break-point distance, d_{bp}::

$$d_{bp} = \frac{4h_t h_r}{\lambda} \tag{2.6}$$

In the millimeter waveband rain and oxygen absorptions must be taken into account, as they introduce an attenuation that cannot be neglected since it can even reach a peak of around 15 dB/m; it means that coverage can be done only with very small cells (with a maximum distance of a few hundreds of meters), much smaller than the ones allowed for the UHF. As a matter of fact, assuming h_r= 1.8 m and $h_t \in$[5, 50] m the break point distance belongs to the interval [7.2, 79.2] km for 60 GHz and [4.8, 48.0] km for 40 GHz, which are much higher than the expected cell radius, meaning that the fourth-power decay law cannot be apply to this system.

As a consequence of this type of approach the average power can be estimated from this simple equation [CBFV94]:

$$P_r[dBm] = K + P_t[dBm] + G_t[dBi] + G_r[dBi] - 10\alpha\log(d[km]) \tag{2.7}$$

in which K is a constant and α depends on the type of environment. This equation will be analyzed and corrected further on when the dependence on frequency will be stressed.

2.2.Oxygen absorption and rain attenuation

Oxygen absorption has a strong influence on wave propagation at the millimetre waveband, presenting a peak at 60 GHz, Fig.2.1.

The formulation for the specific attenuation, for the suitable bands, is the following [ITUR90]

$$\gamma_o\left[dBm/km\right]\left(f\left[GHz\right]\right)=\left(0.00719+\frac{6.09}{f^2+0.227}+\frac{4.81}{(f-57)^2+1.5}\right)f^2 10^{-3}, \qquad f\leq 57\,\text{GHz}$$

(2.8)

$$\gamma_o\left[dB/km\right]\left(f\left[GHz\right]\right)=\begin{cases}15.1-0.104(f-60)^{3.26} & ,60\leq f\leq 63\ \text{GHz}\\ 11.35+(f-63)^{2.25}-5.53(f-63)^{1.27} & ,63\leq f\leq 66\ \text{GHz}\end{cases}$$

(2.9)

the attenuation for a given distance *d* being:

$$L_o\left[\text{dB}\right]=\gamma_o\left[\text{dB/km}\right]d\left[\text{km}\right] \qquad (2.10)$$

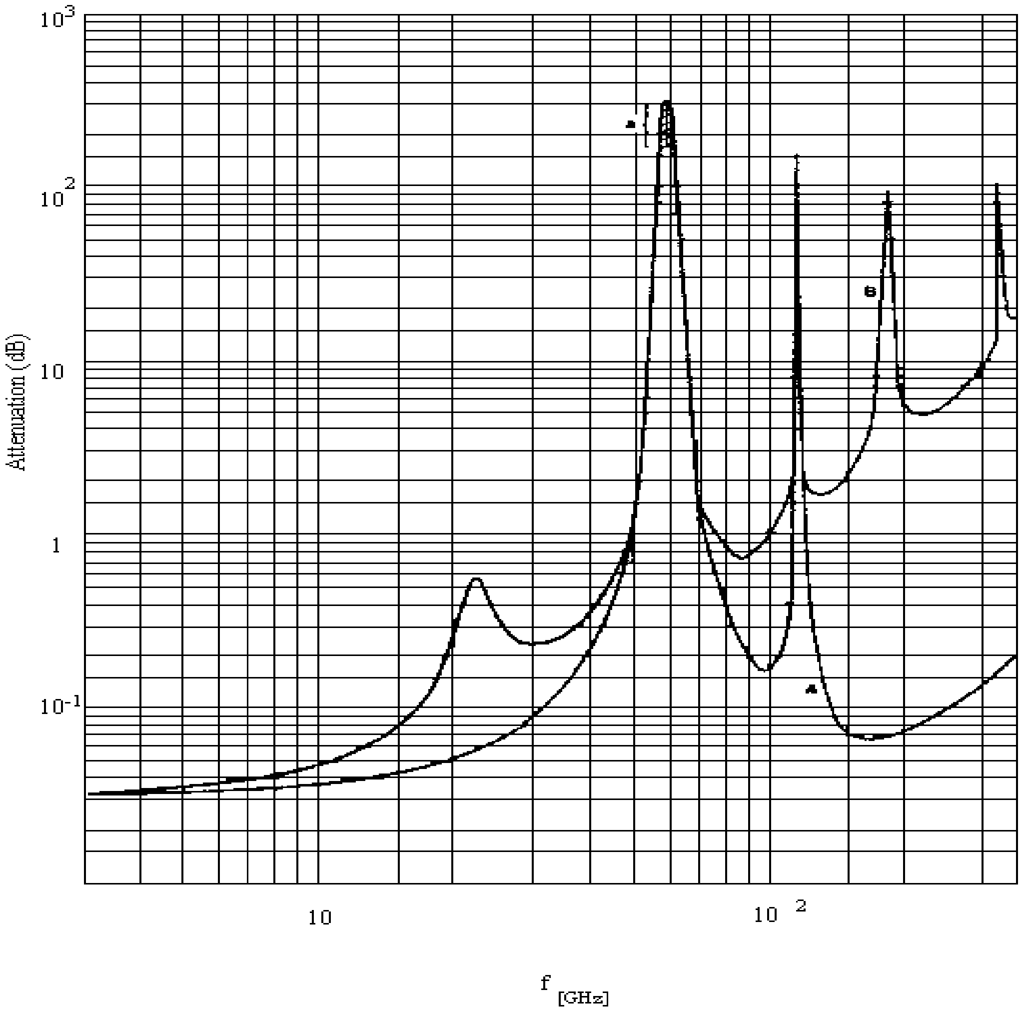


Fig.2.1--Attenuation coefficient dependence on frequency , a) oxygen only, b) water vapor only (extract from [ITUR90]).

This attenuation shows very low values in the 40 GHz band, Tab.2.1, where this contribution can be neglected, while it presents high values for frequencies near 60 GHz, decreasing as frequency increases, Tab.2.2. This must be taken into account in the choice of frequencies for the down and the up links, as BSs present space diversity while MSs do not. It means that for the downlink the range of frequencies with lower attenuation will be chosen, that in terms of power means higher levels..

$L_{o[\mathrm{dBm}]}$	$d_{[\mathrm{km}]}$		
$f_{[\mathrm{GHz}]}$	0.2	0.5	1
39.5	0.01	0.02	0.04
40.0	0.01	0.02	0.04
41.5	0.01	0.03	0.05
42.5	0.01	0.03	0.06
43.5	0.01	0.03	0.07

Tab.2.1--Oxygen absorption at the 40 GHz band.

$L_{o[\mathrm{dB}]}$	$d_{[\mathrm{km}]}$		
$f_{[\mathrm{GHz}]}$	0.2	0.5	1
60	3.02	7.55	15.10
61	3.00	7.50	15.00
62	2.82	7.05	14.10
63	2.27	5.68	11.36
64	1.36	3.41	6.82
65	0.55	1.39	2.77
66	0.18	0.44	0.88

Tab.2.2--Oxygen absorption at the 60 GHz band.

Rain attenuation can be computed considering the following [ITUR90]:

$$\gamma_{r\,[\mathrm{dB/km}]}\left(f_{[\mathrm{GHz}]}, g_{[\mathrm{mm/h}]}\right) = k_r(f)\, g^{\alpha_r(f)} \qquad (2.11)$$

where:

-k_r,α_r are parameters depending on the wave polarization and frequency;

-g is the rain rate.

These parameters are defined for several frequencies [ITUR90] and if one considers a logarithmic interpolation of k_r (versus log(f)) and a linear interpolation of α_r (versus log(f)), between 35 GHz and 45 GHz for the lower band and between 50 GHz and 70 GHz for the upper one, they are given by:

$$f = 40\text{GHz}: \qquad \begin{cases} k_r\left(f_{[\text{GHz}]}\right) = 10^{2.0674\log(f) - 3.7709} \\ \alpha_r\left(f_{[\text{GHz}]}\right) = 0.6962\log(f) + 2.0541 \end{cases} \tag{2.12}$$

$$f = 60\text{GHz}: \qquad \begin{cases} k_r\left(f_{[\text{GHz}]}\right) = 10^{1.2026\log(f) - 2.289} \\ \alpha_r\left(f_{[\text{GHz}]}\right) = 0.4929\log(f) + 1.7025 \end{cases} \tag{2.13}$$

corresponding to a total attenuation of :

$$L_{r[dB/km]} = \gamma_{r[dB/km]} d_{[km]} \tag{2.14}$$

Only horizontal polarization is considered, since it is the one leading to the highest values.

At both the 40 GHz and 60 GHz band the values of rain attenuation cannot be compared with those of oxygen absorption; in fact for normal rain fall rate, attenuation achieves very low values that can be neglected in the computation of the received power. Usually rain does not play an important role in cell coverage reduction; this only happens when it achieves values that are very high, larger than those caused by oxygen absorption, and obviously it depends on the fall intensity. Anyway the values of the attenuation caused by this term cannot be neglected for cells larger than 200 m; moreover, while the influence of oxygen decreases with frequency, the influence of rain increases with it, Tabs.2.3-4.

$L_{r[\text{dB}]}$	$d_{[\text{km}]}$					
	0.2		0.5		1.0	
	$g_{[\text{mm/h}]}$		$g_{[\text{mm/h}]}$		$g_{[\text{mm/h}]}$	
$f_{[\text{GHz}]}$	25	50	25	50	25	50
39.5	1.41	1.41	3.52	6.76	7.04	13.53
40.0	1.43	2.74	3.57	6.84	7.14	13.68
42.5	1.53	2.89	3.81	7.22	7.63	14.43
43.5	1.56	2.95	3.91	7.37	7.82	14.73

Tab.2.3--Rain attenuation at the 40 GHz band.

$L_{r[dB]}$	$d_{[km]}$					
	0.2		0.5		1.0	
	$g_{[mm/h]}$		$g_{[mm/h]}$		$g_{[mm/h]}$	
$f_{[GHz]}$	25	50	25	50	25	50
60	2.02	3.58	2.02	8.95	10.10	17.90
61	2.04	3.60	5.09	9.00	10.18	18.01
62	2.05	3.62	5.13	9.06	10.27	18.11
63	2.07	3.64	5.18	9.11	10.35	18.22
64	2.09	3.67	5.22	9.16	10.44	18.33
65	2.10	3.69	5.26	5.26	10.52	18.43
66	2.12	3.71	5.30	9.27	10.60	18.53

Tab.2.4--Rain attenuation at the 60 GHz band.

One should note that a rain fall higher than 50 mm/h is seldom exceeded in non-tropical climates (probability less than 0.01%).

2.3.A model for the millimetre waveband

In a mobile communication system propagation is affected three basic mechanism: reflection, diffraction, and scattering.

Reflection occurs when an electromagnetic wave impinges on an object which has very large dimensions compared to the wavelength. Reflections can be originated by the ground and by buildings and walls. For a system that works at 60 GHz (λ=5 mm), this is the most important propagation mechanism, since all common objects present in a street have dimensions larger than the wavelength.

Diffraction occurs when the radio path between the transmitter and receiver is obstructed by a surface with sharp geometrical irregularities (edges). The secondary waves resulting from the obstructing surface are present throughout the space and even behind the obstacle, giving rise to a bending of waves around the obstacle, even when a line-of-sight path does not exist between the transmitter and the receiver. At 60 GHz, diffraction provides a very small contribution to the received signal since, because of the small wavelength, every obstacle acting like a wall obstructing the signal.

Scattering (or diffusion) occurs when the medium through which the wave travels consists of objects with dimensions that are small compared to the wavelength.

$\varepsilon_{max[dB]}$	$d_{[km]}$		
$f_{[GHz]}$	[0,0.25]	[0.25,1]	[1,2]
39.5	0.00	0.00	0.04
40	0.00	0.00	0.00
42.5	0.00	0.00	0.02
43.5	0.00	0.00	0.01

Tab.2.9--Maximum error for the approximation, at 40 GHz band in all intervals.

As we have seen in Section 2.2, at 60 GHz the oxygen absorption is much stronger and it deeply affects the value of ζ, while at the higher frequencies as 65 GHz, 66 GHz where the influence of oxygen is lower, the value of ζ falls down as Fig.2.5-2.7 show.

As the distance between MS and BS increases the received power decreases and consequently the values of ζ increases (Fig.2.4). Also the surrounding affects the variation of ζ, which presents higher values with the growth of α, Tab.2.10.

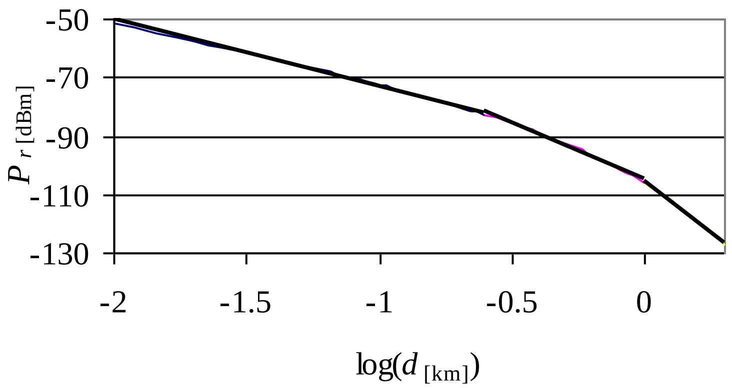


Fig.2.4--Linear fitting of the power decay at 60 GHz.

ζ		$f_{[GHz]}$						
$d_{[km]}$	α	60	61	62	63	64	65	66
[0,0.25]	2	2.28	2.28	2.26	2.21	2.13	2.05	2.01
	2.2	2.48	2.48	2.46	2.41	2.33	2.25	2.22
	2.5	2.78	2.78	2.76	2.71	2.63	2.55	2.52
[0.25,1]	2	4.04	4.02	3.90	3.53	2.92	2.37	2.11
	2.2	4.24	4.23	4.11	3.74	3.12	2.57	2.32
	2.5	4.54	4.53	4.40	4.03	3.42	2.87	2.62
[1,2]	2	7.10	7.06	6.76	5.84	4.30	2.93	2.29
	2.2	7.30	7.26	6.96	6.04	4.70	3.13	2.50
	2.5	7.60	7.56	7.26	6.33	4.80	3.43	2.61

Tab.2.10--Power decay rate, at the 60 GHz band.

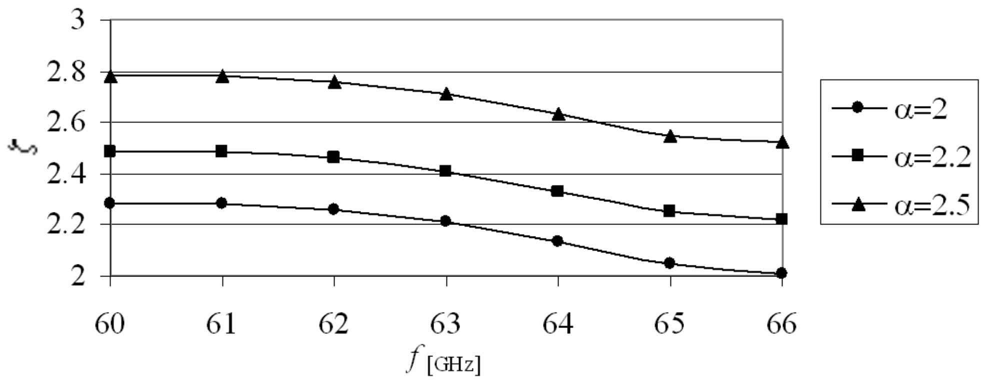


Fig.2.5--Power decay rate at 60 GHz in [0,250] m

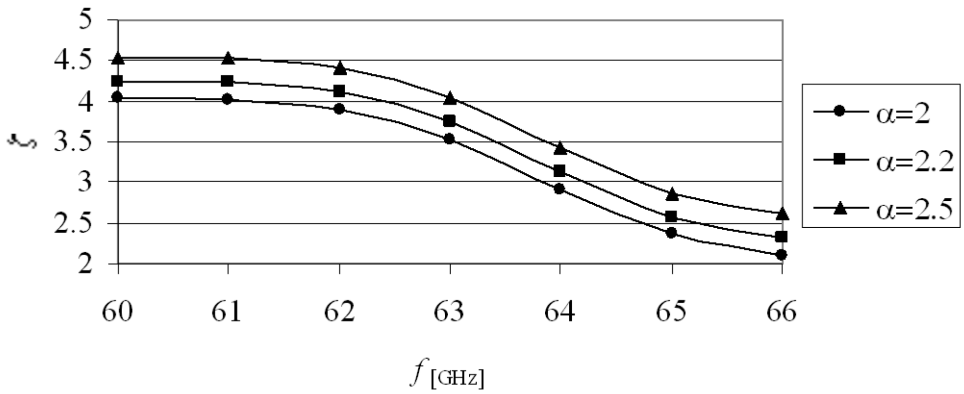


Fig.2.6--Power decay rate at 60 GHz in [250,1000] m.

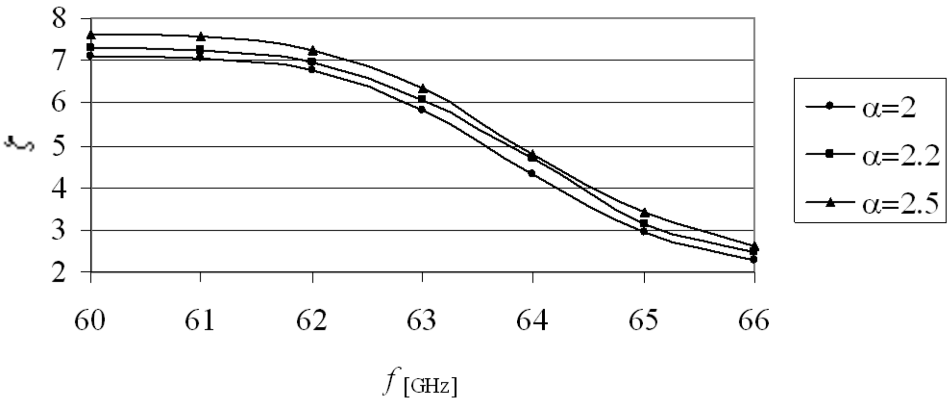


Fig.2.7--Power decay rate at 60 GHz in [1000,2000] m

The dependence of ζ on the frequency, in each interval, can be approximated with a parabolic fitting:

$$d \in [0,250]\,\text{m}: \qquad \zeta = \begin{cases} -0.0065 f^2 + 0.767 f - 20.38 & \alpha = 2 \\ -0.0059 f^2 + 0.693 f - 17.88 & \alpha = 2.2 \\ -0.0059 f^2 + 0.693 f - 17.58 & \alpha = 2.5 \end{cases} \qquad (2.20)$$

$$d \in [250,1000]\,\text{m}: \qquad \zeta = \begin{cases} -0.0456 f^2 + 5.385 f - 154.86 & \alpha = 2 \\ -0.0458 f^2 + 5.415 f - 155.60 & \alpha = 2.2 \\ -0.0450 f^2 + 5.311 f - 152.02 & \alpha = 2.5 \end{cases} \qquad (2.21)$$

$$d \in [1000,2000]\,\text{m}: \qquad \zeta = \begin{cases} -0.1142 f^2 + 13.487 f - 390.90 & \alpha = 2 \\ -0.1210 f^2 + 14.351 f - 418.11 & \alpha = 2.2 \\ -0.1244 f^2 + 14.757 f - 429.81 & \alpha = 2.5 \end{cases} \qquad (2.22)$$

To determine the value of H, the following procedure has been taken: at first the linear power approximation ($P_r(d)$= -10ζ*logd+B) has been considered to find the fitted power values ($P_r(d)$) and further on H has been calculated, in each interval, making use of the following formula:

$$H = P_r(d) - G_t - G_r - P_t + 20\log(f) \qquad (2.23)$$

where d=0.25 km in the first interval, d=1 km in the second and d=2 km in the third. From the following results it is evident that H keeps almost the same dependence on frequency in the last two intervals, Tab.2.11, Figs.2.8-2.9, since it represents the cross of the power with the y axis.

3.Cellular design

3.1 Procedure for design

In the design of a system one has to take care of many parameters from the characteristics of the MS and BS to the satisfaction of the required quality of service. The first step in the determination of the cell design is to choose the inputs of the system, that is supposed to be a non noise-limited one [CBFV94]:

- propagation parameters such as α, γ_o,γ_r;
- the characteristics of the BS (P_t =transmitted power , G_t =gain of the transmitting antenna);
- the characteristics of the MS (P_r =received power, G_r =receiving antenna gain; *B*= bandwidth of the receiver):
- available groups of frequencies.

The purpose in the design of the system can be to minimise the number of bases, *i.e.* to have *R* large, and to have *D* small in order to obtain a higher system capacity, but these requirements do not match with the need of not using too high transmitting power and of keeping the co-channel interference at a low level.

Considering a street covered roughly with rectangular cells with a width of *l*, a length of *2R,* and a reuse distance of *D* Fig.3.1, the area of the cell is *2lR,* while the area in which a given frequency cannot be reused is *lD.* For a total coverage of length *L* the number of cells is *L/(2R)*; if *T* is the total number of frequencies and *B* is the data rate of each carrier, the carrier density will be *T/D*, the capacity density *BT/D* and the system capacity will be *BTL/D*.

Once the cell radius is fixed, one can use the number of frequency groups and the cell structure to build a low interference system.

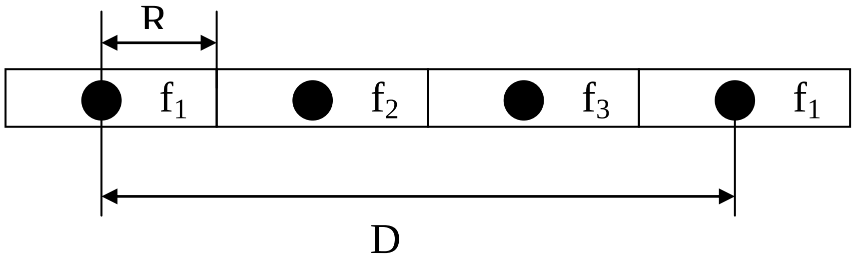


Fig.3.1--Cell structure.

The idea is to reuse a frequency group among those ones that have already been employed, and if none of those groups satisfy the *C/I* requirement, then a new group is assigned and a new cluster is obtained. As in the case of MBS the transmission structure is formed by two 1 GHz frequency bands, one for each direction of transmission, considering the number of frequency groups that result from the previous algorithm and the reuse distance it yields to the determination of the transmission density (*T/D),* which can be improved by decreasing the cell size. Following this algorithm, one will obtain as output the position of the cell, the coverage length and the number of the frequency groups (*i.e.* the reuse distance), Fig.3.2.

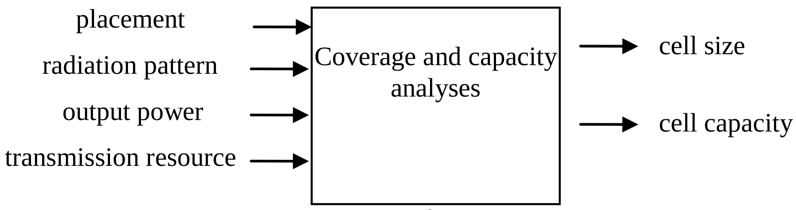


Fig.3.2--Scheme of the cellular design.

In an environment with irregular geometry the determination of the output is quite difficult and computationally heavy. In order to partially automate the computations, less demanding inputs are taken into account. An interactive graphical tool was developed; it shows cell coverage over a 2-D representation of an area to be covered and, introducing system wide parameters (such as the number of frequency groups) and cell specific ones (such as the cell shape and radius), it finds out the best coverage in terms of *C/I.* The cell structures that leads to the greater reuse distance will be analyzed in this chapter.

3.2.Cochannel interference between two cells

Rain and oxygen absorptions play an important role in the received power, and they are very influent in the determination of the carrier-to-interference ratio as well. Considering a cell structure as in Fig.3.1, the worst case for co-channel interference between two cells will be when the mobile is on the border of the cell to which it belongs and the resulting carrier to interference ratio will be given by the power transmitted from the distance (*D*-*R*) and the carrier power received at a distance of *R* [CoFr94]:

$$\left(\frac{C}{I}\right)_{[dB]} = P_r\left(d = R\right)_{[dBm]} - P_r\left(d = D - R\right)_{[dBm]} \tag{3.1}$$

Using (2.14), taking α =2 and assuming that the transmitted power and the antenna gain are the same for both BSs the ratio gets:

$$\left(\frac{C}{I}\right)_{[dB]} = 20\log\left(\frac{D-R}{R}\right) + (D-2R)_{[km]}\gamma_{\ [dB/km]} \qquad (3.2)$$

In the case of Fig.3.1 we can express the reuse distance in terms of the number of intermediate cells between the co-cells N_{ic} and of the radius ($D=2R(N_{ic}+1)$), the co-channel carrier-interference ratio resulting in:

$$\left(\frac{C}{I}\right)_{[dB]} = 20\log(2N_{ic}+1) + 2N_{ic}R_{[km]}\gamma_{\ [dB/km]} \qquad (3.3).$$

The ratio *C/I* is heavily influenced by the oxygen absorption and it depends on the frequency, thus one can use the 60 GHz band in order to increase the isolation between co-cells, but for a fixed *R* and a fixed N_{ic} (i.e. fixed reuse factor $r=D/R$) an increase of frequency in this band will determine a decrease of *C/I*, as we can see from Tab.3.1 and Fig.3.3 [CoFr94].

$(C/I)_{[dB]}$	$f_{[GHz]}$						
N_{ic}	60	61	62	63	64	65	66
1	17.09	17.04	16.59	15.22	12.95	10.93	9.98
2	29.08	28.98	28.08	25.34	20.80	16.75	14.86
3	39.55	39.40	38.06	33.95	27.13	21.06	18.22

Tab.3.1--*(C/I)* at the 60 GHz band, for different number of intermediate cells and *R*=0.25 km.

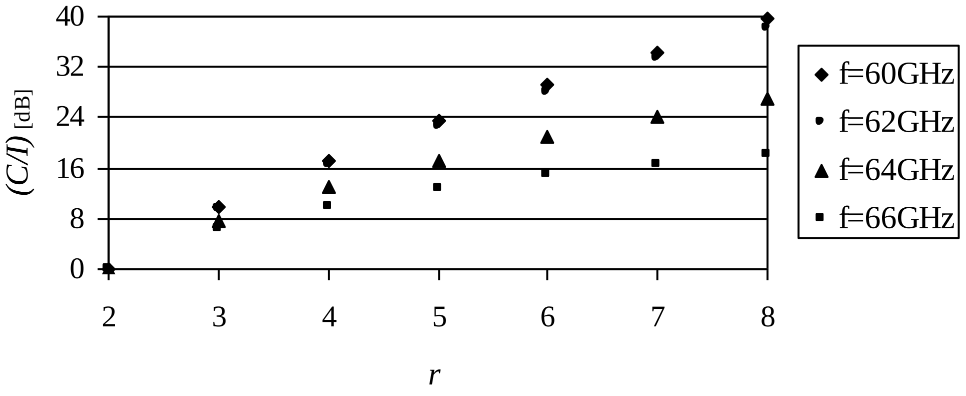


Fig.3.3--*(C/I)* at the 60 GHz band, dependence on the number of intermediate cells, *R*=0.25 km.

For 40 GHz band the values are lower, as oxygen absorption does not reduce the interference of the co-cell, Tab.3.2-Fig.3.4.

(C/I)[dB]	*f*[GHz]			
N_{ic}	39.5	40.0	42.5	43.5
1	9.56	9.56	9.57	9.57
2	12.07	12.07	12.08	12.08
3	14.01	14.01	14.03	14.03

Tab.3.2--*(C/I)* at the 40 GHz band, for different number of intermediate cells and *R*=0.25 km.

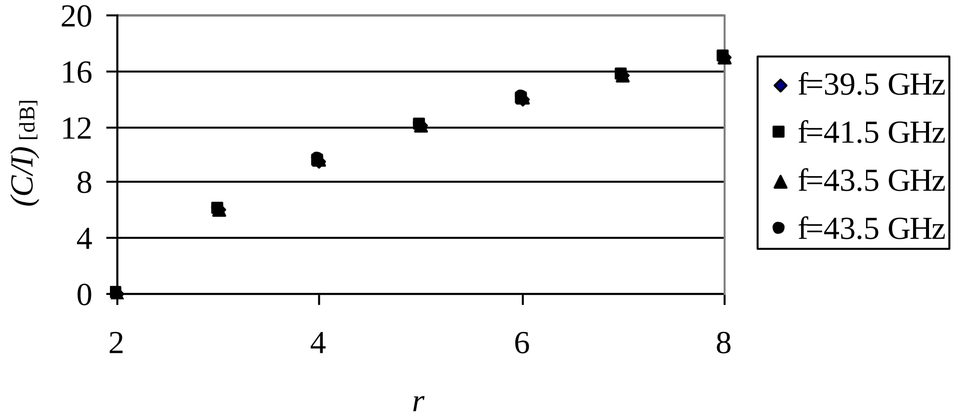


Fig.3.4--*(C/I)* in the absence of rain at the 40 GHz band.

In the presence of rain, the carrier to interference ratio improves greatly, Tabs.3.3-4 but at the same time the received power from the belonging BS is lower and it assumes worst values as the distance grows up, Tab.3.5.

Δ(C/I)[dB]	*f*[GHz]			
N_{ic}	39.5	40.0	42.5	43.5
1	6.93	7.00	7.30	7.40
2	10.44	10.50	10.95	11.10
3	13.85	14.00	14.60	14.80

Tab.3.3--*Δ(C/I)* in the presence of rain at the 40 GHz band.

$\Delta(C/I)_{[dB]}$	$f_{[GHz]}$						
N_{ic}	60	61	62	63	64	65	66
1	8.95	9.00	9.06	9.10	9.16	9.21	9.27
2	17.90	18.01	18.11	18.21	18.33	18.43	18.53
3	26.85	27.01	27.17	27.31	27.49	27.65	27.80

Tab.3.4--*Δ(C/I)* in the presence of rain at the 60 GHz band.

$Pr_{[dBm]}$	$d_{[km]}$					
	0.2		0.5		1.0	
$f_{[GHz]}$	Rain	No rain	rain	no rain	Rain	no rain
40	-76.21	-73.47	-88.28	-81.44	-101.17	-87.49
60	-83.58	-84.61	-101.44	-97.89	-123.96	-112.06

Tab.3.5--Received power at both 40 and 60 GHz with or without rain.

In order to describe the co-channel interference at the 60 GHz band without rain, a different and more general approach can be used; based on the general formulation for the received power and taking into account the approximations for both parameters. Assuming a radius of 250 m and a growing number of intermediate co-cells *C/I* can be found as follows:

$$N_{ic}=1\begin{cases}\left(\dfrac{C}{I}\right)_{[dB]}=H_{[0,250]m}-10\zeta_{[0,250]}\log(0.25)-H_{[250,1000]m}+10\zeta_{[250,1000]m}\log(0.75)\\ D-R=2(N_{ic}+1)R=750m\end{cases}\tag{3.4}$$

$$N_{ic}=2\begin{cases}\left(\dfrac{C}{I}\right)_{[dB]}=H_{[0,250]m}-10\zeta_{[0,250]}\log(0.25)-H_{[1000,2000]m}+10\zeta_{[1000,2000]m}\log(1.25)\\ D-R=2(N_{ic}+1)R=1250m\end{cases}\tag{3.5}$$

$$N_{ic}=3\begin{cases}\left(\dfrac{C}{I}\right)_{[dB]}=H_{[0,250]m}-10\zeta_{[0,250]}\log(0.25)-H_{[1000,2000]m}+10\zeta_{[1000,2000]m}\log(1.75)\\ D-R=2(N_{ic}+1)R=1750m\end{cases}\tag{3.6}$$

$(C/I)_{[dB]}$	$f_{[GHz]}$							
N_{ic}	60		62		64		66	
	lin.fit	exact	lin.fit	exact	lin.fit	exact	lin.fit	exact
1	18.10	17.09	17.53	16.59	13.43	12.95	10.00	9.98
2	29.90	29.08	28.83	28.08	21.18	20.80	14.86	14.86
3	40.28	39.55	38.71	38.06	27.47	27.13	18.20	18.22

Tab.3.6--*(C/I)* with the use of the exact or linear fitted formula, *R*=0.25km.

The corresponding values, for $\alpha = 2$, do not differ very much from the previous ones, Tab.3.6. Similar values are obtained with parabolic fitting.

The differences between these two methods are shown in the Figs.3.6-7 where the linear curves, computed with the linear fitting and the ones deriving from parabolic approximation are represented.

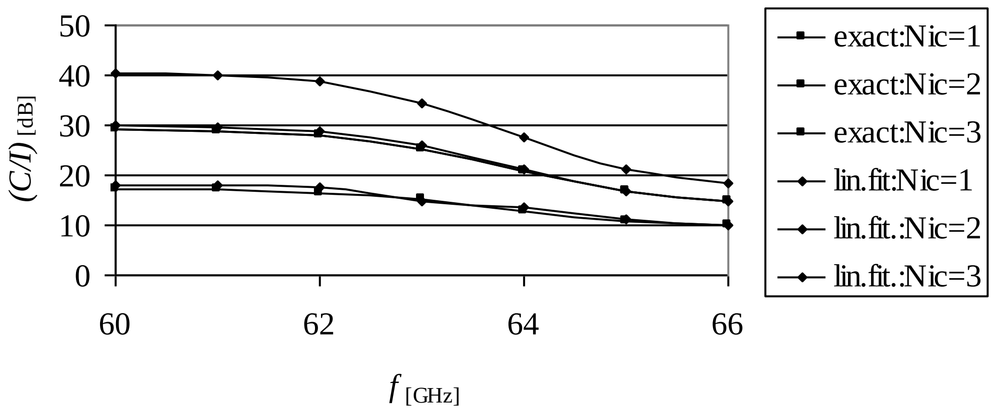


Fig.3.5--*(C/I)* with the use of linear approximation and exact curve.

In the presence of rain the ratio *C/I* takes advantages, besides of the oxygen attenuation, also of the rain attenuation. This determines a greater isolation which means an increase of the *C/I* in the two bands in use. At 60 GHz due to the higher oxygen attenuation, the ratio achieves higher values, in Fig.3.6. Also with the increase of number of intermediate cells the ratio grows up, Tab.3.7.

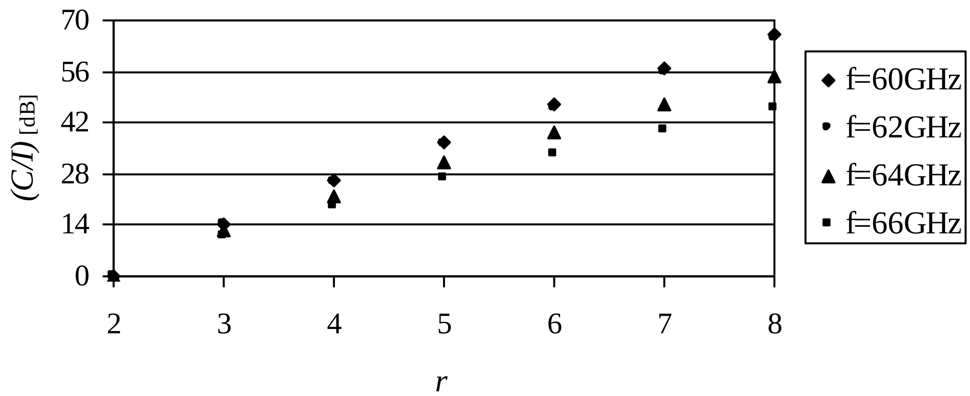


Fig.3.6--*(C/I)* in the presence of rain at the 60 GHz band.

$\Delta(C/I)_{[dB]}$	$f_{[GHz]}$						
N_{ic}	60	61	62	63	64	65	66
1	8.95	9.00	9.06	24.33	9.17	9.21	9.27
2	13.42	13.50	13.59	43.55	13.74	13.82	13.90
3	17.90	18.00	18.12	61.26	18.33	18.43	18.53

Tab.3.7--Increment of *(C/I)* at the 60 GHz ban, for different number of intermediate cells and *R*=0.25 km, due to rain.

For 40 GHz band the values are lower, as oxygen absorption does not reduce the interference of the co-cell but are greater than in the case of absence of rain, Fig.3.7.

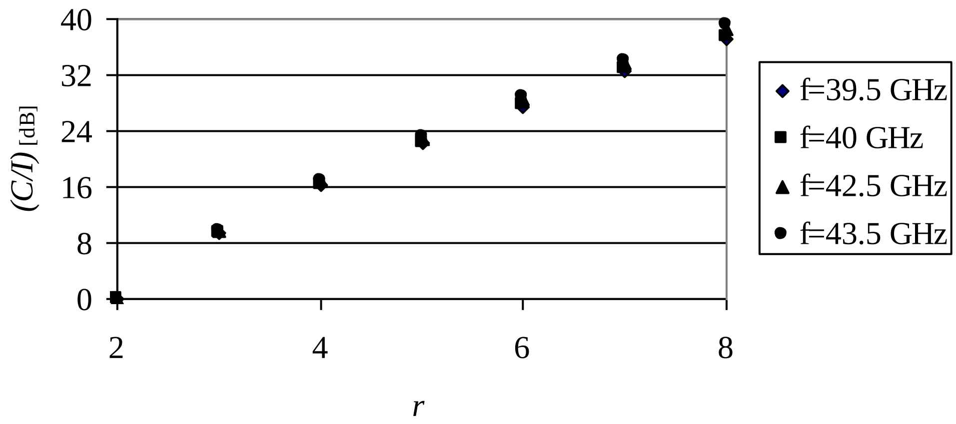


Fig.3.7--*(C/I)* in the presence of rain at the 40 GHz band.

A comparison between the two cases shows that greater advantages can be taken when the number of intermediate cells grow up, Tab.3.8.

$\Delta(C/I)_{[dB]}$	$f_{[GHz]}$			
N_{ic}	39.5	40.0	42.5	43.5
1	6.77	6.84	7.22	7.36
2	10.20	10.26	10.82	11.05
3	13.53	13.68	14.43	14.73

Tab.3.8--Increment of *(C/I)* at the 40 GHz band, for different number of intermediate cells and R=0.25 km, due to rain.

All the approximations that have been proposed so far can be adopted for a cellular planning as the error will not be that large. A limitation of this analysis is that it was made considering only one co-channel interference source, while in a real situation there are interfering BSs at both sides of the considered mobile, whose interference in the worst case comes from a BSs located at a distance of *mD-r* where *m*=1,...T (T being the number of relevant tires of interference) [VeCo97]. But, considering that the contribute of the higher tires of interference (m>2) to the ratio will be small (power decays at least as d^2) the model represents a good approximation of the reality. In the urban case the interference is due to the 2 co-cells around the cross (Fig.3.8), thus the carrier to interference ratio decreases of 6 dB:

$$\left(\frac{C}{I}\right)_{[\mathrm{dB}]} = P_{r[\mathrm{dBm}]}(R) - 10\log\left(10^{P_{r[\mathrm{dBm}]}(D+R)/10} + 10^{P_{r[\mathrm{dBm}]}(D-R)/10}\right) \quad (3.7)$$

The additional term is due to the co-cell situated at a distance of *D*+*R*. Worst values are obtained in comparison with the case of only one cell, as there are co-channel interference sources at both side of the cell . The degradation is worst as the reuse factor grows up.

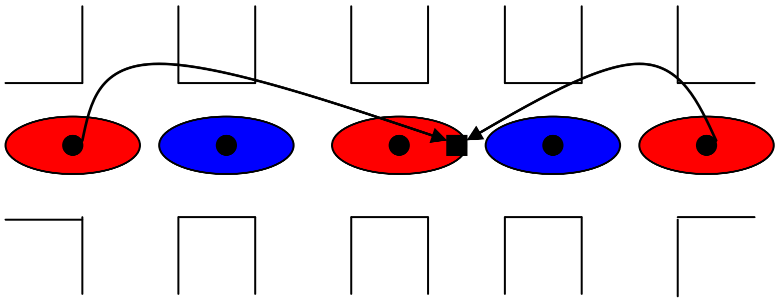


Fig.3.8--Interference at the BS, in an urban area.

The purpose of the following sections will be to determine cell shapes and placements, in a regular street city, in order to minimize the level of relevant tiers of interference.

Cellular design for urban environments in the millimeter wave band requires a different approach than the one applied for systems at the UHF band like GSM. In the latter, considering an omnidiractional antenna, the coverage is done by hexagonal cells; on the other hand, for an urban micro-cellular environment, the shape of the cells is dependent on the specific geometry of the area to be covered. It means that an heuristic approach has to be followed and that the placement of the cell and frequency assignment is made case by case. A typical city structure is the so called Manhattan grid one, Fig.3.9, and possible coverage shapes, that will be object of study, are the one-sided cell ("cigar" shaped), two sided cell ("L" shaped) and intersection of 2 streets ("cross" shaped), Fig.3.10.

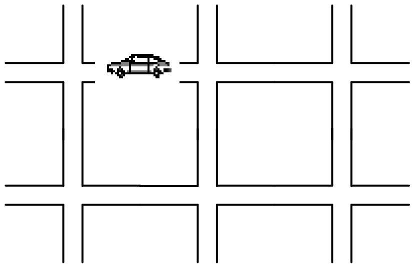


Fig.3.9--Manhattan grid streets.

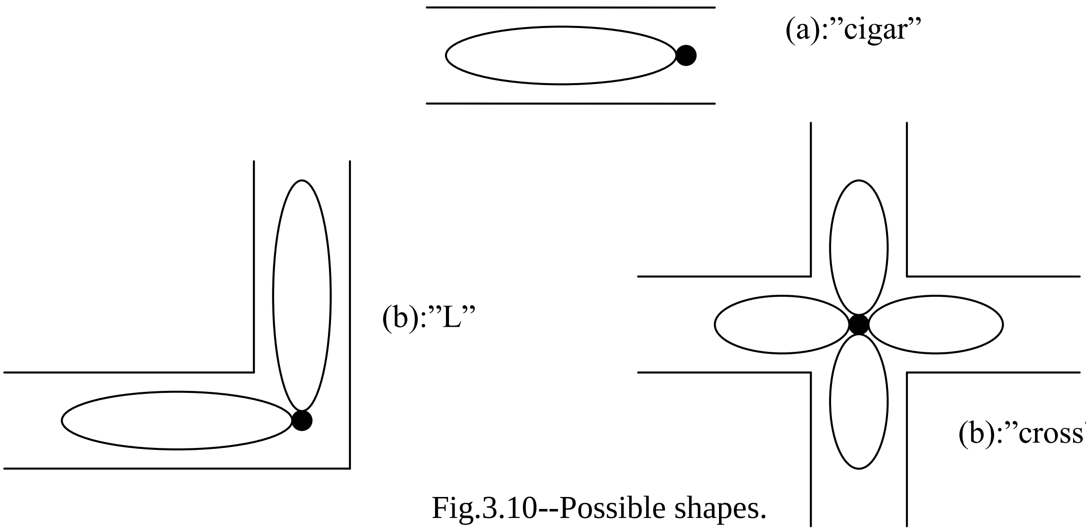


Fig.3.10--Possible shapes.

The geometrical characteristics of the 3 types of cells that will be taken into account are summarised in Tab.3.9 where L_s is the distance between two crosses, and L_c is the total length covered by a cell.

Shape	*Lc*
"cigar"	L_s
"L"	$2L_s$
"cross"	$4L_s$

Tab.3.9--Geometric characteristics of cells.

The three cell types correspond to different coverage situations, assuming that the problems of coverage for the antennas are solved. The next step is to start with a given number of frequency groups, to place the cells in the grid and than to control if the group of frequencies satisfy the requirements of minimum quality of service; if it does not a new group will be introduced.

3.3.Basic cellular coverage concepts

The theory of cellular patterns will be applied in the design of the system; the symmetry resulting from it allows an easy and generic calculation of *(C/I)*, in presence of different numbers of intermediate cells. The fundamental idea of the cellular patterns theory is to divide an entire plane in regular regions, i.e. cells, and to translate the fundamental area in a regular way thus obtaining a pattern; a tessellation is done until the whole area is filled up and these rules will be adopted in the case of Manhatann grid streets. A feature that is exploited is the color symmetry, which in radio terms means that each set of channels corresponds to a color. In order to determine the cell pattern, i.e. the cluster, the fundamental procedure is to place the same colors (co-cells) at equidistant points from a reference one and to repeat this procedure for other color. By translation, the first pattern can be replicated around the initial reference, and then the pattern is set; it is assumed that a cluster is a contiguous group of cells. Each cell must have the same number of nearest co-channel cells and this must be valid for any arbitrary cell. Although the theory of symmetry is well established, the creation of a pattern is open to imagination [Yaco93].

The theory of cellular patterns can be applied to GSM as well as to MBS, with the difference that in the former the coverage is done with the use of regular polygons while in the latter is done with the use of segments, each one representing a cell, since the MBS environment is mostly confined to streets, thus being filled up with a linear coverage.

The basic scenario is the one formed by one long avenue, where the linear structure is maintained. Transposing the previous ideas to this kind of scenario it means filling up the street with simple cells, Fig.3.8 in order to get a regular repetition of the same pattern; applying the same rules to grid streets, the symmetry of the system must result in all directions, Fig.3.11.

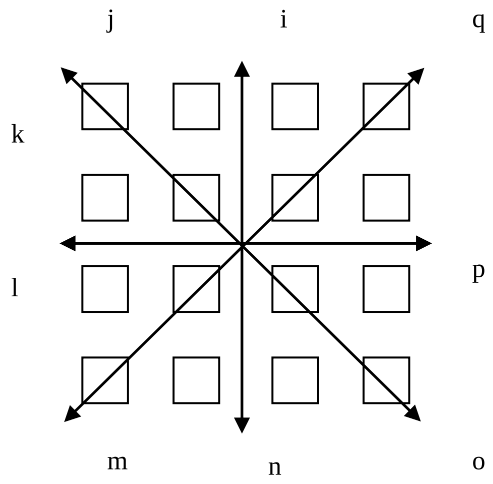


Fig.3.11—Symmetry in the cellular coverage.

The structure that was considered is a simplified model, assuming a uniform grid of streets with infinite extension; all the streets are identical everywhere and the city extends infinitely in both direction. This is an idealisation of a real urban structure which is much more complicated. For instance, there are parks, houses that are very different one from the others, the streets do not have the same width, the elevation along the streets can differ considerably, but despite of it this model can be considered as a good starting point.

3.4.Cellular patterns for MBS

The creation of a pattern can be carried out in different ways: the adopted technique is replicating a motif with symmetry devices, shift and mirroring operations. The attempt to cover streets with a regular structure helps in the determination of *C/I*, since calculating the co-channel interference at the border of a cell, means calculating it for any other group of frequency, in whatever position of the plan the MS is placed. Due to the obstruction by blocks of buildings, interference occurs only in LOS, coming from the directions associated with each street [Gudm89]. The two basic structures that are considered are the linear one, Fig.3.12 and the grid one, Fig.3.13, which must be filled up with the cell shapes shown in Fig.3.10. To analyze the quality of a coverage some parameters can be introduced: N_{fg} , N_{cc} and η_{cell}. The former represents the number of frequency group and the greater this parameter is the lower is the capacity of the system, keeping the same cell dimension; also the second one deals with the capacity of the system and represents the number of channels per cell, being higher as the number of frequency groups is lower, it is calculated as the ratio between the number of available carriers (N_{ac}) and N_{fg}; the latter one deals with the frequency distribution along the system, being the ratio between N_{cc} and the cell length (L_c). Dividing for the number of available frequencies one obtains the normalised values:

$$n_{cc} = \frac{N_{ac}/N_{fg}}{N_{ac}} = \frac{1}{N_{fg}} \tag{3.8}$$

$$\eta_{cell} = \frac{N_{cc}}{N_{ac}} \frac{1}{L_c} \tag{3.9}$$

A comparison between two systems with the same cell shape but with different N_{fg}, enables to say that the better is the one that reaches a greater n_{cc}; it means that the greater n_{cc} is the better frequencies are exploited. Considering the same type of cells in two different coverages, one arrives at the same conclusions taking into account η_{cell}. The last parameter is much more linked with the cell capacity when different kinds of cell shapes are to be compared: large cell extension leads to a low coverage density. If more than one configuration with the same number of frequency groups is possible, the one that presents a larger reuse factor is better, since the resulting *(C/I)* will be higher.

In the long avenue structure the adopted cell is the simple one. The coverage of this kind of street can be easily done with different number of frequencies alternating the available frequency groups all along the street (Fig.3.12). Considering N_{ac}, the variable number of available carrier the characteristics are described in Tabs.3.10-3.11, with the help of (3.7) where the results for 2,3,4 and 5 groups of frequencies are shown. A trade off between the capacity of the system and the interference suffered by the MS must be done.

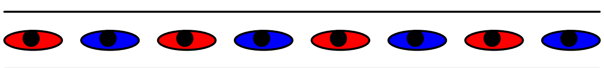


Fig.3.12--Coverage in a linear structure, two groups of frequencies.

N_{fg}	Type of structure	*r*	N_{ic}	n_{cc}	η_{cell}
2	Reg.	4	1	0.50	1.00
3	Reg.	6	2	0.33	0.67
4	Reg.	8	3	0.25	0.50
5	Reg.	10	4	0.20	0.40

Tab.3.10--Frequency density and carriers per cells in a regular coverage, L_s=0.5 km.

(C/I)	N_{fg}			
$f_{[GHz]}$	2	3	4	5
39.5	-0.46	5.07	8.23	10.48
43.5	-0.45	5.08	8.25	10.51
62	-0.09	9.34	16.30	22.25
66	-0.42	5.35	8.76	11.23

Tab.3.11--*(C/I)* for different numbers of frequency groups, L_s=0.5 km.

For the grid structure the first cell shape that has been taken into account is the "cigar" one. Since at each crossing 4 streets intersect, in order to have a total coverage 4 groups of frequencies are needed, at least, and this is a valid rule for whatever cell shape. With 4 groups, the basic pattern can be the repetition of a cross, formed by the 4 groups, in all directions (i,j,k,l,m,n,o,p), Fig.3.13.

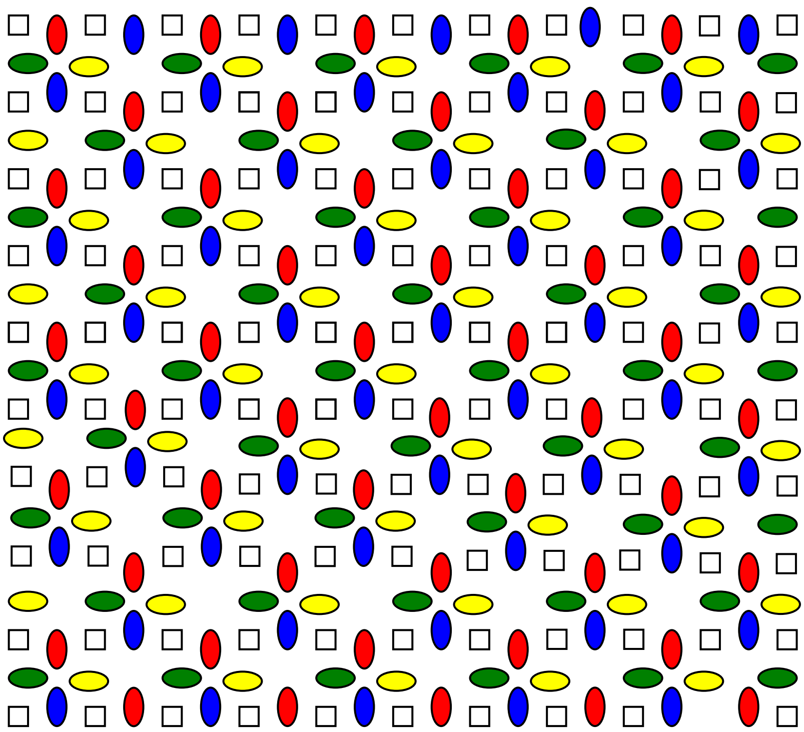


Fig.3.13--Coverage with 4 groups of frequencies, "cigar" cell.

As in the linear case the interference is due only to the two side cocells on the same street and the main results in terms of *(C/I)* are obtained (Tab.3.13).

Any effort to enlarge the coverage to 5 groups of frequencies does not lead to a regular grid since repetitions of the same pattern in all directions is not possible. Also with 6 groups of frequencies a "radial" symmetry cannot be applied. A structure which is not perfectly symmetrical, as in Fig.3.14, but that satisfies the requirements because of the antenna side lobe shape that are in the direction of orthogonal streets, is predictable. Considering the interference deriving from co-cell in LOS, i.e. $r = 6$, *(C/I)* improves a lot.

Increasing the number of groups would lead to a decrease in capacity to which would not correspond an advantageous growth of *(C/I)*, as can be observed in N_{cc} or in η_{cell}.

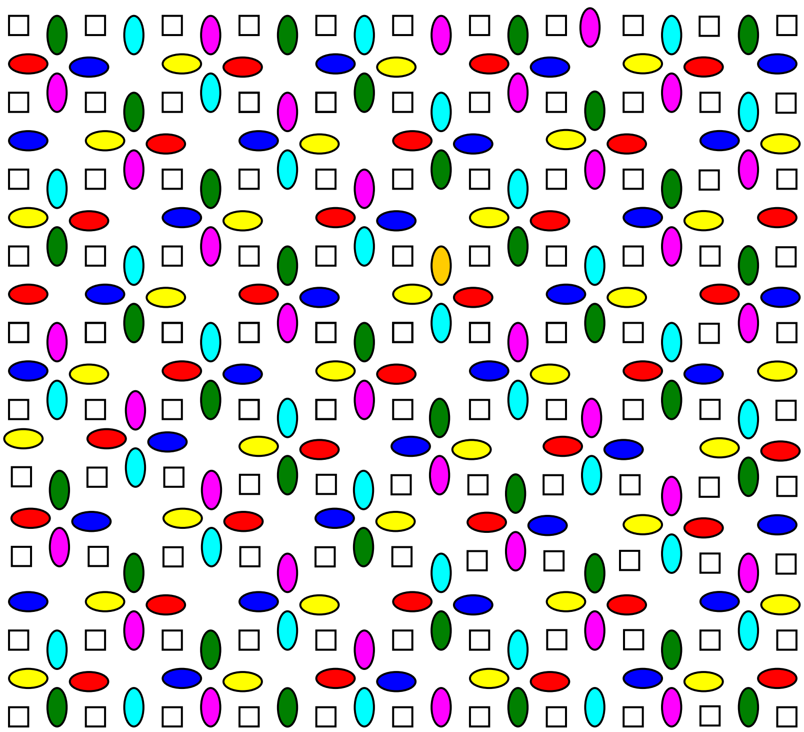


Fig.3.14--Coverage with 6 groups of frequencies, "cigar" cell.

A comparison between these kinds of coverage, considering the same L_s, is done in Tab.3.14:

The coverage can be done with the use of "cross" shaped cells; starting the coverage with the minimum group of frequencies required the repetition pattern can be as shown in Fig.3.15.

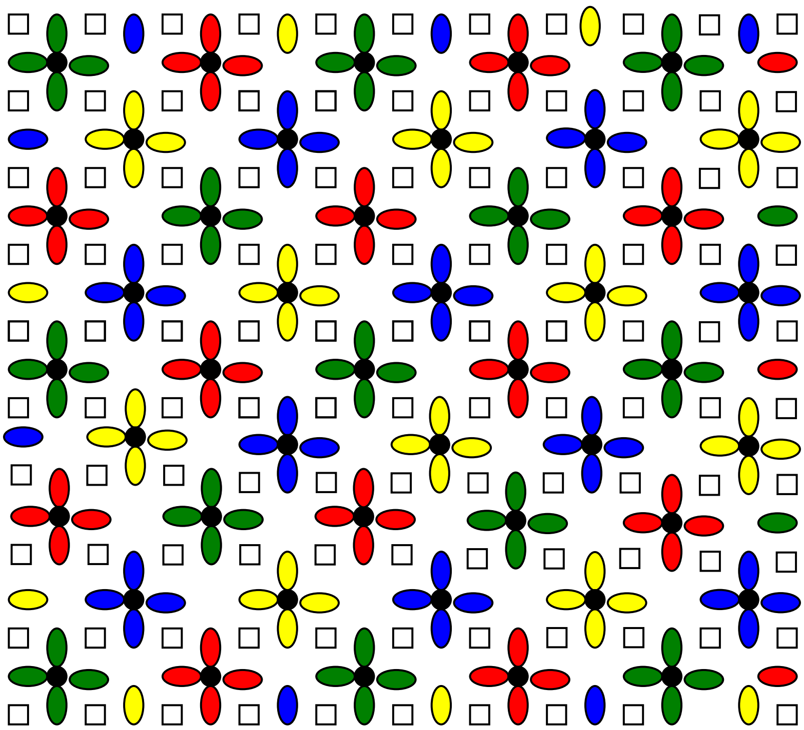


Fig.3.15--Coverage with 4 groups of frequencies, cross structure.

The *(C/I)* deriving from (3.2), assuming a street length of 0.5 km, (which corresponds to a *Lc*=2 km) is shown in Tab.3.13. Also in this case the interference comes only from the cocells present in the same street even if the antenna irradiates in all the directions. The result is the same of the four frequency groups case, Fig.3.16, but the difference is that the density offered by this kind of cells is smaller than the previous one; in order to compute the "efficiency" of each kind of cell one refers to η_{cell}, Tab.3.12.

Covering the grid with 5 groups of frequencies leads to the repetition of alternative frequencies in all directions, Fig.3.16.

From Tab.3.15 it is clear that *(C/I)* does not increase a lot, in comparison with the case of 4 groups. It is due to the fact that there are two additional cocells in the crossing street (one at a reuse factor equal to 7 and the other equal to 3) when considering the MS at the border of the cell. At the same time the efficiency decreases.

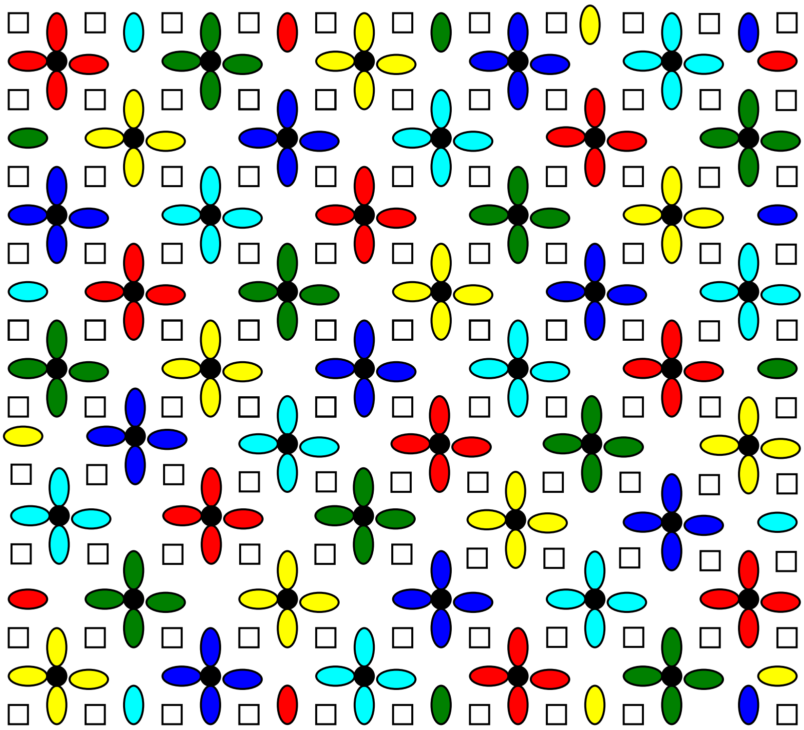


Fig.3.16--Coverage with 5 groups of frequencies, cross structure.

Considering the co-channel interference deriving only from in LOS BSs and taking advantage of the blocking of buildings, a semi-regular structure for 6 groups of frequency can be found, Fig.3.17.

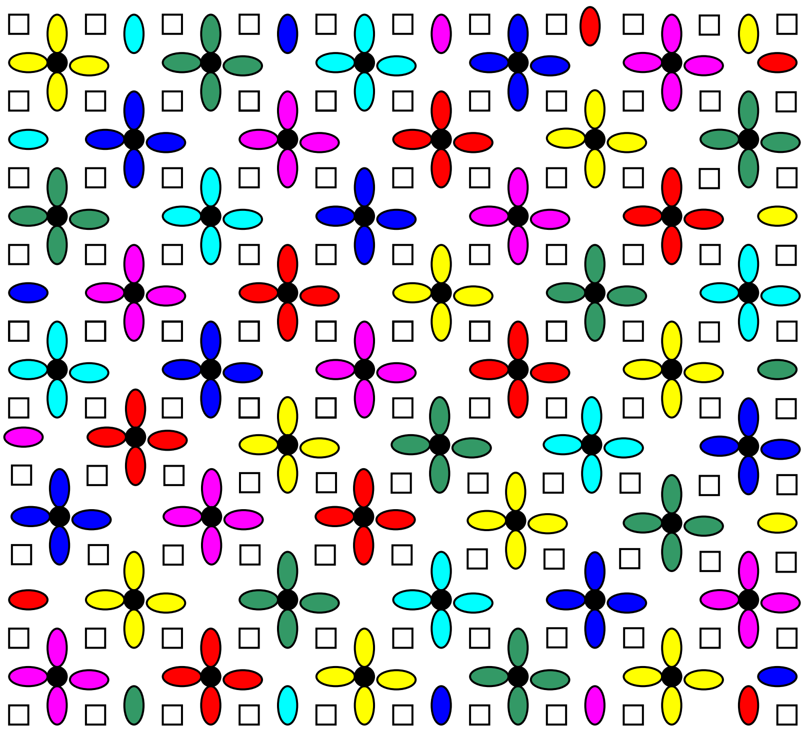


Fig.3.17--Coverage with 6 groups of frequencies, cross structure.

This configuration presents the same problems of the previous coverage as the MS suffers the interference from four cocells collocated respectively at a r = 13, r = 12, r = 7, r = 5.

Another way to fill up the grid is with the use of “L” shaped cells. With 4 groups of frequencies a repetition of the same module, formed by all different groups, set a coverage, Fig.3.18.

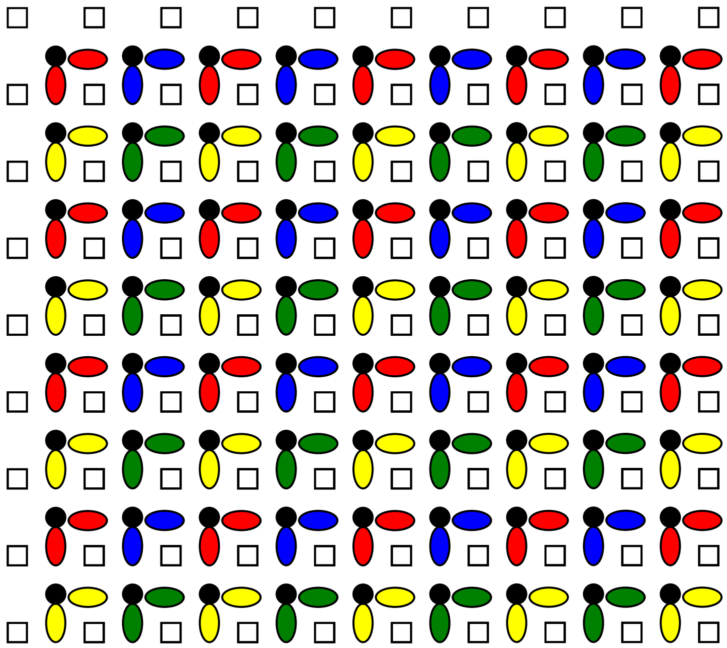


Fig.3.18-- Coverage with 4 groups of frequencies, “L” structure.

Something better can be made with the same number of frequencies but with a greater reuse distance considering a non symmetrical structure. It consists in repeating the same sequence of four frequencies in all the lines, shifting the pattern of one place, Fig.3.20.

In this configuration one takes advantage of the antenna radiation pattern as it irradiates only in p-n directions meaning that coquilles in the crossing streets do not influence the propagation.

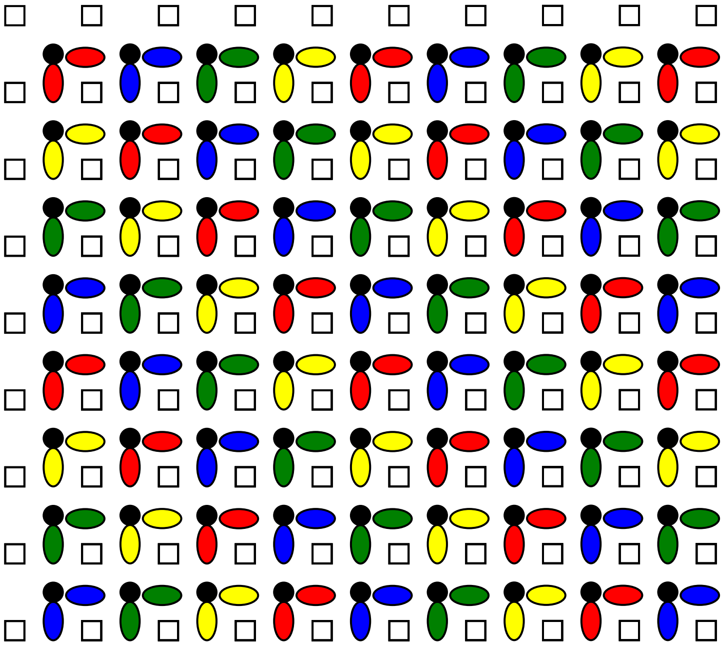


Fig.3.19--Coverage with 4 groups of frequencies, “L” irregular structure.

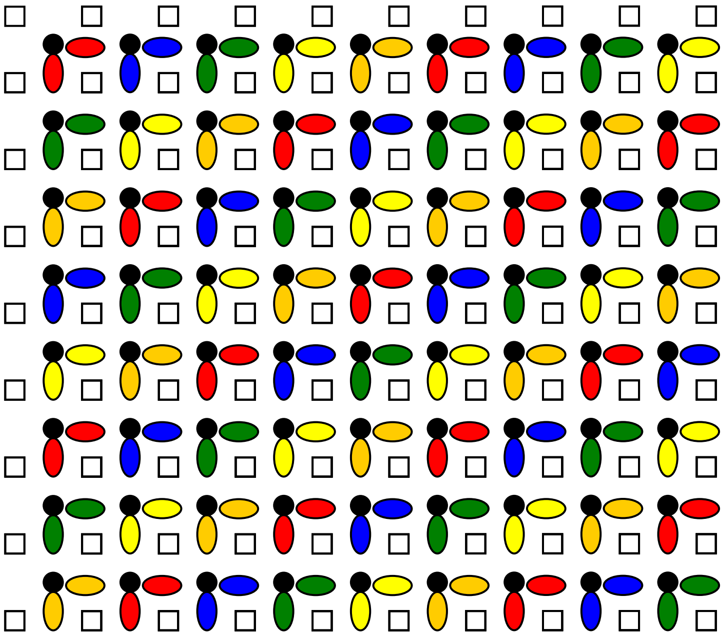
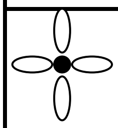
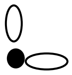
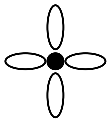
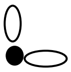


Fig.3.20-- Coverage with 5 groups of frequencies, “L” structure.

A perfectly radial structure, with 5 groups of frequencies, shifting the line pattern of two places in each street, Fig.3.20. This coverage does not present any advantage in comparison to the 4 frequency groups one as the reuse factor keeps the value of 2 while the system capacity decreases (Tab.3.13).

Shape	N_{fg}	Type of structure	r	N_{ic}	n_{cc}	η_{cell}
	4	Reg	4	3	0.25	0.50
	6	Semi-Reg	6	5	0.17	0.33
	4	Reg	4	3	0.25	0.13
	5	Reg	10	4	0.20	0.10
	6	Semi-Reg	12	5	0.17	0.08
	4	Reg	2	1	0.25	0.25
	4	Semi-Reg	4	3	0.25	0.25
	5	Reg	5	4	0.20	0.20

Tab.3.12--Frequency density and carriers per cells in a regular and semi regular coverage, street length equal to 0.5 km.

Shape	r	$R_{[km]}$	*(C/I)*
	4	0.25	17.09
	6	0.25	29.08
	4	0.50	24.80
	10	0.50	24.85
	12	0.50	44.32
	2	0.50	0.00
	4	0.50	24.64
	5	0.50	34.69

Tab.3.13--*(C/I)* for different numbers of frequency groups, L_s=0.5 km, f=60 GHz.

In all the structures that have been considered a trade off between the *C/I* and the capacity of the system must be found and an easy and direct way to visualize the results shown in the tables can be with graphical instruments..