Electronic Communications Committee (ECC)
within the European Conference of Postal and Telecommunications Administrations (CEPT)

SPECTRUM EFFICIENCY OF CDMA-PAMR and OTHER WIDEBAND SYSTEMS FOR PMR/PAMR

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EXECUTIVE SUMMARY

This report considers the spectrum efficiency of CDMA-PAMR and other wideband PMR/PAMR systems, and is the output from the study of this subject that has been conducted within CEPT PT SE37. The spectrum efficiency has been calculated for both voice and data services, for a range of different usages scenarios, for the following PMR/PAMR systems:

- CDMA PAMR (as described in the system reference documents [C1] [C9])
- TAPS
- GSM-R (as specified for interoperability in the Eirene specification for PMR applications [G1])
- TETRA.

The methodology that has been used in this study to compare the spectrum efficiency of CDMA-PAMR with other PMR/PAMR systems can be broken down into the following stages:

- Calculation of basic capacity/spectrum efficiency of the technology, in terms of number of voice channels per carrier (for voice services) and data throughput (kbps) per carrier (for data services).
- Application of different usage scenarios/traffic mixes, for both voice and data services, in order to calculate the relative spectrum efficiency of the different systems (without guard bands) under different usage conditions.
- Adjustment of the spectrum efficiency figures in order to take account of the impact of guard bands.

Network planning and traffic forecasts are not addressed by this report. Parameters used by this report are not consistent with normal adjacent band compatibility studies (with typical traffic loading) because this report evaluates the spectrum efficiency independently of deployment.

It should be noted that, in the calculation of the number of channels per carrier and per cell, a common value of cell radius has been assumed for the systems under comparison. However, for CDMA systems, there is a relationship between the cell coverage and the maximum number of the users that can be supported in the cell. Due to the small density of traffic with respect to cellular systems, having large cell size is an important factor for PAMR applications. Consequently, additional calculations have been performed to reflect the decrease of the number of available channels per carrier and per cell when the cell radius is increasing (or vice versa).

The basic spectrum efficiency for voice services, in terms of the number of voice channels, is significantly higher for CDMA PAMR than for TETRA and for GSM-R (using the restricted subset of capabilities required for railway interoperability). On the basis of the assumptions in this report, the spectrum efficiency of CDMA-PAMR has been found to be significantly higher than that of these other systems, with the actual relative efficiency dependent on the system conditions.

Applying different PMR/PAMR usage scenarios for voice services, for the emergency services PMR scenario, which has a large percentage of group calls each involving large numbers of users, TETRA and GSM-R were found to be significantly more efficient than CDMA-PAMR. For other PMR and PAMR scenarios, CDMA-PAMR was generally found to be as or more efficient than TETRA and GSM-R, and significantly more efficient for the typical PAMR scenario.

For data services, data rates and throughputs vary according to velocity, link quality, etc, and the mix of data rates also makes some difference, however CDMA-PAMR was found to be more spectrum efficient than TAPS (with ideal frequency hopping). The spectrum efficiency is here measured in terms of the throughput in kbps per MHz per cell, for a particular combination of velocity, FER, and data rates to be used.

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1 INTRODUCTION

ERC Report 52, published in 1997, presented a methodology for assessing the spectrum efficiency of analogue and digital PMR and PAMR systems. As well as comparing different open and proprietary technologies against a benchmark of 25 kHz analogue FM, it also explored the operational factors which characterise PMR and PAMR. Considering the recent interest in using CDMA technology as a platform for delivering PMR/PAMR functionality for wide area networks, the current report explores the conditions in which it might be spectrum efficient to use CDMA as a PMR/PAMR platform, bearing in mind the existing technology base in the various land mobile bands and the likely services to be offered. Network planning and traffic forecasts are not addressed by this report. Parameters used by this report are not consistent with normal adjacent band compatibility studies (with typical traffic loading) because this report evaluates the spectrum efficiency independently of deployment.

In Europe, the main frequency allocations for PMR/PAMR systems, which today are almost exclusively analogue and digital narrowband systems, are in the sub-bands 68-87.5 MHz, 146-174 MHz, 380-400 MHz, 406.1-470 MHz and 870-876/915-921 MHz. In line with the various decisions on digital narrowband and wideband systems, this report focuses on the following UHF bands, as these are most appropriate for the evolution of PMR/PAMR towards digital duplex narrowband and wideband technologies:

- 410-430 MHz
- 450-470 MHz
- 870-876/915-921 MHz.

The range of different technologies for PMR/PAMR systems can generally be broken down according to the type of multiple access scheme used, as follows:

- FDMA (Frequency division multiple access), where each traffic channel utilises a separate radio frequency carrier.
- TDMA (Time division multiple access), where frequency carriers are divided into timeslots corresponding to control or traffic channels.
- CDMA (Code division multiple access), where users share the same (wideband) frequency carriers, with different users/channels being distinguished according to different pseudo-random sequences (codes).

The technologies studied in this report are predominantly based on TDMA and CDMA technology.

In accordance with the Strategic Plan for PMR/PAMR (ECC Report 25), a wide area PMR/PAMR system will generally require an amount of spectrum in the order of 2 x 3 MHz to 2 x 5 MHz to be able to operate effectively. The minimum amounts of spectrum required for the different technologies considered in this report are discussed in Annex A.

2 PMR AND PAMR

Work within the ECC has provided definitions of PMR and PAMR in terms of the way in which users and user groups operate and operators control them. This is largely technology independent, although the size of a system in terms of number of users and the traffic communicated over it, both in terms of capacity and data rates, are factors to be considered in the design of the system.

The following definitions and descriptions are extracted from the Strategic Plan for PMR/PAMR (ECC Report 25). These definitions/descriptions are used for PMR, PAMR and public land mobile networks based on the ERC Report 052 (Methodology for the assessment of PMR systems in terms of spectrum efficiency, operation and implementation, December 1997), ERC Report 073 (Investigation of the possibilities of harmonising (licensing and fees for) the PMR service within CEPT Administrations, April 2000) and ERO Report on PMR and PAMR licensing (July 1997).

2.1 PMR

Definition:
PMR is part of the land mobile service based on the use of simplex, half and possibly full duplex modes at the terminal level in order to provide closed user group communications.

PMR can be either:

- traditional, self provided and self-owned by business users small area networks

Example: network in an industrial plant;
or

- tightly controlled set of inter-related closed user groups.
- Can either be outsourced, or can be owned by a dominant user who allows other related user groups to use the network.[1]

Example: closed network of inter-related municipal organisations such as utility, public transportation, water supply and road maintenance.

Description:
Professional mobile radio (PMR) covers mobile radio systems used by an organisation to establish communications in support of its own activities. PMR products follow standards such as EN 300 086, EN 300 113, EN 300 392 and equivalent technical specifications. Typical PMR systems can be described as follows:

- Wide area, encompassing systems with a range of more than 1 km to regional or national coverage. Voice is used in majority but data is increasing.
- On-site (single, two and/or multi-frequency systems) systems for voice, voice and data or data only. They are typically used to provide communications with personnel on the move within the organisation's premises. These systems can be linked into a telephone system managed by an organisation (sometimes completed by other wireless devices). The range is less than 1-3 km, typically a few hundred metres. This includes short-range professional mobile radio, typically now PMR 446, covering a few hundred metres.

2.2 PAMR

Definition:
Operator provided, commercially open networks designed for business professional users, dedicated user groups but no limitation on the nature or type of the user groups and no need for these to be related. Not generally intended for these groups to communicate with each other.

Description:
PAMR is a type of service offered by an operator to subscribers over a large-scale network. The networks are operated to provide, on a commercial basis, professional communications facilities comparable to those available using dedicated PMR networks. PAMR operators provide such services to business professional user groups on a local, regional or national basis. Scale efficiencies allow for the provision of a cost effective solution to many users who prefer this to owning and/or operating their own PMR system.

Usually, PAMR operators provide radio services to a large variety of closed user groups over a wide coverage area (regional or national). However, they do not necessarily provide all PMR services, e.g. PAMR operators rarely offer Direct Mode Operation (DMO).
Subscription fees to a PAMR network are often based on a fixed price for a given number of services.
Dedicated mobile data networks offer specific services for data only transmission. These networks can be categorised either as PMR or PAMR.

2.3 PMR/PAMR features and services

The features and services provided by PMR and PAMR networks are areas where professional users have specific needs. The features are linked to the definitions. An extensive list of detailed features is given in Annex 1 of the Strategic Plan for PMR/PAMR (ECC Report 25) and is reproduced below.

The following is a list of features and system considerations that are relevant for PMR and/or PAMR. The first part lists PMR/PAMR services and service-related features that are required to meet the needs of professional users -

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[1] Predominantly local networks but could be national.

these are largely common to both PMR and PAMR, with a few exceptions. The latter part lists system considerations related to the way in which PMR systems and PAMR networks are implemented.

2.3.1 PMR/PAMR services and service-related features

Features that are common to PMR and PAMR:

- Push-to-talk voice services
- One-to-many / group calls
- Instant and broadcast messaging
- Packet data
- Dispatch services
- Fast call set-up
- Automatic and priority call queuing when system busy
- Guaranteed access for emergency calls
- Dynamic group management
- Talking party identification
- Closed user groups
- Simultaneous voice and data
- Direct mode operation (DMO), typically PMR
- Talk-around / fall-back mode, typically PMR
- Ability to provide virtual private network (VPN) services to users
- Ability to directly interconnect with other public networks (e.g. PSTN, data networks, etc), typically PAMR

2.4 System considerations

System considerations for PMR:

- Spectrum efficiency primarily measured in terms of the number of users that can be supported in a given amount of spectrum/number of frequencies in a local area
- Possibility to share a frequency between a number of different small PMR systems with low occupancy
- Wide range of different quality of service requirements depending on users and operational conditions
- Flexibility to vary number of frequencies used in order to provide required grade of service, within frequency bandwidth allocated to the system
- Tailored networks and customised features, for example to allow hundreds of terminals to use a single narrow band frequency, or to provide system resilience for multiple level operations
- Ability to provide specific and tailored coverage in spectrum shared with other PMR systems
- Non-sensitive modulation allowing to share the co-channels and provide good adjacent channel compatibility
- Compliance with standards for (narrow band) frequency compatibility (e.g. EN 300 086, EN 300 113 and EN 300 392)
- Reliable use of frequencies in harsh RF environments (intermodulation, co-channel and adjacent channel interference)
- Different system lifetimes, introduction dates and system closures in the same band (few months to 10+ years)
- Command of the network
- Systems built according to the needs of specific organisations (typically for security and operational purposes).

System considerations for PAMR:

- Spectrum efficiency primarily measured in terms of the capacity that can be provided by a wide area network within a given amount of spectrum
- Ability to support different quality of service requirements for different users
- Resilience and availability requirements generally accommodated by the PAMR operator at a network level
- Networks generally designed to cover a wide geographic area as effectively as possible, rather than being customised for a specific user group
- Ability to give users suitable degree of control over their operational usage of the services and visibility of their billing information
- Subscriber management facilities, such as for billing and provisioning, that are capable of dealing effectively with large numbers of subscribers/users
- Ability to provide lawful call interception as required by national security authorities.

3 INTRODUCTION TO CDMA-PAMR AND OTHER TECHNOLOGIES BEING COMPARED

This section, together with Annex A and the references quoted therein, gives a brief introduction to CDMA-PAMR and the other systems for which the spectrum efficiency is calculated later in this report, in particular TETRA Release 2/TAPS, GSM-R (as implemented by the European railways) and TETRA V+D, each of which is based on TDMA/FDMA technology.

In CDMA-based systems, users share the same (wideband) frequency carriers, with different users/channels being distinguished according to different pseudo-random sequences or "codes". TDMA systems generally utilise a larger number of (narrower) radio frequency carriers, and the frequency carriers are divided into timeslots corresponding to control or traffic channels. The nominal bandwidth of a carrier in a CDMA-PAMR system is 1.25 MHz, with the carrier being usable by a relatively large number of users simultaneously in the same cell. TAPS and GSM-R are both based on GSM technology, with a carrier bandwidth of 200 kHz and each carrier divided into 8 timeslots. In TETRA, the nominal bandwidth of each carrier is 25 kHz, divided into 4 timeslots.

An important distinction between systems based on CDMA and those based on TDMA/FDMA technology is that in a CDMA-based system, the same radio frequency can be used in every cell/sector in the system, whereas in a wide area TDMA/FDMA system, a number of different radio frequencies are required for the different cells, with the frequencies being re-used according to a cellular re-use pattern.

The characteristics of GSM-R used for the evaluation are based on a minimum subset of capabilities which have been defined by the Eirene Project for European railways for PMR applications. This implementation does not include a number of capabilities in the GSM-R specifications and optional features in the Eirene specification. These include Adaptive Multirate Codecs (AMR), voice activity detection and discontinuous transmission (VAD/DTX). Any future implementations of GSM-R could take advantage of these additional functions, which would significantly improve the potential spectrum efficiency of the GSM-R system.

The technical characteristics of CDMA-PAMR used for the evaluation are based on the description in the System Reference Documents from Lucent Technologies [C1] as also described in the Systems Reference Document from ETSI [C9].

Annex A provides a brief introduction to each of the different systems that are studied in detail in this report, namely:

- CDMA-PAMR (section A.1)
- TAPS (section A.2)
- GSM-R, as implemented by the European railways (UIC Project EIRENE for PMR applications) (section A.3)
- TETRA (section A.4).

Further details regarding technical parameters, characteristics, performance and spectrum efficiency of the different technologies can be found in later sections of this report.

4 METHODOLOGY

4.1 Review of methodology in ERC Report 52

An initial task to be performed in this study was to review the methodology for analysis of spectrum efficiency that was developed in ERC Report 52, and to assess its suitability for CDMA. The methodology described in Report 52 was examined and the calculations were found to be not applicable to CDMA technology.

ERC Report 52 concentrated almost entirely on narrowband PMR/PAMR technologies, and the methodology presented in that report is primarily applicable to FDMA and TDMA systems providing voice services and relatively low speed data. The Report 52 calculations are less applicable to CDMA-based systems, and more generally it is also less applicable for calculating spectrum efficiency for higher speed data services. Hence, it is not applicable to use the Report 52 methodology to calculate the spectrum efficiency of CDMA-PAMR, and other wideband PMR/PAMR systems such as TAPS and GSM-R.

4.2 Introduction to new methodology

Overview of methodology

This section describes a method for comparing the spectrum efficiency of CDMA-PAMR with other PMR and PAMR technologies. The methodology chosen is based on a procedure originally outlined in [K1]. The overall methodology is summarised by the flowchart below:

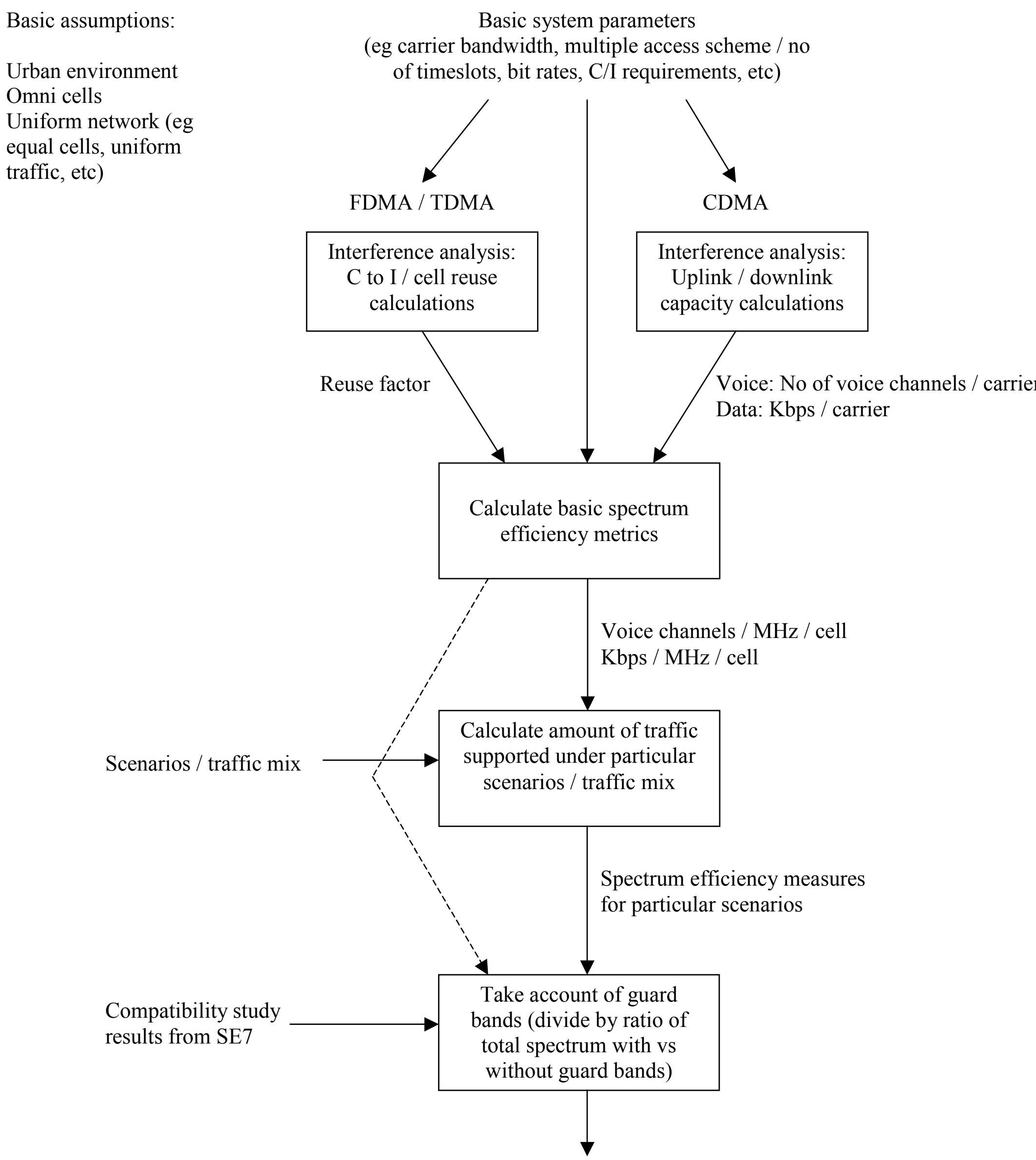


Figure 4.2-1: Spectrum efficiency methodology flowchart

The different stages shown in this flowchart are described in more detail in the sub-sections below, together with key assumptions and descriptions of the various parameters used. Details of input parameter values and calculations of spectrum efficiency using the methodology are contained in Section 6.

Basic assuptions

The following table summarises some of the key assumptions underlying the methodology and used in the spectrum efficiency calculations:

Aspect	Assumptions
Scenarios - Wide area or small systems	Scenarios based on wide area networks - scenario for a series of small PMR networks sharing spectrum within a city derived from this.
Scenarios - Urban or rural	Urban - The greatest pressure on spectrum occurs in urban areas, and these should form the basis for comparison.
Services - Traffic mix	First step in the assessment of the service mix is the calculation of the number of channels available and the bit rate supported. These are elements from which traffic scenarios for different service mixes can be developed. These figures are then extended in two ways:- - Examples of traffic mixes are applied in order to extend the above data to reflect a typical real environment (see Sections 5 and 6). - The formulae used to calculate the results presented in this report are included in Section 4, such that they can be used to calculate the performance for a user-defined traffic mix.
Net bit rate	The bit rate that is measured is the net bit rate, which is linked to the capacity and the quality of service.
CDMA – Uplink or downlink limited	Initial calculations were performed for both the CDMA uplink and the downlink, but it was found that the uplink capacity was the limiting factor for CDMA, and so subsequent focus was on uplink calculations.
C to I	See separate sub-section on Cell Re-use below.
Sectorisation	Sectorisation of cells imposes complications due to the imperfect performance of sectored antennas, and hence omni-directional antennas are assumed.
Erlang 'B' / Erlang 'C'	All channel capacities are calculated before the application of Erlang's formula for the calculation of the total number of channels required to support a given amount of traffic.
Cell planning assumption	All comparisons between different technologies for a given scenario use the same cell radii. Additional calculations are provided within section 6 to quantify the relation between cell radius and number of channels per carrier for CDMA PAMR.
Indicative coverage quality	A coverage probability of approximately 90% at the cell edge is generally taken to be the baseline. This corresponds to a coverage probability of around 97% across the cell area. This figure was used as a background assumption in the development of a model for the systems - it does not significantly affect the relative efficiency, and is mainly relevant for link budget calculations.
Spectrum	The studies are executed using between 2x3 and 2x5 MHz of spectrum, based on the minimum amounts of spectrum required for different technologies (see Annex A). The bandwidth is modified such that the spectrum used represents the nearest contiguous band of frequencies which comprise an integer number of radio carriers and the guard bands on either side.

Table 4.2-1: Basic assumptions

4.3 Basic calculations for TDMA/FDMA

Calculation of cell re-use

The cell repeat pattern assumed for CDMA is 1 (one), since the same frequencies can be re-used for the carriers in all of the cells in a network. The cell repeat pattern for TDMA technologies is calculated using the following methodology, which yields a cell re-use factor which reflects the number of distinct frequencies required to cover a (wide) area.

A theoretical value for the re-use factor (cluster size) N_R for an FDMA or TDMA system using omni-directional antennas can be calculated using the following equation:

$$N_R = 1/3 \times [(C/I)_T \times M \times K \times A]^{2/a} \quad (4.3\text{-}1)$$

where

$(C/I)_T$	=	carrier to interference ratio at threshold
M	=	margin to account for slow fading
K	=	factor relating to cell geometry
A	=	activity factor
a	=	propagation exponent

To give a brief derivation of this equation:

The relationship between the co-channel re-use ratio d/r (where r is the cell radius and d is the minimum re-use distance) and the carrier to interference ratio C/I in a mobile radio network which consists of a number of cells can be established by modelling the co-channel interference. The C/I value comprises the theoretical or standard value $(C/I)_T$ and the margin M for slow fading effects. Since the field strength distribution follows the log-normal distribution (i.e. normal distribution in logarithmic scale), the additive logarithmic margin acts as a factor in a linear scale. Therefore $C/I = (C/I)_T \times M$.

By considering only the first tier of interferers with 6 co-channel cells:

$$\frac{d}{r} = \left[6\left(\frac{C}{I}\right)\right]^{1/a} \quad \text{(Reference [H1], pp 55-56)} \quad (4.3\text{-}2)$$

where a stands for the propagation exponent.

Considering higher tiers of interferers, equation (4.3-2) can be re-written as:

$$\frac{d}{r} = \left[K\left(\frac{C}{I}\right)\right]^{1/a} \quad \text{(Reference [H2], pp 58-62)} \quad (4.3\text{-}3)$$

where K is a function of the number of tiers of interference considered. For example, considering two tiers of interferers with a total of 18 co-channel cells K will be 7.04.

It may be noted that,

$$\frac{d}{r} = \sqrt{3N_R} \quad (4.3\text{-}4)$$

where N_R is the number of cells per cluster (also referred to as re-use factor or cluster size). Therefore,

$$N_R = \frac{1}{3}\left[K\left(\frac{C}{I}\right)\right]^{2/a} \quad (4.3\text{-}5)$$

Equation (4.3-5) can be modified to include the activity factor A. The activity factor can in principle vary between 0 and 1. The interference power and therefore the C/I ratio varies accordingly. Hence, equation (4.3-5) can now be re-written as follows:

$$N_R = \frac{1}{3}\left[M \cdot K \cdot A \cdot \left(\frac{C}{I}\right)_T\right]^{2/a}$$

which is equation (4.3-1).

Consider each of the elements in the cell re-use equation (4.3-1) in turn:

Carrier to interference ratio $(C/I)_T$:
This figure is dependent purely on the technology. It is widely agreed that for systems based on GSM technology the value of $(C/I)_T$ is 9 dB, and for TETRA the value is 19 dB.

Margin *M*:
This margin or "safety factor" is dependent in particular on two parameters:

- The % quality of service / C/I statistics.
- The standard deviation of the fading (σ).

Factor *K*:
This factor relates to cell geometry and interfering cells. It is assumed that $K = 7$ represents a realistic estimate for the value of *K* (for $a = 3.5$), whenever sectorisation is not employed.

Activity factor *A*:
Activity factor in general includes both voice activity factor and loading. The calculations performed in this study assume that the systems are fully loaded. However the CDMA guard bands used for spectrum efficiency calculations are estimated for a partially loaded system. For GSM public cellular networks where voice activity detection and discontinuous transmission are implemented, the activity factor can be assumed to be significantly less than 1. For GSM-R, TAPS and TETRA, however, such a low activity factor is not considered to be appropriate, and an activity factor $A = 1$ is used in the calculations in section 6.2. Although the standards for GSM-R and TAPS provide the possibility for the use of voice activity detection and discontinuous transmission in principle, these features are not currently implemented in GSM-R or TAPS networks. Furthermore, TAPS is a data network so voice activity is not relevant, and there are no such features in TETRA networks.

Propagation exponent *a*:
The value of the propagation exponent *a* is typically assumed to be in the range 3 to 4. A value of $a = 3.5$ is adopted in this report as a suitable value to use for a typical urban environment. It is recognised that this value may be too low for propagation distances beyond 20 km, and therefore for an environment where larger cells are used, this will give a pessimistic result for cell repeat pattern values for TDMA/FDMA systems. Therefore a sensitivity analysis has been included in section 6.4 to show the effect of this for the lower cell repeat patterns that will result from greater re-use distances and larger cell sizes.

Frequency hopping:
One further factor that has been considered is the possible use of frequency hopping. Although frequency hopping is employed in some GSM public cellular networks, it is likely to be of limited benefit in a GSM-R or TAPS network within the limited spectrum that is available. Reasons include that frequency hopping cannot be used on the broadcast control channel (BCCH), and the low number of hop frequencies limits its effectiveness. Nevertheless, the impact of frequency hopping is included in the calculations of data efficiency for TAPS in section 6.5.

Using appropriate values for the parameters described above, the cell re-use factors N_R for TAPS, GSM-R and TETRA can be calculated using the equation above. The equation yields a theoretical value for N_R, which should be adjusted to be an integer number (cluster size) corresponding to a regular cell repeat pattern that is normally used in cell planning. Although it is a theoretical figure, the cluster size used should also take some account of the sorts of actual cell re-use factors that are achieved in practice for real GSM-R and TETRA networks.

Basic capacity calculations for TDMA/FDMA

It has been decided that the maximum number of users that can be supported will form the basis for comparison of spectrum efficiency, with the queuing effects modelled in the Erlang formula being assumed to be identical for all technologies. The maximum number of users for TDMA/FDMA technologies will be the number of traffic channels. For simplification, the impact of control channels will be neglected.

Once the cell reuse pattern/cluster size has been established, it is straightforward to calculate the number of channels n_s available per cell/sector, based on the total bandwidth available, the carrier bandwidth, and the number of channels (timeslots) per carrier, as follows:

$$n_s = (B/c)/N_R \cdot x \cdot t$$

where

B	=	total bandwidth available for system (excluding guard bands)
c	=	carrier bandwidth (frequency separation between adjacent carriers)
N_R	=	frequency reuse factor (cluster size)
t	=	number of channels/timeslots per carrier.

4.4 Basic capacity calculations for CDMA-PAMR

The basic measure of spectrum efficiency for CDMA-PAMR voice services is the maximum number of users (voice channels) that can be supported on each carrier. This maximum number of users for CDMA-PAMR is based on 9.6 kbps channels and a E_b/N_o value of 5 dB is assumed. For comparison with TDMA/FDMA systems, it will be assumed that the technologies will be using Forward Error Correction at a level which is adequate to support an equivalent level of performance.

The formula that is used to calculate the number of users per cell/sector in a CDMA-PAMR system has been derived by Prof. Dr. Kummert of Wuppertal University. The following is a brief explanation of where this formula comes from - for a more detailed derivation see [K1].

The following symbols are used in this derivation:

n_f	=	number of carriers
v	=	voice activity factor
W	=	chip rate
R	=	data rate
E_b/N_o	=	acceptable signal to noise ratio (energy per bit / noise)
N_{th}	=	thermal noise (including receiver noise)
P_s	=	signal power.

A significant feature of the noise-like signals transmitted in CDMA systems is that the system sensitivity to interference is fundamentally altered compared with FDMA and TDMA systems. Use of noise-like signals, with all users occupying the same frequency channels, makes the effective noise the sum of all other user signals. The receiver correlates its input with the desired code sequence, enhancing the signal to noise ratio of the desired signal at the detector while suppressing the noise terms. If the enhancement overcomes the summed noise to provide an adequate E_b/N_0 value at the detector output, the specified admissible frame error rate will not be exceeded.

Due to the different signal processing architectures for downlink and uplink, the following interference relations occur:

Downlink:

- Interferers from the same cell/sector can be eliminated (nearly) perfectly due to the perfect orthogonality of the Walsh codes used and hence they can be neglected in capacity calculations.
- Interferers from other cells/sectors are nearly orthogonal due to different time offsets of pilots of other cells/sectors, and have to be taken into account for capacity calculations.

Uplink:

- Interferers from the same cell/sector are only nearly orthogonal and thus have to be taken into account.
- Interferers from other cells/sectors are nearly orthogonal and have to be taken into account.

Due to various reasons, uplink and downlink capacity have to be considered separately. We focus initially on the uplink capacity.

Signal quality usually is defined via frame error rate. The latter can be controlled via the quantity

$$E_b/N_0 = \frac{\text{energy per bit}}{\text{power spectral density of thermal noise} + \text{power density of interference}}.$$

E_b/N_0 is a dimensionless signal to noise/interference ratio. For the uplink, E_b/N_0 is influenced by all interferers from the same cell/sector and from other cells/sectors. The maximal admissible number of such interferers limits system capacity if a minimal E_b/N_0 value has to be guaranteed.

The E_b in E_b/N_0 can be expressed in terms of signal power P_s and data rate R as

$$E_b = \frac{P_s}{R}. \qquad (4.4\text{-}1)$$

N_0 is the total noise level spectral density generated by thermal noise N_{th} plus noise generated by all interferers from inside the cell/sector I_{in} plus noise generated by all interferers from outside the cell/sector I_{out}, i.e.

$$N_0 = N_{th} + I_{in} + I_{out}\ . \qquad (4.4\text{-}2)$$

Due to power control, all signals from inside the cell (information bearing signal and interfering signals) generate the same signal power P_s at the receiver of the base station. Since signal power P_s of each interferer is distributed homogeneously over a system bandwidth (= chip rate) of W, it produces a noise power spectral density of P_s/W.

If there are n_s users inside the cell/sector, which are homogeneously distributed over all n_f frequency carriers of the cell/sector, then the number of users of the same frequency band is n_s/n_f and the number of interferers from inside the cell/sector is:

$$\left(\frac{n_s}{n_f} - 1\right).$$

This leads to:

$$I_{in} = v\left(\frac{n_s}{n_f} - 1\right)\frac{P_s}{W} \qquad (4.4\text{-}3)$$

where v is the so-called voice activity factor (typically $v \approx 0.5$ to 0.65), which takes into account that power is reduced during breaks of speech. In other words, only a fraction of all active voice channels is actually sending data on average.

The interference I_{out} from mobiles outside the cell can be taken into account as a fraction of I_{in}. The low transmitter strength and increased distance (path loss) of the surrounding mobiles produces an interference level that can be typically characterised by

$$\frac{I_{out}}{I_{in}} \approx 0.6\ . \qquad (4.4\text{-}4)$$

Note that the expression $1/(1+I_{out}/I_{in})$ is sometimes called the "frequency re-use efficiency".
Taking into account (4.4-1) to (4.4-4) we obtain:

$$\frac{E_b}{N_0} = \frac{P_s/R}{N_{th} + I_{in}\left(1 + \frac{I_{out}}{I_{in}}\right)} =$$

$$= \frac{P_s/R}{N_{th} + v\left(\frac{n_s}{n_f} - 1\right)\frac{P_s}{W}\left(1 + \frac{I_{out}}{I_{in}}\right)} =$$

$$= \frac{W/R}{\frac{WN_{th}}{P_s} + v\left(1 + \frac{I_{out}}{I_{in}}\right)\left(\frac{n_s}{n_f} - 1\right)} \qquad (4.4\text{-}5)$$

where *W/R* is the so-called spreading or processing gain

$$\frac{W}{R} = 128 \rightarrow 21.1dB\ .$$

If we solve (4.4-5) for n_s and take into account (4.4-4) we obtain

$$n_s = n_f\left[\frac{1}{1.6v}\left(\frac{W/R}{E_b/N_0} - \frac{WN_{th}}{P_s}\right) + 1\right]. \qquad (4.4\text{-}6)$$

Equation (4.4-6) shows that there is a hard upper limit on n_s as $W \cdot N_{th}/P_s$ tends to zero. This hard limit serves as a theoretical upper bound for the number of users n_s that can be supported and is called the pole number:

$$n_{pole} = n_f\left[\frac{1}{1.6v}\left(\frac{W/R}{E_b/N_0}\right) + 1\right]. \qquad (4.4\text{-}7)$$

More insight into this limit or pole number can be gained by solving equation (4.4-5) for P_s:

$$P_s = \frac{WN_{th}}{\frac{W/R}{E_b/N_0} - v\left(1 + \frac{I_{out}}{I_{in}}\right)\left(\frac{n_s}{n_f} - 1\right)}.$$

This means that the required power P_s at the base station receiver increases according to the number of mobile stations in the cell. Since the interference power density increases as P_s increases (see equation (4.4-3)), the noise rise, which can be defined as:

$$Noise\_rise = \frac{N_{th} + I_{in} + I_{out}}{N_{th}}$$

also increases accordingly.

The graph below illustrates the dependencies of P_s and noise rise on the number of mobile stations in the cell, for a voice activity $v = 0.65$ and $I_{out}/I_{in} = 0.6$.

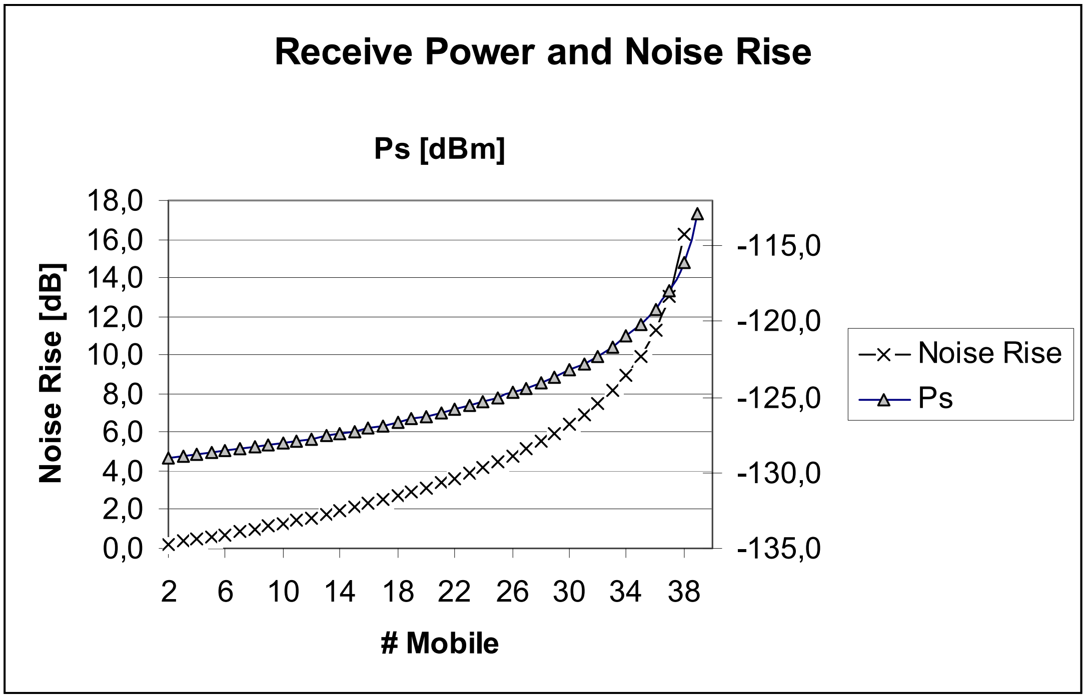


Figure 4.4-1: Noise rise and received power P_S as a function of number of mobiles in the cell

Note that for higher numbers of mobiles, the interference power from users inside and outside the cell is significantly higher than the thermal noise power. The calculation of spectrum efficiency involves the computation of the maximum number of users that can be supported by the system under given assumptions, hence it is higher numbers of mobiles that are of interest here. Recall also that the spectrum efficiency calculations are being performed under the assumption of an urban environment where the system will be interference limited.

As shown in figure 4.4-1, both receive power and noise rise grow without bound at the pole point, which is a theoretical limit for the uplink capacity. Both curves reach their pole points at:

$$n_s = n_f \left[\frac{\left(\frac{W/R}{E_b/N_0} \right)}{v\left(1 + \frac{I_{out}}{I_{in}}\right)} + 1 \right],$$

For voice activity factor $v = 0.65$, $I_{out}/I_{in} = 0.6$ and $n_f = 1$, the pole capacity = 39.9.

From figure 4.4-1 it can also be seen that the practical uplink capacity limit should be smaller than the pole number. This limit depends on the maximum available P_s, or on the permissible noise rise. Permissible noise rise in the system depends on the power control mechanism. The region of figure 4.4-1 where the curves are relatively flat (extending up to around 80% of the pole point) presents optimum operating conditions for power control, as the sensitivity of the received power and noise rise to changes in system load in this region of the graph is moderate and well manageable in a variety of scenarios.

As already mentioned, n_{pole} represents a theoretical upper bound which will not be reached in practice due to effects such as thermal noise, limit on mobile output power, high degree of mobility, multipath, etc. These effects are usually taken into account by applying a so-called loading factor, by which realistic practical user numbers can be expressed as a percentage of n_{pole}. Various text books and papers on CDMA describe methods for computing the loading factor, interference power and capacity for CDMA networks (for example [H2] (pp 155-157) and [G2] (pp 284-287)). These references relate to different types of CDMA systems. For the purpose of this Report, it has been assumed that the basic principle of computing system capacity for a CDMA system by calculating the pole capacity and then applying a loading factor may also be used for calculating the capacity of a CDMA-PAMR system operating in an urban interference-limited environment.

Hence, applying a loading factor L to the pole capacity n_{pole} (and ignoring the "+1" term for simplicity), the numbers of users that can be supported in a cell can be expressed as a percentage of n_{pole}, which gives (for omni-directional cells):

$$n_s = \frac{L.n_f \, W/R}{1.6v \, E_b/N_0}, \qquad (4.4\text{-}8)$$

where

$$L = \frac{n_s}{n_{pole}}. \qquad (4.4\text{-}9)$$

Typical values of L lie in the range 0.5 to 0.8. This range corresponds to the upper part of the region of the graph shown in figure 4.4-1 where the curves are relatively flat. From a network planning point of view, it is desirable to avoid the steep regions above this range in order to account for varying operating conditions and avoid instability in the system performance. A value of $L = 0.7$ can be considered as a realistic assumption for an urban environment.

The formula (4.4-8) will be used in section 6.3 to calculate the number of users per cell/sector in a CDMA-PAMR system. If we take $n_f = 1$ then we obtain the number of users per carrier.

The above formula for the number of users per carrier (i.e. with $n_f = 1$) represents the uplink capacity of a CDMA-PAMR carrier. It has been demonstrated in [K2] that the capacity (and hence spectrum efficiency) of CDMA-PAMR is uplink-limited, and hence there is in general no further need to consider the capacity of the downlink in the spectrum efficiency calculations.

The dependency between cell size and cell traffic is a cell planning issue. This means that the cells have to be planned in such a way that the network delivers seamless coverage for the forecasted traffic, or alternatively to limit the traffic/noise rise in order to maintain seamless coverage.

In CDMA systems, the coverage area of a cell can be considered as being of an elastic nature: as the number of users in the cell increases, the area of coverage may reduce, down to a level defined as part of the cell planning process. The planned cell coverage is therefore dependent on the maximum number of the users in the cell. This implies that, in a CDMA system, there is a limit on the cell size depending on the maximum traffic per cell. A high traffic tends to lead to a reduction of the maximum cell size.

This is an important point in the case of a PAMR application where the expected traffic density is lower than in a public cellular one and that, consequently larger cell sizes are expected. In order to reflect this fact some additional formulas are provided below and computed in section 6.

The relationship between capacity and cell size can be clearly seen by considering the relation between number of mobiles and noise rise in figure 4.4-1. The maximum allowable path loss (M.A.P.L) in a CDMA-PAMR system is directly related to the noise rise (since an increase in noise rise effectively leads to a corresponding change in receiver sensitivity), as follows:

$$M.A.P.L._{\mathbf{n}}\,[dB] = M.A.P.L._{\mathbf{1}}\,[dB] - Noise\ Rise_{\mathbf{n}}\ (dB) \qquad (4.4.10)$$

Note: Subscript means the number of users in the cell (n in general).

Now *M.A.P.L*$_n$ *[dB]* equates to a certain Cell Radius R_{cn} (n=1…n_{pole}), e.g. by applying the appropriate propagation model. As an example if:

$$(\text{Path Loss})^{-1} = \text{m.a.p.l}^{-1}{}_{\cdot n}\left[linear\right] = C/R_{cn}{}^{\alpha}$$

Then from (4.4.10) we can find the general relationship between R_{cn} and R_{c1}, which, in fact gives the Cell Radius Reduction as the cell is loaded with users:

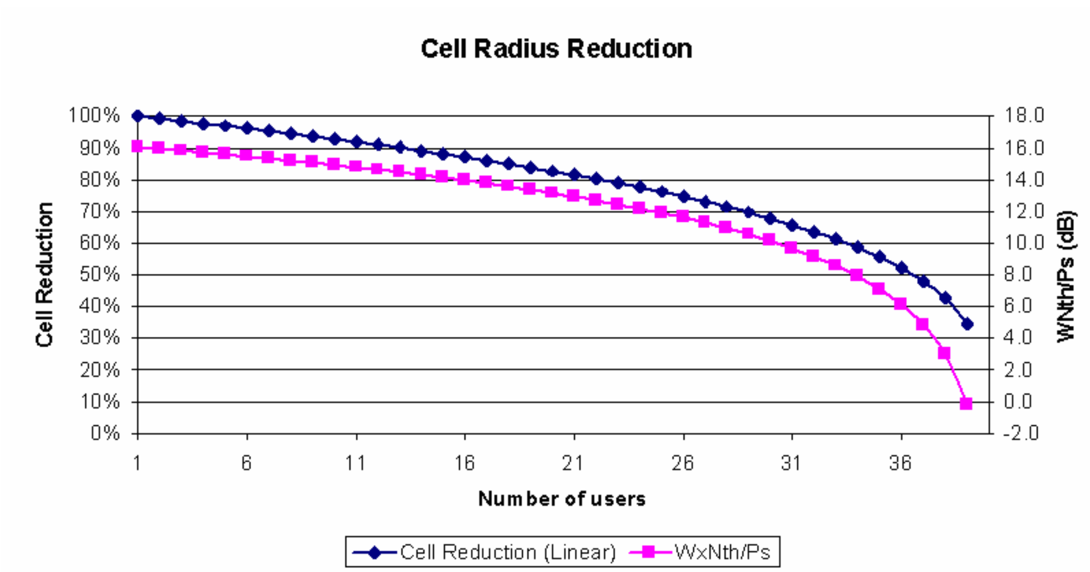
$$CellRadius\,\text{Re}\,duction \equiv \frac{R_{cn}}{R_{c1}} = \sqrt[\alpha]{\frac{m.a.p.l._n}{m.a.p.l._1}} = \sqrt[\alpha]{(noise\_rise)^{-1}} \quad (4.4.11)$$

Hence, the capacity (i.e. maximum number of mobiles that can be supported) has a direct impact on the maximum cell size, according to the noise rise relationship illustrated in figure below (same assumptions as in fig 4.4-1). As referred previously, the values of maximum cell size and capacity selected for a system can be traded-off by the network operator as part of the network planning process.

It is also possible to the relate *noise rise* to the loading factor *L* as:

noise_rise = 1/(1-L) (4.4.12)

By combining (4.4.11) and (4.4.12), it is possible to see the relation between the loading factor and the Cell Radius reduction, see figure below.



4.5 Calculation of efficiency for voice scenarios

Having calculated the basic measurements of spectrum efficiency for the relevant systems, the next stage involves the application of a particular scenario (traffic mix), in order to calculate the amount of traffic supported under the scenario. The analysis of scenarios for voice and data usage can be performed separately.

For voice scenarios, the calculations for a particular scenario require the definition of a set of parameters describing the mix of traffic that is assumed. In particular, the percentages of the traffic corresponding to different types of voice calls need to be selected, for the following categories (and sub-categories) of calls:

- Duplex calls:
  - mobile-fixed
  - mobile-mobile
- Push-To-Talk (PTT) calls:
  - intra-cell
  - inter-cell
- Group calls

In addition, for group calls the following need to be defined:
- average number of users involved in a group call (Ng)
- average number of cells involved in a group call (Nc)

For each technology to be analysed, it is also necessary to define the amount of network capacity (i.e. total number of voice channels) that is consumed for each of the different types of calls. The following table summarises the assumptions that should be made for CDMA-PAMR, TETRA and GSM-R (note that the numbers for TETRA and GSM-R are the same).

	CDMA-PAMR		**TETRA / GSM-R**	
	Uplink	**Downlink**	**Uplink**	**Downlink**
Duplex:				
mobile-fixed	1	1	1	1
mobile-mobile	2	2	2	2
PTT:				
intra-cell	2	2	1	1
inter-cell	2	2	2	2
Group (Ng, Nc)	1	Ng	Nc	Nc

Table 4.5-1: Resource usage factors

The analysis then proceeds by applying the resource usage factors in the above table to the percentages of different call types for each scenario being analysed. For example, to obtain the appropriate figure for intra-cell PTT calls using CDMA-PAMR, then the figure for the percentage of total voice traffic that is intra-cell PTT calls is multiplied by 2, and for group calls using TETRA the percentage of traffic that is group calls is multiplied by Nc. The total traffic usage factor for a particular scenario using a given technology is thus a weighted sum of call type percentages multiplied by corresponding resource usage factors. The resulting weighted sum (total traffic usage factor) gives an average network demand for traffic channels under the scenario being considered. Examples of the results obtained for particular scenarios can be found in section 6.4.

In order to compare the spectrum efficiency of different technologies, the number of available traffic channels also needs to be taken into account. For CDMA-PAMR, the number of available channels is calculated using the formula for n_s given in section 4.4 above, in which the number of channels per carrier is multiplied by the number of carriers per cell. For TDMA/FDMA systems, the number of channels per cell n_s is given as the product of the total number of carrier frequencies available across the system multiplied by the number of timeslots per carrier, divided by the cell re-use factor that is assumed (see section 4.3).

To compare spectrum efficiency between different technologies for a given scenario, the number of available traffic channels per cell/sector (n_s) for each technology is then divided by the appropriate total traffic usage factor to obtain a measure of the spectrum efficiency of the technology under the given scenario. These figures provide a relative measure of spectrum efficiency for the different technologies being compared.

To generalise the above, let:

r(i,j) = resource usage factor for call type i and technology j

p(i,k) = proportion of total traffic that is of call type i for scenario k (%/100)

i = 1…5 (different call types): 1 = duplex (mob-fix); 2 = duplex (mob-mob); 3 = PTT (intra-cell); 4 = PTT (inter-cell); 5 = group call

j = 1…3 (different technologies under comparison: 1 = CDMA-PAMR; 2 = TETRA; 3 = GSM-R

k = 1…4 (different scenarios): 1 = PMR emergency, 2 = PMR companies, 3 = PMR railways, 4 = PAMR

Then total traffic usage factor for technology j under scenario k is given by:

$$T(j,k) = \Sigma(i=1..5)\ r(i,j).p(i,k)$$

and measure of spectrum efficiency E for technology j under scenario k is

$$E(j,k) = n_s(j) / T(j,k)$$

where

$n_s(j)$ = number of available traffic channels per cell (for technology j)

4.6 Calculation of data efficiency

The method for comparing spectrum efficiency can be outlined in the 4 following steps:

1. Define comparable conditions
2. Calculate data capacity for TAPS and CDMA-PAMR
3. Calculate capacity consumption for different usage scenarios
4. Take into account the guard bands (see section 4.7).

The comparison procedure is depicted in the following flowchart:

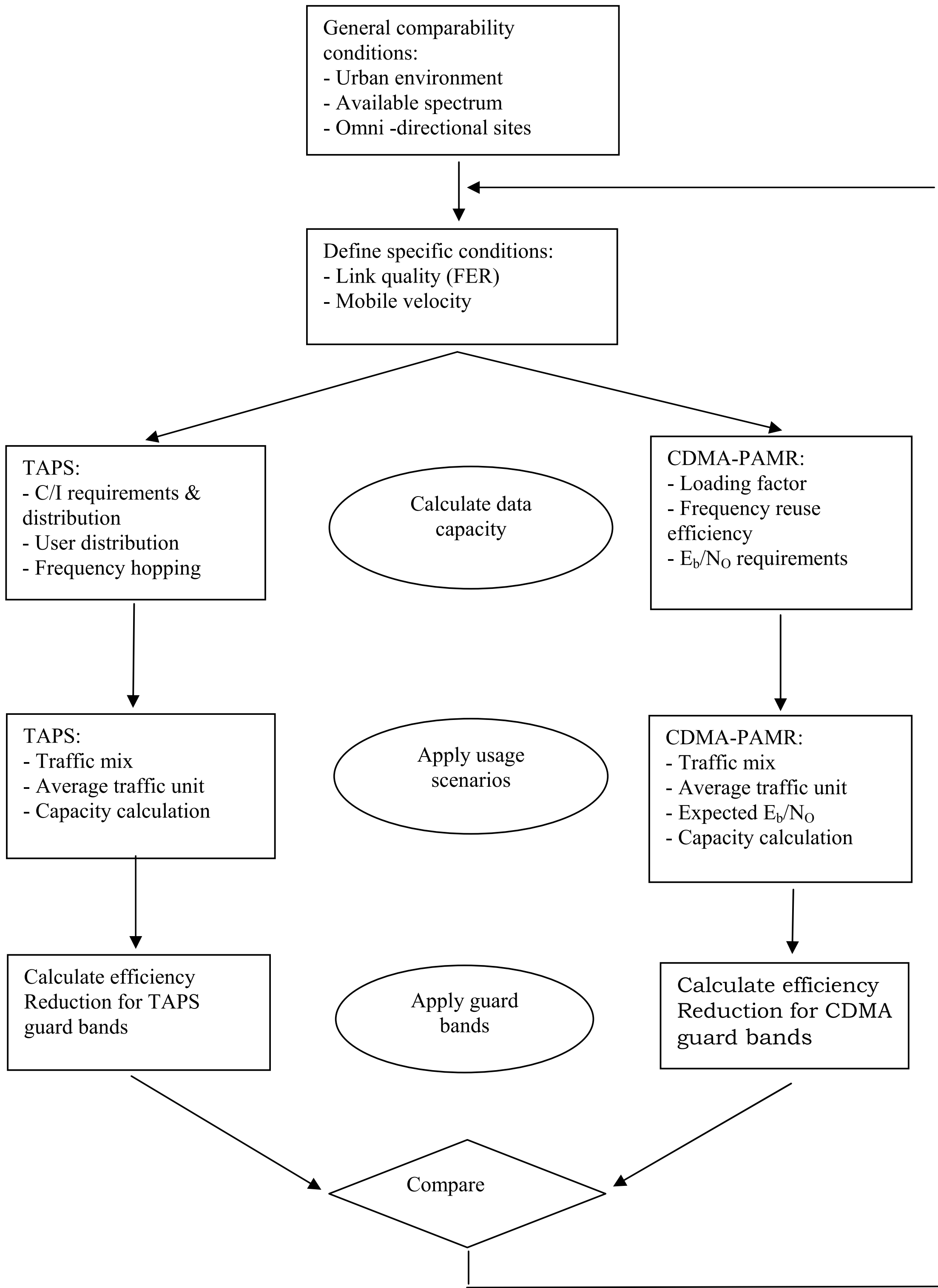


Figure 4.6-1: Calculation procedure for data efficiency comparison

Comparability conditions

General conditions

Urban environment
The capacity and the link quality depend on the propagation conditions. Therefore for the purpose of comparison of the different systems the same propagation conditions must be presumed. Similar to voice efficiency calculations an urban environment is chosen as a common basis with an appropriate propagation factor and slow fading signal statistic.

Available spectrum
The capacity of both systems is directly dependent on the amount of available spectrum. For further calculations in this report the same amount of available spectrum (2x3.75 MHz) is assumed, however the methodology is applicable for other amounts of spectrum also. The required guard band for each technology is taken into account in Section 4.7.

Specific conditions

Link quality (BER vs. FER)
Data connections are realised with different data rates and different FER. For the purpose of system comparison the capacity of links with identical FER should be compared because high quality (low FER) requires in any case more capacity/throughput for the same net data rates. Comparison on the basis of the links with the same BER does not seem to be applicable since bit errors can be eliminated to some extent by implemented error protection algorithms. These algorithms are able to check and correct some bit transmission errors; the correction is more efficient when more protection bits have been used. Only in the case when these algorithms fail the corrupted frames occur. Different data applications require more or less FER, which may lead to message re-send and further capacity consumption. It is assumed for the purpose of this study that the frame re-transmission requirements from the application layer will lead to similar load increments for both investigated systems. Therefore for the purpose of this spectrum efficiency analysis the total throughput capacity will be compared at the same FER.

Mobile velocity
Since different technologies might compensate velocity effects to different degrees, data spectrum efficiency should if possible be investigated for different user velocities which are usual in an urban environment. For the purpose of this study two velocity classes were considered: slow (e.g. 3 - 8 km/h) and medium (e.g. 30 - 50 km/h).

Data capacity
Data rates of links with the same FER can be added to obtain the total data throughput figure assuming the control traffic for multiple connections can be neglected. From the TAPS system capacity point of view it is irrelevant whether capacity is allocated to one or to many users. Similar dependencies can be found in CDMA-PAMR where the system capacity is limited by interference power regardless how many connections are involved.

Spectrum efficiency for data services can be defined as maximum data throughput at a particular communication link quality associated with one base station per unit bandwidth. The maximum data throughput can be understood as the sum of the available maximum data rates for users requesting the same link quality from one base station.

TAPS data capacity

Resources per cell
C/I requirements at the cell edge determine the minimal re-use factor and thus the amount of available radio resources per cell (see section 6.2). Together with the total amount of available spectrum the number of available traffic channels per cell can be calculated [see section 4.4].

Adaptive data rates assignment
A TAPS system assigns different EGPRS modulation and coding schemes (MCS) dependent on the current link quality – i.e. higher data rates for good C/I conditions.

In order to take this adaptive functionality into account for capacity calculations:
- C/I distribution
- User distribution

within a cell area have to be modelled.

The C/I distribution for a regular network structure is shown in [K3]. The radial user distribution required for further calculations can be modelled assuming e.g. equal user distribution within a cell area.

With these distribution functions the total throughput capacity per cell can be calculated for a required FER at different mobile velocities using the statistical analysis method [K3].

CDMA-PAMR data capacity

FER mapping into E_b/N_O
Also for a CDMA-PAMR system a higher link quality can be achieved at the cost of capacity. Therefore for the capacity calculation the same link quality (FER) has to be chosen. The CDMA-PAMR system keeps FER constant for a data connection with a certain data rate by adapting the signal power to the propagation conditions. Higher signal power contributes to the noise level within the cell and thus consumes system capacity.

For a data connection with a certain data rate the FER value can be mapped into the E_b/N_O requirement. The E_b/N_O value depends on the data rate and the mobile velocity as shown in [K1].

Capacity calculation
From E_b/N_O values the total CDMA-PAMR capacity can be derived in accordance with the formula 6.8 from [K1]. The necessary assumptions for the loading factor and frequency re-use efficiency are 70% and 62.5% (1/1.6) respectively. The loading factor is the portion of the pole system capacity and the frequency re-use efficiency describes the contribution of the other cells to the interference to the total noise level. The frequency re-use factor is defined as ratio of the own cell interference to the total (own + other cells) interference.

Consequently a comparison of the total data throughput capacity under the same usage conditions regarding available spectrum, propagation conditions and mobile velocity can be done. The required FER and the mobile velocity are connective links for a comparison of data capacity throughputs on an equivalent basis.

Capacity consumption for different usage scenarios
The network capacity consumption for TAPS and CDMA-PAMR may differ when applying different service mix scenarios. For the sensitivity analysis three sample user profiles have been chosen: Scenario A with emphasis on low speed data, B with emphasis on medium speed data and scenario C with emphasis on high speed data [see section 5.2]. Different usage profiles lead to different average throughputs per usage unit.
The capacity consumption for TAPS can be expressed in the number of throughput units by dividing the total throughput capacity by the average throughput unit. For CDMA-PAMR system the capacity consumption depends on the average E_b/N_O value. Therefore in the first step the expected E_b/N_O value will be derived from the average throughput unit for each scenario. With the specific E_b/N_O value the total capacity will be calculated and expressed in the number of available units in the same way as for TAPS.
In order to compare the spectrum efficiency for different scenarios the number of available units per technology can be evaluated.

4.7 Impact of guard bands

The above stages are used to calculate the spectrum efficiency without guard bands. The impact of guard bands may be taken into account separately from other elements of the calculation by computing the ratio of the total guard bands to the amount of spectrum that is actually occupied by the carriers, and using this ratio to modify the spectrum efficiency calculated without guard bands (i.e. by applying a multiplication factor).

Hence, the methodology for calculation of spectrum efficiency is effectively divided into a number of stages, with the spectrum efficiency without guard bands (*E*) being calculated according to the stages described above, and the results thus obtained then being modified in a final stage in order to take account of guard bands, by simply dividing by the ratio of spectrum required with versus without guard bands.

In other words, the overall spectrum efficiency including guard bands (*F*) is obtained from the spectrum efficiency without guard bands (*E*) by the following formula:

$$F = E / (B+G)/B = E \times B/(B+G)$$

where

> *B* = total spectrum occupied by the carriers (= total number of frequency carriers used x carrier spacing)
> *G* = total amount of guard bands (therefore *B+G* is the total bandwidth allocated for the system).

4.7.1 Definition of guard band and the necessary frequency separation around the duplex transition frequency (termed 'transition band')

Guard bands: The immediate frequency band on either side of a transmitter system where any communications service will have difficulties to operate. Guard bands are determined by the BS-to-MS or MS-to-BS interference scenario.

The frequency separation around the duplex transition frequency (Transition band): The frequency band around the duplex transition frequency necessary to avoid interference that cannot (reasonably) be mitigated. Transition bands are determined by the BS-to-BS or MS-to-MS interference scenario.

4.7.2 Use of guard bands and 'transition bands' in this report

For the assessment of guard bands, the interference identified in the compatibility reports developed for CDMA-PAMR (ECC Reports 38-41) has been predominantly determined by the unwanted transmitter emission produced by the transmitter. Because the interference is caused by the characteristics of the transmitter, this kind of interference can be attenuated by modification of the characteristics of the interfering transmitter, e.g. by introducing filters at the output of the transmitter.

For this reason guard bands are taken into account when calculating the spectrum efficiency of the transmitting system.

In the compatibility reports developed for CDMA-PAMR (ECC Reports 38-41) the interference calculated for the frequency separation around the duplex transition frequency has been dominated by interference caused by blocking or intermodulation of the receivers of the systems adjacent (in frequency and location) to the wide band transmitters. Because the interference is a consequence of the characteristics of the receiver, its effect can be mitigated by modification of the characteristics of the victim receiver (e.g. by introducing filters at the input of the receiver), but cannot be mitigated by modification of the characteristics of the interfering transmitter.

For this reason, the frequency separation around the duplex transition frequency (transition band) is not taken into account when calculating the spectrum efficiency of the transmitting system.

The frequency separation around the duplex transition frequency (transition band) is a constraint on effective use of the spectrum and so needs to be taken in to account by frequency managers in allocating spectrum around the transition frequencies. These transition bands relevant to the deployment of CDMA-PAMR are in the order of 1.8 to 2 MHz and can be found in ECC Reports 38-41.

5 SCENARIO DESCRIPTIONS

In order to reflect the ways that PMR and PAMR systems are used in practice, a number of example scenarios for the usage of different systems were defined and analysed. Separate usage scenarios were defined for voice and data services, and the scenarios were used in order to compare the spectrum efficiency of different PMR/PAMR technologies under different usage conditions.

5.1 Voice scenarios

This section presents examples of typical scenarios of voice traffic applicable to PMR, PAMR and GSM-R. For PMR, the scenario is split between typical systems used for companies and other organisations such as for taxi or road maintenance networks, and emergency service systems. The scenarios have been developed based on practical experiences.

	PMR Emergency	PMR Companies	PMR Railways	PAMR
Duplex				
% traffic (Erlang)	0.1	2	65.5	10
mob-fixed	80	80	80	80
mob-mob	20	20	20	20
PTT				
% traffic (Erlang)	24.9	38	1.5	80
% intracell traffic	50	33	50	50
% intercell traffic	50	67	50	50
Group				
% traffic (Erlang)	75	60	33	10
Avg no of users/call	100	15	9.4	3
Avg no of cells/call	5	3	2	2

Table 5.1-1: Typical PMR/PAMR voice scenarios

The above figures for *Nc* (average number of cells involved in a group call) make implicit assumptions about the sizes of cells, and should be considered as examples of typical values. These figures will in practice depend upon the cell sizes.

5.2 Data scenarios

For voice services a detailed analysis of usage scenarios was necessary because of the major distinction in utilisation of radio resources for group calls by different technologies. Thus the spectrum efficiency for voice services is dependent not only on the amount of available links per cell but also on the traffic percentage and parameters of group calls (average number of users in a group call and number of involved cells).

On the other hand a very detailed scenario analysis for data services is not required since there is no significant difference in realisation of data services by TAPS and CDMA-PAMR.

Furthermore an appropriate mix of different data services and the required link quality for PMR and PAMR is very difficult to forecast because:

- there is no operational experience with wide band services for PMR/PAMR
- there are many ways to realise similar data applications (different coding schemes, different data compression schemes, etc).

Therefore, it was decided to investigate the sensitivity of the efficiency figures to different usage scenarios without characterising which data service mix is appropriate to represent PAMR, private networks, emergency, railways etc.

In order to simplify the sensitivity analysis, the data services have been grouped into 3 categories: Low Speed Data - 9.6 kbps, Medium Speed Data - 38.4 kbps and High Speed Data - 153.6 kbps. Furthermore three scenarios A, B and C have been chosen to represent user profiles with different emphases of the required data speeds.

Scenario	Low Speed Data	Medium Speed Data	High Speed Data
A	60%	30%	10%
B	20%	60%	20%
C	20%	20%	60%

Table 5.2-1: Data usage scenarios with different traffic distributions

Thus a user unit of scenario A is composed of 60% low speed data (9.6 kbps), 30% of medium speed data (38.4 kbps) and 10% of high speed data (153.6 kbps). Scenarios B and C represent a predominance of medium and high data speeds respectively.

Different usage profiles lead to different average throughputs per usage unit. For user scenario A with 60% low speed data (9.6 kbps), 30% medium speed data (38.4 kbps) and 10% high speed data (153.6 kbps), the average data rate is 32.64 kbps. Therefore such a user profile consumes on average a throughput capacity of 32.64 kbps per connection. The average throughput unit of user profile/scenario B is 55.68 and of user profile C 101.76 kbps respectively.

6 SPECTRUM EFFICIENCY CALCULATIONS

This section uses the methodology developed in Section 4 to calculate spectrum efficiency of the different technologies under comparison. Basic spectrum efficiency metrics for the different technologies are first calculated, and then the scenarios described in Section 5 are applied as examples of particular usage scenarios. The section also includes the input parameter values that are used in the calculations. In addition, a sensitivity analysis is provided to show the impact of the variation of some parameters and to quantify the relationship between the capacity and the maximum cell size.

6.1 Basic system parameters

This section contains key parameter values and assumptions that have been used for the calculations for the different systems. These include simplified assumptions regarding overhead for signalling information (see below).

Basic system parameters for CDMA-PAMR

The key system parameters of CDMA-PAMR relate to the carrier spacing/bandwidth (1.25 MHz), and the way in which carriers are shared between different users by means of pseudo-random “codes” and the same carrier frequency can be used in every cell in the network. These system features and parameters are discussed further elsewhere in this report, in particular in sections 3.1, 4.4 and 6.3.

The following table summarises key system parameters of CDMA-PAMR.

Parameter	Value
RF channel bandwidth (= carrier spacing)	1.25 MHz
Chip rate	1.2288 Mchip/sec
Data rate of voice channel	9.6 kbps
Assumed E_b/N_o for voice	5 dB

Table 6.1-1: Key system parameters of CDMA-PAMR

The 9.6 kbps data rate for voice services assumes the use of a single 9.6 kbps Fundamental Channel for each voice channel (see section A.1). For simplicity, the impact of any overhead/signalling information has not been considered.

Basic system parameters for TDMA/FDMA systems

The following table summarises key system parameters of TAPS, GSM-R and TETRA.

Parameter	TAPS	GSM-R	TETRA
RF channel bandwidth (= carrier spacing)	200 kHz	200 kHz	25 kHz
Timeslots per carrier	8	8	4
Nominal C/I requirement	9 dB	9 dB	19 dB

Table 6.1-2: Key system parameters of TDMA/FDMA systems

For GSM-R and TETRA, it is assumed that each timeslot is used to transport a single voice traffic channel. For simplicity, it is assumed that all timeslots are used as traffic channels rather than control channels.

6.2 Basic calculations for TDMA/FDMA

Calculation of cell re-use

Based on the formula and discussion in section 4.3, the theoretical cell re-use factor to be used in evaluating the spectrum efficiency of the TDMA systems TAPS, GSM-R and TETRA can be evaluated using the following equation:

$$N_R = 1/3 \times [(C/I)_T \times M \times K \times A]^{2/a}$$

with the following parameter values:

$(C/I)_T$	=	7.94 (9 dB) for TAPS and GSM-R; 79.4 (19dB) for TETRA
M	=	6.31 (8 dB) (see below)
K	=	7
A	=	1
a	=	3.5

The margin *M* or "safety factor" is dependent in particular on two parameters:
- The % quality of service / coverage probability and C/I statistics.
- The standard deviation of the fading (σ).

Values for the margin *M* between 6 and 12 dB have been suggested. A coverage probability of 90% at the cell edge has been assumed as a suitable value. A margin *M* = 8 dB is used in this report, which roughly equates to a standard deviation σ = 6 dB under such quality of coverage.

Using these values, the above equation yields the following values for the reuse factor N_R:

9.49	for TAPS and GSM-R
35.37	for TETRA

On this basis, combined with experience of practical network deployments, the following are chosen as suitable reuse factors/cluster sizes to be used in subsequent calculations in this report:

9	for TAPS and GSM-R
36	for TETRA

Note that if a higher propagation exponent of 3.7 is used instead of 3.5, the cell re-use factor will reduce to 8 for GSM-R and 27 for TETRA.

Basic capacity calculations for TDMA/FDMA systems

From section 4.3, the number of channels available per cell/sector can be calculated using the following equation:

$$n_s = (B/c)/ N_R \times t$$

where

B	=	total bandwidth available for system (excluding guard bands)
c	=	carrier bandwidth (frequency separation between adjacent carriers)
N_R	=	frequency reuse factor (cluster size)
t	=	number of channels/timeslots per carrier.

Using the cluster sizes calculated above, the number of available communication channels per MHz per cell can be computed as follows (the distinction between traffic channels and control channels is ignored):

- GSM-R: 9 re-use factor: 0.2 MHz channel bandwidth x 8 time slots = 4.44 channels/MHz/cell.
- TETRA: 36 re-use factor: 0.025 MHz channel bandwidth x 4 time slots = 4.44 channels/MHz/cell.

These figures can be converted to total number of channels per cell according to the amount of spectrum available for the network. Note that for each technology there will be a minimum amount of spectrum below which it is not possible in practice to construct a PMR/PAMR network (see Annex A).

Thus the total calculated number of available channels is the same for GSM-R and TETRA. In comparison to GSM-R, TETRA requires a higher C/I figure which implies a larger re-use pattern, but this effect is compensated by the higher number of available channels per Hz from a single carrier for TETRA compared to GSM-R.

6.3 Basic capacity calculations for CDMA-PAMR

In section 4.4 we derived the following expression for n_s, the number of channels per cell/sector:

$$n_s = \frac{L.n_f \, W/R}{1.6v \, E_b/N_0}, \qquad (4.4\text{-}8)$$

Taking $n_f = 1$ gives the expression for the number of users per carrier (n_s/n_f) according to the following parameters:

E_b/N_o	=	acceptable signal to noise ratio (energy per bit / noise + interference)
v	=	voice activity factor
W	=	chip rate
R	=	data rate
L	=	loading factor ($n_s / n_{s_{pole}}$)

Taking the following values for these parameters (as discussed in section 4.4):

E_b/N_o	=	5 dB
v	=	0.65
W/R	=	128
L	=	0.7

we obtain a value of 27 for the number of users per carrier. This figure is consistent with practical experience with existing CDMA networks.

Note that the network capacity figures calculated in this report for the assumptions given may in some circumstances exceed the needs of the market.

We now discuss each of the above parameters in turn, and look at the sensitivity of the calculations to different values of these parameters.

Sensitivity analysis

E_b/N_o:

The value of E_b/N_o used in the calculations is assumed to be 5 dB. This value represents a conservative figure for the value of E_b/N_o that is required in order to achieve a good voice quality in a CDMA-PAMR network. If we perform the calculations for different values of E_b/N_o, however, we obtain the following values for the number of users per carrier:

E_b/N_0	n_s/n_f
4 dB	34
5 dB	27
6 dB	22
7 dB	17

Table 6.3-1: Number of voice channels per carrier (v=0.65, L=0.7)

Activity factor v:

The voice activity factor v is typically assumed to be in the range 0.5 to 0.65 for a system such as CDMA-PAMR, hence 0.65 represents a somewhat conservative assumption. If we perform the calculations for other values of v then we obtain the following values for the number of users per carrier:

v	n_s/n_f

0.5	35
0.55	32
0.6	30
0.65	27

Table 6.3-2: Number of voice channels per carrier (E_b/N_o= 5dB, L=0.7)

The activity factor for systems using CDMA-PAMR for despatch would be expected to be based on the provision of a simplex channel for each despatch transmission for which the activity factor would be one. The figures in the tables reflect the performance of TETRA and GSM-R systems in which a duplex channel would be assigned to a despatch transmission. The simplex channel for CDMA-PAMR is represented by showing the activity factor for CDMA systems which are used for despatch having an activity factor of 0.65. This figure is made up of 0.5 to represent the simplex channel and 0.15 to represent the call maintenance traffic.

Spreading gain *W/R*:

The ratio of the chip rate *W* to the data rate R is fixed at 128 for 9.6 kbps voice services.

Loading factor *L*:

Typical values of *L* lie in the range 0.5 to 0.8, and if P_s is not chosen too small then the value will be towards the upper end of this range. If we perform the calculations for other values of v then we obtain the following values for the number of users per carrier:

L	n_s/n_f
0.6	23
0.7	27
0.8	31

Table 6.3-3: Number of voice channels per carrier (E_b/N_o= 5dB, v=0.65)

Cell radius R_c:

It is possible using 4.4.11 and 4.4.12 to estimate the variations of L and n_s as a function of the maximum cell radius R_c or the maximum distance between base stations D. This is done with reference to the maximum cell radius R_o (or the associated maximum distance between base stations D_o) corresponding to the above calculations with L = 0.7 (or 1 / 1-L = 3.33) leading to n_s = 27. The following table shows the relation between maximum cell size, loading factor and number of voice channels. A propagation coefficient α= 3.5 is assumed.

D/D_o or R_c/R_o	$(R_c/R_o)^{-\alpha}$	1 /1-L	L	n_s
0.891	1.498	5.00	0.80	31
0.9	1.446	4.82	0.79	31
1	1	3.33	0.70	27
1.086	0.749	2.50	0.60	23
1.1	0.716	2.39	0.58	23
1.157	0.600	2.00	0.50	19
1.2	0.528	1.76	0.43	17

Table 6.3-4: Number of voice channels per carrier and loading factor as function of the maximum cell radius (E_b/N_o= 5dB, v=0.65)

When R_c is increasing, the cell capacity n_s is decreasing, which is different from TDMA or FDMA systems where the maximum capacity of a cell is fixed, independent of the cell size. This decreasing behaviour of the cell capacity is mainly important when R_c is large.

The figures calculated in the above sensitivity analysis can be applied also to the subsequent calculations in the report in order to perform sensitivity analysis for voice and data scenarios. This is because the spectrum efficiency figures calculated (excluding guard bands) are proportional to the number of channels/MHz/cell. Thus, for example, if the value of n_s/n_f above is reduced by 10%, then the corresponding spectrum efficiency figure will also be reduced by 10%. Examples of such calculations for voice scenarios are provided in section 6.4.

6.4 Spectrum efficiency calculations for voice scenarios (without guard bands)

By applying the resource usage factors from table 4.5-1 to the traffic type percentages for the voice scenarios from section 5.1, the following table of traffic usage factors results:

	PMR						PAMR	
	Emergency		Companies		Railway		Wide Area Net	
	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink
Duplex								
CDMA	0.0012	0.0012	0.024	0.024	0.786	0.786	0.120	0.120
TETRA	0.0012	0.0012	0.024	0.024	0.786	0.786	0.120	0.120
GSM-R	0.0012	0.0012	0.024	0.024	0.786	0.786	0.120(*)	0.120(*)
PTT								
CDMA	0.50	0.50	0.76	0.76	0.03	0.03	1.60	1.60
TETRA	0.37	0.37	0.63	0.63	0.02	0.02	1.20	1.20
GSM-R	0.37	0.37	0.63	0.63	0.02	0.02	1.20(*)	1.20(*)
Group								
CDMA	4.50	75.00	1.05	9.00	0.49	3.10	0.12	0.30
TETRA	3.75	3.75	1.80	1.80	0.66	0.66	0.20	0.20
GSM-R	3.75	3.75	1.80	1.80	0.66	0.66	0.20(*)	0.20(*)
Total								
CDMA	5.00	75.50	1.83	9.78	1.30	3.92	1.84	2.02
TETRA	4.12	4.12	2.46	2.46	1.47	1.47	1.52	1.52
GSM-R	4.12	4.12	2.46	2.46	1.47	1.47	1.52(*)	1.52(*)

***Note:** The GSM-R system considered in this report is based on the Eirene specifications for PMR applications only, therefore these figures should be considered with special care.

Table 6.4-1: Traffic factors for scenarios and technologies

The traffic factors in table 6.4-1 describe how many network links for uplink and downlink are required for every type of service weighted by percentage of service demand. For CDMA-PAMR the uplink traffic has been estimated with N_g+1 connections, whereby the originating user occupies a channel full time and N_g listeners use 5% of the link capacity to maintain their network connection.

The resulting total traffic factors give an average network traffic demand for a connection in the considered scenario.

Relative efficiency of PMR/PAMR technologies for voice services

As different technologies provide different numbers of links per cell within the same total available spectrum the available link number has to be taken into account.

In order to compare spectrum efficiency the number of available downlink channels per cell is divided by the total downlink traffic factors, and similarly for the uplink. For CDMA-PAMR, although the number of available downlink channels per cell will be greater than the number of uplink channels (see [K2]), for simplicity we use the figures calculated (for the uplink) in section 6.3 as the number of available channels for both directions. The system capacity/spectrum efficiency for CDMA-PAMR will thus in these calculations be limited by the downlink traffic factors, since a greater number of downlink channels than uplink channels will be required for group calls.

For GSM-R and TETRA, we assume that the uplink and downlink capacity is the same, since the opposite paired channel in a conversation cannot be reused. Hence the corresponding values for uplink and downlink in table 6.4-1 are equal. For CDMA-PAMR we use a similar approach, even though the corresponding uplink and downlink channels may be reused for other connections, so that the number of channels consumed for group calls will in general be lower in the uplink direction. Since the uplink in a CDMA-PAMR system has a lower capacity than the downlink in terms of numbers of channels, we use this as the constraining value for calculating spectrum efficiency.

The figures below describe how many average connections per cell can be provided by a PMR/PAMR technology within a limited spectrum of 2 x 3.75 MHz. Note that these figures do not include the impact of guard bands.

	PMR						**PAMR**	
	Emergency		**Companies**		**Railway**		**Wide Area Network**	
	Total cell capacity	relative to TETRA	Total cell capacity	relative to TETRA	Total cell capacity	relative to TETRA	Total cell capacity	relative to TETRA
CDMA	1.07	**0.27**	8.28	**1.22**	20.67	**1.82**	40.10	**3.66**
TETRA	4.04	**1.00**	6.78	**1.00**	11.35	**1.00**	10.96	**1.00**
GSM-R	4.04	**1.00**	6.78	**1.00**	11.35	**1.00**	10.96(*)	**1.00(*)**

***Note:** The GSM-R system considered in this report is based on the Eirene specifications for PMR applications only, therefore its applicability to PAMR scenario is provided here for theoretical purpose onlythese figures should be considered with special care.

Table 6.4-2: Relative spectrum efficiency figures for PMR/PAMR scenarios

Converting these figures to per-MHz-figures gives the results shown in following table.

	PMR						**PAMR**	
	Emergency		**Companies**		**Railway**		**Wide Area Network**	
	Total cell capacity	relative to TETRA	Total cell capacity	relative to TETRA	Total cell capacity	relative to TETRA	Total cell capacity	relative to TETRA
CDMA	0.29	**0.27**	2.21	**1.22**	5.51	**1.82**	10.69	**3.66**
TETRA	1.08	**1.00**	1.81	**1.00**	3.03	**1.00**	2.92	**1.00**
GSM-R	1.08	**1.00**	1.81	**1.00**	3.03	**1.00**	2.92(*)	**1.00(*)**

***Note:** The GSM-R system considered in this report is based on the Eirene specifications for PMR applications only, therefore these figures should be considered with special care.

Table 6.4-3: Relative spectrum efficiency figures per MHz for PMR/PAMR scenarios

The relative figures in comparison with TETRA show the relative efficiency of the considered technology and usage scenario in comparison to TETRA. GSM-R spectrum efficiency is calculated to be equal to that of TETRA. This is because GSM-R cells provide the same number of available links and because the same method of voice service realisation and the same cell sizes have been assumed for both technologies. CDMA-PAMR provides more channels per site and voice services are realised in a different way. For traffic models with a very heavy group call percentage TETRA and GSM-R show some advantages in comparison to CDMA-PAMR. But in other cases (e.g. for the typical PAMR usage) CDMA-PAMR appears more efficient. Note that the above figures do not include the impact of guard bands, which are considered in section 6.6.

Sensitivity analysis for CDMA-PAMR parameters

Based on the sensitivity analysis in section 6.3, the following is an analysis of the sensitivity of the spectrum efficiency values calculated above to changes in input parameters used in the basic capacity calculations for CDMA-PAMR. For each of the voice scenarios considered above, the relative spectrum efficiency figures for CDMA-PAMR are recalculated for different values of these input parameters. The results are presented in tables 6.4-4 - 6.4-6 below

E_b/N_0	**PMR - emergency**	**PMR - companies**	**PMR - railways**	**PAMR**
4 dB	0.33	1.54	2.29	4.61
5 dB	0.27	1.22	1.82	3.66
6 dB	0.22	1.00	1.48	2.98
7 dB	0.17	0.77	1.15	2.30

Table 6.4-4: Spectrum efficiency of CDMA-PAMR relative to TETRA for different values of E_b/N_0

v	PMR - emergency	PMR - companies	PMR - railways	PAMR
0.5	0.34	1.58	2.36	4.74
0.55	0.31	1.45	2.16	4.33
0.6	0.30	1.36	2.02	4.06
0.65	0.27	1.22	1.82	3.66

Table 6.4-5: Spectrum efficiency of CDMA-PAMR relative to TETRA for different values of voice activity v

L	R_c/R_o	PMR - emergency	PMR - companies	PMR - railways	PAMR
0.43	1.2	0.17	0.77	1.15	2.30
0.5	1.16	0.19	0.86	1.28	2.57
0.58	1.1	0.22	1.02	1.52	3.06
0.6	1.09	0.23	1.04	1.55	3.12
0.7	1	0.27	1.22	1.82	3.66
0.79	0.9	0.30	1.39	2.07	4.16
0.8	0.89	0.30	1.40	2.09	4.20

Table 6.4-6: Spectrum efficiency of CDMA-PAMR relative to TETRA for different values of loading factor L and variation in maximum cell radius R_c/R_o

Sensitivity analysis for TDMA re-use factors

In a similar way to the CDMA-PAMR parameters above, it is also possible to analyse the sensitivity of the spectrum efficiency values to changes in key parameters for TETRA and GSM-R, in particular the cell re-use factor calculated in section 6.2. This re-use factor reflects the values of the parameters used to calculate it, including the carrier-to-interference ratio $(C/I)_T$, the fading margin M, and the propagation exponent a. Consecutive values of the cell re-use factors in the tables below correspond to 2 dB changes in either $(C/I)_T$ or M. Similarly, an increase in the assumption regarding the propagation exponent a will lead to a reduction in the cell re-use factor that is calculated.

For each of the voice scenarios considered earlier in this section, the relevant relative spectrum efficiency figures are recalculated for different values of the cell re-use factors. The results are presented in table 6.4-7 and 6.4-8 below.

Cell re-use factor for TETRA	PMR - emergency	PMR - companies	PMR - railways	PAMR
21	0.15	0.71	1.06	2.13
27	0.20	0.92	1.37	2.74
36	0.27	1.22	1.82	3.66
48	0.35	1.63	2.43	4.88

Table 6.4-7: Spectrum efficiency of CDMA-PAMR relative to TETRA for different TETRA cell re-use factors

Cell re-use factor for GSM-R	PMR - emergency	PMR - companies	PMR - railways	PAMR
7	1.29	1.29	1.29	1.29(*)
9	1.00	1.00	1.00	1.00(*)
12	0.75	0.75	0.75	0.75(*)

***Note:** The GSM-R system considered in this report is based on the Eirene specifications for PMR applications only, therefore these figures should be considered with special care.

Table 6.4-8: Spectrum efficiency of GSM-R relative to TETRA for different GSM-R cell re-use factors

6.5 Data efficiency calculations (without guard bands)

The method for spectrum efficiency calculation described in section 4.6 shall be applied to both technologies under comparable conditions. Note that the results presented in this section exclude the impact of guard bands (see section 6.6).

TAPS

The maximum data throughputs for TAPS in an urban environment at some mobile velocities can be found in [K3].

For example for the mobile velocity of 3 km/h and FER=0.01 the maximal throughput capacity is 600 kbps when assuming ideal frequency hopping (FH) and 466 kbps without frequency hopping.

In order to compare technologies with regard to the usage scenarios, 3 usage profiles with different emphases on data speeds have been chosen. For each usage profile a throughput unit can be defined expressing average data consumption per user connection. A technology providing more units under similar conditions (available spectrum, propagation, velocity, etc.) is more efficient.

A TAPS system does not assign a constant data rate to a connection but varies the data rates as a function of the C/I conditions. The resulting throughout capacity can be calculated for the different FER and different mobile velocities (see [K3]). The results are summarised in the following table:

	Throughput capacity [kbps] with ideal FH		Throughput capacity [kbps] without FH	
FER	low velocity	medium velocity	low velocity	medium velocity
0.01	600	537	466	529
0.05	696	667	624	642
0.1	722	707	682	700

Table 6.5-1: TAPS data rate capacity per cell

The approximate number of available units for each usage profile can be obtained by dividing the total throughput by the average data throughput unit. Thus for different usage scenarios A, B, C as defined in table 5.2-1, the following number of units can be obtained (assuming ideal frequency hopping):

	Scenario A		Scenario B		Scenario C	
FER	low velocity	medium velocity	low velocity	medium velocity	low velocity	medium velocity
0.01	18.4	16.5	10.8	9.6	5.9	5.3
0.05	21.3	20.4	12.5	12.0	6.8	6.6
0.1	22.1	21.7	13.0	12.7	7.1	6.9

Table 6.5-2: TAPS data capacity in number of throughput units for different usage scenarios

CDMA-PAMR

In order to be able to calculate the corresponding data throughput per cell the required E_b/N_O values for the available data services need to be known. CDMA-PAMR offers data services with data rates between 1.5 kbps up to 153.6 kbps on the uplink (up to 307.2 kbps on downlink). The dependencies between E_b/N_O and the maximum CDMA-PAMR cell throughput were derived in [K1]. The system requirements for E_b/N_O vary with the mobile velocity and the predefined FER. The diagrams regarding this relationship for different data services can be found in [K4].

For the simplicity of the study only radio configurations with 9.6, 38.4 and 153.6 kbps were considered. For low speed data applications when use of only a fundamental channel is sufficient, 9.6 kbps will generally be used. 153.6 kbps will usually be the most efficient data rate for high speed data applications. 38.4 kbps represents an intermediate value, e.g. for medium speed data applications.

The following total E_b/N_O values (including power for pilot signals) are required in order to maintain a required signal quality (FER):

	9.6 kbps		**38.4 kbps**		**153.6 kbps**	
FER	**low velocity**	**medium velocity**	**low velocity**	**medium velocity**	**low velocity**	**medium velocity**
0.01	2.6	3.5	1.7	2.3	1.3	1.8
0.05	2.0	2.5	1.1	1.6	0.6	1.2
0.1	1.7	1.9	0.7	1.1	0.4	0.8

Table 6.5-3: Required E_b/N_O values in dB for different data rates and mobile velocities using convolutional coding

Using these E_b/N_O values the total throughput capacity of the CDMA cell can be calculated on the basis of the formula (6.8) from [K1]. This formula takes into account the loading factor 70%, frequency re-use efficiency of 62.5% and an average net/gross bit rate ratio of 0.9.

Hence the following total throughput capacities are obtained:

	9.6 kbps		**38.4 kbps**		**153.6 kbps**	
FER	**low velocity**	**medium velocity**	**low velocity**	**medium velocity**	**low velocity**	**medium velocity**
0.01	794	645	977	851	1071	954
0.05	911	812	1121	999	1258	1096
0.1	977	933	1229	1121	1317	1202

Table 6.5-4: Maximum throughput capacity for CDMA-PAMR in kbps for different FER and mobile velocity

For a low mobile velocity (8 km/h), FER=0.01 a CDMA-PAMR cell provides a total throughput capacity of 794 kbps, 977 kbps and 1071 kbps for 9.6 kbps 38.4 kbps and 153.6 kbps links respectively. Under similar conditions a TAPS data capacity model provides approximately 600 kbps total throughput (with ideal FH) regardless of particular link data rates.

In the next step data usage scenarios as defined in table 5.2-1 will be applied for a CDMA-PAMR system. Similar to the TAPS analysis the average throughput units for each scenario (usage profile) are used for further calculations. But in distinction to the TAPS analysis where the total throughput is not dependent on the share of particular services, the CDMA-PAMR analysis requires an intermediate step. From the average throughput units the average required E_b/N_O values have been derived. The following table shows the average throughput units and the corresponding E_b/N_O values.

	A ↔ 32.64 kbps		B ↔ 55.68 kbps		C ↔ 101.76 kbps	
FER	**low velocity**	**medium velocity**	**low velocity**	**medium velocity**	**low velocity**	**medium velocity**
0.01	1.8	2.4	1.5	2.1	1.4	1.9
0.05	1.2	1.7	0.9	1.4	0.7	1.3
0.1	0.8	1.2	0.6	1.0	0.5	0.9

Table 6.5-5: Required E_b/N_O values in dB for different scenarios

The intermediate E_b/N_O values are interpolated from data provided by Lucent for different radio configurations. With these E_b/N_O values the total throughput capacity can be derived using formula (6.8) from [K1] and expressed as the number of available throughput units for a particular scenario. Table 6.5-6 shows the total throughput capacity in kbps and table 6.5-7 the capacity in throughput units.

	A		B		C	
FER	**low velocity**	**medium velocity**	**low velocity**	**medium velocity**	**low velocity**	**medium velocity**
0.01	961	831	1016	887	1059	928
0.05	1108	972	1169	1049	1227	1083
0.1	1215	1108	1267	1161	1299	1185

Table 6.5-6: CDMA-PAMR data capacity in kbps for different scenarios

	A		B		C	
FER	**low velocity**	**medium velocity**	**low velocity**	**medium velocity**	**low velocity**	**medium velocity**
0.01	29.4	25.5	18.2	15.9	10.4	9.1
0.05	33.9	29.8	21.0	18.8	12.1	10.6
0.1	37.2	33.9	22.8	20.9	12.8	11.6

Table 6.5-7: CDMA-PAMR data capacity in number of throughput units for different usage scenarios

TAPS vs. CDMA-PAMR

The following table compares the maximum throughput capacity per cell for TAPS and CDMA-PAMR for different velocities and FERs, and for a range of different CDMA-PAMR data rates. In each case, the first figure applies to a network using 2x3.75 MHz of spectrum (excluding guard bands), and the figure in brackets is the throughput per MHz.

Velocity	**FER**	**TAPS throughput [kbps]**		**CDMA-PAMR throughput [kbps]**		
		(no FH)	**(ideal FH)**	**9.6 kbps**	**38.4 kbps**	**153.6 kbps**
low	0.01	466 (124)	600 (160)	794 (212)	977 (261)	1071 (286)
	0.05	624 (166)	696 (186)	911 (243)	1121 (299)	1258 (335)
	0.1	682 (182)	722 (193)	977 (261)	1229 (328)	1317 (351)
medium	0.01	529 (141)	537 (143)	645 (172)	851 (227)	954 (254)
	0.05	642 (171)	667 (178)	812 (217)	999 (266)	1096 (292)
	0.1	700 (187)	707 (189)	933 (249)	1121 (299)	1202 (321)

Table 6.5-8: Data throughput rates per cell (and per MHz) for TAPS and CDMA-PAMR

To take account of different usage scenarios, the efficiency comparison can be concluded with a ratio matrix containing ratios of corresponding efficiency figures for CDMA-PAMR (table 6.5-7) and TAPS (table 6.5-2). There are minor differences between the exact velocities used to calculate the figures being compared in the ratios, however these will be relatively insignificant. The TAPS figures assume ideal frequency hopping. Such an efficiency matrix shows the relative efficiency figures for different usage scenarios.

	Relative efficiency figures CDMA/TAPS (without guard bands)					
	Scenario A		**Scenario B**		**Scenario C**	
FER	**low velocity**	**medium velocity**	**low velocity**	**medium velocity**	**low velocity**	**medium velocity**
0.01	1.6	1.5	1.7	1.7	1.8	1.7
0.05	1.6	1.5	1.7	1.6	1.8	1.6
0.1	1.7	1.6	1.8	1.6	1.8	1.7

Table 6.5-9: Efficiency matrix for the comparison of CDMA-PAMR and TAPS data efficiency in relative number of throughput units for different usage scenarios

6.6 Impact of guard bands

General discussion

It was seen in section 4.7 that the impact of guard bands on spectrum efficiency can be taken into account by dividing by the ratio of spectrum required with versus without guard bands. In other words, the overall spectrum efficiency including guard bands (F) is obtained from the spectrum efficiency without guard bands (E) by applying the formula:

$$F = E / (B+G)/B = E \times B/(B+G)$$

where

B = total spectrum occupied by the RF carriers
G = total amount of guard bands.

ECC Report 39 dealing with the compatibility between CDMA-PAMR and narrowband PMR/PAMR systems in the 400 MHz band indicates that a guard band of 200 kHz is required in the uplink and downlink bands on either side of the spectrum that is occupied by the CDMA carriers (we assume here that the frequencies used for the CDMA-PAMR base station transmissions are sufficiently far away from the transition frequency at 420 or 460 MHz). Hence, for a CDMA-PAMR system with 3 carriers then the ratio $(B+G)/B$ = (3750+400)/3750 = 1.11, and for a 2-carrier system the ratio is (2500+400)/2500 = 1.16 and (1250+400)/1250 = 1.32 for a 1-carrier system.

ECC Report 22 dealing with compatibility between TAPS and narrowband PMR/PAMR systems in the 400 MHz band concluded that a guard band of 100 kHz is required in the uplink and downlink bands on either side of the spectrum that is occupied by the block of 200 kHz TAPS carriers. Hence, for a TAPS system utilising 19x200 kHz carriers the ratio $(B+G)/B$ = (3800+200)/3800 = 1.05. Similar guard bands and hence a similar ratio would be expected for GSM-R, since they are both based on the same (GSM) radio technology. For TETRA, a guard band of 0 or 1x12.5 or 25 kHz channels would need to be left between TETRA and an adjacent narrowband PMR/PAMR system, hence we will assume that the ratio $(B+G)/B$ is close to 1.

In the 900 MHz band, ECC Report 38 dealing with the compatibility between CDMA-PAMR and UIC radio systems indicates that a guard band of 125 or 200 kHz is required between the spectrum that is occupied by the CDMA carriers and the UIC radio systems above 876/921 MHz. For TAPS, the equivalent guard band required was found to be 200 or 400 kHz (ECC Report 14). On the other side of the frequencies used for the CDMA-PAMR or TAPS system, the guard band required between CDMA-PAMR / TAPS and an adjacent narrowband PMR/PAMR system will be approximately the same size as the equivalent guard band required in the 400 MHz band (i.e. 200 kHz or 100 kHz respectively). Hence it can be seen that the total guard bands required in the 900 MHz band are roughly the same as those required in the 400 MHz band.

Note that there may be different guard bands required according to which systems are assumed to be adjacent to the technology under consideration.

The above ratios can be applied to any of the “per-MHz” spectrum efficiency figures in the previous sub-sections, i.e. by dividing the “without guards bands” figure by the appropriate ratio to obtain the spectrum efficiency figure “with guard bands”.

The simulations which have been performed in the CDMA-PAMR compatibility reports (ECC Reports 38-41) for the determination of guard bands were based on typical traffic densities in PAMR systems.

Guard bands and frequency separation around the duplex transition frequency (termed 'transition band')

The guard bands and the frequency separations at the duplex transition required for the deployment of CDMA-PAMR have been calculated in ECC Reports 38-41, the results of which are summarised in Annex B. For the reasons indicated above in 4.7.2, the transition separations are not relevant to the calculation of spectrum efficiency of different technologies, but are constraints to be considered by frequency managers.

In the case where there are 2 CDMA-PAMR networks operating in adjacent spectrum (and assuming that co-location of base stations is not possible), a guard band of 200 kHz is recommended between the 2 networks. No guard band is needed between adjacent CDMA-PAMR carriers that are co-located.

Results for voice services

Beginning with the basic spectrum efficiency metrics for voice services that were calculated in sections 6.2 and 6.3 for TDMA and CDMA systems respectively, the following are the numbers of voice channels per MHz per cell (excluding guard bands) that can be provided with the different technologies:

CDMA-PAMR	27 channels / 1.25 MHz carrier	= 21.6 channels/MHz/cell
GSM-R for PMR	16.7 channels / 3.75 MHz	= 4.4 channels/MHz/cell
TETRA	16.7 channels / 3.75 MHz	= 4.4 channels/MHz/cell.

Dividing by the factors derived above in order to take account of the effect of guard bands, we obtain the following basic spectrum efficiency metrics including guard bands:

CDMA-PAMR (3 carrier system)	19.5 channels/MHz/cell
CDMA-PAMR (2 carrier system)	18.6 channels/MHz/cell
CDMA-PAMR (1 carrier system)	16.4 channels/MHz/cell
GSM-R for PMR	4.2 channels/MHz/cell
TETRA	4.4 channels/MHz/cell.

If we consider the network spectrum efficiency figures for different voice scenarios in table 6.4-3 (which exclude the impact of guard bands), then these can be converted to figures that include the effect of guard bands by dividing each figure by the appropriate ratio $(B+G)/B$. The results are provided in table 6.6-1 below.

	PMR						**PAMR**	
	Emergency		**Companies**		**Railway**		**Wide Area Network**	
	Capacity per MHz	relative to TETRA	Capacity per MHz	relative to TETRA	Capacity per MHz	relative to TETRA	Capacity per MHz	relative to TETRA
CDMA-PAMR (3 carriers)	0.26	**0.24**	1.99	**1.10**	4.98	**1.65**	9.66	**3.30**
CDMA-PAMR (2 carriers)	0.25	**0.23**	1.90	**1.05**	4.75	**1.57**	9.22	**3.15**
CDMA-PAMR (1 carrier)	0.22	**0.20**	1.67	**0.93**	4.18	**1.38**	8.10	**2.77**
TETRA	1.08	**1.00**	1.81	**1.00**	3.03	**1.00**	2.92	**1.00**
GSM-R	1.02	**0.95**	1.72	**0.95**	2.88	**0.95**	2.78(*)	**0.95(*)**

***Note:** The GSM-R system considered in this report is based on the Eirene specifications for PMR applications only, therefore these figures should be considered with special care.

Table 6.6-1: Spectrum efficiency figures for PMR/PAMR scenarios including guard bands

Sensitivity analysis

The results of the sensitivity analysis performed in section 6.4 without guard bands can be re-calculated to include the impact of guard bands simply by dividing by the appropriate ratios as described above. Tables 6.6-2 to 6.6-4 below present the relative spectrum efficiency values for CDMA-PAMR that are obtained for different values of CDMA-PAMR input parameters, for each of the voice scenarios. The values here assume a 2-carrier CDMA-PAMR network.

E_b/N_0	PMR - emergency	PMR - companies	PMR - railways	PAMR
4 dB	0.29	1.33	1.98	3.97
5 dB	0.23	1.05	1.57	3.15
6 dB	0.19	0.86	1.28	2.57
7 dB	0.14	0.66	0.99	1.98

Table 6.6-2: Spectrum efficiency of CDMA-PAMR relative to TETRA for different values of E_b/N_0

v	PMR - emergency	PMR - companies	PMR - railways	PAMR
0.5	0.30	1.36	2.04	4.09
0.55	0.27	1.25	1.86	3.74
0.6	0.25	1.17	1.74	3.50
0.65	0.23	1.05	1.57	3.15

Table 6.6-3: Spectrum efficiency of CDMA-PAMR relative to TETRA for different values of voice activity v

L	R_c/R_o	PMR - emergency	PMR - companies	PMR - railways	PAMR
0.43	1.2	0.14	0.66	0.99	1.98
0.5	1.16	0.16	0.74	1.11	2.22
0.58	1.1	0.19	0.88	1.31	2.64
0.6	1.09	0.19	0.90	1.34	2.69
0.7	1	0.23	1.05	1.57	3.15
0.79	0.9	0.26	1.20	1.79	3.58
0.8	0.89	0.26	1.21	1.80	3.62

Table 6.6-4: Spectrum efficiency of CDMA-PAMR relative to TETRA for different values of loading factor L and variation in maximum cell radius R_c/R_o

Similarly, tables 6.6-5 and 6.6-6 analyse the sensitivity of the spectrum efficiency values to changes in the cell re-use factors for TETRA and GSM-R, by re-calculating the values in tables 6.4-7 and 6.4-8 to include the impact of guard bands. As indicated in section 6.4, these re-use factors reflect the values of input parameters including carrier-to-interference ratio $(C/I)_T$, fading margin M, and propagation exponent a. Consecutive values of the cell re-use factors in the tables below correspond to 2 dB changes in either $(C/I)_T$ or M. An increase in the assumption regarding the propagation exponent a will lead to a reduction in the cell re-use factor that is calculated.

Cell re-use factor for TETRA	PMR - emergency	PMR - companies	PMR - railways	PAMR
21	0.13	0.61	0.92	1.84
27	0.17	0.79	1.18	2.36
36	0.23	1.05	1.57	3.15
48	0.31	1.40	2.09	4.20

Table 6.6-5: Spectrum efficiency of CDMA-PAMR relative to TETRA for different TETRA cell re-use factors

Cell re-use factor for GSM-R	PMR - emergency	PMR - companies	PMR - railways	PAMR
7	1.22	1.22	1.22	1.22(*)
9	0.95	0.95	0.95	0.95(*)
12	0.71	0.71	0.71	0.71(*)

***Note:** The GSM-R system considered in this report is based on the Eirene specifications for PMR applications only, therefore these figures should be considered with special care.

Table 6.6-6: Spectrum efficiency of GSM-R relative to TETRA for different GSM-R cell re-use factors

Results for data services

Similarly, the spectrum efficiency figures calculated in section 6.5 for data services excluding the impact of guard bands can be converted to figures including guard bands by dividing by the appropriate factors. The following table is derived from table 6.5-8 in such a way, and compares the maximum throughput capacity per MHz per cell for TAPS and CDMA-PAMR for different velocities and FERs, and for a range of different CDMA-PAMR data rates. A 2-carrier CDMA-PAMR network is assumed.

Velocity	FER	TAPS throughput per MHz [kbps]		CDMA-PAMR throughput per MHz [kbps]		
		(no FH)	(ideal FH)	9.6 kbps	38.4 kbps	153.6 kbps
low	0.01	118	152	183	225	246
	0.05	158	176	209	258	289
	0.1	173	183	225	283	303
medium	0.01	134	136	148	196	219
	0.05	163	169	187	230	252
	0.1	177	179	214	258	276

Table 6.6-2. Data throughput per MHz per cell for TAPS and CDMA-PAMR (including guard bands)

The ratios in table 6.5-9 comparing data efficiency figures for CDMA-PAMR and TAPS for different data usage scenarios (without guard bands) can also be converted to include the impact of guard bands. The resulting matrix showing the relative spectrum efficiency figures for different data scenarios is shown in table 6.6-3 below.

	Relative efficiency ratios CDMA-PAMR / TAPS (with guard bands)					
	Scenario A		Scenario B		Scenario C	
FER	low velocity	medium velocity	low velocity	medium velocity	low velocity	medium velocity
0.01	1.5	1.4	1.5	1.5	1.6	1.6
0.05	1.4	1.3	1.5	1.4	1.6	1.5
0.1	1.5	1.4	1.6	1.5	1.6	1.5

Table 6.6-3. Comparison of CDMA-PAMR and TAPS data efficiency (including guard bands) in relative number of throughput units for different usage scenarios

7 CONCLUSIONS

This report has calculated the spectrum efficiency of CDMA-PAMR for both voice and data services, for a range of different usage scenarios, and has compared the spectrum efficiency results for CDMA-PAMR with corresponding results for other PMR/PAMR systems. It can be seen from these results (e.g. those in section 6.6) that:

- The basic spectrum efficiency for voice services, in terms of the number of voice channels, is significantly higher for CDMA PAMR than for TETRA and for GSM-R (using the restricted subset of capabilities required for railway interoperability). On the basis of the assumptions in this report, the spectrum efficiency of CDMA-PAMR has been found to be significantly higher than that of these other systems, with the actual relative efficiency dependent on the system conditions.

- Applying different PMR/PAMR usage scenarios for voice services, for the emergency services PMR scenario, which has a large percentage of group calls each involving large numbers of users, TETRA and GSM-R were found to be significantly more efficient than CDMA-PAMR. For other PMR and PAMR scenarios, CDMA-PAMR was generally found to be as or more efficient than TETRA and GSM-R, and significantly more efficient for the typical PAMR scenario. Differences between results for different scenarios are primarily due to CDMA-PAMR not including a broadcast channel that can be used to provide spectrum efficient group calls.

In addition, due to uncertainty in some parameters, sensitivity analysis has been performed. Additional calculations have also been performed to reflect and quantify the decrease of the number of available channels per carrier and per cell for CDMA-PAMR systems when the maximum cell radius is increasing (or vice versa).

For data services, data rates and throughputs vary according to velocity, link quality, etc, and the mix of data rates also makes some difference, however CDMA-PAMR was found to be more spectrum efficient than TAPS (with ideal frequency hopping). The spectrum efficiency is here measured in terms of the throughput in kbps per MHz per cell, for a particular combination of velocity, FER, and data rates to be used.

8 REFERENCES

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ANNEX A: COMPARISON OF BASICS ON CDMA-PAMR AND OTHER TECHNOLOGIES

A.1. CDMA-PAMR

The following text is based on information contained in the System Reference Document for CDMA-PAMR that was submitted to CEPT by Lucent [C1], where further information about CDMA-PAMR can be found.

CDMA-PAMR is a system that uses CDMA radio technology in order to provide PAMR services to users. The air interface used in CDMA-PAMR is known as CDMA-1X and is specified in the relevant parts of the TIA standards IS-2000.1 to IS-2000.5 [C2-C6], with the radio performance being specified in IS-97 and IS-98 [C7-C8]. The PAMR functionality is achieved using a combination of PAMR application software and hardware, and services and features in the underlying radio access network.

CDMA-PAMR is designed for use for PAMR networks in the frequency bands 410-430 MHz, 450-470 MHz, and 870-876/915-921 MHz. A separation of 1.25 MHz is employed between the centre frequencies of adjacent CDMA-PAMR carriers. The same carrier frequencies can be used by all of the base stations in a network. Power control is employed on both the downlink and the uplink, with a large dynamic range, such that both base stations and mobile terminals in a CDMA-PAMR network are almost always transmitting at output powers that are significantly below the maximum values.

The minimum amount of spectrum required for a wide area CDMA-PAMR network will typically be 2 x 2.5 MHz, plus guard bands (i.e. sufficient to support 2 CDMA carriers), although it may be possible in some circumstances for an initial deployment to use only a single carrier.

A typical application of CDMA-PAMR will be for a wide area PAMR network operated by a network operator and covering the major parts of a country, or region of a country. The number of subscribers for such a network would typically be expected to rise to a few hundred thousand, giving a user density (in urban areas) that is far lower than a typical public cellular network, but higher (on average) than for a wide-area PMR system (although without the concentration of user density exhibited by some localised PMR systems, e.g. those serving a single site or campus).

Services available using CDMA-PAMR technology include, among others:

- Push-to-talk (PTT) voice services
- Group calls
- Dispatch services
- Prioritisation and queuing
- Status and short data messages
- Packet data / IP services
- Simultaneous voice and data
- Dynamic group management
- Over-the-air reprogramming of terminals
- Location services.

Further details of services provided by CDMA-PAMR can be found in [C1]. Some key aspects are highlighted below.

PTT calls in CDMA-PAMR are implemented by means of the PAMR application layer (including PTT server/media controller in the network and client application in the terminals) utilising services and features in the lower layers of the CDMA radio access network. The PTT services are implemented using Voice-over-IP technology in the core network, however specific radio resources over the air interface are dedicated to a call for its duration, and the use of header removal techniques provides for speech frames to be transported over the radio interface in a similar fashion to circuit switched voice. The voice information is transmitted over the air interface using a 9.6 kbps Fundamental Channel.

When a PTT call is initiated, the network sets up the necessary traffic channels (if they are not already active) and the speech information is distributed to the intended recipients by means of a PTT server/media controller using a subscriber database/location server. In order to provide fast call set-up for PTT calls, the PAMR application layer utilises a range of techniques, including specific services and features in the lower layers of the CDMA radio access network. In current implementations, a separate (downlink) traffic channel is required for each user involved in a group call, however the use of broadcast channels for group calls is under development and will allow group calls to be provided in a more spectrum-efficient way in the future.

CDMA-PAMR provides packet data services with a range of data rates up to 307 kbps in the forward direction (downlink) and 153 kbps in the reverse direction (uplink). Data rates up to 9.6 or 14.4 kbps can be supported on a Fundamental Channel that is assigned to a particular user for a data session, but higher data rates are supported by means of Supplemental Channels that can be shared between users. The system can establish multiple Supplemental Channels and support multiple data sessions for a user. Time and rate of data services are controlled by resource management entities/schedulers, which consider factors such as RF conditions, nature and priority of data, data waiting to be sent, last time when a user was served, etc, in order to optimise the use of the available resources. Data rates can be automatically adjusted during data sessions, as appropriate.

A.2. TAPS

The following text is taken largely from the System Reference Document for TAPS [T1] that was approved by ETSI TC ERM in March 2003. Further details of TAPS can be found in EN 301 979 [T2] and TS 101 962 [T3]. TAPS is implemented as an extension of the core GSM specification to include the necessary frequency ranges.

TAPS adapts (E)GPRS technology to provide an overlay network for TETRA systems. TAPS provides high speed packet data at speeds approximately ten times that available in existing TETRA, to support multimedia and other high speed data applications required by existing and future TETRA users. TAPS is also designed to complement the existing V+D services of TETRA.

TAPS is a packet switching data only system, it does not support circuit switched voice or data or DMO. The TAPS standard is designed to cover the bands 380-400 MHz, 410-430 MHz, 450-470 MHz, and 870-876/915-921 MHz. These bands are covered by ERC DEC (96)01 and ERC DEC (96)04 with uplink in the lower half of the band and downlink in the upper half. The duplex separation is 10 MHz for the 400 MHz bands and 45 MHz for the 800/900 MHz band. Channel numbering has been adapted to allow for a flexible frequency allocation within the boundaries of the frequency bands.

The minimum amount of spectrum required for a wide area TAPS network is around 2 x 3 MHz, which is sufficient to provide a single 200 kHz carrier per cell using a re-use factor of 12, plus a small number of additional frequencies for fill-in cells.

In terms of spectrum utilisation in the 400 MHz bands TAPS is capable of a maximum utilisation of 2 x 8 MHz of each 2 x 10 MHz band. This has been achieved by limiting the necessary separation between uplink and downlink frequencies to 2 MHz. The position of the separation may be entirely in the downlink band, entirely in the up link band, or may be spread between the up- and downlink bands. The concept used in the 400 MHz bands has been developed to allow for a flexible frequency allocation rather than a maximum utilisation.

The TAPS (EGPRS) standard includes a range of different modulation and coding schemes, which are listed in the following table, together with the corresponding (nominal) maximum data rates for each coding scheme. These maximum data rates do not necessarily reflect the actual data rates that will usually be available to a user in practice - they essentially represent upper bounds on what can be achieved, assuming that all received errors are successfully corrected by the FEC.

Coding scheme	Modulation	Gross bit rate (kbps per carrier)	Max user data rate (kbps per carrier)	Max user data rate (kbps per timeslot)
MCS-1	GMSK	270.8	70.4	8.8
MCS-2	GMSK	270.8	89.2	11.2
MCS-3	GMSK	270.8	118.4	14.8
MCS-4	GMSK	270.8	140.8	17.6
MCS-5	8-PSK	812.5	179.2	22.4
MCS-6	8-PSK	812.5	236.8	29.6
MCS-7	8-PSK	812.5	358.4	44.8
MCS-8	8-PSK	812.5	435.2	54.4
MCS-9	8-PSK	812.5	473.6	59.2

The first 4 of these modulation and coding schemes (using GMSK modulation) roughly correspond to the coding schemes used in GSM/GPRS (CS-1 to CS-4), which are themselves also included in the TAPS standard. Going up the list of coding schemes using a given modulation (e.g. from MCS-1 to MCS-4) then the level of error protection applied to the user information bits is reduced, and hence the nominal maximum user data rate is increased (although the information bits will generally be received with more errors). The system can select whichever coding scheme is most appropriate, adapting the data rate and level of protection according to the conditions.

A.3. GSM-R

The following text is largely taken from the UIC Project Eirene System Requirements Specification [G1]. The GSM-R system studied in this report is based on the implementation of GSM-R by the European railways, under UIC Project EIRENE.

The GSM-R system is based on the ETSI GSM standard. Many of the basic technical parameters of GSM-R are therefore essentially the same as those of GSM, including GMSK modulation, 200 kHz carrier spacing, and 8 timeslots per carrier. The system is designed to operate in the UIC frequency band 876-880/921-925 MHz. The minimum amount of spectrum required for a GSM-R network is around 2 x 2.8 MHz.

GSM-R supports the current voice and data services in the GSM standard. To meet additional functionality and performance requirements, this standard is supplemented by:

- the following additional GSM services:
  - voice broadcast service;
  - voice group call service;
  - enhanced multi-level precedence and pre-emption;
  - General Packet Radio Service (GPRS);

- railway specific applications:
  - exchange of number and location information between train and ground to support functional and location dependent addressing;
  - emergency calls;
  - shunting mode;
  - multiple driver communications;

- direct mode facility for set-to-set operation (using analogue FM PMR);

- railway specific features, network parameters and standards:
  - link assurance signal;
  - calling and connected line presentation of functional identities;
  - cab radio, man-machine and other interfaces;
  - environmental specifications;
  - controller position functional specifications;
  - system configuration (numbering plans, priority levels, subscriber details, closed user groups, etc).

The system is based on the GSM architecture, and comprises the following elements:

- Base station sub-systems (BSSs) of base station controllers (BSCs) controlling base transceiver stations (BTSs) each containing a number of transceivers (TRXs).
- Network sub-systems (NSSs) interfacing to the BSS via the GSM 'A' interface. The NSS contains mobile services switching centres (MSCs) with primary responsibility for call control. The MSC is supported by a visitor location register (VLR) containing temporary details of subscribers active within the MSC area, a group call register (GCR) containing attributes of voice group and broadcast call configurations for the related MSC area, and home location registers (HLRs) holding subscriber details on a permanent basis.
- General Packet Radio Service (GPRS) infrastructure elements supporting the respective packet radio services, in particular serving GPRS support nodes (SGSNs) and gateway GPRS support nodes (GGSNs).
- Mobile equipment (ME) interfacing to the BSS via the air (Um) interface.
- Subscriber Identity Modules (SIMs) containing information specific to single subscribers.
- Operation and Maintenance Centre (OMC) for managing the network.
- Billing Centre.

Railway networks may also implement a short message service centre to be interfaced to the GSM network in order to support railway specific messaging applications.

A.4. TETRA

TETRA is a trunked digital mobile radio (PMR/PAMR) system. The TETRA standards have been developed in ETSI in order to provide systems that may be used for PMR and PAMR applications, including for emergency services/public safety, other PMR systems, and PAMR networks. The air interface for TETRA V+D (Voice plus Data) is specified in ETSI EN 300 392-2 [T4].

TETRA is designed to operate in the frequency range 300 MHz – 1 GHz, and in particular in the bands that are referred to in ERC Decisions (96)01 and (96)03, namely 380-400 MHz, 410-430 MHz, 450-470 MHz and 870-876/915-921 MHz.

The minimum amount of spectrum required for a wide area TETRA network is around 2 x 2 MHz, however additional spectrum will often be required in practice for a network covering urban areas in order to provide reasonable capacity and quality of service.

The TETRA standards cover a number of interfaces. The main interface used in current TETRA PMR and PAMR networks is the air interface for TETRA V+D (Voice + Data) trunked mode operation (TMO), which is the interface between a TETRA network base station and radio terminals. This is distinct from TETRA Release 2, which includes air interfaces for TAPS and TEDS for high speed packet data. Other interfaces covered by the TETRA standards include:

- Direct Mode Operation (DMO) air interface, to allow terminals to operate in local radio nets independent of the main TETRA network infrastructure.
- Peripheral Equipment Interface (PEI), which provides for standardised connection of a radio terminal to an external intelligent device.
- PSTN/ISDN/PABX interface, to enable TETRA to interface with the PSTN, the ISDN and/or PABXs as required.
- Inter-System Interface (ISI), to allow TETRA network infrastructures supplied by different manufacturers to interoperate with each other.

TETRA V+D is a TDMA system, and uses π/4-QPSK modulation. The carrier spacing is 25kHz, and each carrier is divided into 4 timeslots.

The TETRA V+D standard supports a variety of services and facilities, including:

- Individual speech calls
- Group calls
- Broadcast calls
- Prioritisation and queuing
- Short Data Service (SDS)
- Status messages
- Packet / IP services and circuit data (unprotected up to 28.8 kbps, protected up to 19.2 kbps)
- Simultaneous voice and data
- Dynamic group management
- Various supplementary services.

In addition, TETRA can support the following:

- Dispatch services
- Location services
- Over-the-air reprogramming of terminals.

ANNEX B: RESULTS FROM CDMA-PAMR COMPATIBILITY STUDIES

This annex has been produced to summarise the results from the CDMA-PAMR compatibility studies in CEPT PT SE7, as provided in ECC Reports 38-41. Further details can be found in the ECC reports 38-41.

The compatibility studies have been undertaken by SE7 in accordance with the work programme that was presented to WG SE, which divided the work into the following 4 sub-areas (corresponding to the 4 ECC Reports that were produced for TAPS):

- Impact of CDMA-PAMR on PMR/PAMR systems in the 400 MHz bands
- Impact of CDMA-PAMR on UIC DMO and GSM-R systems in the 900 MHz band
- Impact of CDMA-PAMR on GSM systems below 915 MHz
- Impact of CDMA-PAMR on short range devices below 870 MHz.

The 400 MHz study has investigated the compatibility between CDMA-PAMR and narrowband PMR/PAMR systems in the 410-430 and 450-470 MHz bands, including 12.5 and 25 kHz analogue systems and digital systems including TETRA and Tetrapol. The work has considered in particular the following 4 scenarios:

- Scenario 1, CDMA-PAMR MS into PMR/PAMR MS (at frequencies around the duplex transition frequency, i.e. 420 or 460 MHz).
- Scenario 2, CDMA-PAMR MS into PMR/PAMR BS (at frequencies in the uplink band).
- Scenario 3, CDMA-PAMR BS into PMR/PAMR MS (at frequencies in the downlink band).
- Scenario 4, CDMA-PAMR BS into PMR/PAMR BS (at frequencies around the duplex transition frequency).

In discussing the results of the CDMA-PAMR compatibility studies, it is important to recognise the difference between a guard band and a transition band/separation. A guard band represents spectrum that is left unused between two systems that are using adjacent blocks of spectrum, in order to avoid interference from one system to the other. A guard band is generally required between 2 adjacent systems in both the uplink and downlink bands, e.g. between CDMA-PAMR uplink and narrowband PMR uplink, and between CDMA downlink and PMR downlink. These guard bands are calculated based on the modelling performed for Scenarios 2 and 3 above. The dominant interference mechanism is generally interference to one system as a result of unwanted emissions from the other.

A transition band/separation, on the other hand, is the separation between the downlink band of one system and the uplink band of another (or vice versa) around a duplex transition frequency, e.g. between CDMA-PAMR base station transmissions (downlink) and narrowband PMR base station receivers (uplink) around 420 MHz. A transition separation thus represents a frequency management constraint, where there needs to be a separation between two systems on either side of the transition frequency with the possibility to use the spectrum between for other purposes. The size of the minimum transition separation that is required between 2 systems is calculated based on modelling for Scenario 1 or 4 above. As in the case of other technologies, possible uses of the transition band have not been studied in the CDMA-PAMR compatibility studies. For the considered transition band sizes, the dominant interference mechanism is generally desensitisation of the receiver of one system due to the presence of transmitted power from the other. This manifests itself as blocking, and in some cases intermodulation.

The 400 MHz compatibility study concluded that a guard band of 200 kHz needs to be left between CDMA-PAMR and adjacent narrowband PMR/PAMR systems in both the uplink and downlink bands. This is shown in Figure 1 below.

The 400 MHz study also concluded that a separation of 1.875 MHz is required between CDMA-PAMR downlink band and PMR/PAMR uplink band around the duplex transition frequency at 420 or 460 MHz. This transition separation is less than that envisaged in ECC Report 25, which proposes that the spectrum for CDMA-PAMR systems should be allocated from around the centre of the relevant uplink and downlink bands. The spectrum between the two systems may be used for other purposes (e.g. narrowband PMR/PAMR downlink). A transition separation is also required between CDMA-PAMR uplink band and PMR/PAMR downlink band around the duplex transition frequency (420 or 460 MHz), however the size of this transition separation need not be more than 125 kHz.

Figure 1 below shows an example of how the 410-430 MHz band could be used, illustrating the position of the above-mentioned guard bands and transition separation, and showing a CDMA-PAMR system with other

PMR/PAMR systems on either side. The 410-430 MHz band is taken as an example, with the duplex transition frequency at 420 MHz.

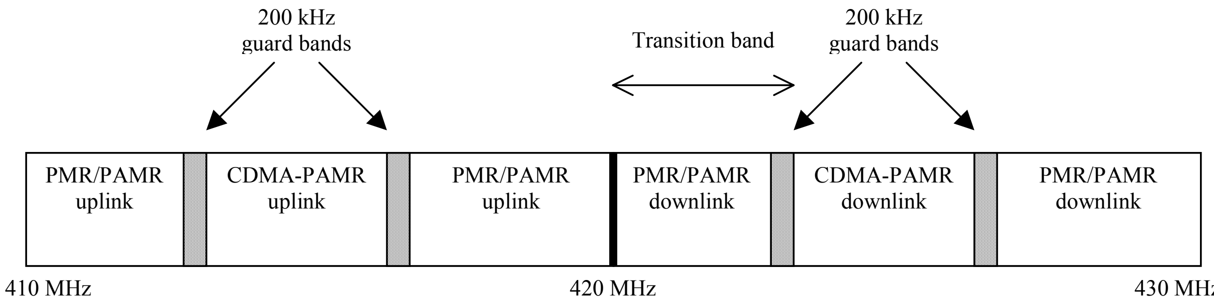

Figure 1

A similar diagram can also be drawn for the 450 - 470 MHz band. Note that the adjacent band above 470 MHz is a broadcasting band.

The UIC study has considered the impact of introducing CDMA-PAMR in the band 870-876/915-921 MHz on UIC DMO and GSM-R radio systems in the band 876-880/921-925 MHz. The study has concluded that a guard band of 125 or 200 kHz is required between the CDMA-PAMR and UIC bands, i.e. in the uplink band around 876 MHz and in the downlink band around 921 MHz. These guard bands are shown in Figure 2 below.

Compatibility between CDMA-PAMR and GSM systems around 915 MHz is concerned with the potential impact of CDMA-PAMR base station transmissions above 915 MHz on GSM base station receivers below 915 MHz. The results of the study indicate that with a transition separation of 2 MHz around the transition frequency the two systems can co-exist, although co-ordination and mitigation for some base stations will be required. The CDMA-PAMR downlink carriers are in practice likely to be deployed within the band 917-921 MHz. As an example for a 3 carrier system the most likely position will be 917.05-920.8 MHz (i.e. 3 x 1.25 MHz channels, with a 200 kHz guard band between CDMA-PAMR and UIC).

The study into the impact of CDMA-PAMR on Short Range Devices (SRD) below 870 MHz has found that the probability of interference to SRD is extremely low. Furthermore, there will in practice be a separation of at least 2 MHz between CDMA-PAMR mobile transmissions and SRD below 870 MHz, as a result of the transition separation between CDMA-PAMR downlink and GSM uplink around 915 MHz.

The spectrum below CDMA-PAMR in the band 870-876/915-921 MHz may be used for other systems, e.g. other PMR/PAMR systems or for military purposes, although such usage has not been studied in detail in the compatibility studies. The guard band required between CDMA-PAMR and such other systems will depend on the other system. For narrowband PMR/PAMR the guard band will be approximately the same as for the 400 MHz band (i.e. 200 kHz), and for TAPS it will be the same as for GSM-R (i.e. 125 or 200 kHz).

Figure 2 below illustrates a general example of how the 900 MHz band could be used.

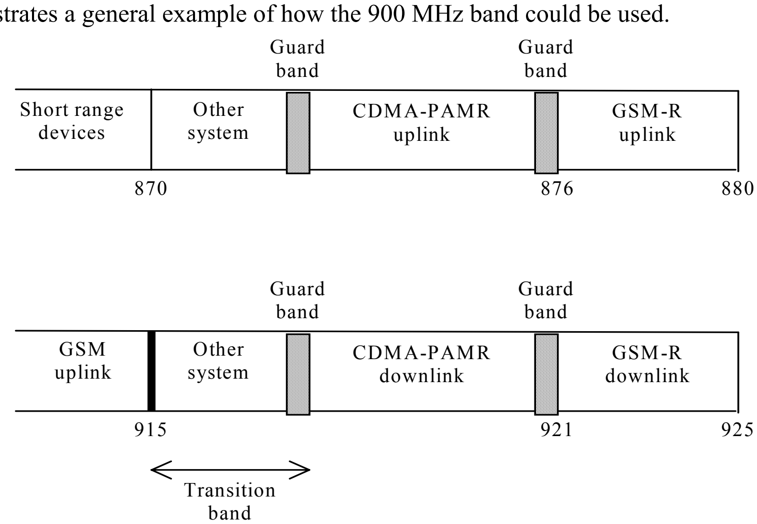

Figure 2