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METHODOLOGY FOR THE ASSESSMENT OF PMR SYSTEMS IN TERMS OF SPECTRUM EFFICIENCY, OPERATION AND IMPLEMENTATION

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1 INTRODUCTION

Spectrum congestion in dense urban areas is a reality in conventional PMR bands, which in most European countries are around 80 MHz, 160 MHz and 450 MHz. In the major European cities, assigning frequencies for new users or extending the capacity of existing networks is becoming a real challenge. Regulatory bodies, PMR system manufacturers and users are aware of this fact and have already acted in different ways in order to confront the spectrum congestion issue. The following 'solutions' have been implemented:

- introduction of data transmission
Many mobile radio speech systems are currently used to send instructions from a base station to the mobile unit, followed by a short acknowledgement from the mobile unit to the base station. For such routine transactions, it appears that the exchange of data is more secure and can be more spectrum efficient than voice communication.

- introduction of trunked networks
Trunking refers to the fact that different users have access to a pool of channels. Spectrum resources and infrastructure are shared with channels being assigned on demand.

These actions have however proved to be insufficient or inappropriate in many cases, and other ways need to be found of optimising the use of the limited spectrum dedicated to PMR applications. The SE23 Project Team (PT) has therefore been requested by the SE Working Group to assess different PMR technologies in terms of spectrum efficiency, implementation and operation.

Due to the lack of time relative to the complexity of the task, this report mainly deals with methods of assessing the spectrum efficiency for PMR networks. The main aim of the report is to provide a methodology whereby the spectrum efficiency of candidate systems can be evaluated. The PT has concluded that it would be better to provide a means of categorisation of systems rather than absolute calculation of their spectrum efficiency. This report therefore identifies the principal characteristics of PMR systems and describes the operational scenarios in which they work, and the limiting factors of each of these scenarios. A methodology is presented whereby the spectrum efficiency of candidate systems can be evaluated for the various scenarios. General system limitations, general methods by which spectrum efficiency can be improved and operational factors such as introduction of systems into the spectrum are discussed. The report contains tables giving technical parameters relevant to spectrum efficiency calculations of various general and proprietary analogue and digital PMR systems, and contains the results of these calculations. A worked example is provided, using the reference technology, 25 kHz PM.

2 SCOPE OF THE REPORT

The report deals with professional or private mobile radio (PMR) which is clearly distinct from public radiotelephone (e.g. GSM).

The operational needs of public radio telephone subscribers are very different from those of most PMR users. For instance, important requirements that cannot be satisfied by the public radiotelephone system are, among other things, fast channel access, direct mobile-to-mobile communication, open channel and flexible group organisation - with various possibilities of individual and group calling facilities.

3 DEFINITIONS, ACRONYMS & TABLE OF SYMBOLS

3.1 Definitions

Dual Frequency Operation: A dual frequency system is one where a pair of frequencies is used for transmitting and receiving. e.g. a base station transmits on one of the frequencies (this is also the mobiles' receive frequency) and receives on the other (the mobiles' transmit frequency).

Duplex: A Duplex system is one where any party has the capability to receive and transmit at the same time. e.g. a telephone system.

Gross bit rate: The inverse of the duration of each transmitted bit. It is therefore the theoretical maximum transmission rate since it does not account for guard times (TDMA), frame synchronisation, error correction, etc.

Unprotected bitrate: defined as being equal to the total number of usable bits transmitted per unit time per traffic channel. It thus accounts for the guard time between TDMA slots and includes any bits used for synchronisation and other overheads.

Network controlled mode: network controlled use of a centrally defined channel (which may include frequency and time information).

Direct mode: channel usage independent of a centrally defined channel.

Protected bitrate R_{BN}**:** the number of bits containing useful information transmitted per unit time per traffic channel. It excludes bits used for error correction, synchronisation, equalisation etc.

PAMR: Public Access Mobile Radio:
provides PMR type services to different users usually on a subscription basis, mostly on trunked network systems. Historically, connection to the PSTN may have been limited by regulatory action. Extensive connection to the PSTN and the corresponding range of services may be available in the future due to the liberalisation of connection (regulatory).

PMR: Professional or Private Mobile Radio:
is intended for business operations, a PMR network is operated on a 'closed user group' basis. PMR is designed for short call holding times which enables a large number of users to be accommodated within a particular frequency allocation.

Public radiotelephone (GSM, DCS1800...)
Public radiotelephone provides point-to-point mobile telephone services with full connection to the PSTN.

Repeater: A repeater is a **Duplex** device that receives a radio signal and re-transmits it on either the same or on a different frequency. It can be used in simplex, half-duplex or full duplex systems.

Semi or **Half-Duplex mode:** Semi or Half-Duplex mode is where for instance, a base station can receive and transmit at the same time, but the mobile units responding cannot, e.g. a dispatch operation.

Simplex mode: Simplex mode is where no party can receive and transmit at the same time.

Single Frequency mode: Single frequency mode is where all radio transceivers transmit and receive on the same frequency.

Typical combinations of the above include **Single frequency Simplex** operations, such as a low power hand held ‘walky talky’ set up and **Dual frequency Semi-Duplex** operations utilising a **Repeater** to connect one mobile unit with any number of other mobile units on the same system.

3.2 Acronyms

APCO	Association of Public Safety Communications Officers (US)
CDMA	Code Division Multiple Access
DCS 1800	Digital Communications System (operates at 1800 MHz)
DECT	Digital Enhanced Cordless Telecommunication
DMO	Direct Mode Operation
DPMR	Digital PMR

DQPSK	Differential Quadrature Phase Shift Keying
DRX	Discontinuous reception
DTX	Discontinuous transmission
ETS	European Telecommunications Standard
ETSI	European Telecommunications Standards Institute
FDMA	Frequency Division Multiple Access
FM	Frequency Modulation
FSK	Frequency Shift Keying
GMSK	Gaussian Minimum Shift Keying
GSM	Global System for Mobile (Communications)
iDEN	integrated Dispatch Enhanced Network
MOS	Mean Opinion Score
PABX	Private Automatic Branch Exchange
PDO	Packet Data Optimised
PM	Phase modulation
PSK	Phase Shift Keying
π/4-DQPSK	π/4 Differential Quadrature Phase Shift Keying
PSTN	Public Switched Telephone Network
RF	Radio Frequency
RTC	Radio Traffic Channel
RVE	Reference Vector Equalisation
TC RES	Technical Committee on Radio Equipment and Systems (of ETSI)
TDMA	Time Division Multiple Access
TETRA	Trans European Trunked Radio
VAD	Voice Activity Detection

3.3 Table of symbols

α	Propagation exponent
$B_{M98\%}$	Modulation bandwidth (denotes bandwidth containing 98% of transmitted power)
B_{RX}	Receiver acceptance bandwidth
B_{Syst}	System bandwidth
B_{TX}	Modulation bandwidth of the transmitter, typically for -60 or -70dBc
$(C/I)_D$	Dynamic carrier to interference ratio
$(C/I)_S$	Static carrier to interference ratio
δf_{RX}	Receiver frequency tolerance
δf_{TX}	Transmitter frequency tolerance
ΔF_c	Carrier separation
η_I	Spectral efficiency of interference limited systems
η_N	Spectral efficiency of noise limited systems
N_A	Access factor
N_C	Cluster factor
N_I	Number of radio traffic channels in interference limited systems
N_L	Load factor for system
N_{LI}	Load factor of interfering cells
N_M	Mode (of operation) factor
N_N	Number of radio traffic channels in noise limited systems
R_{BN}	Protected bit rate (net bit rate)

4 MAIN CHARACTERISTICS OF PMR

4.1 Limiting factors

PMR systems differ widely in the number of users, the service area, the traffic density and operational requirements. Some are limited by noise (coverage), some by co-channel interference caused by frequency reuse and some by a combination of these two and/or additional phenomena (see 5.2, 5.3 & 5.4). Measures of frequency efficiency are different in these cases.

4.2 Planning difficulties

Demand for frequency resources for PMR is difficult to predict. Thus in practice the 'first come first served' method is applied in many cases. The cellular approach, which is usually adopted for public radiotelephone networks, (GSM, DCS1800 ...), and associated spectrum optimisation methods may be used for interference limited PMR networks. Such geographical lattices are in use for PMR frequency assignment procedures in several European countries.

However, in dense conurbations, the demand for frequencies, particularly for self provided systems, is such that planning based on geographical lattices cannot be easily applied. Each base site will cover an area containing a large number of potential users. With high demand for and limited availability of channels, this will result in two or more uncoordinated networks with roughly the same coverage areas or with overlapping coverage areas having to share the same frequencies. This sharing is possible when there is infrequent usage by users of one or more of these networks, or when message lengths are short, i.e. when traffic levels from any one network are not sufficient to fully load the channel and sharing does not result in heavily overloaded channels.

Usually it is accepted that one frequency can be shared by approximately 100 users distributed between 3 or 4 networks. In some cases it is possible to accommodate more than 600 users. Sharing of frequencies by many uncoordinated networks is possible with good access protocols (manual or automatic). These access protocols may be the determining factor for efficient use of spectrum.

4.3 Variety of network types

Due to the wide range of requirements of PMR users, network configuration and type of use differ greatly from one network to another. Moreover, in order to deal with frequency congestion, spectrum efficiency may not always be the relevant criterion on which to focus. For instance, a fund transportation company with around 1000 mobiles will have far less efficient spectrum usage measured in Erlang/($km^2 * Hz$) than a taxi company. Consequently, PMR networks need to be classified in the following categories:

a) **on site systems** of up to 3 km radius
These systems are generally set up inside commercial or industrial buildings or yards, but can cover wider areas such as those required by e.g., quarry or mining companies. Their basic requirements usually cannot be satisfied by wireless PABXs, such as DECT or CT2, for operational reasons. The number of terminals and their mobility is limited. Frequencies are often geographically reused by different networks.

In practice, there is no frequency co-ordination.

b) **urban and suburban networks** with radii from short distances to 20 km or more covering an urban area.
Large urban area coverage is one of the requirements of many organisations, such as taxi companies, ambulances, messengers, police, public transport etc.

For PMR systems, the availability of large cells is fundamental because of
- low traffic density (compared to cellular public radiotelephone)
- half duplex and group calls
- cost of infrastructure
- no hand-over facilities (generally)
- simple location and switching facilities.

Within the frequency bands used by PMR systems, networks can achieve urban wide area coverage with a limited number of cells. Therefore, the optimisation of spectrum use is more closely associated with the available number of communications per time in a given area with independent networks than with the geographical reuse of a given frequency.

The network may be interference limited or noise (coverage) limited or both. In the former case, frequency co-ordination is beneficial, but in practice it is not always possible due to the high demand for channels in urban areas.

c) **rural networks** with radii ranging from a few km to several tens of km.
These are generally 'coverage limited' and require cells covering as large an area as possible with generally only low traffic capacity requirements. Spectrum efficiency cannot be considered an important issue in this case as no spectrum congestion is expected.

4.4 Operational scenarios

PMR voice traffic may be dispatch (group calls involving multiple mobiles) or individual calls (one unit in communication with one other unit). Spectral efficiency is clearly enhanced by dispatch operation, the gain being dependent on the number of units covered by one site and being involved in one call.

Typical system configurations may affect the efficient use of a channel and are summarised as follows:

a. Single frequency simplex operation, in which users share the channel resources. Selective calling may or may not be implemented so that individual calls and group calls are possible.

b. Dual frequency half duplex and duplex operation without repeaters. Essentially the considerations are similar to a. above, except for a doubling of the bandwidth required.

c. Trunked or non-trunked dual frequency operation with repeaters. Typically such systems are multi-site and may allow network-wide group calls. Many multi-site systems do not allow traffic on unused uplinks or downlinks during inter-site calls.

d. Direct Mode operation. In this case, single frequency simplex mode communication takes place between mobiles outside the central control of the network. In digital direct mode systems employing either TDMA or FDMA techniques, the specific problem of reliable transfer of synchronisation information between mobiles in a communication group must be overcome. In direct mode systems employing TDMA techniques, support of more than one communication channel per radio frequency carrier is much more difficult because it requires that specific factors relating to inter channel synchronisation be resolved. The TETRA system is believed to be the first TDMA system to propose direct mode communication - future TDMA systems may also include DMO.

It is important to include data in the available operational scenarios. Efficient protocols can optimise channel use (e.g. by minimising channel occupation and losses), particularly where packet switched techniques are used such that rapid channel sharing is possible.

5 OPTIMISING RADIO SPECTRUM RESOURCES

5.1 General considerations

Optimising radio spectrum resources is a pressing issue especially in relation to 4.3a and 4.3b, where congestion frequently occurs.

Parameters in assessing the spectrum efficiency are:

- geographical reuse of a given radio channel and of the adjacent radio channels
- type and quantity of information per traffic channel
- number of RF carriers (radio channels) in a given amount of spectrum
- number of traffic channels per RF carrier.

In a public cellular system, the number of radio channels to be activated for a call is equal to the number of mobiles involved in that call and is thus independent of the number and size of cells. The number of cells needed is determined by the cell size and the size of the service area of the whole system. The cell size itself may be traffic or coverage limited. The cellular lattice is more or less regular and permits a regular reuse of radio frequencies with a cluster size dependent on the propagation conditions and equipment performance. Therefore this number is independent of the size of each cell.

In contrast to the full duplex service offered by public cellular networks, PMR offers essentially half-duplex services - i.e. during a call only one participant is talking (transmitting) at a time with all the others listening (receiving). Consequentially, in PMR, group calls (or conferences, or open channels) are more common, easier to implement and more spectrally efficient than in cellular.

In a PMR system however, the number of activated channels is equal to the number of cells involved in the coverage of the call independently of the number of participating mobiles. Therefore the larger each cell is, the more spectrally efficient the system is (less channels to be activated per call). However, frequency reuse can then become more limited, which can affect the frequency economy adversely. The sensitivity of the receivers is therefore an important parameter for cell dimensioning and has a major influence on the spectral efficiency of such systems. The coverage depends on the link budget and therefore also on the transmitted power which, however, is limited by the power consumption, regulatory requirements, spurious emission limitations and technological, ergonomic and economical constraints.

In conclusion, the type of traffic or, more precisely, the mode of operation also has an important influence on the spectrum efficiency. If point-to-point links are compared to point-to-multipoint links, which are to be found in a high percentage of the total traffic within a PMR system, the latter show a considerable spectrum efficiency improvement. The main reason is that in such cases more than one subscriber is served in parallel.

The evaluation of the spectrum efficiency of a given system is a difficult task when all the influencing factors of complex real systems have to be taken into account. However, for basic types of systems, the spectrum efficiency can be evaluated without unreasonable difficulty and therefore basic system comparisons are possible. If necessary, additional features and their influences can be added step by step, e.g. VAD with DTX and DRX, and their additional benefit can be evaluated.

Finally it is not necessary to calculate the spectrum efficiency to extreme precision but rather to categorise systems to be compared. Taking analogue 25 kHz systems as a yardstick, the categorisation might be:

A : 0.5 to 1.5 times the reference spectrum efficiency
B : 1.5 to 2.5 times the reference spectrum efficiency
C : > 2.5 times the reference spectrum efficiency.

This offers an opportunity to pre-select systems with comparable spectrum efficiency from a range and to base the final choice of system on other important factors like coexistence properties, economic considerations, migration strategies, frequency management problems and various others.

The evaluation tools for the fundamental types of PMR systems are given in the following clauses. All equations are taken from reference [2].

5.2 Noise or coverage limited systems

The first type of basic system is the noise or coverage limited system. It is characterised by the fact that, for a given transmit power, the coverage achieved is maximum, being limited only by thermal and man-made noise and natural propagation conditions and not by any significant level of interference. This type of system is generally characterised by low traffic densities with the consequence that capacity and frequency efficiency are generally not limiting factors.

An appropriate basic measure of spectrum efficiency in this case could be the number of radio traffic channels (RTC) per given bandwidth in RTC/MHz or the ratio of the net bit rate to carrier separation in (bit/s)/Hz. The number N_N of traffic channels in noise limited systems depends on the system bandwidth B_{Syst}, the carrier separation ΔF_c, the access factor N_A and the mode factor N_M and provides the theoretical upper bound of the available radio capacity:

$$N_N = \frac{N_A \cdot N_M \cdot B_{Syst}}{\Delta F_c} \qquad \text{[RTC]} \qquad (1)$$

where $N_A = \begin{cases} 1 \text{ for FDMA} \\ >1 \text{ for TDMA (and CDMA)} \end{cases}$

and $N_M = \begin{cases} 1.0 \text{ for single frequency simplex operation} \\ 0.5 \text{ for 2 frequency simplex operation with and without repeater and 2 frequency full duplex operation without repeater} \\ 0.25 \text{ for 2 frequency full duplex operation with repeater employing 4 frequencies} \end{cases}$

The system bandwidth B_{Syst} is the overall bandwidth including up and downlink, repeater feeder links etc. The access factor N_A describes the number of traffic channels per carrier; in TDMA trunked systems with a proportion of traffic between unsynchronised mobiles, the number of usable time-slots per carrier may be reduced. The mode factor N_M takes into account the mode of operation. With these definitions it is assumed that the temporarily unused radio capacity during a conversation, e.g. the reverse channel in duplex systems, is not used for other purposes. This might not be true in particular cases, e.g. packet radio systems. In these cases, N_M is increased above its conventional system value.

Without trunking only a limited percentage of the available radio capacity can be used in practice and even with efficient trunking methods the efficiency of channel usage is well below 100%. However, trunking is applicable to all mobile radio systems and thus can be disregarded in the comparison method. It should also be noted that the use of omnidirectional antennas in the base stations as well as in the mobiles and a uniform distribution of the mobiles is assumed.

The interrelation of modulation bandwidth B_M and carrier separation ΔF_c should also be considered:

$$\Delta F_c = 0.5 \cdot (B_{RX} + B_{TX}) + \delta f_{RX} + \delta f_{TX} \geq B_M \qquad (2)$$

δf_{RX} and δf_{TX} are the frequency tolerances of the receiver and transmitter which are often negligible compared to the modulation bandwidth. Generally the modulation bandwidth B_M is identical to the receiver modulation acceptance bandwidth B_{RX} and denotes about 98% of the transmitted power. In special cases the receiver pass bandwidth may be smaller than the modulation bandwidth but then distortions have to be expected and compensated. In other cases the receiver centre frequency tolerance is not explicitly taken into account because it is already included in the receiver pass bandwidth. B_{TX} is the modulation bandwidth arising from the transmitter, defined as including all modulation products attenuated by less than a certain amount from the level of the carrier. When considering channel separation, the value of B_{TX} to be taken is that related to the -60 dBc or -70 dBc points, since, particularly for simplex systems, is it important that receivers are protected from excess adjacent channel power. Using Carson's rule, the maximum possible transmission modulation bandwidth is 16kHz for a 25kHz system, derived using the peak frequency deviation at the maximum modulating frequency - 5kHz and 3kHz respectively for 25kHz systems. The -60 or -70dBc bandwidth is approximately twice the Carson bandwidth. Neglecting tolerances, equation (2) results in a carrier separation of 24kHz. In the limits sometimes the transmitter's frequency tolerance may also be included. It should be noted that for constant envelope FM and PM systems $B_M \ll B_{TX}$ is valid while for linear modulation schemes, e.g. π/4-DQPSK as used in TETRA, $B_M \approx B_{TX}$ is valid. Lastly it should be noted that for systems with strictly separated frequency bands for up- and down-link, the system design may be based on $B_M \approx B_{TX}$. All these general considerations are also valid for systems which are not solely noise or coverage limited.

With digital transmission the frequency efficiency for noise limited systems could be defined straightforwardly:

$$\eta_N = \frac{R_{BN} \cdot N_A \cdot N_M}{\Delta F_c} \qquad [\text{(bit/s)/Hz}] \qquad (3)$$

Since various trade-offs can be made between coding rate or gross bit rate R_{BG} and modulation bandwidth, the only measure of interest therefore is the net bit rate R_{BN} per traffic channel.

It should be noted that in coverage or noise limited systems, an increased link budget (the difference between the radiated transmitter power and the minimum permissible receiver input level, or receiver sensitivity) leads to an increase in coverage and thus a reduction in the system costs per user and km^2 provided the system remains unsaturated. However outside congested areas and for systems with spare capacity, the spectrum efficiency is of minor interest.

5.3 Interference limited systems

The second type of basic system is limited mainly by co-channel interference as a consequence of frequency reuse under natural propagation conditions. This type of system is generally characterised by high traffic densities and high overall capacity which can be achieved by frequency reuse to cover a large area composed of a large number of radio cells. In such systems, additional attention has to be paid to adjacent channel and intermodulation interference.

An appropriate basic measure for spectrum efficiency in this case should take into account the frequency reuse cluster size and could be the number of traffic channels per given bandwidth and per cell in RTC/(MHz * cell) or the net bit rate per cell to carrier separation in (bit/s)/(cell * Hz). The number N_I of traffic channels in interference limited systems depends on the system bandwidth B_{Syst}, the carrier separation ΔF_c, the access factor N_A and the mode factor N_M and additionally the cell cluster size N_C and gives the theoretical upper bound of the available radio capacity:

$$N_I = \frac{N_A \cdot N_M \cdot B_{Syst}}{N_C \cdot \Delta F_C} \quad \text{[RTC/cell]} \qquad (4)$$

where $N_C = a^2 + a\,b + b^2$ (5)

a and b being integers ≥ 0. This is valid for the case of regular, isotropic, homogeneous, hexagonal cells. In other cases, N_C can take other integer values.

The access factor N_A and the mode factor N_M are defined as in sub-clause 5.2. The cell cluster size N_C depends on the propagation conditions as described by the propagation exponent α and the dynamic carrier to interference ratio $(C/I)_D$.

Normally the cluster size $N_C >> 1$. In most PMR systems, the range is about $9 \le N_C \le 19$. In the case $N_C = 1$, the frequency efficiency of interference limited systems becomes identical to that of noise or coverage limited systems. (For CDMA the cluster size is generally defined as the ratio of the maximum number of available channels per cell in a monocell system to the maximum number of available channels per cell in an infinite uniformly loaded multicell system. It is claimed that this ratio lies between 1.5 and 2.0)

For heavily loaded systems with strong co-channel interference and $\alpha = 4$, the number of channels can be expressed using $(C/I)_D$ instead of N_C.

$$N_I = \frac{N_A \cdot N_M \cdot B_{Syst}}{\Delta F_C \sqrt{(2 N_{LI} / 3) \cdot (C/I)_D}} \quad \text{[RTC/cell]} \qquad (6)$$

N_{LI} is the average load factor of the interfering cells. If these belong to the same system then $N_{LI} = N_L$ can be assumed. The load factor $N_L = 0...1$. In congested areas $N_L = 0.3$ may be taken for non-trunked systems while an estimate of $N_L = 0.7$ might be more appropriate for very heavily loaded trunked systems with a large number of available traffic channels. All these considerations need great care and the results may vary from case to case particularly when mixed scenarios have to be evaluated.

In most PMR systems $\alpha = 3.5$ is a more correct assumption but then the formula becomes much more complicated without giving significantly different results in the case of rough system comparisons. For absolute figures the formula is:

$$N_I = \frac{N_A \cdot N_M \cdot B_{Syst}}{(\Delta F_C / 3) \cdot [(6 N_{LI}) \cdot (C/I)_D]^{2/\alpha}} \quad \text{[RTC/cell]} \qquad (7)$$

It should be noted that $(C/I)_D$ is the carrier to interference power ratio under fading conditions including shadowing. This means that fading and shadowing, which are very dependent on the propagation conditions, have a great influence on $(C/I)_D$ and reuse distance and consequently on the spectral efficiency. However, if different systems are compared under identical propagation conditions then all these factors generally have only small or negligible influence. For the purpose of the calculations used in these comparisons, only fading has been taken into account, because $(C/I)_D$ for most digital systems is known and can be estimated easily for analogue systems [2] .

Using digital transmission the spectrum efficiency η_I for interference limited systems also has to take the cluster size into account:

$$\eta_I = \frac{R_{BN} \cdot N_A \cdot N_M}{N_C \cdot \Delta F_c} \quad \text{[(bit/s)/(Hz * cell)]} \qquad (8)$$

Again only the net bit rate R_{BN} per traffic channel is of interest.

5.4 Other system limitations

There are additional system limitations. In contrast to the limitations above which are based on hard physical facts, the limitations referred to hereafter are by nature 'soft facts' and can be overcome with increased technical effort. Some of the limiting factors affect simulcast systems more than normal systems, requiring exceptional care to be taken in such cases.

Delay limited systems exhibit a poor ratio of burst to guard time which is a problem associated with TDMA but not with FDMA. For large coverage areas and long signal travelling times therefore the duration of guard time and burst ramping time must be shortened in order to improve efficiency if the burst time cannot be made longer. The guard time can be considerably shortened if time advance methods are introduced. This means that the mobile transmits its bursts with varying time advance compared to the received base station TDMA frame to compensate for varying signal propagation times. However, the guard and ramping times together cannot reasonably be made shorter than the delay spread as determined by the multipath propagation conditions.

Dispersion limitations occur when intersymbol interference is introduced by multipath propagation conditions. This occurs when the delay spread exceeds a considerable percentage of the symbol duration. Obviously this becomes very critical when half the symbol time is approached. However, this limitation can be overcome by equalising methods where each burst contains a well-known training sequence from which the channel propagation conditions can be calculated and be used to restore the unknown message symbols. The necessary effort is generally significant.

Depending on the type of modulation and the bandwidth the Doppler spread may also limit system performance if it is not negligible compared to the modulation bandwidth. Here again suitable equalising methods might be applied to overcome this problem, requiring additional effort.

Bandwidth on Demand
As mobile and data applications become more prevalent in mobile communication systems, the ability to support increased data rates will become more important. TDMA systems can provide enhanced data capabilities by allocating additional capacity to users when required to increase the data rate available within the same channel separation. For example, in TETRA, a user employing one time-slot can have an unprotected data rate of 7.2 kbps, the same user however can be allocated all 4 time-slots thus providing a 28.8 kbps unprotected data rate capability within a 25 kHz carrier separation.

This may also be possible with FDMA systems if they have contiguous channels.

This feature requires specific terminals with extra processing and transmission mean power capacity.

5.5 Mixed scenarios

In many real systems, a combination of interference and coverage limitations may be observed. In this case, the appropriate measure for spectrum efficiency is a function of the type of services. For group calls, it is desirable to ensure as many members of the group as possible are in the same cell and thus coverage limited systems seem preferable; for individual calls with a fixed party, the interference limited approach seems more suitable.

Moreover, with the advent of new technology, using FDMA techniques to split the radio resource from 25/20/12.5 kHz channels into for instance 12.5/10/6.25/5 kHz channels, or using TDMA techniques to split the radio resource into time slots can be ways to provide extra capacity i.e. a greater number of physical channels per MHz and cell than is available with conventional old technology. In addition, it may be more economical and more spectrally efficient for a small user group with low traffic requirements to subscribe to a national or regional PAMR system rather than invest in a self-provided system (PMR).

5.6 Methods for the improvement of spectrum efficiency

For a basic given system, the spectrum efficiency can be further improved. This is directly possible by the introduction of trunking techniques. Methods such as voice activity detection (VAD), discontinuous transmission (DTX), transmitter power control and in a limited sense also discontinuous reception (DRX) reduce interference directly or at least reduce its appearance in the receiver. This makes additional capacity available which can be used to carry additional traffic. Improved coding, interleaving, equalisation and detection with improved data compression techniques will also result in improved spectrum efficiency.

Since most of these methods are applicable with similar results to all systems, they need not necessarily be taken into account for the purpose of the evaluation of basic systems, for which the theoretical maximum possible spectrum efficiency should be evaluated assuming for comparison purposes that one single frequency simplex channel provides the capacity of one radio traffic channel (RTC).

Concerning the influence of the multiple access mode, FDMA or TDMA, on the spectrum efficiency of PMR systems, the two parameters 'net data (or information) rate to channel separation ratio' and 'limit of the dynamic signal to interference ratio' are, in the first approach, the same for the two modes of access provided identical modulation schemes, but different symbol lengths, are used, with perhaps a small advantage in favour of FDMA which is less sensitive to distortions due to multipath propagation. Instead of the ratio 'net data rate to modulation bandwidth', which is a precise theoretical measure, the ratio 'net data rate to channel separation' is more relevant for real systems because this also reflects operational requirements among other things.

However due to the specific configurations (relatively small coverage) and the specific services (group calls, half-duplex operation) of PMR with respect to public radiotelephone networks, the potential for achieving the largest possible individual cell coverage is an important factor for increasing the efficiency of the radio systems and decreasing the cost of the networks. All other things being equal, in particular for the same transmitter peak power and with the same modulation and coding schemes, a FDMA system (one channel per carrier) will provide wider coverage than a TDMA system (several channels per carrier). However, if the average power per traffic channel is the same, the coverage will be the same; provided all other parameters are kept the same. When the density of traffic is low or irregular and the system is coverage limited, FDMA is more flexible and efficient than TDMA for PMR applications.

6 OTHER CONSIDERATIONS

Not all of the parameters of a radio transmission system are relevant for spectrum efficiency. However they must fulfil the user needs and some of them must be taken into account when comparing systems, e.g.:

- Doppler effect

If the Doppler degradation of a highly spectrum efficient system is bad, then this system may be useless for mobiles travelling at high speed.

- C/I

If the C/I of one system is much better than that of another, this may have additional benefits in a multipath propagation environment, where this may permit considerable reduction of radio channel equalisation needs.

- channel access

It is not believed possible to increase the capacity of spectrum to the extent that radio channels can be made available on an exclusive basis in dense urban areas, thus channels must be shared. The protocols for access to shared channels will affect the overall efficiency of the use of spectrum.

- adaptation to the PMR environment, robustness, ease of implementation

It is necessary to examine the feasibility of implementation of new techniques in the PMR environment. Whereas public radiotelephone operators are able to invest in order to have good sites, PMR users generally have to install equipment without close consideration of site engineering dependent radio parameters (intermodulation due to non-linearity etc.). The technology must be easy to implement and use, whilst being robust and cost effective.

- functionality

PMR users historically have not usually needed elaborate functionality and features from their systems. When comparing different systems, one must be aware of the difference in functionality offered. For example, the functionality of analogue and digital speech transmission may be very different. Advanced PMR systems make use of digital voice transmission which provides on average a superior speech intelligibility and quality compared to conventional analogue speech transmission. Digital voice transmission also permits privacy by encryption which can be more easily implemented and is much more secure than is the case with analogue systems. Additionally all kinds of data transmission are possible ranging from short pre-coded messages to more demanding requirements like text and data files and even pictures. For special applications, the technology allows the possibility of slow motion video with limited resolution.

- digital versus analogue: other considerations

For comparing analogue systems, the static C/I has to be replaced by the dynamic value giving a sufficient speech quality which for example can be expressed as MOS (mean opinion score). For comparing digital systems with analogue, the same overall speech quality measure, e.g. MOS, should be used for the evaluation of spectrum efficiency. This means that any individual comparison between different codings, interleavings, types of modulation, voice coders' performance etc. is of no interest for the user because the only real awareness is of the overall speech quality. The same is true for comparisons between digital voice transmission systems, however an improved codec with reduced bitrate may allow for an improved frequency efficiency independent of the type of modulation. Similarly, for data transmission, only the net bit rate is of interest for the user.

- fragmentation of the market

A choice of technology should be available for all types of PMR networks. It would not be desirable to have too many different technologies dedicated to a specific market. So, it is necessary to examine all parameters before adopting a basic standard acceptable to PMR users.

- market trends

There is a move towards very large shared networks in both Public Safety and PAMR. In PAMR, traditional users such as the Utilities and transportation companies may move towards "out-sourcing" as a more cost effective solution than private procurement.

- regulatory

The eventual adoption of spectrum pricing combined with encouragement to utilise out-sourced communications solutions could encourage efficient use of the spectrum.

7 STATE-OF-THE-ART

7.1 Summary of characteristics

The following paragraphs list some of the characteristics which, in whole or in part, generally describe and define current state-of-the-art PMR technologies. System specific parameters are not described as the purpose of this document is to give a general, unbiased, overview of all current/future PMR technologies. The list is neither exhaustive, nor given in a particular order.

- Narrow Band Technology

A technique which occupies less spectrum per traffic channel by operating on narrower RF channels, subdividing the existing channels in the available finite spectrum resource, yet which provides better spectrum efficiency than that available with conventional technology.

- TDMA

A technique which can result in greater spectrum efficiency. The radio resource is split by multiplexing (in the time domain) several traffic channels (time slots) in a single physical RF channel. This is more efficient than conventional technology when the number of channels per MHz and cell is greater.

- Digital Modulation and Coding

Digital modulation and coding techniques provide security, more consistent reception quality and performance and are appropriate for the transmission of data and other non-speech applications. Examples of such digital modulation techniques are QPSK and GMSK.

Systems are considered to represent state-of-the-art if they meet the spectrum efficiency requirements for category C in section 5.1. This corresponds to >2.5 times the spectrum efficiency of 25kHz FM.

7.2 General properties of current PMR systems

This section contains a collection of the main parameters and characteristics of PMR systems currently in use or just being specified.

Concerning speech transmission, the codec properties and bit rates have considerable influence on the spectrum efficiency. For comparisons of different systems employing analogue or digital transmission an appropriate measure for the speech transmission quality and intelligibility has to be chosen. One candidate might be MOS but it should be noted that comparisons of the results obtained in different investigations are critical, e.g. the accuracy and reliability of such comparisons are somewhat limited.

The technical parameters in Tables A1 and A2 are taken from the relevant ETSI standards or from the system documentation or simulation results provided by the manufacturers of proprietary systems. Footnotes give additional information where this is necessary.

7.3 PMR system properties of relevance for spectrum efficiency

In order to give a better overview of properties related to spectrum efficiency, the relevant system properties are compared in Table B. Estimates of spectrum efficiency of these systems for application in noise or coverage limited environments and interference limited environment are given in Table C. For ease of comparison, N_M is set to 0.5 for the reference technology, and for the other systems is set to the value assumed to be most appropriate in each case - with the exception of TETRA DMO this is also 0.5, corresponding to the value for PMR systems operating in half duplex mode without connection to the PSTN. Additionally B_{Syst} is always set equal to 1 MHz for comparison purposes.

Frequency engineering and management must in real life take into account additional effects like interference by adjacent channels, intermodulation, blocking, spurious emissions and responses, transmitter wideband noise and harmonics etc. However, for first basic system comparisons, these effects can be regarded as having lesser importance.

7.4 Use of TDMA and FDMA for PMR applications

For PMR systems with low traffic density and where low infrastructure cost is of main importance, FDMA systems are best suited due to their better sensitivity performance (larger cells) and smaller RF carrier separation.

If cell size needs to be small in order to accommodate medium to high traffic density, a TDMA approach might be more appropriate for the reasons of reduced individual base station cost and smaller cell size due to the need for channel reuse. FDMA and TDMA are more appropriate for PMR applications.

7.5 Spread Spectrum Techniques

Spread spectrum techniques (e.g. CDMA) might also be considered for PMR systems. However, due to particular modes of operation, e.g. open channel, flexible group formation and reorganisation and direct mode, particular problems have to be solved. Moreover CDMA requires fast and precise power control for the uplink with an accuracy of about 1 dB, while the dynamic range must be 80 to 100 dB in typical PMR cases, in order not to limit the system capacity. Very precise synchronisation of all base and mobile stations is needed which is difficult for some operational cases typical for PMR e.g. direct mode without involvement of the base station. All these reasons make it very difficult to apply CDMA to PMR.

Lastly due to the large bandwidth of the spreaded modulation and the carrier separation of one to several MHz, CDMA is not well suited to PMR, especially if only limited traffic capacity is needed, because all existing PMR frequency allocations are based on narrowband applications and new unoccupied frequency bands are not available for this purpose.

7.6 Additional possibilities

Under certain circumstances, the requirements of the PMR market could be met by new or existing systems, e.g. GSM 2+, GSM-R and UMTS. In these systems, combinations of known modulation schemes and access techniques are used. Such systems would need dedicated spectrum.

8 SYSTEM EVALUATION AND COMPARISON

For the evaluation and comparison of different systems, some basic parameters of the systems in question are needed. These have been collected for current PMR systems, DPMR systems which are currently in the standardisation process and also some proprietary DPMR systems. The basic parameters for these systems are to be found in Tables A1 and A2. These tables give a general system overview and therefore contain more parameters than are needed for the evaluation of the spectrum efficiency. Table B lists all those parameters needed for the evaluation of spectrum efficiency and Table C contains the results.

In order to make the evaluation method and the results more transparent, the methodology is first applied to current analogue PMR systems, using a channel separation of 25 kHz. The result will then be used as a yardstick against which other systems can be compared.

For noise or coverage limited systems, the calculations are based on formulae (1) and (3).

For PM25, with B_{Syst} = 1 MHz, ΔF_C = 25 kHz, N_A = 1 and N_M = 0.5 (i.e. 2-frequency simplex use),
we obtain **N_N = 20 RTC/MHz**,
and with a protected bitrate of R_{BN} = 2.4 kbit/s,
we find **η_N = 0.048**.

The upper bound of the radio capacity for interference limited systems can be calculated according to formulae (4) and (6) from where the cluster size can be derived:

$$N_C = 1/3 \cdot \left[6 N_{LI} \cdot (C/I)_D\right]^{2/\alpha} \qquad (9)$$

For the calculations two additional assumptions have to be made:
i) α = 3.5 [1]
ii) N_{LI} = 0.5 [2]

Hence we obtain **$N_C \geq 5.85$** for PM25, using $(C/I)_D$ = 17 dB (the static value + 9 dB). Note that the linear value of $(C/I)_D$ (e.g. 50.12 for 17dB) must be used in the equation.

N_I and η_I can be calculated easily once N_N, N_C and η_N are known. Using (4) and (8), or (7) directly for PM25 we obtain:
N_I = 3.42 RTC/(MHz x cell)
and **η_I = 0.008 bit/s/(Hz x cell)**.

For categorisation, all values of N_I have to be divided by 3.42 for comparison with PM25 in 2-frequency simplex mode and the categorisation can be done according to para. 5.1.

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1 For a MS antenna height of 1.5m, a BS antenna height of 30 to 50m and a frequency range of 150 to 900 MHz, the propagation coefficient α varies between 3.34 and 3.57 according to Okumura and Hata

2 Values of N_{LI} between 0.3 and 0.7 are taken as representative of typical system loads.

9 INTRODUCTION OF NEW TECHNOLOGY

a) Unoccupied spectrum

The spectrum efficiency of new systems being introduced in unoccupied spectrum depends mainly on their co-channel interference (C/I) and also on their adjacent channel interference (A/C) tolerance. These dictate the reuse distance for a given frequency, and also the extent to which near channels can be utilised in adjacent cells. In licensing regimes in which no guarantee of grade of service is offered, where ad-hoc time sharing is the method of channel access (e.g. in dense conurbations), then the introduction of new technology will provide an increase in physical channels over conventional 12.5 kHz FM technology, thus allowing more users per per MHz and km^2 or cell, provided that the co-channel interference performance is adequate.

b) Occupied spectrum

In existing PMR bands, new technology will need to co-exist with equipment already in place. This will require co-channel interference and adjacent channel interference tolerance between new and old systems to be maximised. Where possible, the new technology should allow the change to more spectrally efficient systems to be implemented in phases. This allows the greatest flexibility of implementation with least disruption to existing users. It should be possible to both replace existing equipment on a channel by channel basis and add new equipment where system planning constraints allow.

The use of narrow band modulation schemes can allow new RF carriers to be used in the low energy 'guard bands' that exist between old channels so long as co-channel protection is engineered with care.

Where groups of existing channels are to be replaced with new technology to improve spectral efficiency, a transition plan can be evolved to minimise interference with users still utilising old equipment. For example a 12.5 kHz channel can be divided into two 5 kHz channels so as to create a 2.5 kHz gap in the centre of the 12.5 kHz channel. This will improve co-channel interference with 12.5 kHz FM equipment that continues to use the channel. Later, full utilisation of the spectrum using narrow band channels can be introduced on a gradual basis.

Similar approaches can be derived for other channel spacings, but it is critical that the new system provides flexibility to the regulator and has characteristics as good or better than the existing system. TDMA systems may also enable users to operate more efficiently in occupied spectrum, as long as the existing services continue to be protected.

If the key radio parameters between new and existing systems are very similar, then there is unlikely to be a problem in superimposing new technology. However, if the parameters differ substantially, mismatches may occur that cause interference in some scenarios. For example, old equipment may interfere with a new system when there is a large mismatch in transmit powers or receiver sensitivity.

10 CONCLUSION

1) Different types of spectrum efficiency factors apply when considering either interference limited or coverage limited networks.

2) Nevertheless, guidelines in order to solve the spectrum congestion for conventional PMR have been identified:

- increase the load per channel by
    - trunking - sharing resources when possible
    - dynamic multiple access for trunked networks in dense areas
    - efficient protocol for access to the channel
    - data transmission

- increase the resistance to noise and interference
    - decrease the reuse distance
    - increase each cell coverage

- increase the number of channels
    - channel splitting (5/6.25 kHz)
    - use of TDMA techniques if this produces a gain in traffic channels over conventional technology

3) In certain configurations and for some requirements that cannot be satisfied by sharing resources within a trunked network, channel splitting (5/6.25 kHz) is necessary.

4) TDMA and FDMA techniques are both available for trunked and non-trunked PMR applications. For certain PMR networks, when the traffic density is low, an FDMA solution provides better frequency assignment flexibility. However, for various technical and frequency management reasons CDMA at present does not seem to be beneficial for PMR applications, because it is a broadband approach for high traffic capacity.

5) Under the assumptions made above, it can be seen that some of the new systems offer improved spectrum efficiency. For full details, refer to Table C.

11 TABLES

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System Parameter	PM 25	PM 20	PM 12	APCO 25		TETRA 25 V+D	TETRA 25 PDO	TETRA 25 DMO	PMR6 **[1]**
Reference document	4,5			14,23		7	8	10	based on 7
Frequency band [MHz] **[2]**	68..87.5,146..174,Band 111,406..470			150/400/800		~380/~900 **[3]**			nya
Tx-Rx separation [MHz] **[4]**	9.8,4.6,10			3&5/39&45		10	10/45	0	nya
Carrier separation [kHz], ΔF_C	25	20	12.5	6.25	12.5	25	25	25	6.25
Access mode/Mode of operation **[5]**	FDMA/S,HD,FD	FDMA/S,HD,FD	FDMA/S,HD,FD	FDMA/S, HD,FD		TDMA/HD,FD	Packet	TDMA/S	~FDMA/S,HD,FD
No. of channels per carrier, N_A	1	1	1	1		4	1	1,2 **[6]**	1
Type of modulation	PM,SC-FSK	FM,PM,SC-FSK	PM,SC-FSK	CQPSK	C4FM	π/4-DQPSK	π/4-DQPSK	π/4-DQPSK	π/4-DQPSK
Baseband width [Hz]	300-3000	300-3000	300-2550						
Modulation bandwidth (kHz), $B_{m98\%}$	12.5 **[7]**	10.5 **[7]**	7.5 **[7]**	5.76	8.1	18.0	18.0	18.0	~4.0
Burst length [ms]	-	-	-			14.167	14.167	14.167	56.67
Frame length [ms]	-	-	-			56.67	-	56.67	56.67
Type of code	BCH	BCH	BCH	BCH, RS, Hamming, Golay trellis		16-state RCPC		16-state RCPC	Y
Gross bitrate [kbit/s]	≤4.8	≤4.8	≤2.4	9.6		4 x 9.0	≤36.0	1..2 x 9.0	8.0
Unprotected bitrate [kbit/s]				9.6		4 x 7.2	-	1..2 x 7.2	<7.0
Protected bitrate [kbit/s], R_{BN}	≤2.4	≤2.4	≤1.2	4.8	7.2	4 x 4.8	19.2	1..2 x 4.8	4.8
Error detection/correction	various	various	various	FEC		FEC	FEC	FEC	FEC
Speech Codec [Type/kbit/s]				IMBE/4.4		ACELP 4.6	N	ACELP 4.6	
Codec interleaving depth				1		1,4,8		1,4,8	1,4,8
Tx RF power, base station [dBm]	≤54	≤54	≤54	≤57		28..46	28..46	-	~ ≤46
Tx RF power, mobile [dBm]	≤54	≤54	≤54	≤50		15..45	15..45	25..40	~ ≤45
Tx RF power, handportable [dBm]	≤37	≤37	≤37	≤37		15..35	15..35	25..40	15..35
BS power level control range [dBm]	-	-	-	-		28..46		-	~28..46
MS power level control range [dBm]	-	-	-	-		15..45		25..40 Gateway, Repeater only	~15..45
Tx spurious emissions [dBm/dBc]	-36/70	-36/70	-36/60	-36dBm		-36/75..100	-36/75..100	-36/75..100	-36/75..100
Rx sensitivity, static [dBm] (typical/limit)	-119/-107	-117/-107	-114/-107	-116/-110		-112..-115 **[8]**	-112..-115 **[8]**	-112..-115 **[8]**	-118..-121 **[8]**
Rx sensitivity, dynamic [dBm]	~-110	~-108	~-105	-105		-103..-106 **[8]**	-103..-106 **[8]**	-103..-106 **[8]**	-109..-112 **[8]**
C/I, static [dB], $(C/I)_s$	≤8	≤8	≤12	≤12		~6..8 **[9]**	~6..8 **[9]**	~6..8 **[9]**	~6..8 **[9]**
C/I, dynamic [dB] **[10]**, $(C/I)_d$	17	17	21	16.5		≤19	≤19	≤19	≤19
Adjacent channel rejection, stat. [dB]	≥70	≥70	≥60	60		~55..60 **[9]**	~55..60 **[9]**	~55..60 **[9]**	~55..60 **[9]**
Adjacent channel rejection, dyn. [dB]	~58	~58	~48	-		≥45	≥45	≥45	≥45
Spurious responses, static [dB/dBm]	70/-37	70/-37	70/-37	80(m)/70(h)/90(b) **[11]**		-/-45	-/-45	-/-45	-/-45
Rx blocking, static [dBm] at ≥1MHz	-23	-23	-23	-26		-25	-25	-25	-25
Rx dynamic range, static [dBm]	-119..-7 **[12]**	-117..-7 **[12]**	-114..-7 **[12]**	-116..-10		-106..-29	-106..-29	-112..-20	-112..-29
Multipath equalisation [μs]	-	-	-	50		55/110	55/110	-	N

Table A1: General Properties of selected PMR Systems

1. proposal
2. differing in Europe
3. Frequency bands for TETRA are still under consideration
4. main cases
5. S = simplex, HD = half duplex (2-frequency simplex), FD = full duplex
6. Normal mode - 1 traffic ch per 25kHz; frequency efficient mode - 2 traffic chs per 25kHz
7. Typical values - obtained by using Carson's rule (2x[pk dev+max mod freq]) on the adjacent channel power test in ETS 300 086, 113, 219 etc - 1250Hz tone modulated at pk dev 5 (25k), 4 (20k), 2.5 (12.5k). Unlikely to have 5kHz dev at 3kHz mod freq in speech
8. MS..BS
9. estimated
10. $(C/I)_D$ for analogue systems has been calculated as $(C/I)_S$+9dB to account for fading but not shadowing
11. m = mobile, h = handheld, b = base
12. According to FTZ 17 TR 2049.

nya = not yet allocated
N = no or not applicable   Y = yes, no details available

System Parameter	ASTRO	EDACS	iDEN	MOBITEX 11 **[1]**	MODACOM RD-LAP**[1]**	MPT 1327	SR 440 **[1]**	TETRAPOL	RVE
Reference document			14	15	17	4,5,25	20, 21	13	12
Frequency band [MHz]	~160	160/450/800/900	800/900/1500	400/900	410..430	150/400/570	80/160/450	~80/380/450	80/160/B11
Tx-Rx separation [MHz]		4..45	45	10	10	10	1..20		1..15
Carrier separation [kHz], $\boldsymbol{\Delta F_C}$	25/20/12.5	12.5 25	25	12.5	12.5	12.5	12.5 25	10 12.5	5
Access mode/ Mode of operation **[15]**	FDMA	FDMA	TDMA	FDMA/HD,FD **[7]**	FDMA/HD,FD	FDMA/HD **[9]** FD	FDMA/S,HD,FD	FDMA/S,HD	FDMA/S,HD
No. of channels per carrier, $\boldsymbol{N_A}$	1	1	6 **[11]**	1	1	1	1	1	1
Type of modulation	QPSK-C	GFSK	m16QAM **[2]**	GMSK BT=0.3	4FSK	PM,SC-FSK	CP-BFSK	GMSK	RVE SSB
Baseband width [Hz]		300..3300		N - no voice transmission	N	300...2550	10..3200		300..3000
Modulation bandwidth (kHz), $\boldsymbol{B_{m98\%}}$		8.5 16	≤ 18	7.5	7.5	7.5	7.0 11.0	<8	3.6
Burst length [ms]		-	15	37		N	N	20	-
Frame/block length [ms]		21	40	907	14.375	48+16 bits/block	20/100 **[13]**	20	-
Type of code		Y	trellis	Y	Y	(63,48) cyclic	Y	CRC, convol.	-
Gross bitrate [kbit/s]	9.6	9.6	64	8.0	9.6	1.2	4.8	7.6	4.8...14.4
Unprotected bitrate [kbit/s]	7.2	9.1	-	-	4.2	N	4.7	-	
Protected bitrate [kbit/s] $\boldsymbol{R_{BN}}$		7.77	6 x 7.2	4.2	~2.1	~0.7	2.4 for data	~4.8	7.2/2.4 **[14]**
Error detection/correction		FEC	Y	ARQ, CRC, FEC	CRC, FEC	1 bit/block	both (Confidential)	both	various
Speech Codec [Type/kbit/s]		AME	VSELP/4.2	-		N	IMBE/4.0 inc FEC	RPCELP 6.0	-
Codec interleaving depth		-		-		N	Y	20 ms	various
Tx RF power, base station [dBm]	~40..46	56	≤51	46	38	38	33..44	42	44/50
Tx RF power, mobile [dBm]	~37..40	40..50	27..40	40	38	38	33..44	40	44
Tx RF power, handportable [dBm]		38	22..35	33	38	34	20..37	33	37
BS power level control range [dBm]		-		21dB	Y	N	N	N	20 dB
MS power level control range [dBm]		-		18dB	23/33	N	N	20(h) 30(MS)	20 dB
Tx spurious emissions [dBm/dBc]		-36 dBm		-44dBm	-44dBm	-36 dBm	-36dBm	-36dBm/-70dBc	-36dBm
Rx sensitivity, static [dBm]		-115 -116		-113	< -114	-125 **[10]**	-118 -120	-121..-119 **[16]**	-112
Rx sensitivity, dynamic [dBm]		-		≈ -104	< -105	~-110 **[6]**	≈-108 ≈-110	-113..-111 **[16]**	...
C/I, static [dB] $\boldsymbol{(C/I)_s}$		7 5	10	12 **[8]**	12	12	5 3	7	8
C/I, dynamic [dB] **[12]** $\boldsymbol{(C/I)_d}$		16 14	19	~25	20	~21	15 **[3]** 13 **[3]**	15	17/12.5 **[14]**
Adjacent channel rejection, stat. [dB]		80..95 **[4]**		60 **[8]**	60	60	65 75	60/45	50 **[6]**
Adjacent channel rejection, dyn. [dB]		-		~45	~50	50 **[3]**	≈55 **[3]** ≈65 **[3]**	45	...
Spurious responses, static [dB/dBm]		100 **[4]**		70/-37	70/-37	70/-37	70	**[1]**	70/-37
Rx blocking, static [dBm] at ≥1MHz		-		>-23	>-23	> -23	-17	**[1]**	-23
Rx dynamic range, static [dBm]		-		-113..~0	-114..~0	-114...-7	≈-118..+4	-	-120..-10
Multipath equalisation [µs]		52	40/66	N	N	N	N **[5]**	N	Y

Table A2: General Properties of selected PMR systems

1. ETS 300 113 compliant
2. m = 4
3. Estimated value, no test results available
4. BS
5. Reduced data rate for delay spreads up to 40 µs
6. Limit value. Current equipment outperforms this by 10dB
7. BS = FD, MS = HD
8. According to ETS 300 113
9. MS-MS always via BS
10. For signalling
11. The number of usable channels per carrier in TDMA systems may be different for Direct Mode operation
12. $(C/I)_D$ for analogue systems has been calculated as $(C/I)_S$+9dB to account for fading but not shadowing.
13. Speech: frame length 20ms (96 bits), superframe length 100ms; Data: Header length 256 bits, data block length ≤19200 bits
14. For RVE, speech can be achieved at $(C/I)_D$=17dB; data can be achieved at 7.2kbit/s in low interference conditions, however in Table C, η_I (interference case) is calculated using 2.4kbit/s at $(C/I)_D$=12.5dB. See Reference [10].
15. S = Simplex, HD = half duplex (2-freq simplex), FD = full duplex
16. BS..MS

h = hand-held; N = no or not applicable; Y= yes, no details available

Type of System **[1]**	$(C/I)_s$ [dB]	$(C/I)_d$ **[2]** [dB]	$B_{M\ 98\%}$ [kHz]	ΔF_C [kHz]	N_A	R_{BN}/RTC [kbit/s]
PM 25 kHz	8.0	17.0	12.5	25	1	2.4
PM 20 kHz	8.0	17.0	10.5	20	1	2.4
PM 12.5 kHz	12.0	21.0	7.5	12.5	1	1.2
TETRA 25 kHz V+D	~6..8	19.0 **[3]**	18.0	25	4	4.8
TETRA 25 kHz DMO	~6..8	19.0 **[3]**	18.0	25	1**[4]**	4.8
PMR 6.25 kHz V+D	~6..8	19.0 **[3]**	~4.0	6.25	1	4.8
APCO 25 12.5 kHz	12	16.5	8.1	12.5	1	7.2
APCO 25 6.25 kHz	12	16.5	5.76	6.25	1	4.8
ASTRO Motorola 25 kHz				25	1	
ASTRO Motorola 20 kHz				20	1	
ASTRO Motorola 12.5 kHz				12.5	1	
EDACS Ericsson 25 kHz	5	14	16	25	1	7.77
EDACS Ericsson 12.5 kHz	7	16	8.5	12.5	1	7.77
iDEN Motorola 25 kHz	10	19	18	25	6	7.2
MPT 1327 12.5 kHz	12.0	21.0	7.5	12.5	1	~0.7
SR 440 Ascom, Bosch 25 kHz	3	13	11	25	1	2.4
SR 440 Ascom, Bosch 12.5 kHz	5	15	7	12.5	1	2.4
TETRAPOL 12.5 kHz	7.0	15.0 **[3]**	8	12.5	1	~4.8
TETRAPOL 10 kHz	7.0	15.0 **[3]**	8	10	1	~4.8
RVE Securicor 5 kHz **[5]**	8.0	17.0	3.6	5	1	7.2
TETRA 25 kHz PDO	~6..8 **[6]**	19.0 **[3]**	18.0	25	Packet **[7]**	19.2
MOBITEX 11 12.5 kHz	12.0	~25	7.5	12.5	1	4.2
MODACOM Motorola 12.5 kHz	12.0	20	7.5	12.5	1	~2.1

Table B: Parameters of selected PMR systems used in Spectrum Efficiency calculations

1. **The assumed mode of usage for all systems shown in table B is Half Duplex (HD), i.e. $N_M = 0.5$, except TETRA DMO where $N_M = 1$**
2. $(C/I)_D$ for analogue systems has been calculated as $(C/I)_S$+9dB to take into account fading but not shadowing
3. This value is the minimum performance requirement taken from the standard. Manufactured equipment may outperform this limit
4. $N_A = 2$ for frequency efficient mode in TETRA Direct Mode Operation
5. For RVE, 7.2kbit/s data can be achieved in low interference conditions, however η_I in Table C is calculated using 2.4kbit/s at $(C/I)_D$=12.5dB (in this case N_C=3.23). See reference [11]
6. Estimated
7. It is unclear what the access mode factor, N_A, should be for Packet Data Optimised systems as the equivalent of a single traffic channel (in frequency or time) is split into data packets and sent in bursts. In determining N_A it is necessary to know how many traffic channels are multiplexed in a single RF channel. This is as yet undefined for PDO systems.

Type of System	N_N [RTC / MHz]	η_N $\left[\frac{bit/s}{Hz}\right]$	N_C **[1]**	N_I $\left[\frac{RTC}{MHz \cdot Cell}\right]$	η_I $\left[\frac{bit/s}{Hz \cdot Cell}\right]$	Category
PM 25 kHz	20	0.048	5.85 (7)	3.42	0.008	A (1.0)
PM 20 kHz	25	0.06	5.85 (7)	4.276	0.010	A (1.3)
PM 12.5 kHz	40	0.048	9.90 (12)	4.041	0.005	A (1.2)
TETRA 25 kHz V+D	80	0.384	7.61 (9)	10.516	0.050	C (3.1)
TETRA 25 kHz DMO **[2]** (N_M=1)	40	0.192	7.61 (9)	5.258	0.025	B (1.5)
PMR 6.25 kHz V+D	80	0.384	7.61 (9)	10.516	0.050	C (3.1)
APCO 25 12.5 kHz	40	0.288	5.47 (7)	7.306	0.053	B (2.1)
APCO 25 6.25 kHz	80	0.384	5.47 (7)	14.612	0.07	C(4.3)
ASTRO Motorola 25 kHz	20					
ASTRO Motorola 20 kHz	25					
ASTRO Motorola 12.5 kHz	40					
EDACS Ericsson 25 kHz	20	0.155	3.94 (4)	5.076	0.039	A(1.5)
EDACS Ericsson 12.5 kHz	40	0.311	5.13 (7)	7.803	0.061	B(2.3)
iDEN Motorola 25 kHz	120	0.864	7.61 (9)	15.774	0.114	C(4.6)
MPT 1327 12.5 kHz	40	0.028	9.90 (12)	4.041	0.003	A (1.2)
SR 440 Ascom, Bosch 25 kHz	20	0.048	3.45 (4)	5.79	0.014	B (1.7)
SR 440 Ascom, Bosch 12.5 kHz	40	0.096	4.49 (7)	8.9	0.021	C (2.6)
TETRAPOL 12.5 kHz	40	0.192	4.49 (7)	8.9	0.043	C (2.6)
TETRAPOL 10 kHz	50	0.24	4.49 (7)	11.125	0.053	C (3.3)
RVE Securicor 5 kHz **[3]**	100	0.72	5.85 (7)	17.102	0.074	C (5.0)
TETRA 25 kHz PDO **[4]**						
MOBITEX 11 12.5 kHz	40	0.168	16.75 (19)	2.338	0.010	A (0.7)
MODACOM Motorola 12.5 kHz	40	0.084	8.68 (9)	4.610	0.010	A (1.3)

Table C: Spectrum Efficiency of selected PMR Systems

1. Values in this column in brackets are valid for regular, homogeneous, isotropic, hexagonal cells
2. N_I, and η_I will double for TETRA DMO in frequency efficient mode (N_A = 2), putting it in Category C. The formula gives maximum performance - reality includes restrictions relating to mobility management
3. N_I and N_C have been calculated using $(C/I)_D$=17dB (valid for speech), however η_I has been calculated using 2.4kbit/s at $(C/I)_D$=12.5dB (corresponding N_C = 3.23)
4. The efficiency of Packet Data Optimised systems cannot be calculated as the value for N_A is unclear.

The reference system is calculated for half duplex mode of operation (N_M = 0.5) - the other systems are calculated according to the normal, or predominantly used mode of operation. This is half duplex (N_M = 0.5) unless otherwise stated. For those systems capable of operation in simplex mode, the relative spectral efficiency will be twice that quoted (as N_M = 1), whilst for those systems which use 4 frequencies to operate in full duplex mode (e.g. via repeater), the relative spectral efficiency in that case will be half that quoted (as N_M = 0.25).

The calculations are based on dynamic values. Where static values only have been obtained, dynamic values have been estimated. Inaccuracies in estimation may affect the results.

All results are based on parameter values quoted in the tables. Every effort has been made to obtain correct values, but it is appreciated that there may be some inaccuracies.