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Transmission and Multiplexing (TM);
Digital Radio Relay Systems (DRRS);
Point-to-multipoint DRRS in the access network;
Overview of different access techniques

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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Transmission and Multiplexing (TM).

Introduction

Point-to-Multipoint (P-MP) systems are able to provide radio links between the scattered subscribers and the appropriate network node. At the network node a central station is located and provides, in effect a one-to-one line correspondence between each subscriber's terminal (telephone, data terminal, etc.) and each subscriber port on the network node.

The Central Station (CS) radiates via omni-directional or sectored antennas to a number of Terminal Stations (TS). The TSs radiate to the CS through directional antennas. Extension beyond Line of Sight (LOS) can be achieved with repeaters which allows to extend the service area. In urban environment more or less extended cell configurations are used to cover areas of unlimited extension in principle.

TSs may serve one isolated single subscriber, for example a pay phone, or may serve many subscribers (sometimes over 200 in a large town) with a variety of telecommunications. Frequently, because they are isolated, TSs and repeaters may be operated from solar power sources.

The number of subscribers that can be served by one single P-MP system depends on the number of trunks that the systems has. Although systems are currently available to support up to several hundred trunk lines, the typical number is between 10 and 60. With a concentrating air interface, such systems can serve up to several hundred subscribers for a Grade of Service (GOS) that would meet administration requirements.

1 Scope

In the present document an overview of different access techniques Time Division Multiple Access (TDMA), Direct Sequence Code Division Multiple Access (DS-CDMA), Frequency Division Multiple Access (FDMA) and Frequency Hopping Code Division Multiple Access (FH-CDMA) is made, in order to evaluate some parameters such as occupied band, capacity, minimum power at the receiver in threshold conditions. Although it is possible for P-MP systems to support limited mobility, the present document will only consider fixed radio access.

2 References

The following documents contain provisions which, through reference in this text, constitute provisions of the present document.

- References are either specific (identified by date of publication, edition number, version number, etc.) or non-specific.
- For a specific reference, subsequent revisions do not apply.
- For a non-specific reference, subsequent revisions do apply.
- A non-specific reference to an ETS shall also be taken to refer to later versions published as an EN with the same number.

[1] ITU-R Recommendation F.697-1: "Error performance and availability objectives for the local-grade portion at each end of an ISDN connection utilizing digital radio-relay systems".

[2] ITU-R Recommendation F.697-2: "Error performance and availability objectives for the local-grade portion at each end of an ISDN connection utilizing digital radio-relay systems".

[3] ITU-T Recommendation G.821: "Error performance of an international digital connection operating at a bit rate below the primary rate and forming part of an integrated services digital network".

[4] ITU-R Recommendation F.557: "Availability ojective for radio relay systems over a hypothetical reference circuit and a hypothetical reference digital path".

[5] ITU-R Report 338-6: "Propagation data and prediction methods required for the line-of-sight radio-relay systems".

[6] ITU-R Recommendation PN.530-5: "Propagaton data and prediction methods required for the design of terrestrial line-of-sight systems".

[7] EN 301 021: "Transmission and Multiplexing (TM); Digital Radio Relay Systems (DRRS); Time Division Multiple Access (TDMA) point-to-multipoint DRRS in Frequency Division Duplex (FDD) bands in the range 3 GHz to 11 GHz".

3 Symbols and abbreviations

3.1 Symbols

For the purposes of the present document, the following symbols apply:

dB	Decibel
dBi	Decibel gain relative to isotropic radiation
dBm	Decibel relative to 1 mW
GHz	Gigahertz
J	Joule
K	Kelvin (degrees)
kbit/s	Kilobit per second
kHz	Kilohertz
km	Kilometre
Mbaud	Megasymbols per second
Mbit/s	Megabit per second
MHz	Megahertz
ms	Milliseconds
mW	Milliwatt
µs	microsecond

3.2 Abbreviations

For the purposes of the present document, the following abbreviations apply:

A	Attenuation
B	Exponent of frequency f in s_{co}-formula taking care of regional effects
B_{RF}	Bandwidth Radio Frequency
BER	Bit Error Ratio
C	Exponent of link range r in s_{co}-formula taking care of regional effects
CCS	Central Controller Station
CDMA	Code Division Multiple Access
C/I	Carrier to Interference
CRS	Central Radio Station
CS	Central Station
DAMA	Demand Assigned Multiple Access
DBA	Dynamic Bandwidth Allocation
D/R	The minimum Distance between the centre of the cells with the same frequency-Radius of the cell
DRRS	Digital Radio Relay Systems
DS-CDMA	Direct Sequence Code Division Multiple Access
E_b	Energy per information bit
ES	Errored Seconds
ESR	Errored Second Ratio
F	Noise figure in dB
FEC	Forward Error Correction
f	Operative Frequency
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FH-CDMA	Frequency Hopping Code Division Multiple Access
FSK	Frequency Shift Keying
GOS	Grade Of Service
GSM	Global System for Mobile Communications
ISDN	Integrated Services Digital Network
k	Boltzmann constant
KQ	Product of factors describing climatic and terrain effects
ld(n)	Base two logarithm of quantity (n)

LOS	Line-Of-Sight
M	Cluster size
m	Levels (states) of the modulated carrier
M_{BER}	Fade Margin at a certain BER
MIPS	Million of Instructions Per Second
MTBF	Mean Time Between Faliures
MTTR	Mean Time To Restore
NFD	Net Filter Discrimination
N_0	Noise power spectral density
P(.)	Probability (for the event described in brackets)
PAMA	Pre-Assigned Multiple Access
P_{BER}	Power threshold level at a certain BER
PCM	Pulse code modulation
P-MP	Point to Multipoint
P-P	Point-to-Point
PSK	Phase Shift Keying
QPSK	Quadrature Phase shift Keying
R	Code rate ($R \leq 1$) or rain density (mm/h)
R_b	Information bit rate
r	Link range or roll-off factor
r_c	Code rate of convolutional code
RF	Radio Frequency
RLL	Radio Local Loop
RPE	Radiation Pattern Envelope
RS	Repeater Station
Rx	Receive
s_{co}	Multipath Occurrence Factor given in ITU-R
SES	Severely Errored Seconds
SESR	Severely Errored Second Ratio
SFH	Slow Frequency Hopping
T_b	Bit duration
T_0	Environmental temperature
TDM	Time Division Multiplex
TDMA	Time Division Multiple Access
TE	Terminal (Subscriber) Equipment
TM	Transmission and Multiplexing
TS	Terminal Station
Tx	Transmit
WLL	Wireless Local Loop

4 P-MP applications and deployment

4.1 Overview of applications

P-MP systems (also known in the market as WLL, RLL systems) are intended for providing access to a network from fixed telecommunications terminals at scattered locations. The terminals are connected to a TS, a TS being able to serve one or a few terminals. The TS has a two-way radio link to a Central Station (CS), which is in turn connected to the network. Normally the CS is connected to a telephone exchange, and the service provided to each terminal is a telephone line; but P-MP systems can also provide Internet access or radio link for command and control purposes.

Subscribers are offered the full range of services by the particular public or private network. Subscribers have access to these services by means of the various standardized user network interfaces.

P-MP systems provide standard network interfaces and transparently connect subscribers to the appropriate network node. These systems allow a service to be connected to a number of subscribers ranging from a few users to several hundred, and over a wide range of distances.

P-MP systems are generally configured as Pre-Assigned Systems or as Demand Assigned Multiple Access (DAMA) Radio Systems. Both methods guarantee transparency to the services transported.

The essential additional features of a typical P-MP DAMA versus a P-MP PAMA Radio System are:

- efficient use of the radio spectrum;
- concentration.

Radio is often the ideal way of obtaining communications at low cost and almost independent of distance, and over difficult topography. Moreover, only a small number of sites are required for these installations, thus facilitating rapid implementation and minimizing maintenance requirements of the systems.

Concentration means that "m" subscribers can share "n" radio channels (m being larger than n), allowing a better use to be made of the available frequency spectrum and at a lower equipment cost. The term "multi-access" derives from the fact that every subscriber has access to every channel (instead of a fixed assignment as in most multiplex systems). When a call is initiated one of the available channels is allocated to it. When the call is terminated, the channel is released for another call.

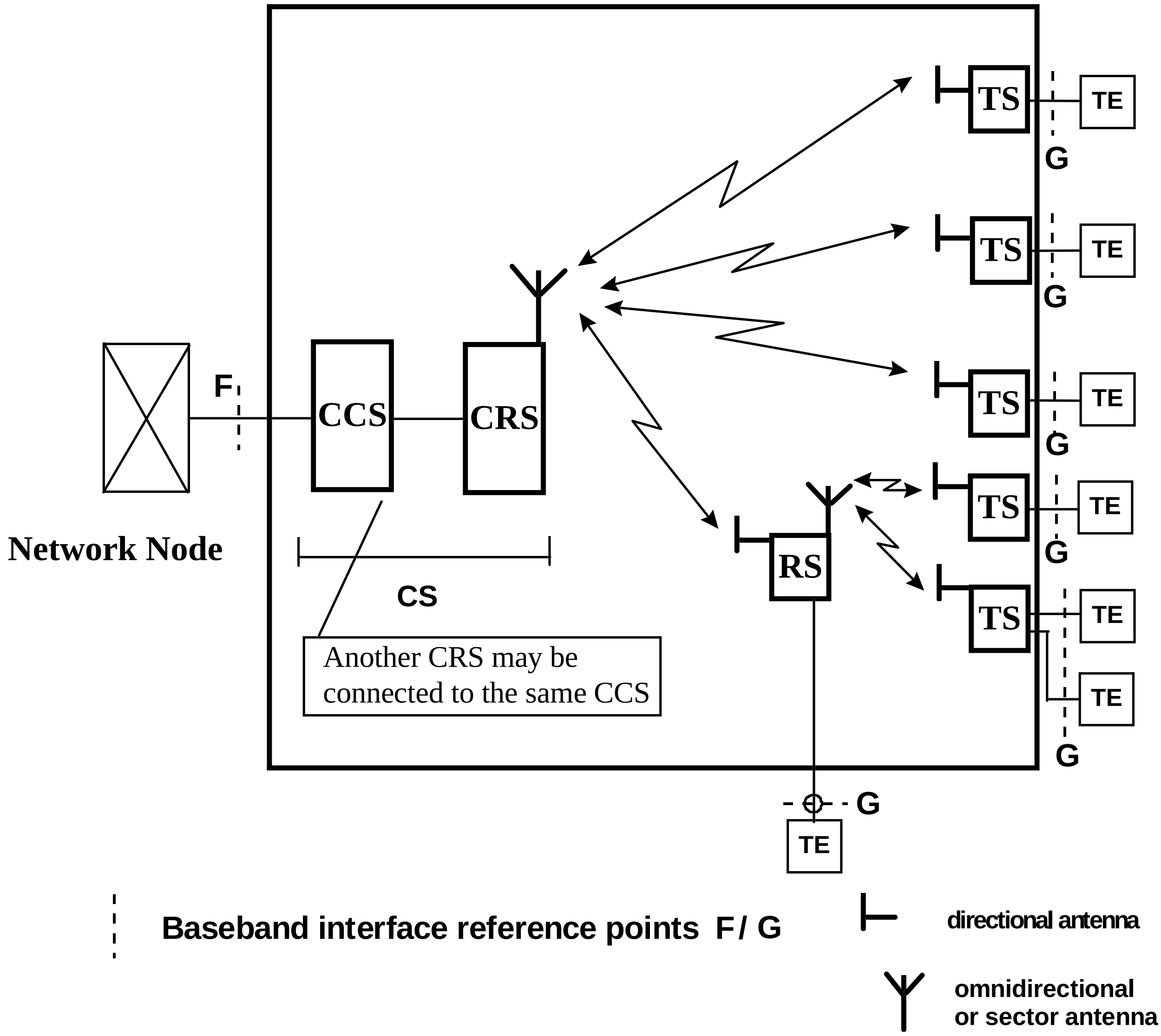
Concentration requires the use of distributed intelligent control which in turn allows many other operation and maintenance functions to be added.

Transparency means that the exchange and the TE communicate with each other without being aware of the radio link.

4.2 Interfaces and Services

4.2.1 Reference model

Figure 1 below is the reference model used by TM4 for the standardization of P-MP systems.



CCS	Central Controller Station
CRS	Central Radio Station
CS	Central Station
TS	Terminal Station
RS	Repeater Station
TE	Terminal Equipment
□	System boundary

Figure 1: TM4 reference model

4.2.2 Services and facilities

Services and facilities for P-MP systems generally require "service transparency" which means that: "the exchange and the terminal communicate without being aware of the radio link". In practice this means that P-MP systems have to support all the transmission and call-control services which are required for supporting fixed analogue or digital telephony. P-MP frequency bands have been identified and shown in table 1.

Table 1: P-MP frequency bands

Frequency bands	1 350 MHz - 1 375 MHz and 1 492 MHz - 1 517 MHz 1 375 MHz - 1 400 MHz and 1 427 MHz - 1 452 MHz 2 025 MHz - 2 110 MHz and 2 200 MHz - 2 290 MHz 2 300 MHz - 2 500 MHz 2 520 MHz - 2 670 MHz 3 410 MHz - 3 600 MHz and 3 600 MHz - 3 800 MHz 10 150 MHz - 10 300 MHz and 10 500 MHz - 10 650 MHz 24,5 GHz - 26,5 GHz

4.3 System deployment and radio propagation

Originally, P-MP systems have been deployed for providing telecommunications in rural areas over long distances. In this situation the locations of the stations can usually be chosen to provide a line of sight between the CS and TSs. Where LOS is not possible a RS can be used to extend the range, as well as to serve nearby customers. For these systems conventional P-P planning methods can be used, using path profiles to identify locations which ensure fresnel zone clearance and conventional methods to predict path loss. Propagation impairments which arise will be typical of P-P systems.

More recently, P-MP systems are being used to provide "ad-hoc" service in urban areas to customers whose locations are not known in advance. For example, an operator may wish to provide service in a city, illuminating an area of the city from one CS and providing service through TSs. The location of the CS will obviously be chosen to optimize coverage of the required area; but a number of constraints typically apply to the TS Installations.

The location of customers is not known in advance, so that coverage can only be predicted statistically (as is the case with a mobile system, for example).

It may be difficult to serve more than one subscriber with a TS because market penetration may be low and installation difficulties in urban areas prevent running long cables.

Zoning regulations may prevent the use of tall masts for TS antennas to optimize the radio path, and the TS can only be mounted on or very near to the subscriber's premises.

So it may be possible that radio paths to some TS will not have good LOS conditions and that there will be a significant degree of shadowing. In addition, multipath propagation may arise due to reflection and diffraction from buildings. Some measurements of typical radio propagation for this type of ad-hoc deployment are reported in annex A. However, for P-MP systems to be operated in frequency bands above 10 GHz good LOS conditions are essential. Hence, in such systems the impact of multipath propagation can be expected to be of minor importance.

4.4 Isolated systems

P-MP systems may be deployed to cover a well-defined set of locations which can be reached from a given central point. In this case, provided that enough capacity is available for the traffic demand, only one P-MP system (or more than one operating at different frequencies from the same central point) needs to be deployed. This will be referred to as an isolated deployment.

4.5 Cellular deployment

If demand has to be met over a large area which cannot be covered from one central point, either because of propagation constraints or capacity constraints or a combination, CSs may be deployed in a cellular arrangement with frequency re-use to optimize spectrum efficiency. This will be referred to as a cellular, deployment.

Cellular deployment consists of a subdivision of the service area in many zones called cells. Each of these cells can be served either by one CRS (Central Radio Station) with a omni-directional antenna or by more CRSs each of these with a sectored antenna. Every CRS has a group of radio channels, that can be reused in other cells or sector properly distanced.

This means that the optimum coverage structure has to be properly defined in order to fit the recommendation on quality and availability. As an example, let us consider a radio coverage with CRS using an omni-directional antenna. The fundamental parameters in such a kind of radio coverage is the co-channel reuse factor defined as D/R, where D is the minimum distance between the centres of cells with same frequency and R is the "radius" of the cell. By defining the cluster size M as the number of adjacent cells that use distinct carrier frequencies, it is possible to show that $D/R = \sqrt{3M}$ for every permitted value of M.

In fact, in a hexagonal cell structure (figure 2), only certain values of M are allowed: $M = \{1, 3, 4, 7, 9, \cdots\}$. The actual formula is $M = i^2 + ij + j^2$ where $i, j = 0, 1, 2, 3, \ldots$.

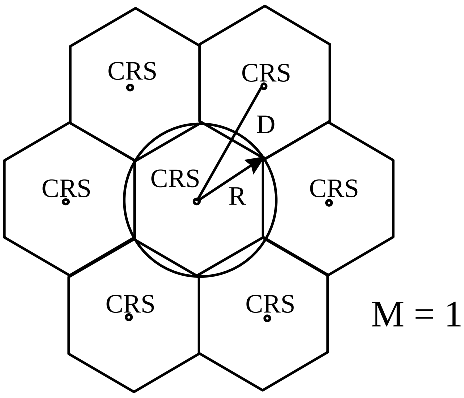


Figure 2: Cellular structure

A reasonable model for propagation path loss between a central station site and a terminal equipment is a model where the loss is the product of an inverse power of the distance and a log-normal random variable to model shadowing effect. Therefore:

$$P_L = \frac{P_T}{P_R} = \frac{(4\pi/\lambda)^2 r^\gamma 10^{\frac{\xi}{10}}}{G_R G_T} \tag{1}$$

where:

- P_L is the path loss;
- P_T is the transmitter power;
- P_R is the received power;
- r is the distance between the central station and the terminal;
- γ is a propagation exponent giving the rate of variation with distance;
- ξ is a random variable log normal distributed with zero mean value and standard deviation 6 dB < σ < 12 dB, that taking into account the shadowing effect, but only slow fading is considered (the value is expressed in decibels);
- G_T antenna gain at the transmitter site;
- G_R antenna gain at the receiver site.

For normal Rician channels, γ is likely to be approximately 2 close to central station site and under LOS conditions. For frequencies below 2 GHz and larger distances i.e. inter-cell propagation, γ is more likely to be near 4. For systems operated at frequencies at or above 10 GHz, LOS conditions are essential and γ = 2 at least for intended paths has to be assumed throughout. However shadowing of interfering paths is more complete than for the low frequencies because diffraction is of minor importance.

Because of the directivity of the TS antenna, the total interference level in downlink results less than in uplink and consequently the dimension of the cluster is based only on the uplink.

The interference contribution due to a TS can be evaluated by finding the average difference in path loss at the interfered CRS site from the interfering TS. For simplicity, the shadowing component will be ignored even though such hypothesis could lead to some inaccuracies. Referring to figure 2 (cluster with M = 1) the difference in path loss L can be expressed by:

$$L(dB) = -\gamma \times 10 \times \log \frac{r_1}{r_2} - g(\theta) \qquad (2)$$

where $g(\theta) = 10\mathrm{LOG}(G(\theta)/G(0))$ is the TS antenna gain reduction due to a θ rotation with respect to the maximum gain direction (where $g(0) = 0 \quad \mathrm{dB}$). It is worth noting that relation (2) can be used even with different cell sizes. Note that the CRS are equipped with omnidirectional antennas.

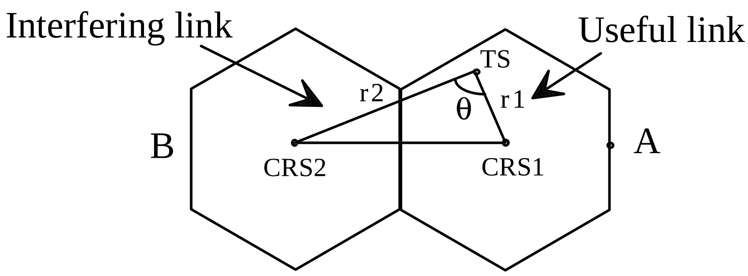


Figure 3: Example of interference in a TS-CRS connection

The signal/interference ratio (measured in dB) at the neighbouring cell (B) is as follow:

$$\frac{C}{I} = -10 \times g \times \mathrm{Log}(1/3) \qquad (3)$$

For clusters greater than 1, the difference in path loss has been reported in table 2.

Table 2: Difference in path loss for different cluster size

Cluster Size	$L/\gamma \quad (dB)$
1	4,77
3	6,02
4	6,99
7	7,78
9	8,45

In the above example, the interference contribution due to a single user placed in the worst site has been calculated; other hypothesis on user sites can be applied such as uniform user distribution as more clearly demonstrated in clause 10.

Another important parameter that has to be taken into account is the antenna pattern either for the CRS or for the TS. In particular, with an omni-directional CRS antenna, the radiation diagram does not have a big influence if the worst user site is considered. By using sectored antennas, however, this parameter might assume a great importance for the following reason:

Generally speaking, the lower sectoring angle for CRS antenna, the higher the overall C/I that can be obtained with the same number of frequencies.

The worst user site is not necessarily related to the higher TS antenna gain direction.

Under these considerations, the interference contributions due to the neighbouring sectors has to be carefully evaluated finding out the worst user site for each of the interfering sectors.

As an example let us consider the structure in figure 4. By supposing two sectors at the same frequency f_A, the worst interfering site lies between point A and point B on the border of the cell. The right point can be obtained only by means of TS and CRS antenna patterns.

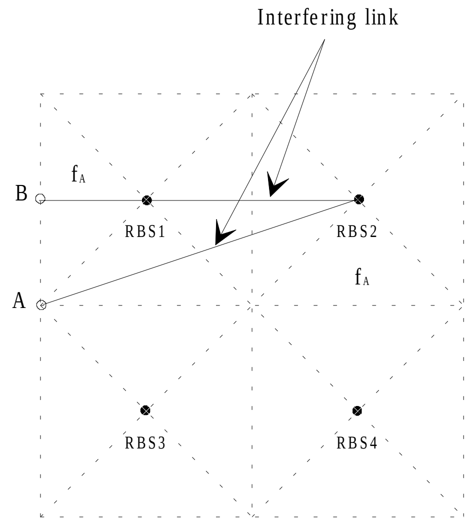


Figure 4: Example of interference in a TS-CRS connection with 90° sectored antenna

In addition, with sectored antennas, the evaluation of each interference contribution between cells (or sectors) should be done by using the antenna's mask in order to take into account the implementation tolerance.

After this introduction, it is useful to introduce some guidelines to be taken into account during radio coverage planning.

1) **CRS site**. The first step is the CRS's site definition which has to be carried out on the basis of LOS constraint. In particular, each candidate site has to be able to cover its area of competence in LOS propagation conditions with the highest reliability (e.g. the highest percentage of candidate users in LOS condition). For this task, the usage of software tools working on geographic data base for LOS prediction is recommended in order to find out the most reliable sites.

2) **Coverage structure**. Having determined a certain number of candidate sites, coverage structure can be planned on the basis of capacity constrain. In particular, the chosen site(s) has to be equipped by a number of CRSs which have to be able to cope with the capacity of their area of service. In such a task, the usage of sectored antenna and/or dual polarized antenna might be useful in order to split the capacity over different CRSs located at the same site.

   However, this task could lead to unacceptable solution for the following reasons:

   - the number of CRSs in each site is too high;

   - the coverage reliability is too low.

   In both cases a higher number of sites is required and a new coverage structure has to be found.

3) **C/I evaluation**. By means of the coverage structure just obtained, a C/I evaluation can be carried out for each couple of cells (or sectors) on the basis of the above criteria. If dual polarized antennas are deployed, a proper depolarization factor has to be taken into account on the basis of cells ray and rain depolarization. Nevertheless, a more realistic C/I evaluation can be obtained by means of software tools able to take into account of geographical environment while finding out the worst user site (e.g. cells behind natural obstacles such as hill or mountain have a lower interference contribution).

4) **Frequency allocation**. In order to make a frequency allocation, a minimum C/I has to be defined. By means of co-channel sensitivity curves provided by the manufacturers; this value could be assumed to be the C/I at which the candidate system has a degradation of 3 dB on the power threshold level or less. After that, the available frequencies can be allocated by hand or by means of software tools pursuing the main goal of having an overall C/I for each cell (or sector) greater than the minimum C/I. The overall C/I can be calculated as follows:

$$\left(\frac{C}{I}\right)_{tot} = \frac{1}{\sum_i \left(\frac{C}{I}\right)_i^{-1}} \tag{4}$$

where:

$\left(\frac{C}{I}\right)_{tot}$ is the overall signal/interference ratio.

$\left(\frac{C}{I}\right)_{i}$ is the contribution due to the i-th cell (or sector) operating at the same frequency.

In addition, the interference due to adjacent channel has to be considered by adding a proper contribution in relation (4) especially for CRSs placed at the same site. This contribution has to be calculated on the basis of spectrum measurement provided by the manufacturers.

As previously stated, all values in (4) can be calculated on the basis of the above criteria and take into account the particular access scheme. The procedure explained in chapter 8 provides a different approach for the evaluation of the overall C/I.

At the end of the analysis, different kind of results could be obtained

- The overall C/I for each cell (or sector) is close to the requirement on the minimum C/I. In this case, a solution has been found and the link budget can be evaluated. However, it could be useful to verify the feasibility of future upgrading for the radio access network just obtained by supposing either a higher capacity requirement or new housing area(s) inside and outside the area of interest.

- The overall C/I is higher than the minimum C/I required. This is due either to the low number of cells (or sectors) or to the high number of deployed frequencies. This is not necessarily a drawback. In this case the designer may consider either a more economical deployment or to keep the extra capacity for a future demand growth.

- The overall C/I is less than the minimum tolerated C/I. In this case, the following counter measures can be adopted:

    - deployment of a higher number of frequencies (if available);

    - increase the number of sites. Sometimes, this action might help to reach a useful result either by exploiting the more finely shared capacity or by exploiting the spatial freedom to guide interference towards different direction;

    - usage of more directive CRS's antenna such as 90° sectored antennas instead of omnidirectional antennas.

At any rate, new coverage evaluation procedure has to be carried out again.

4.6 Link budget

In order to verify either quality or unavailability requirements, a link budget for each cell (or sector) has to be calculated on the basis of system features and propagation condition. In particular it is necessary to know the following parameters:

- receiver power threshold level;
- transmitter output power;
- feeder attenuation;
- cable attenuation;
- co-channel and adjacent channel sensitivity curve;
- propagation environment;
- antenna gains and RPEs.

4.6.1 Quality requirements

Taking into account ITU-R recommendation F.697-2 [2], which is applicable to the local grade portion of an ISDN connection at a bit rate below the primary rate, requirements on error performance can be summarized as follows:

- the SESR should not exceed 0,015 % in any month;
- the ESR should not exceed 1,2 % of any month.

Where:

- SESR represents the ratio between the SES (as defined in ITU-T Recommendation G.821 [3] and the overall number of measured seconds;
- ESR represents the ratio between the ES (as defined in ITU-T Recommendation G.821 [3] and the overall number of measured seconds.

It is worth noting that the SES requirement is equivalent to former requirement (see ITU-R Recommendation F.697-1) [1] recommending that the BER should not exceed 10^{-3} for more than 0,015 % of any month with an integration time of 1 s. For this reason in the present document we will refer to the former requirement.

In order to verify the last requirements, a general expression for link budget calculation has to be considered:

$$P_{Rn} = P_{TX} - A_{FS} + G_{RBS} + G_{TS} - A_C - A_V - A_E - A_K \qquad (5)$$

where:

P_{Rn}	=	Received power level (dBm);
P_{TX}	=	Transmitted power level (dBm);
A_{FS}	=	Free space attenuation (dB);
G_{RBS}	=	CRS's antenna gain (dB);
G_{TS}	=	TS antenna gain (dB);
A_C	=	Cable attenuation (dB);
A_V	=	Vegetation attenuation (dB);
A_E	=	Smooth earth attenuation (dB);
A_K	=	Diffraction attenuation (dB).

Losses associated with the diplexer are included within equipment specification.

All the above attenuation figures have to be included if necessary depending on deployment environment and range of coverage (e.g. for rural application all terms should be included). After having determined the received power level, margins both for BER = 10^{-3} and for BER = 10-6 can be evaluated

$$M_{10^{-3}} = P_{Rn} - P_{10^{-3}} - A^{I}_{10^{-3}} \qquad (6)$$

where:

$P_{10^{-3}}$ = Power threshold level at BER = 10^{-3}

$A^{I}_{10^{-3}}$ = Power threshold level degradation due to co-channel and adjacent channel interference for a BER = 10^{-3}

Both power threshold level degradation terms can be evaluated on the basis of the overall C/I calculated in (4) and using the sensitivity curves provided by the manufacturers.

At this stage, the attenuation statistic can be modelled as follows:

$$P(A > M_{10^{-3}}) = s_{C0} \times 10^{-M_{10^{-3}}/10} \qquad (7)$$

where S_{co} can be calculated as follows:

$$s_{C0} = K \times Q \times f^{B} \times r^{C} \qquad (8)$$

where:

f = operation frequency expressed in GHz

r = link range expressed in km

K, Q, B, C = parameters depending on the propagation environment

For additional references, see ITU-R Report 338-6 [5] and ITU-R Recommendation PN.530-5 [6].

In an average propagation environment, s_{C0} can be evaluated as follows:

$$s_{C0} = 1{,}4 \times 10^{-8} f \times r^{3} \qquad (9)$$

On the basis of ITU-R Recommendation F.697-2 [2] SESR requirement, the following inequality has to be verified

$$P(A > M_{10^{-3}}) < 1{,}5 \times 10^{-4} \qquad (10)$$

Frequency selective multipath fading has to be taken into account even though at the moment this issue is under study (see annex A).

The ESR requirement states that the seconds with at least one error should not be more than 1,2 % of any month. In fact this requirement needs a specific simulation to be estimated or a measure to be evaluated.

4.6.2 Availability requirements

Annex A of ITU-R Recommendation F.697-2 [2] introduces two unavailability types: system unavailability due to equipment unreliability and propagation unavailability due to rain attenuation (which is significant mainly to high frequencies, above 10 GHz). As far as propagation unavailability is concerned, we will refer to ITU-R F.Recommendation 557 [4] definitions. At any rate, no standards have been developed to provide specific values neither for system unavailability nor for propagation unavailability.

4.6.2.1 System unavailability

Annex A of ITU-R Recommendation 697.2 [2] introduces the following relation to evaluate system unavailability:

$$\text{Unavailability } = \left(1 - \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}\right) \times 100\% \quad (11)$$

where:

- MTBF is measured in h;
- MTTR is measured in h.

The parameter MTBF has to be provided by the manufacture and the parameter MTTR has to be estimated by the operators on the basis of the area of deployment, human resources, user and CRS sites, manufacturer data, etc.

4.6.2.2 Propagation Unavailability

As for system unavailability, ITU-R Recommendation F.697-2 [2] does not provide a specific requirement for propagation unavailability. For this reason, from now on we will refer to a general percentage p as a requirement for propagation unavailability and we will show how to verify this requirement.

As for quality requirements, a general expression for link budget calculation has to be considered:

$$P_{Rn} = P_{TX} - A_{FS} + G_{RBS} + G_{TS} - A_C - A_F - A_V - A_H - A_K - A_r \quad (12)$$

where, with respect to relation (5), a rain attenuation term A_r has been added.

In fact, rain causes an additional attenuation which can be expressed as follow:

$$g_r = KR^a \quad (13)$$

where:

- γ_r is measured in dB/km;
- K and α depend on frequency and polarization;
- R is the rain intensity, and is measured in mm/h.

The parameter R depends on the location in which the P-MP system is deployed. Usually, R is assumed to be the value at which the probability of having a greater rain intensity is equal to 10-4. From now on we will refer to $R_{0,01}$ as the value of rain intensity that can be exceeded with a probability of 0,01 % of an average year. Taking into account that K and α depend on polarization, from now on we will also refer to γ_r^h for horizontal polarization and to γ_r^v for vertical polarization.

In table 3 the K and α values for both horizontal and vertical polarization are reported.

Table 3: Parameters for rain attenuation calculation

Frequency (GHz)	K_H	K_V	α_H	α_V
1	3,87E-05	3,52E-05	0,912	0,880
2	1,54E-04	1,38E-04	0,963	0,923
4	6,5E-04	5,91E-04	1,121	1,075
10	0,0101	8,87E-03	1,276	1,264
11	0,0139	0,0124	1,25	1,25
20	0,0751	0,0691	1,099	1,065
25	0,124	0,113	1,06	1,03

For a different frequency the values of K and α can be obtained by a logarithmic or linear interpolation respectively.

In order to calculate the real power attenuation due to rain phenomena, the effective link length L_{eff} has to be introduced:

$$L_{eff} = \frac{90 \times L}{90 + 4 \times L} \tag{14}$$

where L is the real link length measured in km.

The power attenuation due to rain phenomena, can be calculated by means of (13) and (14) as follows:

$$\begin{aligned} A_r^h &= \gamma_r^h \times L_{eff} \\ A_r^v &= \gamma_r^v \times L_{eff} \end{aligned} \tag{15}$$

where A_r^h and A_r^v are measured in dB. In the same way as the rain intensity R, the rain attenuation A_r^h and A_r^v calculated by means of $R_{0,01}$ will be referred to $A^h_{r_{0,01}}$ and $A^v_{r_{0,01}}$.

However, in order to verify the assumed unavailability requirement $p\%$, the terms A_{r_p} have to be calculated which represent the rain attenuation that can be exceeded with a probability $p\%$. With the value $A_{r_{0,01}}$, it is possible to obtain the rain attenuation A_{r_p} as follow:

$$\begin{aligned} A^h_{r_p} &= A^h_{r_{0,01}} \times 0{,}12\, p^{-(0{,}546 + 0{,}043 \times \mathrm{Log}_{10} p)} \\ A^v_{r_p} &= A^v_{r_{0,01}} \times 0{,}12\, p^{-(0{,}546 + 0{,}043 \times \mathrm{Log}_{10} p)} \end{aligned} \tag{16}$$

Now the rain attenuation related to the assumed unavailability requirements, new margins $M_{10^{-3}}$ has to be calculated:

$$\begin{aligned} M^h_{10^{-3}} &= P^h_{Rn} - P_{10^{-3}} - A^{I_h}_{10^{-3}} \\ M^v_{10^{-3}} &= P^v_{Rn} - P_{10^{-3}} - A^{I_v}_{10^{-3}} \end{aligned} \tag{17}$$

where:

> P^h_{Rn} and P^v_{Rn} represent the received power levels calculated by means of relation (12) including the proper rain attenuation (respectively, $A^h_{r_p}$ and $A^v_{r_p}$)
>
> $A^{I_h}_{10^{-3}}$ and $A^{I_v}_{10^{-3}}$ represent the degradation on the power threshold level for both polarization.

It is worth noting that the terms $A^{I_h}_{10^{-3}}$ and $A^{I_v}_{10^{-3}}$ have to be evaluated taking into account the following aspects:

- Each term in relation (4) has to be now evaluated taking into account that the useful link suffers of rain attenuation but, in some cases, the interfering link could not be attenuated.
- Surrounding cells operating on the opposite polarization (if any) will cause an additional C/I contribution to relation (4) due to rain depolarization even thought in most of the cases it is not.

After having determined both margins (17), the assumed unavailability objective will be fulfilled if:

$$M^{h}_{10^{-3}} \geq 0$$
$$M^{v}_{10^{-3}} \geq 0 \qquad (18)$$

4.7 Operating principles

The CS radiates a radio carrier from an omnidirectional or sectored antenna over the area in which service is required. A number of traffic channels are multiplexed on this carrier, plus signalling information to control the allocation of these traffic channels to Terminal Stations. The link between the CS and TSs will be referred to as the downlink. Normally there is an upper limit to the number of traffic channels which the CS can support.

Each TS is equipped (normally) with a high gain directional antenna pointed towards the CS. It receives the multiplexed traffic channels and demultiplexes the control information and any traffic information directed to a terminal served by the TS. It transmits back to the CS, usually on a separate frequency or on a different time slot (the up-link), traffic and signalling information which is multiplexed (usually) by a similar method to the down-link. A TS will only transmit if it is either signalled to do so by the CS (an incoming call); or if the attached terminal requests service (goes "off-hook" - an outgoing call). Each TS in the service area can access only the number of traffic channels supported by the CS. Because calls are made only intermittently from each TE, the number of TEs which can be supported is much larger than the number of traffic channels, and the system operates a Demand Assigned Multiple Access (DAMA) protocol between CS and TSs.

There are several choices for the method by which the traffic channels share the radio carriers (multiplexing on the down-link and multiple access on the up-link). The most common in existing or proposed systems are:

- TDMA;
- DS-CDMA;
- FDMA;
- FH-CDMA.

In principle systems may share several methods. Thus an FDMA system may allow several active TEs to time-share a radio carrier from a TS, where different TSs use different carrier frequencies to access the CS.

5 P-MP common characteristics

In order to make an overview of different multiple access techniques (TDMA, DS-CDMA, FDMA and FH-CDMA) used in P-MP systems, some common parameters, characterizing the radio relay link, have to be specified.

Table 4: Assumption for analysis

Channel Spacing	**1,75 MHz, 2 MHz, 3,5 MHz, 7 MHz and 14 MHz**
Modulation	4 PSK
Central station antenna	Omnidirectional/Sectored
User antenna	directional
Noise figure	6 dB

Even though the most common modulation method is coherent 4PSK, other modulation methods, such as coherent 8PSK and 16PSK or incoherent FSK, are sometimes deployed.

In addition, we suppose an uncoded transmission for TDMA systems and coded transmission for DS-CDMA systems ($r_c = 1/2$). The reason for assuming a convolutional encoding for the case of DS-CDMA systems is that the benefit of FEC are obtained in these systems without any associated reduction in capacity. the assumed bit energy to noise spectral density ratios E_b / N_0 for a given BER are reported in table 5.

Table 5: Assumed E_b / N_0 versus BER

	$E_b / N_0 @\mathrm{BER} = 10^{-3}$	$E_b / N_0 @\mathrm{BER} = 10^{-6}$
TDMA	8,5 dB	12,0 dB
DS-CDMA	4,5 dB	7,0 dB
FDMA	8,5 dB	12,0 dB
FH-CDMA	8,5 dB	12,0 dB

6 TDMA systems

6.1 Broadband TDMA

Broadband TDMA systems generally permit the time sharing of the same frequency band by different users.

The physical layer is normally based on 2 Mbit/s transmission, with a total capacity equivalent to a 2 Mbit/s PCM system but additional signalling to control the radio link. Radio carrier spacing is typically 1,75 MHz or 2 MHz. Systems use frequency-division-duplex, and require an appropriate paired frequency allocation. Some systems are also available using 4 Mbit/s or 8 Mbit/s transmission and providing 60 or 120 traffic channels, with 3,5 MHz or 7 MHz channel spacing.

Access is by TDM (downlink), TDMA (uplink), demand assigned, with frequency FDD. The CS transmits, continuously, a frame structure which is based on PCM but with normal PCM slots concatenated to longer radio slots: the downlink radio frame length is typically 1 to 10 ms (depending on system), much longer than the normal 125 µs PCM frame. The uplink is burst-mode: the reason for concatenating PCM slots is to make the active up-slot length longer and reduce the effect on efficiency of the required up-link guard periods. Adjustable timing advance (e.g. GSM) is provided to make sure all incoming bursts at the central station fit exactly in their allocated slots.

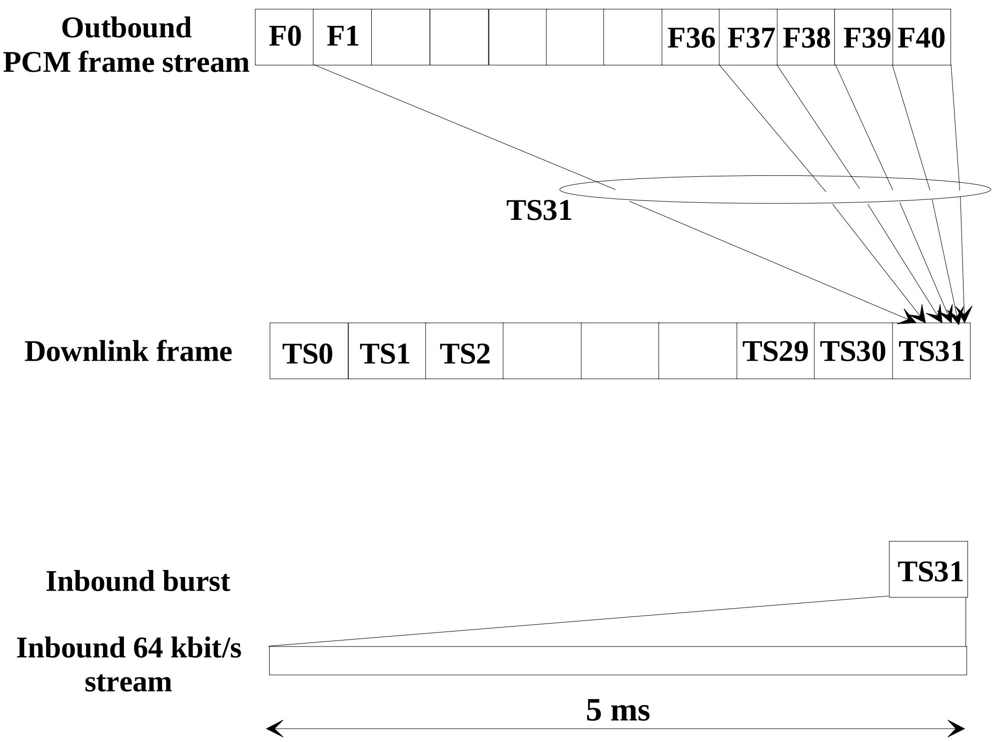


Figure 4: TDMA frame format

Figure 4 shows diagrammatically a possible frame format for a point-to-multipoint system, and how a single 64 kbit/s user accesses the system. On the down-link, a 2,048 Mbit/s PCM stream, which is augmented with additional control information for radio access, is mapped onto the down frame structure. The down-link frame has 32 slots, but in this example its length is 5 ms instead of the normal PCM frame of 125 µs. Therefore the contents of time slot 31 (for example) of 40 successive PCM frames are stored and loaded into time slot 31 of the TDMA frame. Similarly, on the up-link, a single 64 kbit/s tributary stream will be stored for each 5 ms frame period and loaded into a single, 156,25 µs up-link burst. The timing of this burst will be adjusted so that it is received at the central station in synchronism with the down-link frame.

The radio architecture assumes that TS radio transceivers have to be full duplex, and therefore it is not necessary for the downlink and uplink frame lengths to be equal; this may enable a better trade-off of signal delay against minimum overhead in the frame structure.

Since the protocol is based on PCM, traffic is carried in 64 kbit/s channels, and the system is therefore fully transparent to normal speech-band services. Certain suppliers provide terminal equipment with full ISDN 2B+D capability. Terminal equipment is capable of supporting either single subscribers, or groups of subscribers, is generally available.

Systems operate typically at 1,5 GHz or 2,4 GHz in normal "fixed-"reuse" frequency allocations, and frequency rasters are aligned with microwave P-P systems.

Central station to subscriber system range can be typically up to 40 km. Both are installed to obtain a good line-of-sight path. In addition, most systems make provision for a "repeater" mode which allows ranges of several hundred, kilometres to be attained in several "hops".

For systems specifically designed for data applications, packet data transmission can be deployed using contention avoidance protocols.

6.2 Narrowband TDMA

A typical 2 Mbit/s P-MP system as described above according to EN 301 021 [7] has a threshold receive sensitivity of -90 dBm and peak transmit power of +35 dBm (though the transmit power would probably not exceed +30 dBm in practice). The total link budget, assuming CS antenna gain of 10 dBi and TS antenna gain of 18 dBi, would be:

$$30 + 10 + 18 - (-90) = 148 \text{ dB.}$$

At 2 Mbit/s the symbol rate will be 1 Mbaud with a quaternary modulation scheme.

Comparing these figures with the propagation measurements for ad-hoc TS deployment reported in annex A, clearly quite a high proportion of the surveyed points would not receive service because of excessive path loss. Moreover, some measured path impulse responses are significantly longer than the symbol length for a 2 Mbit/s system, so that a high error rate due to intersymbol interference caused by multipath propagation will arise for some TS locations.

For optimum operation with "ad-hoc" deployment, a system with a lower gross RF channel bit rate will be preferable. This allows a better link budget, through a smaller channel bandwidth; makes the system less susceptible to multipath distortion because the symbol rate is lower; and makes it feasible and economical to implement an adaptive equalizer to correct any multipath.

For example, with a minimum channel bit-rate of 0,32 Mbit/s, the system noise bandwidth is reduced by a factor of 6,25, giving 8 dB increase in the link budget relative to a "2 Mbit/s" system; the symbol length (assuming quaternary modulation) is 4 to 6 times longer (depending on the amount of transmission overhead). The example of GSM, which has approximately the same symbol length, shows that a low-cost equalizer realization is feasible for such a symbol rate.

The use of a narrow-band channel leads to a lower system capacity for a single-carrier system. At a minimum bit-rate of 0,32 Mbit/s, five 64 kbit/s traffic channels may be accommodated per carrier. However, the lower bit rate also allows the channel spacing to be significantly reduced. Using frequency stabilization techniques in the CS and TS whereby the transmit and receive channel frequencies are locked to the bit-rate, channel spacing as low as 300 kHz may be employed.

If larger system capacities are then required (e.g. if the CS has to support an El link capacity), multiple radio carriers can be radiated. Clearly 6 carriers would be required to support 30 × 64 kbit/s traffic channels, to be equivalent to a conventional 2 Mbit/s P-MP system. On the other hand, it may be useful for the operator to conserve spectrum by installing fewer carriers to reduce system capacity where penetration is low or where dictated by the constraints of cellular frequency planning.

The total occupied bandwidth for the narrow-band system would be 1,8 MHz, compared to 1,75 MHz or 2,0 MHz for the conventional approach - that is, the systems will be very similar in terms of occupied bandwidth. Greater effective spectral efficiency may also be obtained by using lower rate coding.

It should be noted that, for a given multipath delay spread the processing power of an adaptive equalizer, measured in for example MIPS, has to rise as the square of the system bit rate. This is because the sampling rate varies proportionally to the bit rate, and the number of equalizer taps (assuming a transversal equalizer) also goes up proportionally to the bit rate for a length of impulse response.

For speech traffic this is appropriate, as long as an effective service transparency can be provided, for both narrow-band and broad-band systems.

6.3 Isolated performance for broadband TDMA

As stated in previous paragraph, physical layer for a broadband TDMA systems is normally based on 2,048 Mbit/s transmission, with a total capacity equivalent to 32 traffic channels. Some systems are also available using 4,096 Mbit/s transmission and providing 60 traffic channels. The minimum average power level in threshold condition S_{av} can be calculated by means of the following relationship

$$S_{av} = \left(\frac{E_b}{N_0}\right)_{dB} + 10 \times Log\left(R_b\right) + 10 \times Log\left(KT_0\right) + F_{dB} \qquad (19)$$

where:

$\frac{E_b}{N_0}$	bit energy to noise spectral density ratio (see table 5);
$K = 1{,}38 \times 10^{-23}$ J/K	Boltzman constant;
T_0 = 293 K	environmental temperature;
R_b = 2,048 Mbits, 4,096 Mbit/s	transmission bit rate;
F = 6 dB	noise figure.

Substituting these values the following characteristics of TDMA system in absence of interfering cells result as in table 6.

Table 6: Broadband TDMA capacity (number of 64 kbit/s channels) and threshold power level without interfering cells

	$\mathrm{BER} = 10^{-3}$		$\mathrm{BER} = 10^{-6}$	
Bands	**N**	**S_{av} (dBm)**	**N**	**S_{av} (dBm)**
1,75 MHz	32	-96,3	32	-92,8
2 MHz	32	-96,3	32	-92,8
3,5 MHz	64	-93,3	64	-89,8
7 MHz	128	-90,3	128	-86,8
14 MHz	256	-87,3	256	-83,8

For system supporting packed data transmission for data applications, FSK method should be considered. Table 7 shows the bit energy to noise spectral density ratios E_b/N_0 for various FSK modulation schemes with incoherent demodulation.

Table 7: Assumed E_b/N_0 for FSK modulation schemes versus BER

	$\mathrm{BER} = 10^{-3}$	$\mathrm{BER} = 10^{-6}$
Modulation	**$E_b/N_{0\ (dB)}$**	**$E_b/N_{0\ (dB)}$**
2 FSk	11,5	15,0
4 FSK	18,5	22,0
8 FSK	24,5	28,0

The corresponding sensitivities are shown in table 8.

Table 8: Broadband TDMA capacity and threshold power level without interfering cells for systems using incoherent FSK modulation schemes

			$\mathrm{BER} = 10^{-3}$	$\mathrm{BER} = 10^{-6}$
Bands	**Modulation**	**Bit rate (Mbit/s)**	S_{av} **(dBm)**	S_{av} **(dBm)**
1,75 MHz/2 MHz	2FSK	1	-93,3	-89,8
	4FSk	2	-86,3	-82,8
	8FSK	3	-78,3	-74,8
3,5 MHz	2FSK	2	-90,3	-86,8
	4FSk	4	-83,3	-79,8
	8FSK	6	-75,3	-71,8
7 MHz	2FSK	4	-87,3	-83,8
	4FSk	8	-80,3	-76,8
	8FSK	12	-72,3	-68,8
14 MHz	2FSK	8	-84,3	-80,8
	4FSk	16	-77,3	-73,8
	8FSK	24	-69,3	-65,8

6.4 Isolated performance for narrowband TDMA

Due to the lower bit rate, narrowband TDMA systems are able to provide a lower capacity for a single carrier but with lower power threshold level as well. In fact the useful bit rate provided by narrowband TDMA system is, as a reference value, 0,32 Mbit/s. By means of relationship (11), it is possible to obtain the power threshold level for a narrowband TDMA system based on 0,32 Mbit/s basic rate. By means of table 9 it is possible to verify the gain on power threshold level with respect broadband TDMA stated in subclause 4.4.

Table 9: Threshold power level for narrowband TDMA based on 0,32 Mbit/s the basic rate (e.g. five channels at 64 kbit/s)

Basic Rate	$S_{av}@\mathrm{BER}=10^{-3}$ (dBm)	$S_{av}@\mathrm{BER}=10^{-6}$ (dBm)
0,32 Mbit/s	-104,4	-100,8

6.5 Cellular deployment performance for broadband TDMA

As stated in subclause 4.5, cellular deployment means that a certain number of frequencies are reused in other cells (or sectors) properly distanced. This means that a certain amount of co-channel interference has to be taken into account during link budget calculation. The presence of co-channel interference causes an increment of the power threshold level because it acts like an additional noise power at the input of the receiver. In this context, relation (4) can be evaluated by adding a contribution for each cell (or sector) working at the same frequency on the basis of subclause 4.5 rules. Supposing the interference as a gaussian noise, a general figure on power threshold level with co-channel interference can be evaluated by means of the following equation:

$$(S_{av})_{dBm} = \left(\frac{E_b}{N_0}\right)_{dB} + 10\times Log(R_b) + 10\times Log(KT_0) + F_{dB} - 10\times Log\left[1-\frac{E_b}{N_0}\frac{R_b}{W}\left(\frac{I}{C}\right)_{TOT}\right] \qquad (20)$$

where $\frac{C}{I}_{TOT}$ is the overall signal to interference ratio expressed by relation (4), and W is the equivalent noise bandwidth of the receiving filter.

At any rate, the best way to evaluate this figure is by means of measured sensitivity curves provided by the manufacturers.

6.6 Cellular deployment performance for narrowband TDMA

In cellular deployment for narrowband TDMA the same approach as for broadband TDMA can be assumed even though some differentiation are necessary. As stated in subclause 4.4, the use of narrowband TDMA systems neither allows to improve system's capacity nor to reduce the cluster size. However, such systems introduce a very important degree of freedom which means a higher number of available frequencies. Such a feature has a great impact on frequency management due to the fact that the network designer is able to obtain a better trade off between the number of deployed frequencies and user penetration. In fact, to use a broadband TDMA system to cover a low populated area with a small degree of penetration means to obtain a coverage with a low spectral efficiency. On the other hand, the possibility to deploy a number of frequencies closer to the required capacity allows to obtain a better coverage of the whole area and, perhaps, a lower amount of bandwidth occupation.

As for broadband TDMA systems, a general figure on power threshold levels with co-channel interference can be obtained from relationship (20).

7 DS-CDMA systems

In the following we are going to investigate two different kind of DS-CDMA. In fact DS-CDMA systems separate the signals from the different users by assigning a different spreading code to each signal. If pseudo random codes are used (Pseudo Random DS-CDMA) the interference is reduced by a factor equal to the spreading factor. If orthogonal codes are used (Orthogonal DS-CDMA) the interference is, in principle, eliminated. Orthogonal codes only retain their zero mutual interference property when synchronized together. It is therefore necessary to synchronize the terminal station transmitter codes for Orthogonal DS-CDMA systems. The requirement also applies to all of the signals transmitted from the central station but in this case the implementation is trivial. In practice, full orthogonality can not be achieved due to propagation effects (e.g. multipath) which will reduce the capacity of the systems.

It is worth noting that many DS-CDMA systems can be thought of as a compromise of the two strategies with different degree of synchronization.

7.1 Pseudo Random DS-CDMA

Pseudo Random DS-CDMA systems generally conform to the following operating principles.

In Code Division Multiple Access (DS-CDMA) systems, subscribers are distinctly coded, prior to transmission, in a way which enables the separation at the receiver site. The physical layer permits a maximum number of users depending upon the user bit rate, available bandwidth and performance requirements.

Systems use FDD, and require an appropriate paired frequency allocation. Access is DS-CDMA (Code Division Multiple Access), demand assigned. The CS transmits a frame structure which is based on user data but with normal PCM multiplied by a proper code with a higher rate: the ratio between PCM rate and code rate is defined as processing gain. The downlink radio frame is made by summing individual spread downlink signals in addition to some codes without information (pilot).

After call set-up, each user shares the same spectrum simultaneously without the need for fine synchronization of the individual user's transmitted codes. At the receiver site, each data signal is distinguished from the others by means of a correlation process.

Since all users share the same spectrum, power imbalances at the CS receiver have to be avoided. This is achieved by automatic power control in the TSs which guarantees that all the users on the up-link will be received at the CS with the same power level.

In order to counteract self interference and the interference coming from adjacent cells, DS-CDMA systems encode the user data by means of a channel encoder such as a convolutional encoder before spreading the encoded signal.

Speech coding might be a lower rate than the 64 kbit/s assumed as a reference in this report. Certain suppliers provide terminal equipment with full ISDN 2B+D capability.

7.2 Orthogonal DS-CDMA

As stated in the previous paragraph, in the up-link frame, all user share the same spectrum simultaneously without taking care of time synchronization. If either a time advance or pilots' information is provided at the user site, transmission could be carried out so that, at the CS site, every users are time aligned with each others. In other words, each user will share the channel by taking care of the frame-timing over the air. Moreover, if orthogonal spreading code are used, such a approach will let DS-CDMA removing interference coming from others users. Relationship (21) shows one way to construct orthogonal spreading codes

$$W_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \qquad W_4 = \begin{bmatrix} W_2 & W_2 \\ W_2 & -W_2 \end{bmatrix} \qquad W_{2^n} = \begin{bmatrix} W_{2^{n-1}} & W_{2^{n-1}} \\ W_{2^{n-1}} & -W_{2^{n-1}} \end{bmatrix} \tag{21}$$

In fact, the rows of the above matrices represent a set of $L = 2^n$ orthogonal spreading sequences with length $L = 2^n$; it is possible to show that:

$$(\psi_i^{(L)}, \psi_j^{(L)}) = \frac{1}{T_b} \int_{kT_b}^{(k+1)T_b} \psi_i^{(L)}(t) \psi_j^{(L)}(t) dt = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases} \tag{22}$$

where $T_b = 1/R_b$ is the bit duration. Relation (22) tells us that, thanks to the time alignment, every user can be distinguished from each other without any interference contribution due to the other users. In this case, as stated in (21), the number of simultaneous user is only bounded by the length of the spreading code which is in itself bounded by the available bandwidth.

7.3 Isolated performance for Pseudo Random DS-CDMA

Taking into account that the CS is always able to send a down-link frame in a orthogonal fashion, Pseudo Random DS-CDMA capacity is bounded by the up-link frame. Therefore in the following analyses only the up-link case will be analysed.

The minimum average power level in threshold condition S_{av} and supposing a perfect power control can be calculated by means of the following relationship

$$\frac{E_b}{N_0} = \frac{S_{av} / R_b}{((N-1)\alpha \times S_{av} + \eta) / W} \tag{23}$$

where:

S_{av}	average received power;
α	voice activity factor;
R_b	user bit rate assumed to be 64 kbit/s;
N	number of 64 kbit/s channels sharing simultaneously the transmission channel;
W	equivalent noise bandwidth of the receiving filter;
η	average noise power referred to the noise equivalent bandwidth above defined.

The relationship between the received signal power level in threshold condition and the number of simultaneous active users can be derived from (23):

$$(S_{av})_{dBm} = \left(\frac{E_b}{N_0}\right)_{dB} + 10 \times Log(R_b) + 10 \times Log(KT_0) + F_{dB} - 10 \times Log\left[1 - \frac{E_b}{N_0}\frac{R_b}{W}\alpha(N-1)\right] \tag{24}$$

In addition, the maximum number of simultaneous active users can be derived from (24):

$$N < \left\lfloor \frac{W / R_b}{\alpha \times E_b / N_0} + 1 \right\rfloor \tag{25}$$

where the symbol $\lfloor \; \rfloor$ means the highest integer lower than its argument.

It could be shown that DS-CDMA capacity could be improved by exploiting the voice activity factor with the use of variable rate speech encoders. However, it has been decided to consider no voice factor improvement ($\alpha = 1$) for the following reasons:

- Voice band data calls, ISDN calls, or any calls carrying a link access protocol implicitly demand a continuous channel and the percentage of these connections is expected to rise significantly in the future;
- Various overhead functions (e.g. power control, synchronization, air interface protocol) require a continuous channel.
- No variable rate speech encoders have been taken into account by any standardization body.

The amount of adjacent power interference is scaled by the NFD (Net Filter Discrimination). By supposing a raised cosine filtering with a reasonable roll-off factor and by assuming an equivalent noise bandwidth equal to the channel spacing, the value of NFD factor is grater than 15 dB. For this reason it is reasonable to neglect the effect of adjacent channel interference.

Assuming a bandwidth W = 3,5 MHz and 7 MHz, the Pseudo Random DS-CDMA characteristics resulting from (24) and (25) are reported in table 10.

Table 10: Pseudo Random DS-CDMA capacity (number of 64 kbit/s channels) and threshold power level for a single user without iterfering cells

	BER = 10^{-3}		BER = 10^{-6}	
Bands	**N**	**S_{av} (dBm)**	**N**	**S_{av}(dBm)**
3,5 MHz	20	-98,5	11	-102
7 MHz	39	-98,5	22	-98,6

7.4 Isolated performance for orthogonal DS-CDMA

Orthogonal DS-CDMA systems, as opposed to Pseudo Random DS-CDMA, are able to perform a synchronous transmission over the up-link frame. So that, although all the users share the same channel simultaneously, the minimum average power level in threshold condition S_{av} assuming a perfect power control can be calculated by means of the following relationship

$$S_{av} = \left(\frac{E_b}{N_0}\right)_{dB} + 10 \times Log\left(R_b\right) + 10 \times Log\left(KT_0\right) + F_{dB} \qquad (26)$$

where, with respect to the relation (24), there is not intra-system interference contribution and the system capacity is bounded only by the available bandwidth. The DS-CDMA characteristics resulting from (26) are reported in table 11.

Table 11: Orthogonal DS-CDMA capacity (number of 64 kbit/s channels) and threshold power level for a single user without interfering cells

	BER = 10-3		BER = 10-6	
Bands	**N**	S_{av} **(dBm)**	**N**	S_{av} **(dBm)**
3,5 MHz	32	-115,3	32	-112,8
7 MHz	64	-115,3	64	-112,8

7.5 Cellular deployment performance for Pseudo Random DS-CDMA

In the uplink case, all TSs in surrounding cells (or sectors) operating at the same frequency act together to cause interference to the susceptible CRS. If each CRS is able to support up to N simultaneous users, in the unlikely worst case $Y \times N$ interfering subscribers will be present, where Y is the number of surrounding cells (or sectors) operating at the same frequency.

On the basis of the previous assumption, in the following analysis only the up link case will be taken into account.

In this context, a general figure on power threshold level with adjacent cells (or sectors) can be evaluated by means of the following equation:

$$S_{av} = \left(\frac{E_b}{N_0}\right)_{dB} + 10 \times Log\left(R_b\right) + 10 \times Log\left(KT_0\right) + F_{dB} - 10 \times Log\left[1 - \frac{E_b}{N_0}\frac{R_b}{W}\left[(N-1) + \sum_{i=1}^{N \times Y}\left(\frac{C}{I}\right)_i^{-1}\right]\right] \quad (27)$$

Where the summation refers to the $Y \times N$ users of the adjacent cells (or sectors). All the contributions to the summation can be evaluated by means of the criteria reported in subclause 4.5 or the procedure shown in clause 10.

In addition, the maximum number of simultaneous active users can be derived from (27):

$$N < \left\lfloor \left(1 + \sum_{i=1}^{N \times Y}\left(\frac{C}{I}\right)_i^{-1}\right)\frac{W / R_b}{E_b / N_0} + 1 \right\rfloor \quad (28)$$

7.6 Cellular deployment performance for orthogonal DS-CDMA

In cellular deployment for orthogonal DS-CDMA systems, all users in the adjacent cells (or sectors) operating at the same frequency act together to cause maximum interference to the susceptible central station as well as Pseudo Random DS-CDMA systems. In fact, although each cell avoids intra-cell interference by means of synchronous transmission over the air, adjacent cells interfere with each other asynchronously. This means that no inter-cell synchronization is deployed so that a general figure on power threshold level for orthogonal DS-CDMA systems in the uplink case can be calculated as follows:

$$S_{av} = \left(\frac{E_b}{N_0}\right)_{dB} + 10 \times Log\left(R_b\right) + 10 \times Log\left(KT_0\right) + F_{dB} - 10 \times Log\left[1 - \frac{E_b}{N_0}\frac{R_b}{W}\left[\sum_{i=1}^{N \times Y}\left(\frac{C}{I}\right)_i^{-1}\right]\right] \quad (29)$$

8 FDMA systems

8.1 General characteristics

The basic purpose of FDMA technique is to share the frequency resource among subscribers by use of multiple frequency slots. Technically a frequency slot is occupied by a carrier modulated with the data rate (including FEC if necessary) wanted by a certain subscriber.

A standard channel arrangement is to use one partial RF-band for downlink transmission from the CRS to the TS and another partial band (normally but not necessary of the same bandwidth) for uplink transmission from the TS to the CRS. The separation of Tx- and Rx-band in both CRS and TS by a sufficiently large duplex spacing allows to control interference between CRSs and between TSs so that this type of distortion can be neglected when planning cellular configurations.

Cellular planning tries to apply frequency reuse in adjacent cells as far as possible. The ideal goal would be to use the total assigned RF band in each cell and if possible even in each sector of the whole cellular configuration.

Within a sector a multitude of links can be established, each using an individual RF-carrier which defines the allocated frequency slot. Adjacent carrier interference is controlled by net filter discrimination (NFD). Assuming state of the art signal processing, a carrier spacing within about 1,3 times the symbol rate should provide sufficient NFD to cause the adjacent channel interference to be negligible.

Modulation is certainly not restricted to QPSK. For a consistency with the results derived for TDMA and CDMA, the same kind of encoding has been assumed (uncoded QPSK and convolutional encoding). In addition, different kind of encoding has been presented on the basis of an existing standard.

In a single cell i.e. without interfering cells there is no strong incentive to use FEC. Notwithstanding FEC can be used to reduce transmit power but the price is some loss of bandwidth efficiency. In an extended cellular arrangement however, capacity is more or less limited by interference which can not be combated by increasing transmit power. In that case FEC is an almost inevitable countermeasure and loss of bandwidth efficiency per carrier, due to FEC redundancy, is more than compensated by increased interference resistance.

Due to the nature of FDMA, the downlink signal transmitted by the CS is a multi-carrier signal. The number of carriers can well grow to the order of 100. This shows the necessity to control intermodulation in the high power transmit amplifier. Consequently when verifying the transmit spectrum mask specified for FDMA P-MP systems by conformance testing, a multi-carrier signal should be used, which has to be defined by specifying a standard load in the relevant standard.

Some advanced features are made possible in FDMA and can be used to increase system efficiency:

- Multirate modems allow to chose carrier frequency and bit rate arbitrarily within certain limits. This allows to fill RF-channels of any bandwidth densely with frequency slots which are tailored to the individual bit rate of the customers.

- Different modulation schemes equipped with a variety of FEC of different redundancy and efficiency allow to match each connection, operating in a certain frequency slot, to individual noise and interference conditions. Table 12 shows the bit energy to noise spectral density ratios E_b/N_0 for various modulation schemes available in an advanced FDMA system.

- Dynamic bandwidth allocation (DBA) allows data rate and hence carrier bandwidth to be matched dynamically to the momentary traffic need of the customer.

Table 12: Assumed E_b/N_0 for additional modulation schemes versus BER

	BER = $^{10-3}$	BER = $^{10-6}$
Modulation (note)	**$E_b/N_{0\ (dB)}$**	**$E_b/N_{0\ (dB)}$**
QPSK (1/2)	3,3	5,6
QPSK(3/4)	4,3	6,7
QPSK(7/8)	5,6	7,8
8PSK(2/3)	5,3	7,8
16PSK(3/4)	10,6	12,6
NOTE: Values in brackets: code rate R.		

8.2 Isolated performance for FDMA

In the following the FDMA capacity and the minimum power level in threshold condition S_{av} will be derived assuming absence of interfering cells.

The bandwidth of a modulated carrier is given by the relation:

$$B_C = \frac{(R_b + R_{OH})}{R \times ld(M)} \times (1 + r) \tag{30}$$

where

R_b: information bit rate;

R_{OH} : Overhead bit rate;

R: code rate ($R \leq 1$);

ld(M): base 2 logarithm of number of levels M of the modulated carrier;

r: roll-off factor or roll-off equivalent spacing factor for adjacent carriers (assumed to be 0,2).

System capacity within a RF-channel of bandwidth B_{RF}, characterized by the number N of channels transmitting bit rate R_b is given by:

$$N = \frac{B_{RF}}{B_C} \tag{31}$$

The minimum average power level in threshold condition S_{av} can be calculated by means of the same relation which holds for TDMA:

$$S_{av} = \left(\frac{E_b}{N_0}\right)_{dB} + 10 \times \log(R_b) + 10 \times \log(kT_0) + F_{dB} \tag{32}$$

E_b/N_0: bit energy to noise spectral density ratio (see table 12);

$K = 1,38 \times 10^{-23}$ J/K: Boltzmann constant;

$T_0 = 293$ K: environmental temperature;

R_b : user bit rate assumed to be 64 kbit/s;

$F_{dB} = 6$ dB: noise figure.

Table 13: FDMA capacity (number of 64 kbit/s channels) and threshold power level with R_{OH} equal 16 kbit/s

		BER = 10^{-3}		BER = 10^{-6}	
Mod.	**Band MHz**	**N**	**S_{av} (dBm)**	**N**	**S_{av} (dBm)**
QPSK(1/2)	1,75	18	-115,7	18	-113,4
	2,0	20	-115,7	20	-113,4
	3,5	36	-115,7	36	-113,4
	7,0	72	-115,7	72	-113,4
	14,0	145	-115,7	145	-113,4
QPSK(3/4)	1,75	27	-114,7	27	-112,3
	2,0	31	-114,7	31	-112,3
	3,5	54	-114.7	54	-112,3
	7,0	109	-114,7	109	-112,3
	14,0	218	-114,7	218	-112,3
QPSK(1)	1,75	36	-110,5	36	-107,0
	2,0	41	-110,5	41	-107,0
standard	3,5	72	-110,5	72	-107,0
system	7,0	145	-110,5	145	-107,0
	14,0	291	-110,5	291	-107,0
8PSK(2/3)	1,75	36	-113,7	36	-111,2
	2,0	41	-113,7	41	-111,2
	3,5	72	-113,7	72	-111,2
	7,0	145	-113,7	145	-111,2
	14,0	291	-113,7	291	-111,2
16PSK(3/4)	1,75	54	-108,4	54	-106,4
	2,0	62	-108,4	62	-106,4
	3,5	109	-108,4	109	-106,4
	7,0	218	-108,4	218	-106,4
	14,0	437	-108,4	437	-106,4

8.3 Cellular deployment performance for FDMA system

Due to frequency reuse in surrounding cells, just as in TDMA and CDMA co-channel interference will be present in a certain cell in both downlink and uplink. On downlink the distorted receiver is a TS with a narrow-beam antenna pattern. Due to this angular selectivity the number of interfering CRS/sectors is limited. On uplink the distorted receiver is the CRS/sector with an omnidirectional or sectored pattern. Even in case of sectoring, the beam width is considerably wider than for the TS. Hence in the average the CRS is affected by more sources of interference than the TS which means that the uplink is the capacity limiting link which has to be analysed to investigate performance and or cell capacity.

Bearing this in mind, the impact of co-channel interference coming from TSs placed in surrounding cells on power threshold level can be computed. This leads to the same result as given above for TDMA by equation (20):

$$\left(S_{av}\right)_{dBm} = \left(\frac{E_b}{N_0}\right)_{dB} + 10\times Log\left(R_b\right) + 10\times Log\left(kT_0\right) + F_{dB} - 10\times Log\left[1 - \frac{E_b}{N_0}\frac{R_b}{W}\left(\frac{I}{C}\right)_{TOT}\right] \qquad (33)$$

The last term of equation (33) describes the impact of uplink interference. Computing $(C/I)_{TOT}$ realistically implies the existence of a complete and correct algorithmic procedure for C/I analysis which has to take into account all relevant technical features of the system such as modulation schemes, antenna patterns and polarization. In addition when applying equation (33), a reasonable limit should be introduced for the increase of S_{av} compared to equation (32) which latter describes the system without interference. Even thought relation (33) is correct for any amount of degradation, a value of 3 dB is proposed which means to allow the cumulative power of interference to be equal to noise power.

On the other hand C/I analysis makes only sense in a cell configuration where all links between CRSs and TSs are planned thoroughly by an intelligent planning procedure. This planning procedure has to guarantee sufficient decoupling between links by appropriate allocation of modulation scheme (if available) and frequency to each link. Hence similar to GSM, frequency planning is a very important issue in a fixed cellular P-MP/FDMA system.

However, there is a significant difference compared to GSM and to other existing fixed cellular systems. Downlink analysis shows, that it is possible to partition the area of a sector in zones with different minimum C/I. This applies to any cellular system. In a FDMA with advanced features it is possible to allocate robust modulation schemes with lower spectral efficiency to zones with low C/I and less robust modulation schemes with higher spectral efficiency to zones with high C/I. But normally there also occur small partial zones with a C/I which is too low for any modulation scheme. Only such zones have to be decoupled by appropriate frequency allocation with respect to certain CRS.

NOTE: To identify those zones properly, thorough down- and up-link interference analysis is necessary.

This requires to split off small partial subbands from the RF band and hence reduces the frequency reuse factor below 100 %. The spectral flexibility inherent to FDMA equipped with multirate modems, allows to dimension these subbands individually and with minimum extension. In contrast to GSM not whole cells are frequency decoupled with respect to each other, but partial zones within sectors containing groups of TS have to be decoupled with respect to other sectors. This requires an elaborated combinatorial computer tool for optimum frequency planning.

To the present state of knowledge between 40 % and 60 % of RF-channel bandwidth can be reused in each sector of an extended 90° sectored cell configuration. This applies to a system with advanced features as described in subclause 8.1. Assuming 50 % frequency reuse, a cell consisting of 4 sectors has approximately twice the capacity of an isolated cell with omnidirectional antenna which uses the RF-band once. This however is a very rough estimation. One should bear in mind, that the real capacity of an extended cell configuration not only depends on the basic geometrical conditions such as locations of CRSs and width and orientation of sectored antennas, but also on the distribution of TSs including the required traffic (Erlang) values. And in addition the achieved capacity depends on the quality of the applied planning methodology which by appropriate allocation of modulation scheme (if there are different ones) and/or frequency has to provide a maximum of capacity in connection with sufficient decoupling between the whole multitude of links.

9 FH-CDMA systems

9.1 General characteristics

FH-CDMA systems share the frequency resource between radio links by use of multiple frequency slots, while providing each link with access to the entire allocated bandwidth. Each frequency slot is occupied by a carrier modulated with the data rate (including FEC if necessary) wanted by a certain subscriber, however the centre frequency of that carrier changes in time (hops). The "hopping sequence" is the "code" associated with each link and the assignment of different codes for different links in the same vicinity means that the system is a Code Division system.

The most common FH-CDMA nowadays are SFH (where the hopping rate is less then the symbol rate). This is a spread spectrum technique which when applied to Radio Local Loop systems, switches individual subscriber channels when in use, from frequency to frequency to minimize the effects of fading and narrowband interference.

Fast frequency hopping systems, with hopping rate faster than the symbol rate, can also be found. This type of hopping provides many more samples per symbol and enables non-orthogonal operation, where several users may occupy the same frequency slot in the same time. Presently, commercially available P-MP fast frequency hopping systems do not exist, and the relevant standards do not refer to them. The following analysis refers only to orthogonal SFH-CDMA systems.

From the point of view of the occupied spectrum these systems are very similar to FDMA. Most of the features described in subclause 6.1 apply also to FH-CDMA. On the other hand, being a fully synchronized system it is very similar to TDMA. Frequency planning is very similar to that applied to these systems. However, from the point of view of the user, the system is similar to DS-CDMA, as it uses the entire bandwidth and thus provides the benefit of spread spectrum communication, namely interference suppression, robust radio link and inherent security.

FH can be applied to other techniques like DS-CDMA, TDMA and FDMA by dividing the instantaneous (hop) radio channels in the DS-CDMA code domain, by a further division in the time domain with TDMA techniques or by dividing the hop bandwidth to a number of sub-carriers (frequency slots) when a FDMA technique is used (Multicarrier approach).

Forward error correction, interleaving and erasure enable frequency band reuse in adjacent cells with a re-use factor of one in fixed applications.

A standard channel arrangement is to use one partial RF-band for downlink transmission from the CRS to the TS and another partial band (normally but not necessarily of the same bandwidth) for uplink transmission from the TS to the CRS. The separation of Tx- and Rx-band in both CRS and TS by a sufficiently large duplex spacing allows to control interference between CRSs and between TSs so that this type of distortion can be neglected when planning cellular configurations.

Another typical arrangement is to share the same channel by both the CRS and the TS, but to separate them in time. With proper synchronization, which is intrinsic in FH-CDMA systems, this time-domain separation allows a very good control of interference between CRSs and TSs.

9.2 Isolated performance for FH-CDMA

In the following the FH-CDMA capacity and the minimum power level in threshold condition S_{av} will be derived assuming absence of interfering cells and LOS.

The bandwidth of a modulated carrier is given by the relation:

$$B_C = \frac{(R_b + R_{OH})}{R \times ld(M)} \times (1 + r) \tag{34}$$

where:

- R_b: information bit rate;
- R_{OH}: Overhead bit rate for hopping and synchronization;
- R: code rate (R≤1);
- ld(M): base 2 logarithm of number of levels M of the modulated carrier;
- r: roll-off factor or roll-off equivalent spacing factor for adjacent hop carriers (assumed to be 0,2).

System capacity within a RF-channel of bandwidth B_{RF}, characterized by the number N of channels transmitting bit rate R_b is given by:

$$N = \frac{B_{RF}}{B_C} \tag{35}$$

The minimum average power level in threshold condition S_{av} can be calculated by means of the same relation which holds for TDMA, FDMA:

$$S_{av} = \left(\frac{E_b}{N_0}\right)_{dB} + 10 \times \log(R_b) + 10 \times \log(kT_0) + F_{dB} \tag{36}$$

- E_b/N_0: bit energy to noise spectral density ratio (see table 5 and table 12);
- $K = 1{,}38 \times 10^{-23}$ J/K: Boltzmann constant;
- $T_0 = 293$ K: environmental temperature;
- R_b: user bit rate;
- $F_{dB} = 6$ dB: noise figure.

Table 14 shows the sensitivity for various modulation and coding schemes and for several values of bit rates expressed in kbit/s.

Table 14: System sensitivity as a function of modulation and coding schemes and data bit rates with R_{OH} equal 16 kbit/s

	S_{av} @BER = 10^{-3} **(dBm)**				S_{av} @ BER = 10^{-6} **(dBm)**			
Mod.	**R_b = 64**	**R_b = 128**	**R_b = 384**	**R_b = 2048**	**R_b = 64**	**R_b = 128**	**R_b = 384**	**R_b = 2048**
QPSK(1/2)	-116	-113	-109	-101	-113	-111	-106	-99
QPSK(3/4)	-115	-112	-108	-100	-112	-110	-105	-98
QPSK(1)	-110	-108	-103	-96	-107	-104	-100	-93
8PSK(2/3)	-114	-111	-107	-99	-111	-109	-104	-97
16PSK(3/4)	-108	-106	-101	-94	-106	-104	-99	-92

When FSK modulation is used, the system sensitivity is shown in table 8.

9.3 Cellular deployment performance for FH-CDMA system

As stated in subclause 4.5, cellular deployment means that a certain number of frequencies are reused in other cells (or sectors) properly distanced. This means that a certain amount of co-channel interference has to be taken into account during link budget calculation. The presence of co-channel interference causes an increment of the power threshold level because it acts like an additional noise power at the input of the receiver. In this context, relation (4) can be evaluated by adding a contribution for each cell (or sector) working at the same frequency on the basis of subclause 4.5 rules. Supposing the interference as a gaussian noise, a general figure on power threshold level with co-channel interference can be evaluated by means of the following equation:

$$(S_{av})_{dBm} = \left(\frac{E_b}{N_0}\right)_{dB} + 10 \times Log\left(R_b\right) + 10 \times Log\left(KT_0\right) + F_{dB} - 10 \times Log\left[1 - \frac{E_b}{N_0}\frac{R_b}{W}\left(\frac{I}{C}\right)_{TOT}\right] \qquad (37)$$

where $\frac{C}{I}_{TOT}$ is the overall signal to interference ratio expressed by relation (4).

At any rate, the best way to evaluate this figure is by means of measured sensitivity curves provided by the manufacturers.

10 Impact on performance and capacity due to CRS and TS antenna

In subclause 4.5 a very simple methodology has been provided in order to calculate the overall C/I for a given frequency reuse environment. That methodology is based on the assumption that all the users are located in the worst interfering site. However, this hypothesis could lead to a pessimistic C/I estimation and, in addition, does not show how the TS antenna influences the C/I related to the different frequency reuse environment. In order to investigate these issues it has become necessary to perform simulations: the user traffic in each of the six cells surrounding the cell under analysis has been modelled in order to estimate the interference statistics.

TS antennas have been considered: figure 5 shows a typical antenna characteristics for 1 GHz to 3 GHz bands, and figure 6 show a typical antenna characteristics for 10,5 GHz band. In addition, three frequency reuse environment has been considered with six surrounding cells as shown, for M = 1, in figure 2. In particular, the following assumptions have been made:

- six surrounding interfering cells;
- P-MP system with 32 64 kbit/s channels for each cell;
- uniform users distribution over the interfering cells;
- CRS with omnidirectional antenna;
- poisson traffic model;

- mean call duration = 100 s;
- traffic per cell with GOS = 1 %;
- perfect power control and all interfering links with the same modulation scheme;

On the basis of the previous assumptions, the following case studies have been considered:

- access schemes: TDMA, DS-CDMA, FDMA and FH-CDMA;
- M = 1, M = 3 and M = 4;
- antenna patterns as in figure 5 and figure 6;
- propagation exponent for the useful links: $\gamma = 2$;
- propagation exponent for the interfering links: $\gamma = 2$ and $\gamma = 3$.

The results for several case studies are shown in figures 7 to 14 in terms of the cumulative distribution functions of the overall C/I. In particular, each curve shows, for a given C/I value, the probability of having a lower C/I value. In other words, for a given C/I, each curve provides, for the relevant case study, the percentage of time in which a lower C/I value could be expected. As an example, a C/I with a probability equal to 10^{-3} means that we could expect to have a lower C/I for about 45 minutes during a month with 31 days.

In addition it could be easily found that the usage of a more directive antenna (see figure 6) makes it possible to gain 2 dB on the overall C/I for TDMA, FDMA, FH-FDMA and 4 dB for DS-CDMA.

In order to explain better how to use the results provided by the figures below, two examples shall be analysed: one for DS-CDMA and one for TDMA access scheme.

Cellular deployment for Pseudo Random DS-CDMA can be analysed by means of relation (27). Looking at figure 7, we can read a C/I value of -4,5 dB for a M = 1 and with a probability equal to 10^{-3}. By using this value in (27) instead of the term:

$$\sum_{i=1}^{N\times Y}\left(\frac{C}{I}\right)_i^{-1} = \frac{1}{(C/I)_{tot}} \tag{38}$$

It is possible to find out a degradation in capacity lower than 10 %. It is worth noting that by means of relation (28), the relevant figures for Pseudo Random DS-CDMA can be used also for analysing Orthogonal DS-CDMA cellular deployment.

As far the TDMA, FDMA and FH-CDMA access schemes are concerned, cellular deployment can be analysed by means of relation (20). Looking at figure 13, we can read a C/I value of 16,8 dB for a M = 4 and with a probability equal to 10^{-3}. Using this value in (20) instead of the term $(C/I)_{tot}$, it is possible to find out the feasibility of this cluster size, even with uncoded transmission, for the area of deployment in which the interfering link have a propagation exponent $\gamma = 3$ (e.g. rural application).

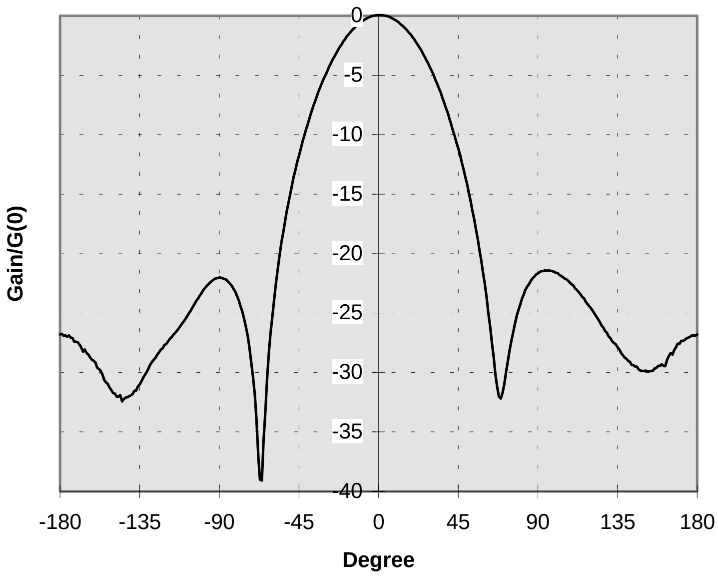


Figure 5: RPE for 1 GHz to 3 GHz bands

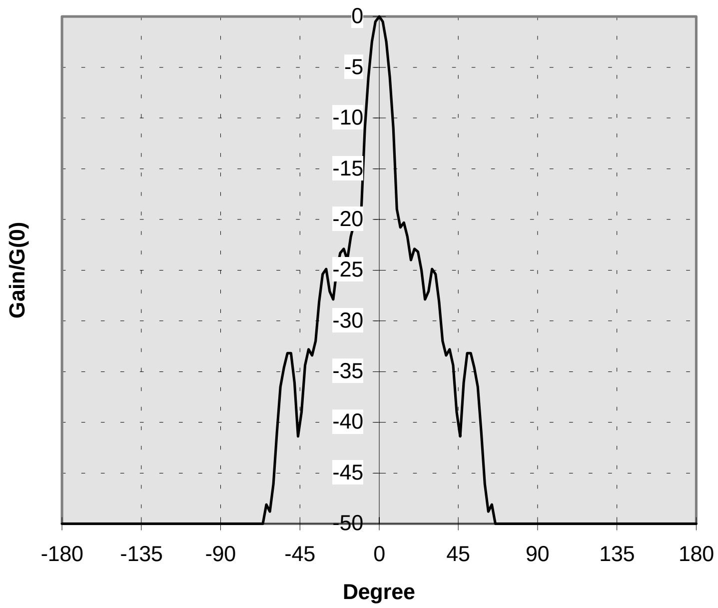


Figure 6: RPE for 10,5 GHz band

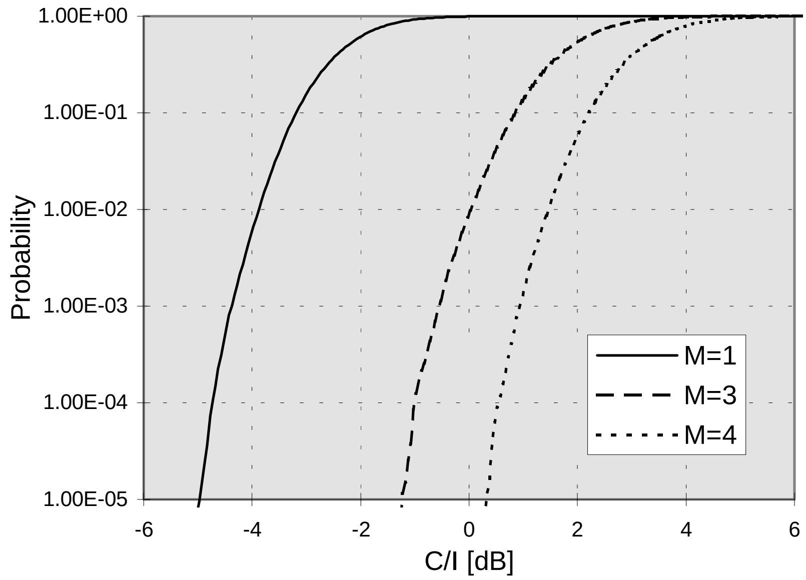


Figure 7: C/I cumulative distribution function for Pseudo Random DS-CDMA with antenna in figure 5 and interfering propagation exponent $\gamma = 2$

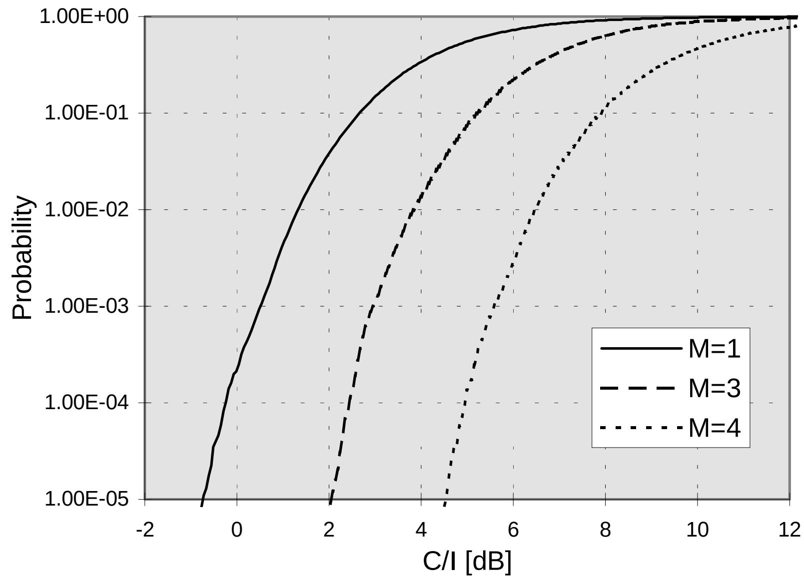


Figure 8: C/I cumulative distribution function for Pseudo Random DS-CDMA with antenna in figure 6 and interfering propagation exponent $\gamma = 2$

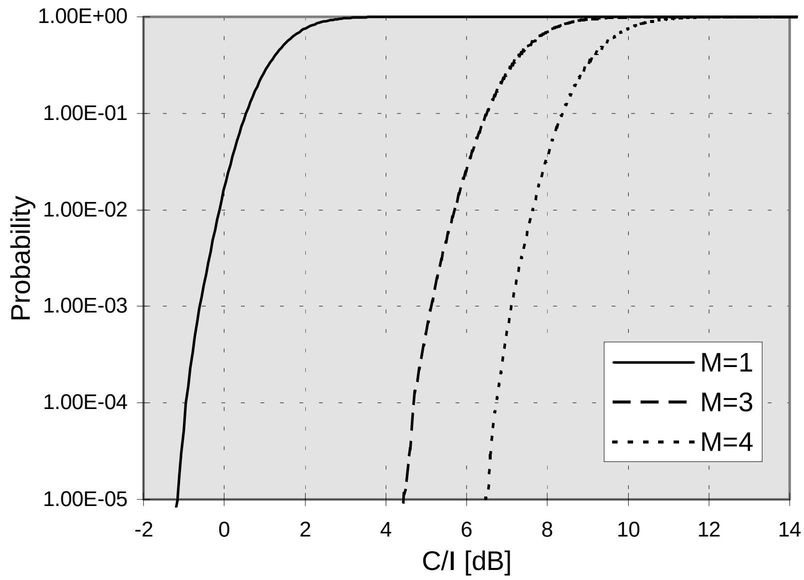


Figure 9: C/I cumulative distribution function for Pseudo Random DS-CDMA with antenna in figure 5 and interfering propagation exponent $\gamma = 3$

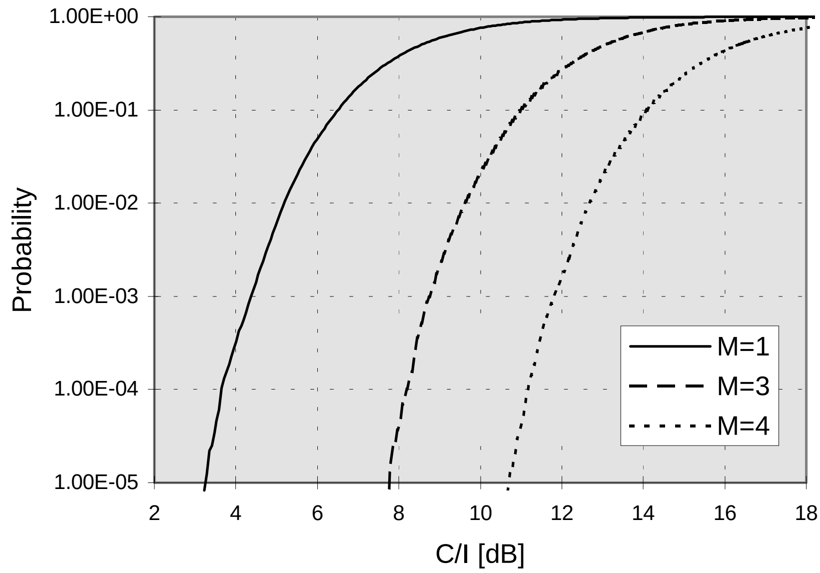


Figure 10: C/I cumulative distribution function for Pseudo Random DS-CDMA with antenna in figure 6 and interfering propagation exponent $\gamma = 3$

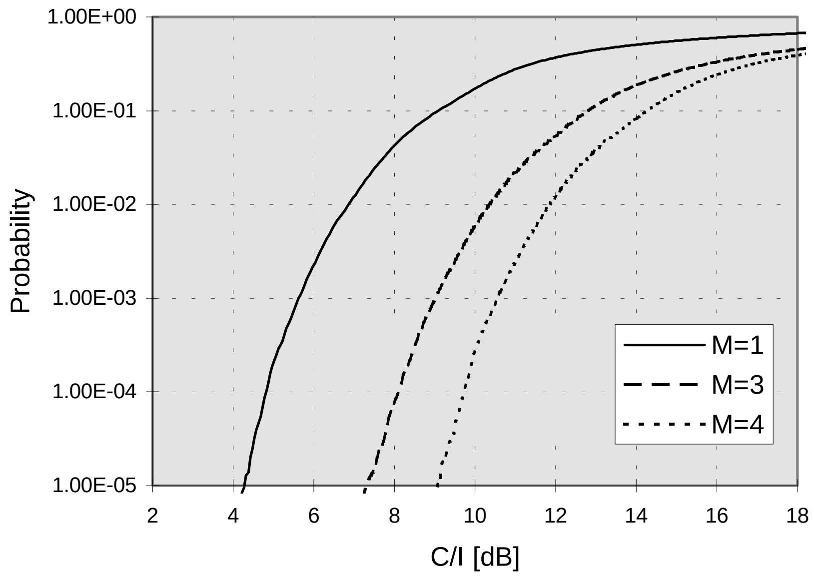


Figure 11: C/I cumulative distribution function for TDMA, FDMA and FH-CDMA with antenna in figure 5 and interfering propagation exponent $\gamma = 2$

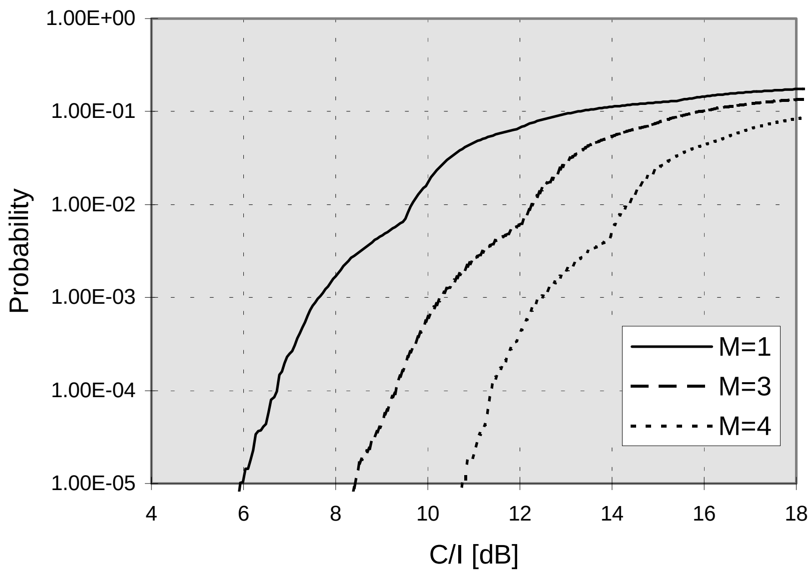


Figure 12: C/I cumulative distribution function for TDMA, FDMA and FH-CDMA with antenna in figure 6 and interfering propagation exponent $\gamma = 2$

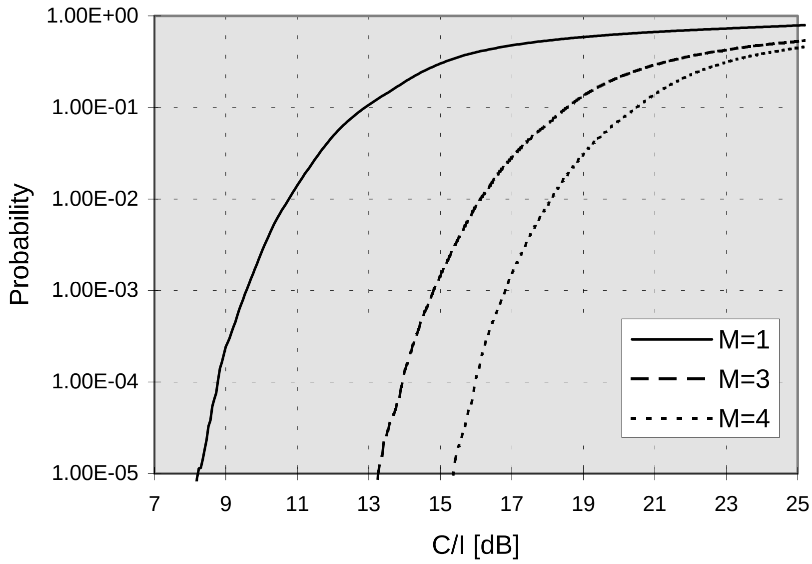


Figure 13: C/I cumulative distribution function for TDMA, FDMA and FH-CDMA with antenna in figure 5 and interfering propagation exponent $\gamma = 3$

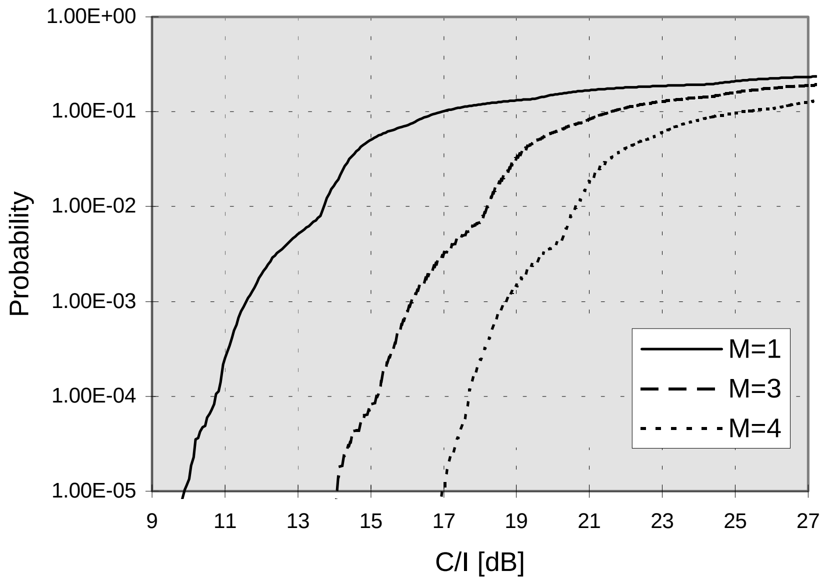


Figure 14: C/I cumulative distribution function for TDMA, FDMA and FH-CDMA with antenna in figure 6 and interfering propagation exponent $\gamma = 3$

Annex A: Propagation measurements for ad-hoc deployment

A.1 Method

A number of propagation measurement campaigns have been carried out for ad-hoc deployment in UK and Finnish cities in the 3,4 GHz band. In general, the method used was as follows.

Transmitters were set up at typical CS locations chosen to illuminate the desired area. Transmitting antennas were either omnidirectional or "sectored"; for an omnidirectional antenna the typical gain was 10 dBi (achieved by the narrow vertical beamwidth). Somewhat higher gains are achievable with sectored antennas. Vertical polarization was used throughout. The radiated carrier was unmodulated, allowing the use of narrow receiver bandwidth to maximize dynamic range.

Received signal levels were measured at a vehicle equipped with a telescopic mast, at a large number of randomly chosen locations. The receiving antenna mounted on the mast was pointed at the CS location from each measurement point and the mast set to rooftop height to measure the signal level. The level was measured over a period of time to assess the variability of the signal. The receiving antenna gain was 18 dBi.

With the transmit power and receiver bandwidth used the total dynamic range possible was approximately 180 dB.

Separate tests have been done to characterize multipath propagation using wideband channel sounding and swept frequency measurements in cities in both the UK and Finland.

A.2 Results

Figure A.1 plots the measured path loss from one typical trial. For each measurement location, the median path loss and the path loss exceeded for 99 % of the measurement period are shown, as a function of the range of the point from the CS location. Also plotted is the free space path loss.

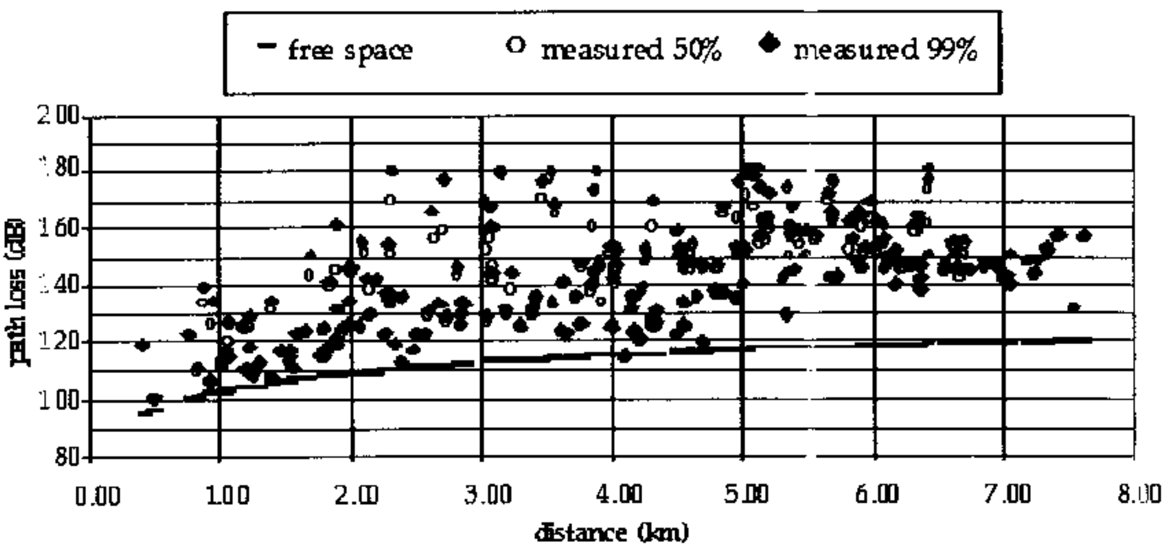


Figure A.1: path loss measurements

The results clearly show the large excess loss and variability expected when a LOS path cannot be guaranteed. It is obvious that the maximum possible system range will be required to maximize the probability of providing service at any particular point from the given CS.

Multipath measurements have also shown that delay spread is found on a proportion of paths, with a maximum recorded delay spread of up to 4 µs. The existence of multipath at any given TS location is unpredictable, and to maximize the service probability the system has to cope with this level of delay spread.

For P-MP systems in frequency bands at or above 10 GHz, line-of-sight conditions are an inevitable condition for each link. On the one hand this reduces coverage, because a prospective TS location can no longer be supplied by means of the physical effects of reflection or diffraction. This negative effect has to be taken into account. On the other hand the highly positive effect is a strong reduction of dynamic range of receive power in any CRS or TS. This is in contrast to the measurement results discussed above. In particular the impact of multipath transmission is reduced drastically because these unintended paths depend on reflection and/or diffraction and can be assumed to show considerably higher path loss than the wanted line-of-sight path. Hence all the negative effects of multipath propagation such as Intersymbol Interference and loss of power will be reduced in the higher frequency bands.

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