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Contents

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Foreword

This ETSI Technical Report (ETR) has been produced by the ETSI Project TErrestrial Trunked RAdio (TETRA) Technical Body of the European Telecommunications Standards Institute (ETSI).

ETRs are informative documents resulting from ETSI studies which are not appropriate for European Telecommunication Standard (ETS) or Interim European Telecommunication Standard (I-ETS) status. An ETR may be used to publish material which is either of an informative nature, relating to the use or the application of ETSs or I-ETSs, or which is immature and not yet suitable for formal adoption as an ETS or an I-ETS.

This ETR consists of 4 parts as follows:

Part 1: "Overview, technical description and radio aspects";

Part 2: "Radio channels, network protocols and service performance";

Part 3: "Direct Mode Operation", (DTR/TETRA-01011-3);

Part 4: "Network Management".

Introduction

This ETR has been produced to provide an introduction to the TETRA system for potential system purchasers, network operators and service users.

It should be understood that, as in all standard setting activities, there is an inherent conflict between the wish to have as broad a standard as possible and at the same time wanting to have as much of that broad standard available and implemented right from the beginning. Potential system purchasers, network operators and service users should make sure they influence the suppliers to have their required functionality available when they need it.

Equipment manufacturers will use the broad flexibility provided within the standard to develop and implement systems in various ways, and still be conforming according to the standard. This broad availability of systems, each optimized around certain features and functionalities, needs to be carefully analysed by a network operator and system user to find the supplier with a system suited best for their needs.

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1 Scope

This ETSI Technical Report (ETR) is written as a "Read-me-first" manual or "Getting started with TETRA Voice plus Data (V+D)". It is not intended to be a complete guide to the TETRA standards. If any conflict is found between this ETR and the clauses in the TETRA standards then the standards take precedence.

The aims of this ETR are many, for example:

1) to provide the reader with sufficient knowledge to engage in qualified discussions with the equipment and service suppliers;

2) to expose the reader to the specific language and technical terminology used in the TETRA standards;

3) to enable the reader to understand the flexibility in system design, system network topography, system availability, various modes of operation and security features;

4) in the radio aspects part of this ETR, sufficiently detailed design information is given to allow link budget calculations to be carried out and outline radio coverage planning to be performed.

2 References

For the purposes of this ETR, the following references apply:

[1] ETS 300 392-1: "Radio Equipment and Systems (RES); Trans-European Trunked Radio (TETRA); Voice plus Data (V+D); Part 1: General Network Design".

[2] ETS 300 392-2: "Radio Equipment and Systems (RES); Trans-European Trunked Radio (TETRA); Voice plus Data (V+D); Part 2: Air Interface (AI)".

[3] ETR 300-2: "Radio Equipment and Systems (RES); Trans-European Trunked Radio (TETRA); Voice plus Data (V+D); Designers guide; Part 2: Traffic aspects".

[4] ETR 300-3: "Radio Equipment and Systems (RES); Trans-European Trunked Radio (TETRA); Voice plus Data (V+D); Designers guide; Part 3: Direct Mode Operation (DMO)".

[5] ETR 292: "Radio Equipment and Systems (RES); Trans-European Trunked Radio (TETRA); User requirements for network management".

[6] ETS 300 086: "Radio Equipment and Systems (RES); Land mobile group; Technical characteristics and test conditions for radio equipment with an internal or external RF connector intended primarily for analogue speech".

[7] ETS 300 113: "Radio Equipment and Systems (RES); Land mobile service; Technical characteristics and test conditions for radio equipment intended for the transmission of data (and speech) and having an antenna connector".

[8] ETS 300 393-1: "Radio Equipment and Systems (RES); Trans-European Trunked Radio (TETRA); Packet Data Optimized (PDO); Part 1: General network design".

3 Definitions and abbreviations

3.1 Definitions

For the purposes of this ETR, the following definitions apply:

access code: A subdivision of Mobile Stations (MSs) for random access opportunities.

advanced link: An advanced link is a bi-directional connection oriented path between one MS and a Base Station (BS) with provision of acknowledged and unacknowledged services, windowing, segmentation, extended error protection and choice among several throughputs. It requires a set-up phase.

announced cell re-selection: Cell re-selection where MS-MLE informs the SwMI both in the old cell (leaving cell) and in the new cell (arriving cell) that cell change is performed. There can be three types of announced cell re-selection.

- type 1: The MS-MLE knows the new cell and the traffic channel allocations on the cell before deciding to leave its serving cell;

- type 2: The MS-MLE knows the new cell before changing to it, but does not know the channel allocation on the new cell in advance;

- type 3: The MS-MLE need not to know the new cell before changing to it. The old cell is only informed by the MS-MLE that it want to change cell.

TETRA V+D may support all three types of announced cell re-selection.

assigned channel: A channel that has been allocated by the infrastructure to certain MSs using channel allocation command(s) addressed to those MSs. An assigned channel may be allocated for secondary control purposes or for a circuit mode call.

Associated Control CHannel (ACCH): The dedicated signalling channel associated with a channel that has been assigned for circuit mode traffic. It comprises the Fast Associated Control CHannel (FACCH) which uses frames 1 to 17 (if they are not used by traffic) plus the Slow Associated Control CHannel (SACCH) which is always available in frame 18.

attached: A MS is said to be attached to a cell when the MS is camped and registered on the cell. The MS may be in idle mode (i.e. not actively processing a transaction) or in active mode (i.e. actively processing a transaction in reception and/or in transmission). It is the Mobility Management (MM) which decides when a MS is said to be attached.

bearer service: A service which provides information transfer between user network interfaces (NT or MT) involving only low layer functions (layers 1 to 3 of the OSI model). Circuit mode data calls and packet mode data calls are examples of bearer services (see annex A, clause A.1).

Bit Error Ratio (BER): The limit ratio of the bits wrongly received to all bits received in a given logical channel.

broadcast: A unidirectional point to multipoint mode of transmission.

call owner: In a group call the call owner is the only party with authority to clear the call. By default it is usually the group call initiator. Ownership of the group call can be transferred by use of the Transfer of Control (ToC) supplementary service. In some implementations if ownership of an ongoing group call is not transferred then the system may automatically clear the call if the call owner de-registers or goes out of range. To cope with this issue, in some implementations the call owner of all group calls may be designated as a permanent dispatcher.

call transaction: All of the functions associated with a complete unidirectional transmission of information during a call. A call can be made up of one or more call transactions. In a semi-duplex call these call transactions are sequential.

camped: A MS is said to be camped on a cell when the MS is synchronized on the cell BS and has decoded the Broadcast Network CHannel (BNCH) of the cell. The synchronization procedure is performed by the Medium Access Control (MAC) layer and the interpretation of the network information from the BNCH is performed by a procedure in the Mobile Link Entity (MLE). It is the MLE which decides when a MS is said to be camped on a cell.

cell re-selection: The act of changing the serving cell from an old cell to a new cell. The cell re-selection is performed by procedures located in MLE and in the MAC. When the re-selection is made and possible registration is performed, the MS is said to be attached to the cell.

channel: In the Time Division Multiple Access (TDMA) slot structure arrangement a channel comprises the pair of same numbered slots on the uplink and downlink duplex frequencies.

Common Control CHannel (CCCH): The control channel transmitted by the infrastructure to control the MS population. The CCCH comprises the Main Control Channel (MCCH) and common Secondary Control Channels (SCCH).

Control-plane (C-plane): A system signalling scheme characterized by the need for addressing on each message (see also figure 5).

coverage area: Geographical area within which the received signal strength from a radiating BS exceeds the specified threshold value (see "Microwave Mobile Communications", page 126).

downlink: The radio path from the BS to the MS (sometimes called the outbound path).

group call: A point-to-multipoint tele-service in which the talking party transmission is received by the multitude of MSs and Line Stations (LSs) which comprise the group. When the talking party stops transmitting (e.g. releases pressel) and relinquishes control of the traffic channel any other member of the group may apply to have transmit permission. Group calls can only operate in voice half duplex i.e. one party speaks whilst the other parties listen.

half duplex operation: In half duplex operation, each MS or LS needs to ask for permission to transmit for each transaction.

individual call: A point-to-point tele-service providing a circuit mode connection between two terminals (MSs or LSs). An individual call can operate either in voice half duplex or voice full duplex, i.e. one party speaking or both parties allowed to speak together.

interoperability: Ability of MS equipment from different manufacturers (or different systems) to communicate together on the same infrastructure (same system). This capability relies on the specification of the air interface I1, line interface I2 and terminal interface I4 (see figure 3).

inter-working: Ability of equipment from the same system to communicate together from different systems. This capability relies on the specification of the Inter-System Interface (ISI) I3 (see figure 3).

Location Area (LA): The minimum area in which a MS my be registered.

logical channel: A generic term for any distinct data path. Logical channels are considered to operate between logical end-points.

MAC block: The unit of information transferred between the upper MAC and lower MAC for a particular logical channel (e.g. SCH/F, SCH/HD or SCH/HU). The lower MAC performs channel coding for insertion into the appropriate physical slot, half slot or sub-slot.

Main Control CHannel (MCCH): The principal CCCH transmitted by the infrastructure to control the MSs in a cell. The frequency of the main carrier for the cell is broadcast by the infrastructure, and the MCCH is located on timeslot 1 of the main carrier.

Message Erasure Rate (MER): The limit ratio of the messages detected as wrong by the receiver to all messages received in a given logical channel.

message trunking: A traffic channel is permanently allocated for the complete duration of the call, which may include several separate call transactions (several pressel activation's by separate terminals). The channel is only de-allocated if the call is (explicitly) released or if a time-out expires.

minimum mode: A mode of operation in which the infrastructure allocates all four timeslots of the main carrier for traffic or assigned control purposes. In this mode, only frame 18 can be used for common control without disturbing the established services.

monitoring: The act of measuring the power of neighbour cells and calculate the path loss parameter C2 based upon information on neighbour cells broadcasted by the serving cell.

normal mode: A mode of operation in which the MCCH is present in timeslot 1 of all frames 1 to 18.

pressel: The press-to-talk switch used in semi-duplex and simplex radio applications when the user wishes to speak. The switch can be activated manually by the user pressing a contact or can be activated electronically, for instance by a Voice Activity Detector (VAD).

random access attempt: The period from the initiation of the random access procedure until the MS receives a response from the BS or abandons the procedure (e.g. after sending the maximum permitted number of retries).

registration/de-registration (MS view): The network procedure whereby the MS informs the infrastructure that it will respond and/or not respond to paging messages. It is a network operator option whether MSs are required to de-register at power down (switch-off). This may be implemented on a per site basis.

registration (infrastructure view): The network procedure in which messages to the called MS are directed to the MS registration area. The MS is required to inform the infrastructure whenever it enters a new registration area. It is a network operator option whether the previous registration area should be immediately removed or remain active for a further period of time (to allow re-entry to the previous registration area without needing to re-register). The infrastructure may also forward register the MS in surrounding registration areas.

registration area: The sum total of all location areas in which the MS is registered and in which paging messages to locate the MS will be issued.

Secondary Control CHannel (SCCH): A control channel other than the MCCH. There are two types of SCCH:

- a common SCCH, which has the same functionality as the MCCH but is used only by a subset of the MS population;

- an assigned SCCH, which may be allocated to certain MSs after an initial random access or paging message.

segment: A LLC segment is the advanced link unit of transmission and re-transmission. A segment is the numbered piece of a TL-SDU fitting into one MAC layer PDU (MAC block).

serving cell: The cell that is currently proving service to the MS.

subscriber class: A subscriber class has no other defined usage than offering a population subdivision. The operator defines the values and meaning of each class.

supplementary service: A service which modifies or supplements a tele-service or bearer service. A supplementary service can not be offered as a stand-alone service; it must be offered in conjunction with a tele-service or bearer service (see annex A, clause A.2).

tele-service: A service to clients offered by network operators or service providers in order to satisfy specific telecommunication requirements. Individual speech calls and group speech calls are examples of tele-services (see annex A, clause A.1).

transmission trunking: A traffic channel is individually allocated for each call transaction (for each activation of the pressel). The channel is immediately de-allocated at the end of the call transaction (subject to unavoidable protocol delays).

User-plane (U-plane): a system traffic scheme providing constant delay characteristics without addressing (see also figure 5).

uplink: The radio path from the MS to the BS (sometimes called the inbound path).

3.2 Abbreviations

For the purposes of this ETR, the following abbreviations apply:

AACH	Access Assignment CHannel
ACCH	Associated Control CHannel
AP	Access Priority
ARFA	Allied Radio Frequency Agency
ASSI	Alias Short Subscriber Identity
AWGN	Additive White Gaussian Noise
BSCH	Broadcast Synchronization Channel
BBK	Broadcast BlocK
BCCH	Broadcast Control CHannel
BNCH	Broadcast Network CHannel
BS	Base Station
BU	Bad Urban
BER	Bit Error Rate
CB	Control (uplink) Burst
CCK	Common Cipher Key
CLCH	Common Linearization CHannel
CLNP	ConnectionLess Network Protocol
CMCE	Circuit Mode Control Entity
CONP	Connection Oriented Network Protocol
DCK	Derived Cipher Key
DMO	Direct Mode Operation
DQPSK	Differential Quadrature Phase Shift Keying
DTE	Data Terminal Equipment
ECCH	Extended Control CHannel
e.m.f.	electro-motive force
FACCH	Fast Associated Control CHannel
FEC	Forward Error Correction
FM	Frequency Modulation
GB	Guard Band
GSM	Global System for Mobile communications
GSSI	Group Short Subscriber Identity
GTSI	Group TETRA Subscriber Identity
ISDN	Integrated Services Digital Network
ISI	Inter-System Interface
ITSI	Individual TETRA Subscriber Identity
LB	Linearization Burst
LMN	Land Mobile Network
LS	Line Station
LLC	Logical Link Control
MAC	Medium Access Control
MCCH	Main Control CHannel
MER	Message Erasure Rate
MLE	Mobile Link Entity
MM	Mobility Management
MMI	Man Machine Interface
MS	Mobile Station
MT	Mobile Termination
MTU	Mobile Termination Unit
NDB	Normal Downlink Burst
NT	Network Termination
NUB	Normal Uplink Burst
OSI	Open System Interconnect
PD	Packet Data
PDN	Packet Data Network
PDO	Packet Data Optimized
PDU	Protocol Data Units
PMR	Private Mobile Radio
PPC	Pre-emptive Priority Call
PSTN	Public Switched Telephone Network

PTN	Private Telephone Network
p.w.	psophometric weighted
QS	Quasi Synchronous
RA	Rural Area
RF	Radio Frequency
RSSI	Radio Signal Strength Indication
SACCH	Slow Association Control CHannel
SAGE	Security Algorithms Group of Experts
SAP	Service Access Point
SB	Synchronization Burst
SCCH	Secondary Control CHannel
SCH	Signalling CHannel
SCK	Static Cipher Key
SCLNP	Specific Connectionless Network Protocol
SF	Stealing Flag
SIM	Subscriber Identity Module
SINAD	Signal to Noise Ratio
SNAF	Sub-Network Access Function
SwMI	Switching Management Infrastructure
STCH	Stealing CHannel
SYSINFO	System Information broadcast PDU
TCH	Traffic CHannel
TDMA	Time Division Multiple Access
TE	Terminal Equipment
TEI	Terminal Equipment Identifier
TETRA	TErrestrial Trunked RAdio
TU	Typical Urban
TCH	Traffic Channel
TMV-SAP	Tetra MAC virtual SAP
VAD	Voice Activity Detection
VC	Virtual Call
VSSI	Visitor Short Subscriber Identity
V+D	Voice plus Data

4 Overview of TETRA

4.1 Introduction

TETRA is a powerful multi-function mobile radio standard that provides a comprehensive tool kit from which system planners may choose in order to satisfy their requirements. The TETRA suite of mobile radio specifications provide a radio capability encompassing trunked, non-trunked and direct mobile-to-mobile communication with a range of facilities including voice, circuit mode data, short data messages and packet mode data services. TETRA supports an especially wide range of supplementary services, many of which are exclusive to TETRA.

The TETRA suite of mobile radio specifications is illustrated in figure 1 with the relevant parts of this ETR.

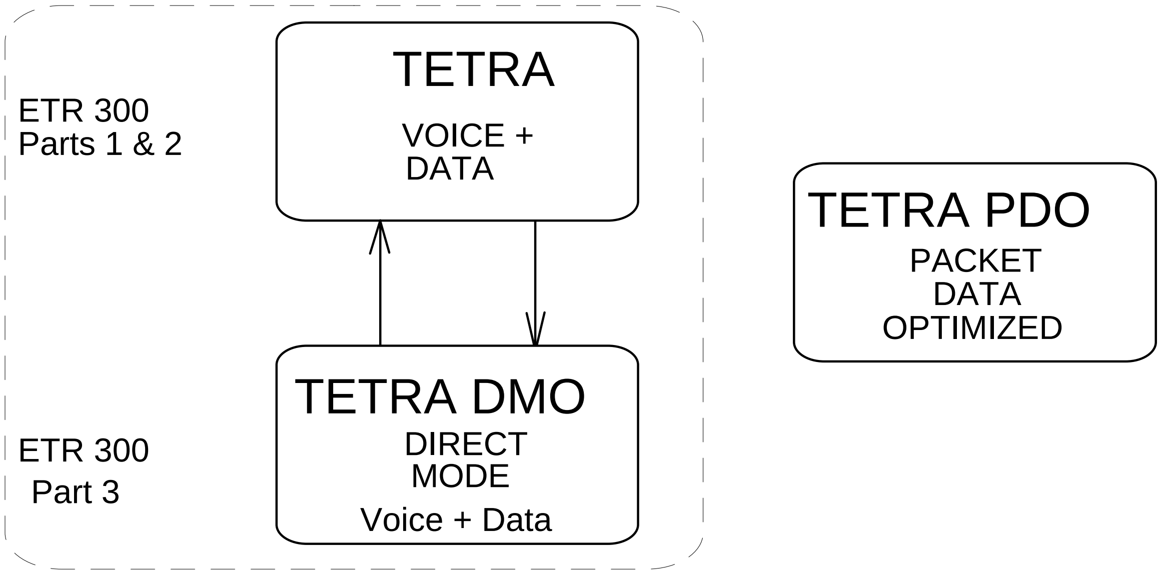


Figure 1: TETRA suite of standards

The specifications cover two distinct services areas corresponding to:

- Voice plus Data (V+D); and
- Packet Data Optimized (PDO).

Equipment conforming to the V+D specification will, depending on the options supported, provide a wide range of bearer services, tele-services and supplementary services relevant to a joint voice and data capability. Equipment conforming to the PDO specification will support only packet data services. It is anticipated that the packet data services on the PDO system will be superior to similar services on the V+D system. However for many applications the extra versatility offered by the V+D system will outweigh the few percent throughput advantage of the PDO system.

The V+D and PDO specifications are based on the same physical radio platform (the same modulation techniques and possibly the same operating frequencies) but implementations are not expected to inter-operate at the physical layer. Full inter-operability is foreseen at layer 3 (see clause 5 for a discussion of layers).

Direct Mode Operation (DMO) provides direct mobile-to-mobile communications when the MS is outside the coverage of the network or it can be used as a more secure communication channel within network coverage. A gateway terminal can provide trunked TETRA/DMO interoperability at layer 3 if the terminal is within radio coverage. The specification ensures compatible communication channel operation at layer 1. The specifications are written such that a MS operating in TETRA V+D can be contacted by a DMO MS that is within (mobile-to-mobile) range, and vice versa, an MS operating on DMO can be contacted by the TETRA system (if it is within network coverage). This facility, which requires the MS to monitor operation on the alternative transmission system is called "Dual Watch".

The arrows between TETRA V+D and TETRA DMO indicate the "Dual Watch" compatible operation at the physical level described above. Interoperability at layer 3 is assured by use of common layer 3 protocols for V+D, DMO and PDO.

This clause is concerned primarily with the TETRA V+D specification and so will concentrate on the design aspects pertinent to that specification, including inter-working with DMO.

NOTE: Detailed aspects of DMO will be covered in a future part of this ETR.

4.2 TETRA

The TETRA V+D specification was developed explicitly to give (for the appropriate class of MS) a multi-media radio platform able to support simultaneous voice, data and image applications to each MS radio platform. This capability was deemed attractive to the potential market and by incorporating it on to a single radio platform minimized the blocking and intermodulation problems common with other multi-function radios.

The radio access protocol is based on a four slot per carrier TDMA arrangement. The protocol is sufficiently flexible to allow four independent circuit mode applications (i.e. voice or circuit mode data) and/or any number of independent packet data applications to be simultaneously supported, up to the limit of the capability of the radio or the channel capacity of 28,8 kbit/s (gross) 19,2 kbit/s (net).

We could imagine a high performance multi-media radio terminal using one channel for voice communication, perhaps two for slow scan video (giving an acceptable image quality), leaving the last channel for circuit mode or packet mode data. There still remains a slow signalling channel that could be used for control signalling, status messaging or location updating. Alternatively, all of the available bandwidth could be used for video if it was required to achieve the best possible image quality. The reverse channel can be used in the same manner as the forward channel or simply for reverse signalling.

The network operator may, for financial or planning reasons, choose initially to install an "entry level" system with only simple half duplex single channel terminals supported (i.e. one slot at a time in the uplink and downlink). At a later date further system options can be added and full duplex or integrated radio terminals added alongside the basic radio terminals. Thus the integrated radio approach outlined above supports a rational and economic upgrade path. There is no doubt that the provision of voice, data and image on the same radio platform is inherently more cost efficient than separate systems if there is to be widespread access to these facilities.

There are of course many drawbacks to the integrated radio approach. The major difficulty arises from the inherent complexity of the system and the need for the customer to be literate in the technical approach adopted so that informed decisions can be taken to gain maximum benefit when planning, procuring and using a TETRA system. It is this audience to which this ETR is primarily aimed, providing an introductory text which explains the intricacies of the TETRA specifications in sufficient detail so that the many trade-offs between performance (transmit power, coverage technique, cell size etc.) and cost can be understood. Some quantitative design figures that can be used in deciding system parameters are given for informative purposes. However, it should be realized that this guide does not purport to provide sufficient information for a detailed system design.

4.3 Telecommunication services

An important purpose of this ETR is to introduce the reader to new system concepts and to some of the specialist vocabulary that is used for the sake of precision in the TETRA standard. It is inevitable that much of this specialist vocabulary will be seen as "jargon" at the outset but it is hoped the present introduction to the "new" expressions will facilitate their acceptance. One such important concept to understand is the separation of tele-services and bearer services.

A tele-service is a system service as seen by the end user through the Man Machine Interface (MMI) (e.g. the keyboard). An individual call or a group call is a tele-service, invoked for instance by keying the call button on the MMI. On the other hand, circuit mode or packet mode data services are not accessed at the MMI but actually within the radio system.

A convenient way to categorize basic telecommunication services is thus to divide them into bearer services and tele-services, depending on the point of access. This is illustrated in figure 2.

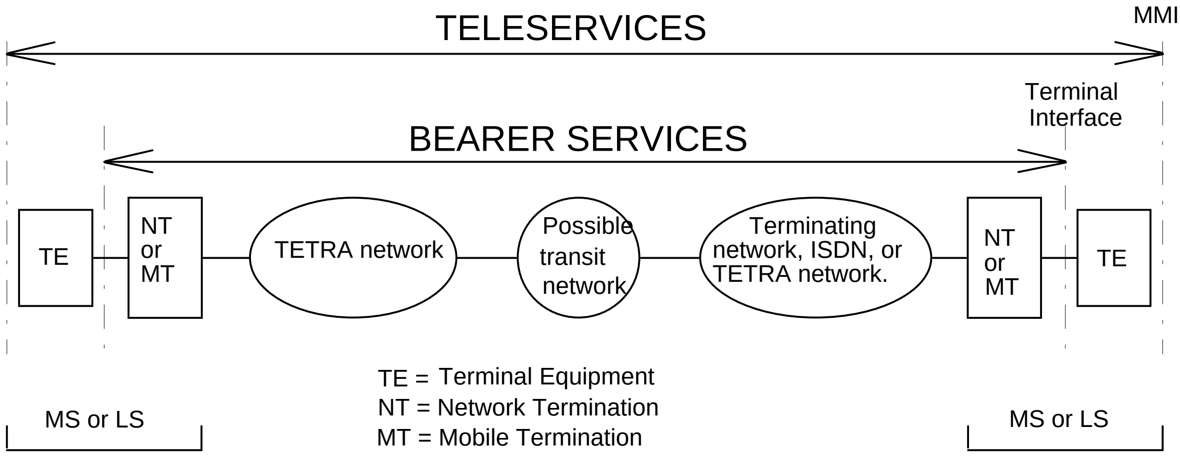


Figure 2: Bearer services and tele-services supported by the TETRA Land Mobile Network (TLMN)

A bearer service provides communication capability between terminal network interfaces, excluding the functions of the terminal. It is characterized by some lower layer attributes (layers 1 to 3).

NOTE: See subclause 5.1 for an explanation of OSI layers.

A tele-service provides the complete capability, including terminal functions, for communication between users. Thus in addition to the lower layer attributes it also includes high layer attributes (layers 4 to 7).

A supplementary service modifies or supplements a bearer service or tele-service.

The list of bearer services and tele-services supported by TETRA is given in annex A, clause A.1. The list of supplementary services supported by TETRA is given in annex A, clause A.2. The supplementary services are applicable to most bearer services and tele-services.

4.4 Network architecture

The TETRA specification places no constraints on the form of the radio network architecture. The infrastructure (often called the Switching and Management Infrastructure (SwMI) in the TETRA standards) is defined only in terms of the six specified interfaces. The interfaces defined in the specification are those required to ensure interoperability, inter-working and network management.

A number of defined system entities can be identified in the functional network diagram (see figure 3):

a) an individual TETRA system comprising BSs, switches, operations and management centre and the associated control and management facilities (i.e. everything inside the TETRA 1 box);

b) the MS comprising the Mobile Termination Unit (MTU) and the Terminal Equipment (TE), if fitted. These two entities are connected via the defined interface I4;

c) the LS comprising the Line Termination Unit (LTU) and the Terminal Equipment TE, if fitted. These two entities are connected via the defined interface I4;

d) the central network management unit (see ETR 292 [5]) connected via the defined interface I5;

e) the MSs operating in a DMO "net". These MSs communicate with each other directly using the defined "DM radio air interface" I6. They communicate with each other via a Direct Mode REPeater (DM-REP) using the defined interface I6'. They communicate with the TETRA trunked mode system using a defined "dual watch" mode of operation which allows a MS to operate on the I1 air interface and simultaneously monitor the I6 air interface and vice versa.

It is important to understand that the system entities shown in figure 3 are all within the TETRA domain, meaning that they are all in the same address space. Subject only to the different capabilities of the V+D LS, the V+D MS and the DM-MS, the functions and facilities available are all very similar. The mode of operation and the addressing techniques are all very similar.

The defined gateways to Public Switched Telecommunication Network (PSTN), Integrated Services Digital Network (ISDN), Packet Data Network (PDN) and Private Telephone Network (PTN) provide access between TETRA and the outside world. Some form of address conversion or dual addressing mechanism is required to communicate between TETRA and the other systems. It is expected that this will be considered in more detail in future standards..

The functional sub-entities identified within the TETRA 1 system of figure 3 (BTS, LSC, MSC etc.) are not defined within the standard and the interfaces between them are non-standard (proprietary). They are shown only for informative purposes.

Of particular interest for many applications is the functionality required in local and remote control rooms. The TETRA specifications take account of some limited network management functions that may need to be performed at a remote network management centre over the I5 interface (see ETR 292 [5]) but it is anticipated that the majority of system management functionality will be proprietary to a particular equipment manufacturer.

A standard LS will only have access to a set of services similar to a MS (i.e. bearer services, tele-services and supplementary services). However this will be sufficient to support most dispatcher functionality. Some special capabilities (such as monitoring multiple on-going calls) will need to be implemented as "special applications" on top of the standard services.

4.5 Network functions

In addition to the normal call handling functions required to provide the telecommunication services identified above a number of standard network procedures are needed for the smooth running of the system and to provide an acceptable grade of service to the users. These network procedures are described in ETS 300 392-1 [1] and are expanded here in the light of the implementations embodied in the specifications.

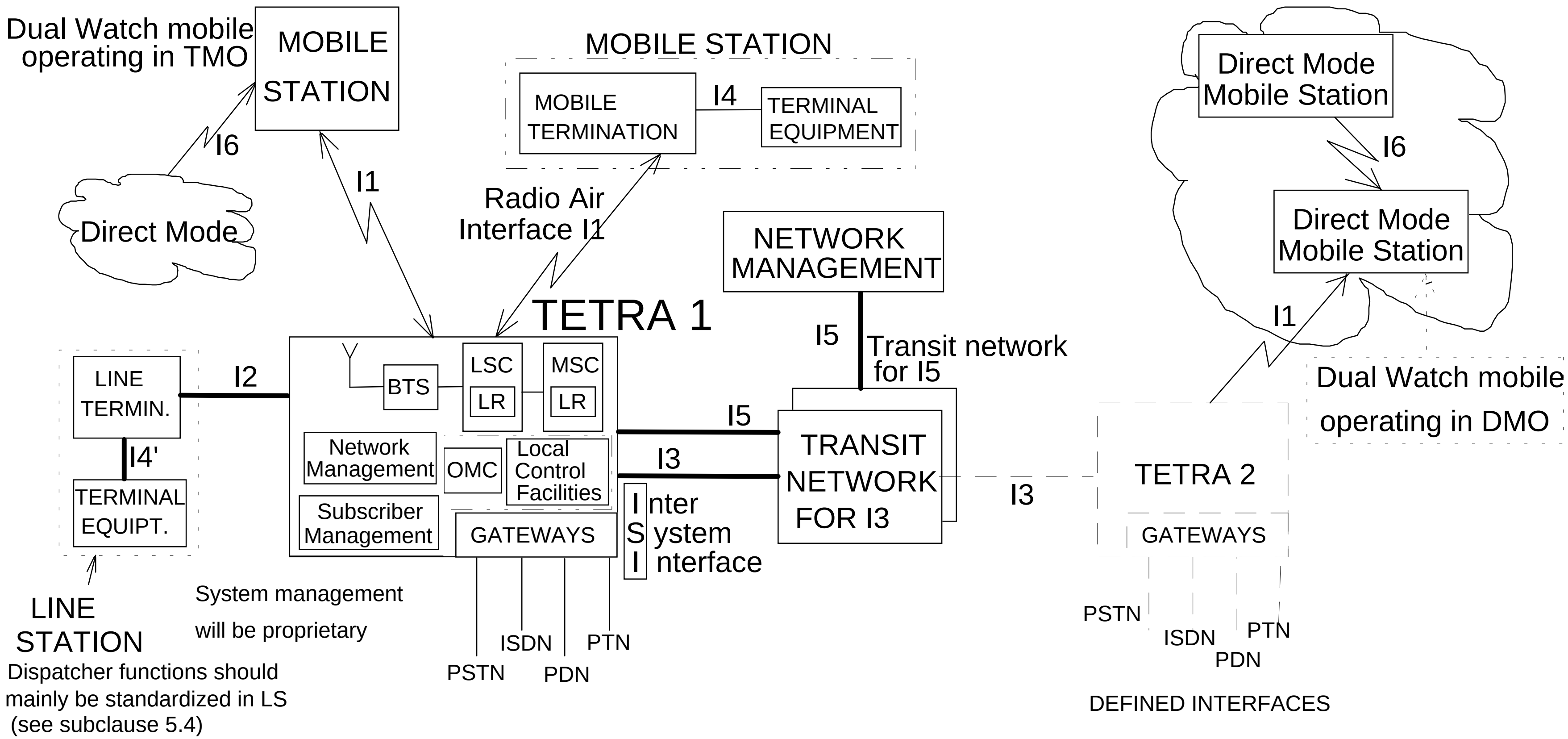
4.5.1 Establishing service

A notable feature of the TETRA V+D radio system (as with most modern advanced radio systems) is that channel acquisition is performed automatically when the radio is powered up. In V+D operation (as opposed to DMO) the user does not need to manually select channels. The relevant channel is contained in the MS memory or a search is performed to find a channel. Details of the technical procedures are given in subclause 5.8.1

4.5.2 Location registration

The coverage area of a TETRA network is divided into a number of Location Areas (LAs). A LA may correspond to a single cell or to a group of cells. A MTU is only paged in the LA(s) in which it is registered. The registration area is the sum total of the LAs.

Implicit registration is the network functionality that registers the location of the MS without need for an explicit registration message. Implicit registration can be performed by any system message that conveys the identity of the MS, e.g. call request, response to paging, cell change request.



DEFINED INTERFACES

I1 Radio air interface
I2 Line station interface
I3 Inter-system Interface
I4 Terminal equipment interface between MS and TE
I4' Terminal equipment interface between LS and TE
I5 Network management interface
I6 Direct mode radio air interface
PSTN, ISDN, PDN, PTN

ABBREVIATIONS

BTS Base Transceiver Station
ISDN Integrated Services Digital Network
LR Location Register
MSC Main Switching Centre
OMC Operations & Maintenance Centre
LSC Local Switching Centre
PDN Packet Data Network
PSTN Public Switched Telecommunication Network
PTN Private Telephone Network
DMO Direct Mode Operation
TMO Trunked Mode Operation

Figure 3: Functional network configuration showing defined interfaces

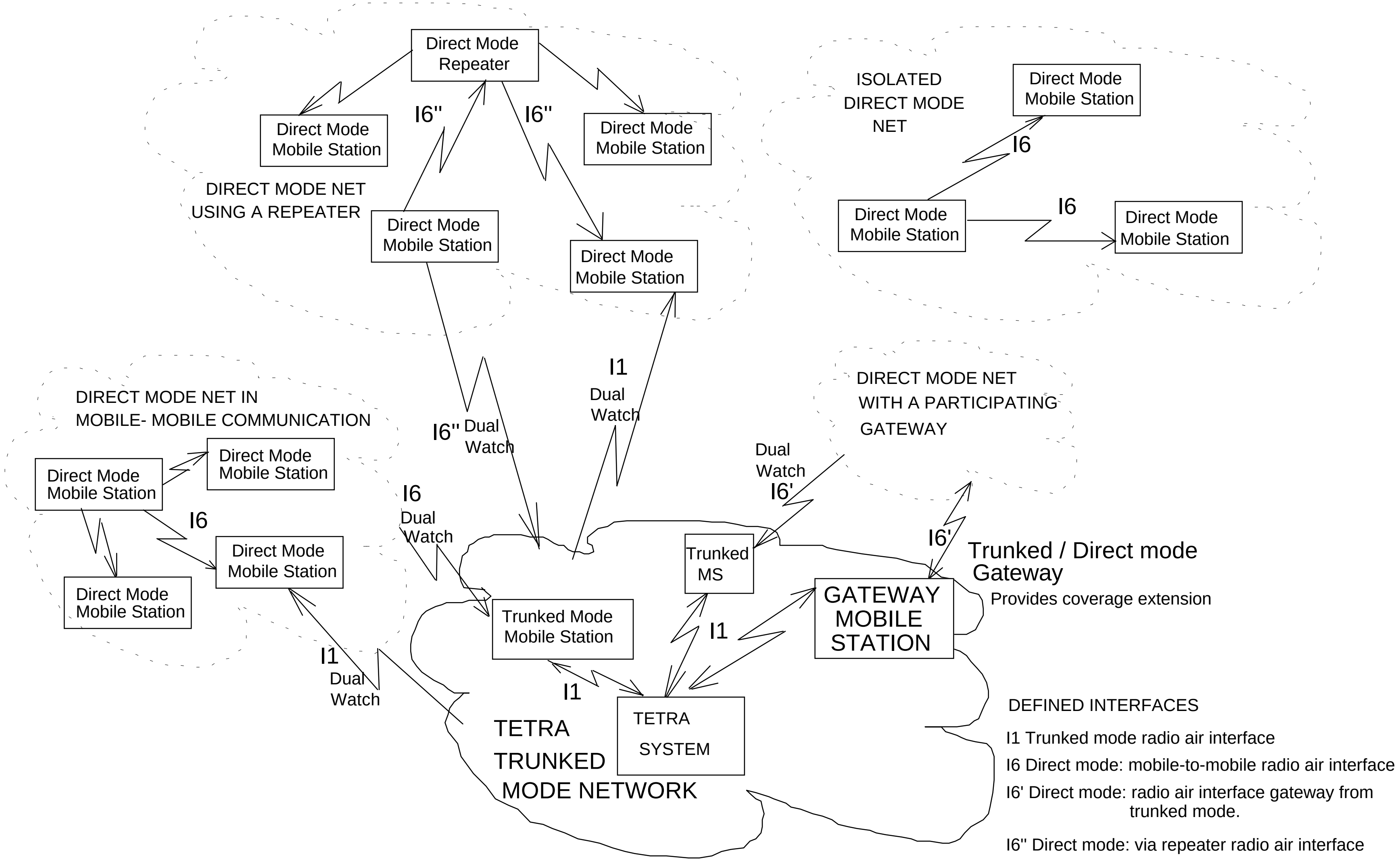


Figure 4: Functional network configuration showing DM air interfaces

It is a network operator option whether the system or part of the system will accept call requests from a MS that is not registered. This feature is likely to change during the course of the day and the MS should continuously monitor system broadcasts to ascertain whether it needs to register before making a call request.

In secure radio implementations an implicit registration will activate the authentication function in the same way as an explicit registration.

4.5.3 Register/de-register

A possible (implementation dependent) scenario is where a large fleet of vehicles leaves the depot in the morning. It is possible that if the MSs were allowed to register immediately on leaving the depot there could be a control signalling overload. It is more likely that registration messages would be invited at suitable times during the morning.

In theory the system would not page a de-registered MS, but for the above scenario it would be sensible to page a MS in its last registered LA even if it has not yet sent a registration message.

4.5.4 Connection restoration

A number of network procedures are supported in the TETRA specifications to provide continuity of service when a MS encounters adverse propagation effects, moves between different cells or encounters interference. Connection restoration may also be required for traffic reasons, e.g. to re-distribute the load on a particular cell such as during minimum mode operation, to allow the frequency allocations at a particular cell to be re-organized, for maintenance or equipment fault reasons.

The responsibility for initiating the connection restoration procedures can rest with the MS or with the BS, depending on the reason for restoration.

The MS is responsible for monitoring the quality of the downlink transmissions and may request an alternative channel on the same serving cell if interference is encountered or may request service on another cell if the received signal strength drops below a pre-defined level.

The BS may choose to move the MS to another channel on the same serving cell if interference on the uplink is encountered. The BS may wish to force a MS to an adjacent cell if the loading becomes too high on a particular site (load sharing). This would be performed by altering the acquisition and relinquishing criteria defined in the SYSINFO broadcasts (see ETS 300 392-2 [2]).

4.5.5 Call re-establishment

The TETRA air interface protocol provides a range of call re-establishment procedures of different quality which a network operator may wish to install, and to which users may choose to subscribe. These range from a totally unprepared call re-establishment taking several seconds (typically 15 s to 20 s) during which time the connection is broken, to seamless handover where the break in service is imperceptible to the user.

4.5.6 Security features

The high danger of overhearing sensitive conversations is the classical example of a security risk in radio networks. Research in modern cryptography has provided us with efficient cipher algorithms for digital data that, at least to current knowledge, would take an opponent many years or decades to break. It is one of the advantages of digital voice transmission that these high-grade security mechanisms can economically be integrated into the radio system.

In practice, eavesdropping is just one of many security threats to a radio system. Others are manipulation and replay of voice and data, user and network authentication, user anonymity, jamming and theft of MSs.

The TETRA standard supports two levels of security:

- a basic level employing air interface encryption for those users who expect security at a level comparable to the fixed telephone network or GSM;

- a higher level employing end-to-end encryption for those users who require it and are ready to undertake the cost and burden involved with end-to-end key management.

The higher level of security is a unique requirement of special user groups, such as public safety organizations. These user groups employ proprietary cryptographic algorithms. The TETRA standard, therefore, only specifies an interface for end-to-end speech encryption without prescribing a specific algorithm. Mechanisms for end-to-end authentication and key management are not covered by the standard, as they are supposed to be part of the higher layers of the system and mostly application specific.

The TETRA air interface security services comprise unilateral or mutual authentication of users and the infrastructure, the protection of confidentiality of communications and signalling, as well as provisions to prevent replay of messages. The cryptographic algorithms for air interface security will be specified by the ETSI Security Algorithms Group of Experts (SAGE).

Air interface encryption is also specified for DMO. Encryption in DMO is done using a set of Static Cipher Keys (SCKs) which can be distributed either manually or by a standardized mechanism over the air.

Traffic confidentiality can be provided after the first contact of the user with the infrastructure by using a temporary Individual TETRA Subscriber Identity (ITSI) (called an alias identity) instead of the unique (ITSI) identifier. With each registration of the user, the alias identity can be replaced by a new one. In addition, Group TETRA Subscriber Identities (GTSIs) can be protected by encryption on the air interface.

A certain level of protection against jamming is provided by the ability to change the frequencies of control and user channels in case of unsatisfactory transmission quality.

The unique Terminal Equipment Identifier (TEI) can be used by the infrastructure to disable certain terminals, e.g. those which have been reported as stolen. The security of this mechanism relies on the difficulty of reprogramming an individual terminal's TEI.

4.6 Services supported at the defined system interfaces

It is anticipated that all tele-services, bearer services and supplementary services will be supported across the defined system interfaces I1, I2, I3, and I4 except at the ISI, where the supplementary service "discreet listening" will not be supported.

There are however some "grade of service" aspects to be taken into account. For instance it is a network operator option whether interconnection of TETRA systems would be supported with leased lines or dial-up lines. Some network operators will co-operate very closely to the extent that high performance inter-working will be supported as if their two systems were a single system. Other network operators will support only a lower grade of service for intersystem working.

4.7 Services supported at the defined system gateways

At the time of publication of this ETR these services were still under discussion and so the precise services are not known.

4.8 Trunking methods

Depending on the traffic distribution and traffic profile the different trunking methods will provide optimal solutions (defined in terms of efficient use of resources, time to access the system, reliability of call retention or other suitable parameter). Unfortunately to gain any significant insight will require extensive simulations to be performed. This will be covered in a future part of this ETR.

The TETRA standard supports all the trunking methods described in the following subclauses. It is a network operator/manufacturer option which trunking method will be implemented. So far as a MS is concerned there is no difference between performing the system trunking strategies, each MS must simply obey the channel change instructions directed to it.

4.8.1 Message trunking

Message trunking is a traffic channel allocation strategy in which the same traffic channel is continuously allocated for the duration of a call (which may include several separate call transactions i.e. pressel activation by separate terminals). The traffic channel is only de-allocated when the call is explicitly cleared by the call owner in the case of a group call, either party hanging up during an individual call or if an activity timer expires.

Once a traffic channel has been allocated the users will experience the minimum delay at each "over" (each new call transaction) since there is no queuing for the allocation of channel resources. The absence of any perceptible delay when the pressel is activated ensures that a conversation can proceed without interruption. This strategy is likely to minimize the processing and signalling overheads in the infrastructure.

The disadvantage of this strategy is that the channel remains allocated even when there are significant gaps in the speech and this may result in less efficient use of the available channel capacity. Less efficient use of the available channels means that the initial call set-up time is likely to be increased under heavy load conditions.

4.8.2 Transmission trunking

Transmission trunking is a traffic channel allocation strategy in which a traffic channel is allocated only for the duration of each transaction (i.e. for each activation of the pressel). The traffic channel is de-allocated at the end of each transaction and control signalling for the next transaction takes place on the control channel.

Transmission trunking makes efficient use of the available traffic channels since a traffic channel is only allocated when the users are actually speaking. The advantage is most pronounced in situations where a query-response mode of operation prevails i.e. a question is asked and there is an idle time while the other party provides an answer.

The disadvantage of this strategy is that on a heavily loaded system or a system which has few traffic channels, the users are likely to notice significant access delays on pressel activation. This may result in the natural flow of conversation being lost requiring repetition of earlier parts of the conversation. If this happens the gains in throughput may be lost due to an increase in overall conversation duration. These problems will be exacerbated in systems with few traffic channels since the average interval between pressel releases will be longer. To benefit from this strategy the time taken to re-allocate a channel has to be short.

4.8.3 Quasi-transmission trunking

Quasi-transmission trunking is a traffic channel allocation strategy in which a traffic channel is allocated for each call transaction but the channel de-allocation is delayed for a short period, called the channel "hang" time, at the end of each transaction (i.e. after each pressel release). During the "hang" time the traffic channel may be re-allocated for a new call transaction that is part of the same call. During the "hang" time control signalling is carried out on the traffic channel. If the "hang" time expires the traffic channel returns to the trunked channel pool and control signalling has to be performed on the control channel.

Quasi-transmission trunking provides a compromize between message trunking and transmission trunking. Some of the improved traffic throughput of transmission trunking is obtained without breaking up the flow of conversations.

However, satisfactory operation relies on careful selection of the channel "hang" time. In a system which carries a mix of dispatcher traffic and peer-to-peer conversations it may be difficult to select a suitable value for this parameter. In a heavily loaded system with a mix of user types, users may find that there appears to be no consistent pattern of delays in traffic channel allocation. In a system with a mix of two way conversations and query-response transactions, parties to the query-response transaction find that, due to their slower response, they are inhibited from access to the system by prolonged conversations.

5 Technical description

5.1 OSI reference model

Communication networks have to support the following two cardinal aspects of protocol transfer to ensure correct functioning :

- data has to arrive at the destination correctly and in a timely manner;

- data delivered to the user at the destination has to be recognizable and in the proper form for its correct use.

This has led to defining network protocol operation in terms of lower level network services to provide the first capability and higher level protocols to satisfy the second requirement. As this conceptual model for the protocol architecture has evolved further layers have been introduced. The OSI reference model shown in figure 5, with seven functional layers identified, is now generally accepted for description and specification of layered communication architectures.

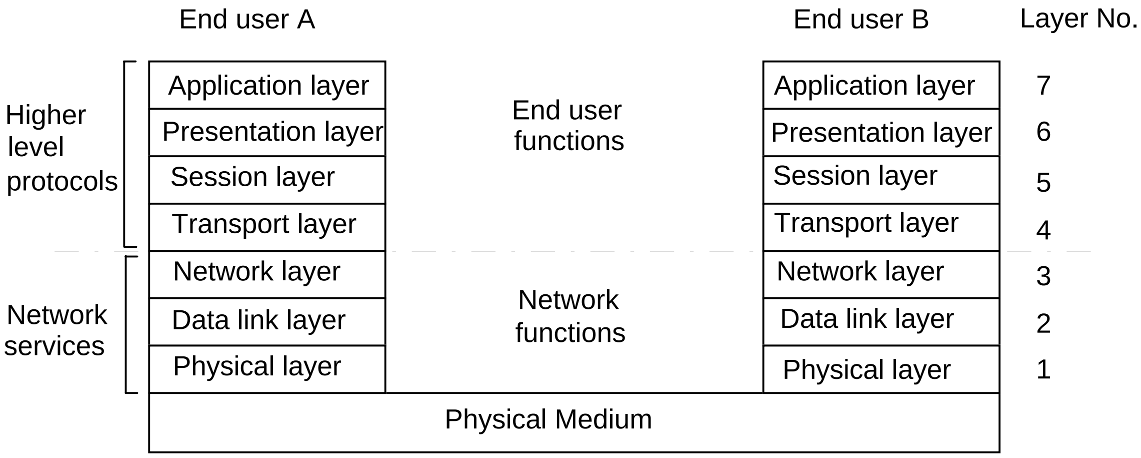


Figure 5: OSI reference model for communication architectures

The bottom three layers of the protocol stack are associated with the network services and have to be implemented in every node of the network (i.e. infrastructure and MSs). The upper four layers of the protocol stack provide services to the end users and are thus associated with the end users, not with the networks.

The philosophy of layered architectures is based on each layer being independently specified in terms of the services it provides to its immediately higher layer and the services it relies on from its immediately lower layer. The whole layered architecture concept is based on "peer-to-peer" exchanges in which each layer exchanges information with its peer entity at the remote end. Layers at each location are thus self contained and isolated from one another.

The layered architecture concept leads to equipment (usually with large software content) in which each layer can in theory be developed separately The result of any changes to a layer is transparent to the layers above and below provided the interface signals passed between layers remains unchanged (see subclause 5.1.1). One of the driving forces in development of the TETRA V+D layered protocol was to re-use the upper network layer of the MS in the LS.

The TETRA standard defines the network protocols only up to layer 3 of the OSI model.

5.1.1 Testable boundaries

It is important to realize that the layered architecture represents only a conceptual model and does not impact on the implementation of the protocol except at the testable boundaries. The testable boundaries are at the bottom of the physical layer and at the top of layer 3. Defining the tests to be performed at the testable boundaries is a meticulously detailed task that has to be carried out for the conformance test specifications.

In the following subclauses the protocol architecture of the radio air interface is described in more detail.

5.1.2 Description of MS/BS air interface protocol architecture

The MS/BS air interface protocol stack is shown in figure 6.

NOTE 1: The BS and MS work in complementary operation and are not identical e.g. BS generates and transmits system broadcast messages whilst the MS receives system broadcasts.

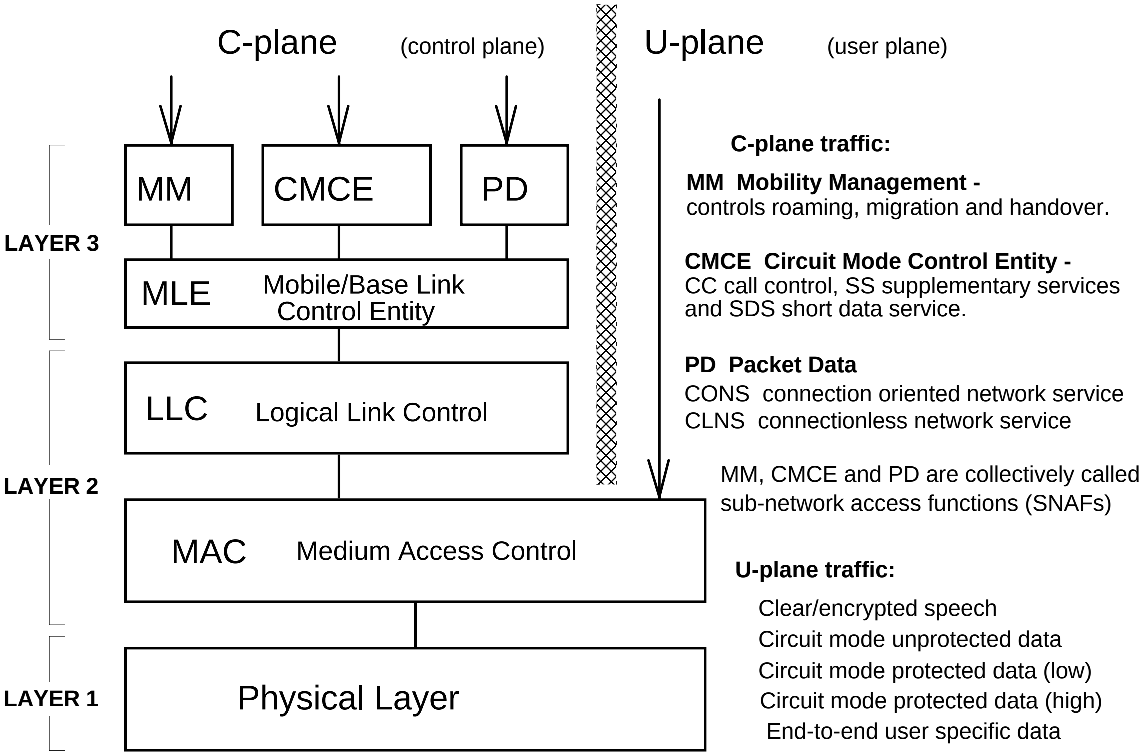


Figure 6: MS/BS protocol stack

The network service layers 1 to 3 illustrated in figure 5 can be identified in this more detailed representation. A significant point to notice is the level where separation of the signalling channels (C-plane) and traffic channels (U-plane) takes place. Separation takes place above the MAC sub-layer.

C-plane information corresponds to all signalling information, both control and data.

U-plane information corresponds to circuit mode voice or circuit mode data plus end-to-end user specific data.

It is appropriate to bear in mind the different requirements of C-plane and U-plane information. C-plane information needs only a discrete (or non-continuous) physical link to pass information although it needs a continuous virtual link to support the service. Acknowledgements may, or may not, be requested. U-plane information, on the other hand, requires a regular physical link to be available so that a constant delay service can be supported.

The initial state for operation of the radio air interface link relies on C-plane signalling. However after exchange of the preliminary call set-up signals the link may change to a U-plane link to support circuit mode services.

NOTE 2: C-plane signalling is always possible in TETRA due to the TDMA slot/frame structure described in subclause 5.2.2, albeit at variable bandwidth.

The physical layer deals with radio oriented aspects such as modulation and demodulation, receiver and transmitter switching, frequency correction, symbol synchronization and power control (MS only).

The Data Link Layer (DLL) (layer 2) identified in figure 5 has been further sub-divided in the air interface protocol shown in figure 6 to separate the functionality of MAC and LLC. This separation is often performed in radio air interface protocols due to the specialized nature of these two tasks. Such separation is not present in the LS protocol stack.

The MAC layer performs TDMA frame synchronization, interleaving/de-interleaving, channel coding, random access procedures, fragmentation/re-association, RSSI and MER (on AACH) measurements for radio link quality purposes and MER measurements to support LLC re-transmission procedures. It is at this level that separation of the C-plane and U-plane is performed. U-plane traffic is routed to the user plane whilst C-plane information continues up the protocol stack.

The LLC layer is responsible for data transmission and re-transmissions, segmentation and re-assembly, logical link handling.

The network layer (layer 3) is applicable only to the C-plane and is responsible for network procedures. Layer 3 is divided into two sub layers, the lower dealing with the mobile-base link control which is common to all higher C-plane layers and the individual sub-network access functions (i.e. MM, CMCE, PD).

The MLE performs management of the mobile to base/base to mobile connection, mobility within a registration area, identity management, quality of service selection and protocol discrimination (i.e. routing to the higher layer entities).

The sub-network access functions MM, CMCE and PD provide individual connection for the following functions:

a) mobility management;

b) circuit mode control entities (call control, supplementary services, short data services); and

c) packet data services (connectionless and connection oriented data).

5.1.3 Mapping of higher layer data on to the physical layer

The mapping of signalling and traffic information from C-plane and U-plane higher layer entities on to the physical layer represents a complex process. The higher layers are not (and do not need to be) aware of detailed transport mechanisms, dealing only in terms of data primitives (request/indication/response/confirm) and PDUs. Conversely the physical layer follows a pre-determined (rigid) timing mechanism and is completely oblivious of the content of each data packet.

NOTE: Due to the TDMA slot structure even circuit mode voice is in a sort of packet format although it has constant delay characteristics like analogue voice.

It is the job of the DLL (layer 2) to perform this mapping from layer 3 to layer 1. Within layer 2 the LLC sub-layer is responsible for dealing with multiple logical links to support simultaneous services, for segmentation/re-assembly and for re-transmissions. It is the MAC sub-layer that is responsible for channel allocation and the multiplexing of data on to the physical layer. To perform this function the MAC communicates to higher layers with primitives and to lower layers by means of logical channels.

By grouping together certain types of higher level information and identifying it with hypothetical MAC logical channels it is possible to devise a scheme whereby the transmitted information is associated with the physical means of conveying the information. This provides an effective and intuitive method of describing the mapping functions performed by the MAC in the air interface protocol.

In the following subclauses the elements that make up each layer of the protocol will be described. Then the process of mapping between layers will be illustrated.

5.2 Physical layer

5.2.1 Physical resources

The physical resource available to the radio sub-system is an allocation of part of the radio spectrum. This resource is partitioned both in frequency and time.

TETRA BSs operate in frequency duplex (uplink and downlink frequencies operational at the same time). MSs may operate in frequency duplex or half duplex depending on the capability of the MS.

One pair of radio frequencies (uplink and downlink) per cell, known as the main carrier, is used to carry the MCCH.

The outline radio characteristics are as follows:

Modulation:	π/4 DQPSK;
Transmission rate:	36 kbit/s;
Duplex spacing:	10 MHz (45 MHz in 900 MHz band);
RF carrier spacing:	25 kHz.

TETRA V+D has been designed to work in the frequency range from VHF (150 MHz) to UHF (900 MHz). In December 1995 harmonized bands were released in the frequency range 380 MHz to 400 MHz for Public Safety users.

CEPT have made additional recommendations for use in the following frequency bands:

- 410 MHz to 420 MHz and 420 MHz to 430 MHz;

- 450 MHz to 460 MHz and 460 MHz to 470 MHz;

- 870 MHz to 888 MHz and 915 MHz to 993 MHz.

5.2.2 TDMA frame structure

The TETRA frame structure has four slots per TDMA frame. This is further organized as 18 TDMA frames per multi-frame of which one frame per multi-frame is always used for control signalling. This 18th frame is called the control frame and provides the basis of the SACCH, one of the most powerful features of the protocol.

In circuit mode voice and data operation traffic from an 18 frame multi-frame length of time is compressed and conveyed within 17 TDMA frames, thus allowing the 18th frame to be used for control signalling without interrupting the flow of data. This capability provides the background control channel signalling that is always present, even in minimum mode when all channels are allocated to traffic.

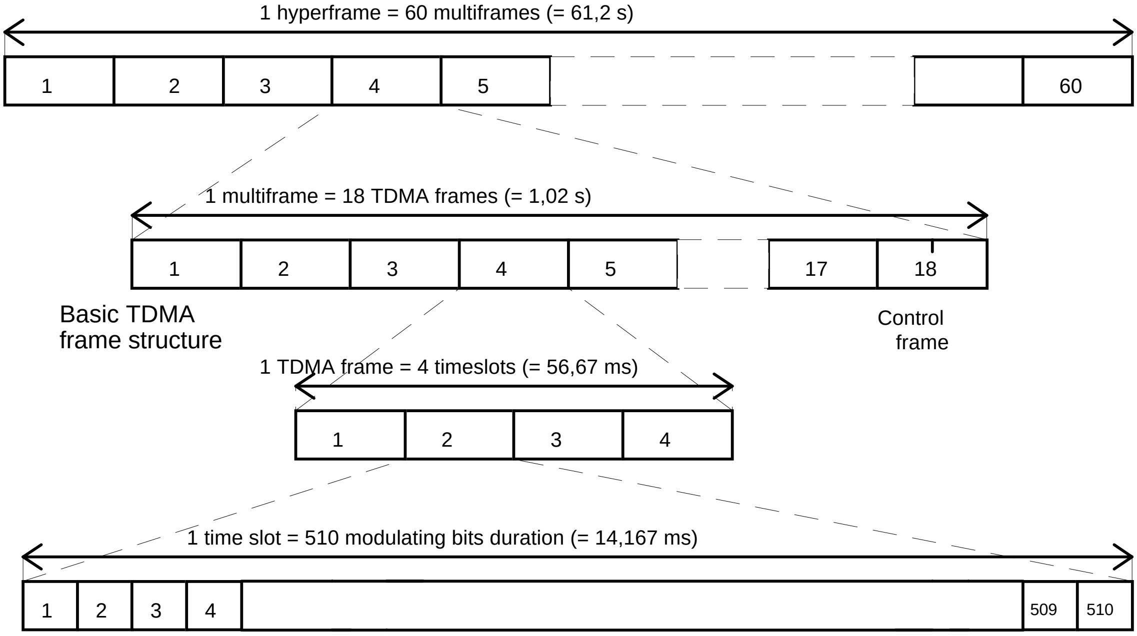


Figure 7: TETRA TDMA frame structure

Besides the basic TDMA frame structure described above, there is a hyper-frame imposed above the multi-frame structure. This is for long repeat frame purposes such as encryption synchronization. Each time slot has 510 modulation bits duration and has the basic structure shown in figure 7.

5.2.3 Slot structure

There are powerful constraints on the slot structure due to the nature of the anticipated traffic (see figure 8).

For instance, by its very nature, vocoded voice has a fixed frame size and is the same in the uplink and downlink directions. However, due to the need to ramp up the MS transmitter power and linearize the MS power amplifier, the downlink transmission capacity is slightly greater than the uplink capacity, i.e. approximately 30 bits gross capacity more in the downlink even allowing for insertion of an extra intermediate training sequence in the downlink.

The extra downlink capacity has been used to transmit "low layer" MAC information. At the physical level the field has been designated the "broadcast block" since it is present on every downlink slot. At the MAC level the field is designated the Access Assignment CHannel (AACH). This field is not visible above the MAC level.

The AACH is primarily used for two purposes:

- on traffic channels it conveys the "usage marker", indicating the intended destination of the downlink slot, and the allowed user of the uplink slot. This feature makes the protocol much more robust by reducing the occurrence of crossed calls caused by intermittent MS coverage ("under bridge or tunnel" phenomena) in which the MS emerges to find that the system has allocated the channel to another call. By noting the usage marker the receiving and transmitting MSs can continuously verify that they have access rights to the channel, if not then they must return to the MCCH;

  NOTE: Uplink and downlink channels can be allocated to different calls or to a mix of circuit mode traffic in one direction and signalling (control or packet mode data) in the other direction.

- on signalling (control and user data) channels the physical broadcast block (AACH at the MAC level) is used to convey the access control elements (Access code and ALOHA frame length). This will be examined further in the random access procedures subclauses. Independent information on each access half slot can be conveyed in the AACH or a mix of traffic in one direction and signalling in the other.

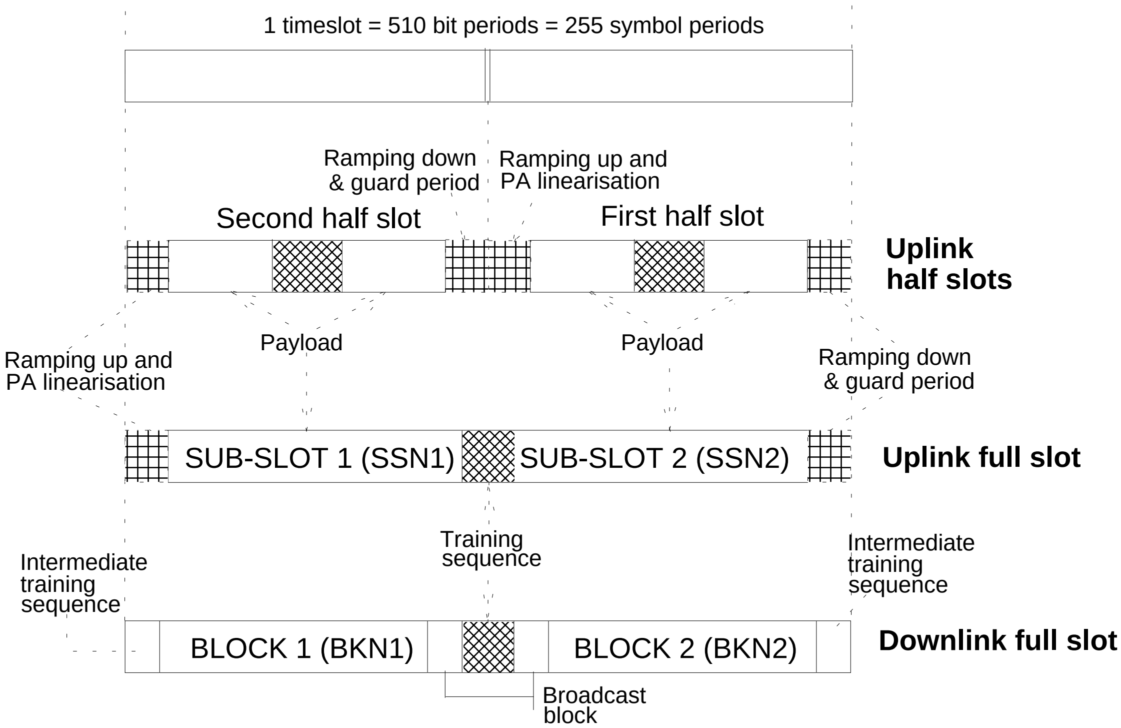


Figure 8: Basic slot structure seen at the physical layer

5.2.4 Radio transmission burst structure

A transmission burst is a period of RF carrier that is modulated by a data stream. From the three basic slot structures outlined in the previous subclause (uplink half slot, uplink full slot and downlink full slot) five basic types of physical bursts can be derived for use by the air interface protocol:

a) control uplink - half slots used both for random and reserved access;

b) normal uplink - full slot format used by MSs after initial access to the system;

c) linearization uplink;

d) normal downlink;

e) synchronization downlink.

In addition, two special cases of bursts d) and e) are used for discontinuous transmissions (time shared carrier or control channels) but these will not be described here.

The extra ones on this list (over those considered in the previous subclause) are the linearization uplink burst and the synchronization downlink burst. The linearization uplink burst is an opportunity for linearizing MSs to transmit "on-air" when they first tune to a new frequency (such as when they first go to a traffic channel after being on the control channel). No information is transferred on the linearization burst.

The synchronization downlink burst is a special case of the normal downlink burst characterized by conveying a unique bit synchronization pattern in the first half of the slot. Normal signalling messages can be conveyed in the other part of the burst.

Bursts may be further divided into fields containing contiguous modulation bits of the same type.

The downlink bursts contain 3 independent fields, called Broadcast BlocK (BBK), BlocK Number 1 (BKN1) and BlocK Number 2 (BKN2) as shown in figure 8. The normal uplink burst contains two independent blocks, called SSN1 and SSN2. A separate logical channel may be mapped on each block.

Both of the normal uplink and downlink bursts contain 216 scrambled bits gross for higher layer information exchange (124 bit net). The error control scheme for this signalling channel is shown in the next subclause.

NOTE: Normal uplink and downlink bursts are also used for transporting circuit mode voice and data traffic.

The broadcast block contains 30 scrambled bits gross (14 information bits net) and is used exclusively for the AACH.

Uplink half slots each convey 168 scrambled bits gross, 92 information bits net.

Scrambling is performed on transmitted signals to minimize the possibility of co-channel and adjacent channel interference from generating valid messages. The scrambling code contains the mobile network identity which is broadcast unscrambled on the Broadcast Network CHannels (BNCH).

5.2.5 Slot structure formats within the physical layer

The following structures are defined within the physical layer and are used to describe exchanges between the lower MAC sub-layer and the physical layer:

Uplink transmissions: MS to BS

Control Burst	CB;
Normal Uplink Burst	NUB;
Linearization Burst	LB;
Slot Flag	SF.

Downlink transmissions: BS to MS

Broadcast Block	BBK;
Synchronization Burst	SB;
Normal Downlink Burst	NDB;
Slot Flag	SF.

The only item we have not yet encountered is the SF. The SF is visible at the physical and lower MAC level and corresponds to one of two training sequences present (mid slot) of uplink and downlink normal bursts. This flag is used to indicate the presence of one or two logical channels on the blocks 1 and 2 of the burst. It will be shown later that this is the way of distinguishing slot stealing. It also has some other applications.

5.3 Organization of layer 2 - Data Link Control (DLC)

Following the approach outlined in figure 6 we find that the information delivered to or received from higher layers can be grouped as follows:

1) U-plane traffic information comprising circuit mode voice and data, plus end-to-end user signalling information;

2) C-plane information comprising two way control messages and packet data;

3) C-plane broadcast information concerned with system operation and only present in the downlink (BS to MS) direction.

This grouping of information flow is represented in figure 9, showing how the layer 2 entities (LLC and MAC) communicate with the next higher layer via three Service Access Points (SAPs) whilst communicating via a single SAP at the physical layer.

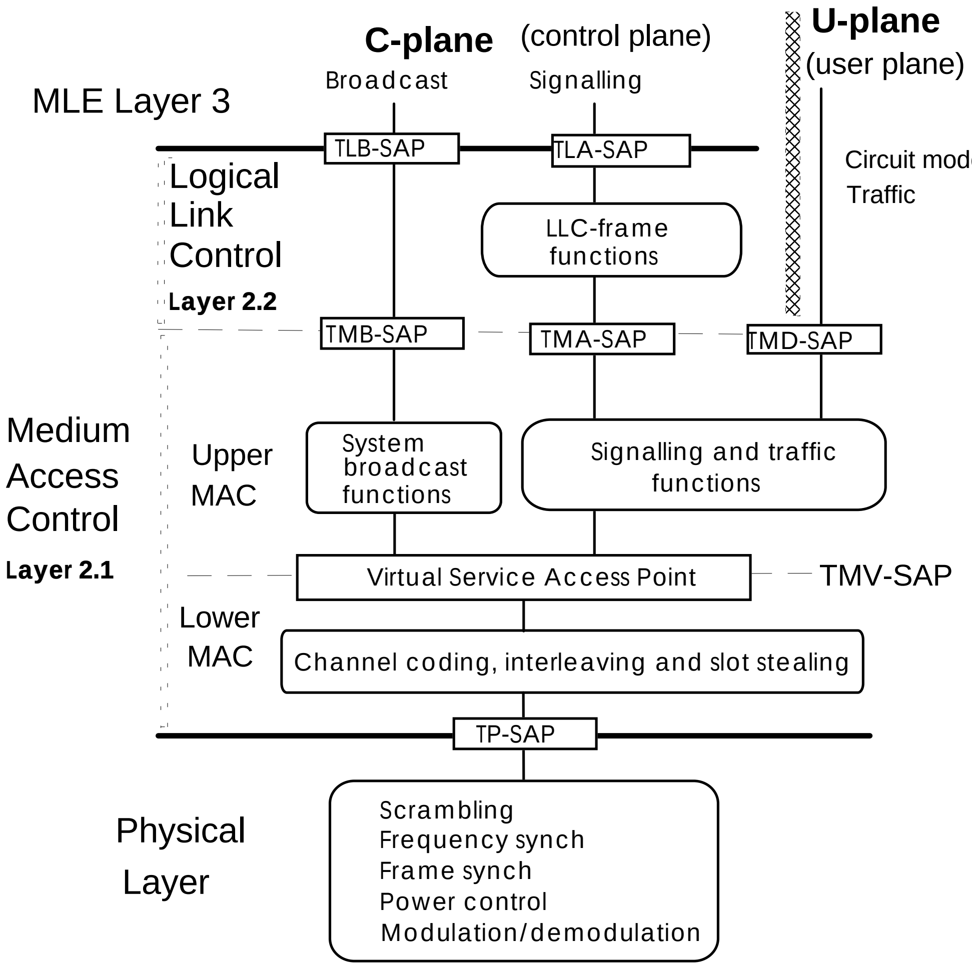


Figure 9: Protocol organization in layer 2 of the air interface.

5.3.1 Logical channels in the lower MAC

The uplink and downlink logical channels are slightly different to take account of the different functionality required in each direction (for instance system information only needs to be broadcast in the downlink). The following logical channels are defined within the lower MAC layer and are used to describe information exchanges at the TMV-SAP between the upper and lower MAC sub-layers:

Signalling CHannel (SCH) :	uplinks and downlinks;
Access Assignment CHannel (AACH):	downlink only;
Broadcast Synchronization CHannel (BSCH):	downlink only;
STealing CHannel (STCH):	uplinks and downlinks;
Broadcast Network CHannel (BNCH):	downlink only;
Common Linearization CHannel (CLCH):	uplink mainly (but discontinuous BSs may also need to linearize);

Traffic CHannel (TCH): up and downlinks:

- 7,2 kbit/s net rate (TCH/7,2);
- 4,8 kbit/s net rate (TCH/4,8);
- 2,4 kbit/s net rate (TCH/2,4).

Speech (TCH/S).

Higher net rate data up to 28,8 kbit/s, 19,2 kbit/s or 14,4 kbit/s may be used. They are obtained by allocating up to 4 traffic channels to the same communication. These 4 traffic channels have to comprise 4 consecutive slots on the same frequency.

5.3.2 Logical channels in the upper MAC

The following logical channels are defined within the upper MAC layer and are used to describe information exchanges between the upper MAC and higher layers (i.e. LLC or U-plane). The SAP associated with each logical channel is indicated.

TMA-SAP signalling channel

- Common Control CHannel (CCCH) comprising:

  - Main Control CHannel (MCCH);
  - Extended Control CHannel (ECCH);

  These channels deal with control information addressed to or received from MSs not actively involved in a circuit mode call.

  NOTE: In transmission trunked systems, MSs may be involved in a circuit mode call but at an "over" are on the CCCH sending or awaiting further signalling.

- Associated Control CHannel (ACCH) comprising:

  - Fast Associated Control CHannel (FACCH);
  - Stealing CHannel (STCH);
  - Slow Associated Control CHannel (SACCH).

  These channels deal with control information intended for or received from MSs involved in a circuit mode call.

TMB-SAP Broadcast channel

- Broadcast Common Control CHannel (BCCH) comprising:

  - Broadcast Synchronization CHannel (BSCH);
  - Broadcast Network CHannel (BNCH).

  These channels carry the downlink system broadcast information.

TMD-SAP U-plane

- Traffic CHannels (TCH) comprising:

  - Speech Traffic CHannel (TCH/S);
  - Speech or data traffic channels (TCH/7,2, TCH/4,8, TCH/2,4);
  - end-to-end user specific data;

  These channels carry the circuit mode voice or data traffic information.

5.4 Use of the logical channels and mapping between layers

Let us briefly examine how messages are passed down the protocol stack. In layer 3 and higher, messages are conveyed in the form of PDUs. These are messages (in the form of bits and bytes) with pre-defined format.

When these PDUs are presented at the TMx-SAP (i.e. TETRA MAC A, B, or D Service Access Point) the MAC has to decide in which logical channel they are to be conveyed. The appropriate logical channel depends on the source of the PDU (which SAP) and on the state of the physical channel, both of which are known to the MAC (from its own internally generated data and via the C-SAP, associated with inter-layer management). The logical channel is further mapped at the TM virtual SAP and finally is mapped on to a physical burst at the physical layer.

A good intuitive understanding of this process will be obtained if we examine what happens in both directions, from the bottom up and from the top down.

First let us examine the slot and frame structure at the physical layer and establish which processes are free-running and which need to be controlled.

5.5 Physical layer functionality

Let us examine the TDMA slot and frame structure outlined in figure 7. Four slots are grouped together to make a TDMA frame and 18 frames are grouped to make a multi-frame. Other groupings will for the moment be ignored.

The structure is the same on the uplink and downlinks except that the same numbered slots on the uplink follow the downlink by two slots as shown in figure 10.

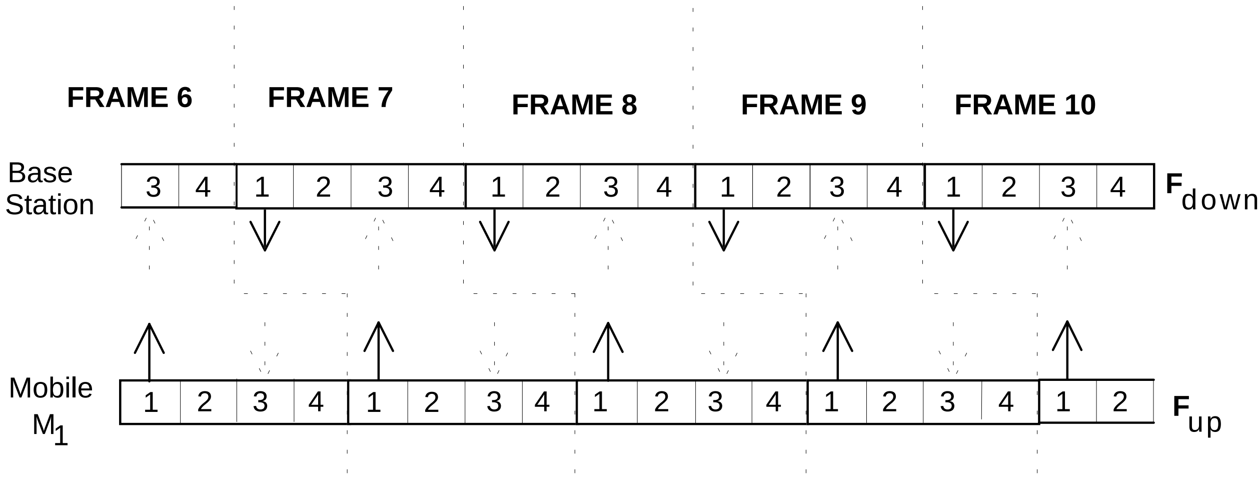


Figure 10: Uplink and downlink slot and frame arrangements

This slot arrangement allows simple half duplex MSs to transmit and receive on alternate slots, providing the basis for full duplex voice operation.

NOTE 1: If both of the parties in a duplex call are on the same site then a separate channel (uplink and downlink pair) is needed for each party.

Even in half duplex operation the transmitting MS is required to monitor the downlink AACH message associated with its particular slot to ensure that the uplink slot is still allocated to its call. This facility makes the protocol robust to crossed calls and other phenomena resulting from unreliable propagation.

The composite uplink and downlink slot and frame numbering scheme is based on the convention that slot 1 of each frame corresponds to the MCCH on the uplink and downlink duplex frequency pair. In figure 10, time is shown running from left to right, so frame 6 is the first to appear (i.e. oldest) and frame 10 is the last to appear (i.e. newest).

The BS MCCH transmission in frame 7 slot 1 is received by the MS in its frame 6 slot 3. The MS then has time to decide the relevant action to be performed in its similarly numbered frame 7 slot 1 which follows two slots later. This shows how the broadcast block on the downlink transmissions (see subclause 5.2.3) can be used to convey control or usage information for the same numbered uplink slot. Transmission by the MS in its slot 1 is received by the BS in its slot 3.

NOTE 2: Whilst the particular example in figure 10 corresponds to transmissions on channel 1 (i.e. slots 1 on the uplink and downlink frequencies), exactly the same arguments apply to transmissions on channels 2, 3 and 4.

As stated previously, frame 18 is designated the control frame. All four slots in frame 18 are used exclusively for either system control (network broadcasts) or for control of ongoing calls (SACCH).

The traffic that would have been conveyed in frame 18 has been distributed amongst the other 17 frames and a small degree of compression imposed overall on the data to allow this to happen. So far as the user (or application) is concerned they see a continuous transfer of data (or speech) without any gaps. The only disadvantage of this technique is the introduction of an inherent latency time to the transfer of speech and circuit mode data. This is of the order of 200 ms. It should not be confused with the call set-up delay encountered at the start of a call. A brief description of the TDMA frame structure intrinsic delay and its contribution to the end-to-end delay is given in annex B.

One frequency pair per site is designated to carry the MCCH. In normal mode of operation slot 1 of every frame on this frequency pair (both uplink and downlink) is allocated for control purposes. This is the MCCH.

It is a characteristic of the TETRA protocol that MSs are able to make half slot accesses in the uplink direction. This allows more efficient use of the radio resources.

In frame 18 the network broadcasts are being continually transmitted. There are basically two types of network broadcast; the synchronization broadcast and the system information broadcast. The design strategy for the protocol has been to ensure that there is at least one half slot downlink and one half slot uplink available in each of the slots of frame 18 for access control purposes, either common or assigned control.

NOTE 3: Assigned means that the channel is for the exclusive use of an individual or group.

However there is much more information needed to be transmitted in the network broadcasts than will fit into each of the remaining half slots. Consequently the broadcast information is transmitted over a number of half slots in frame 18 with the result that it may take several seconds for a MS to receive all of the network information. This is not usually important since MSs will generally be switched on at non-critical times. It is a manufacturer/operator option to transmit extra network information in frames 1-17. In this case the time to acquire network information will be much shorter.

NOTE 4: It is a requirement of the standard that all MSs, transmitting MSs included, have to maintain a defined monitoring pattern of the network broadcasts in frame 18 to ensure that they receive all the network broadcasts.

So far everything that has been described in this subclause works autonomously and never changes. This is the so-called free running "clockwork mechanism" which is characteristic of the physical layer. In steady state operation, as opposed to channel switching, the physical layer is unaware of the tasks demanded by higher layers. As we progress higher up the layers then there is more variability in the operation of the protocol.

5.5.1 Lower MAC functionality

The lower MAC performs channel coding, interleaving and logical channel routing.

The lower MAC runs semi-autonomously. There are a limited set of rules for mapping to the different logical channels. Once chosen the logical channel is fixed and can only be changed by stealing.

The joint operation of the lower MAC and the physical layer for the SCH is illustrated in figure 11.

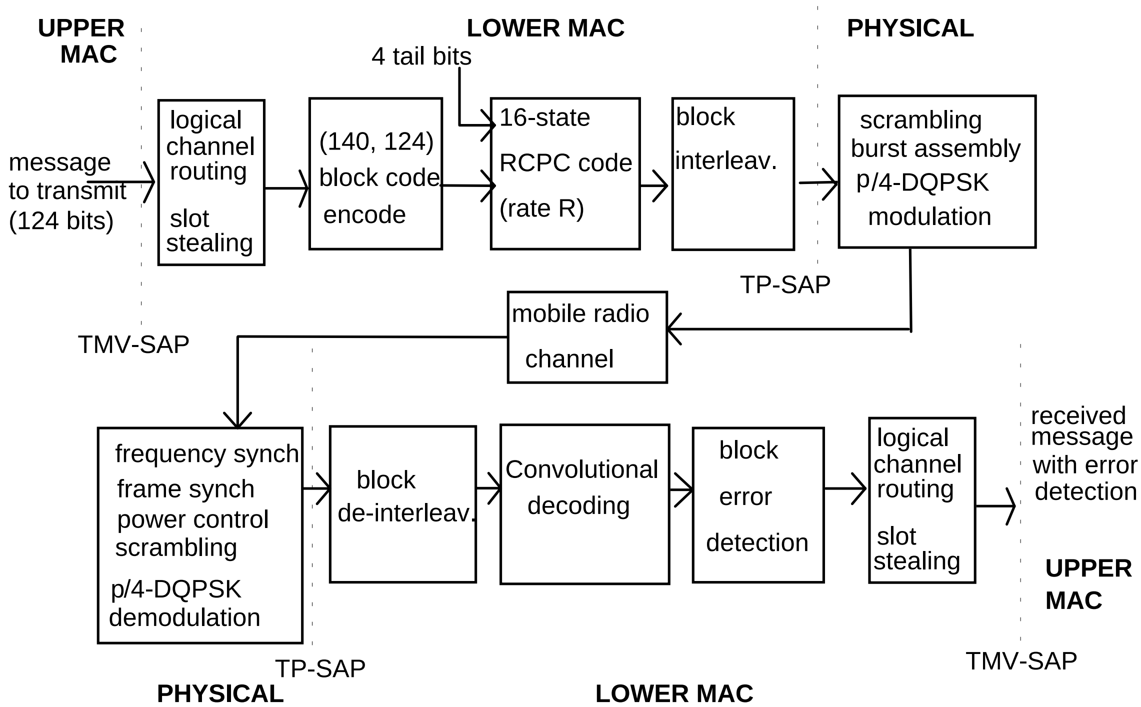


Figure 11: Operation of the lower MAC and the physical layer for the SCH

This is one of several logical channels which the lower MAC supports. A fuller picture will be obtained by examining figure 12 which shows the range of different logical channels supported in the lower MAC.

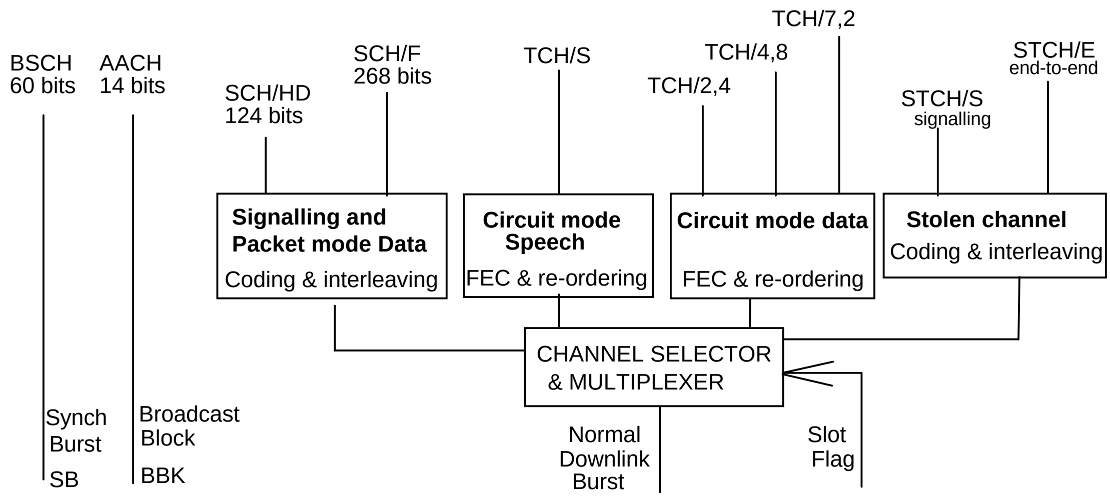


Figure 12: Logical channels supported in the Lower MAC - MS downlink

Figure 12 shows the net size of messages (per slot) and indicates the range of channel coding schemes which need to be supported in the MAC. This aspect will become more apparent in clause 6 when we deal with radio propagation and coverage issues. Because of the range of message sizes and the different coding schemes needed each logical channel will have a different BER and MER.

5.6 How it all hangs together

The picture we have not yet established, but will now seek to do so, is how the layer 3 PDUs are mapped on to the physical layer, which logical channels in layer 2 are used and what controls this mapping process?

It should be realized at the outset that this is a very constrained process. There are only a few permitted channel arrangements. It is the MAC which controls the process. First let us make two clear statements:

- layer 3 messages are not concerned about the transport mechanism which conveys them; and

- the physical layer is not concerned about what it is conveying.

Despite this apparent lack of concern by the layered protocol, not all the layer 3 PDUs can be conveyed on any physical burst. To establish what is, and what is not, allowed let us go back and re-examine the logical channels, but this time from the top down.

The protocol architectures and the logical channels examined in the following subclauses (see figures 13 and 14) apply equally to MSs and BSs except that the information flow clearly is in the reverse direction and they perform complementary functions. To avoid confusion, information flow in all cases is shown from the MS's viewpoint.

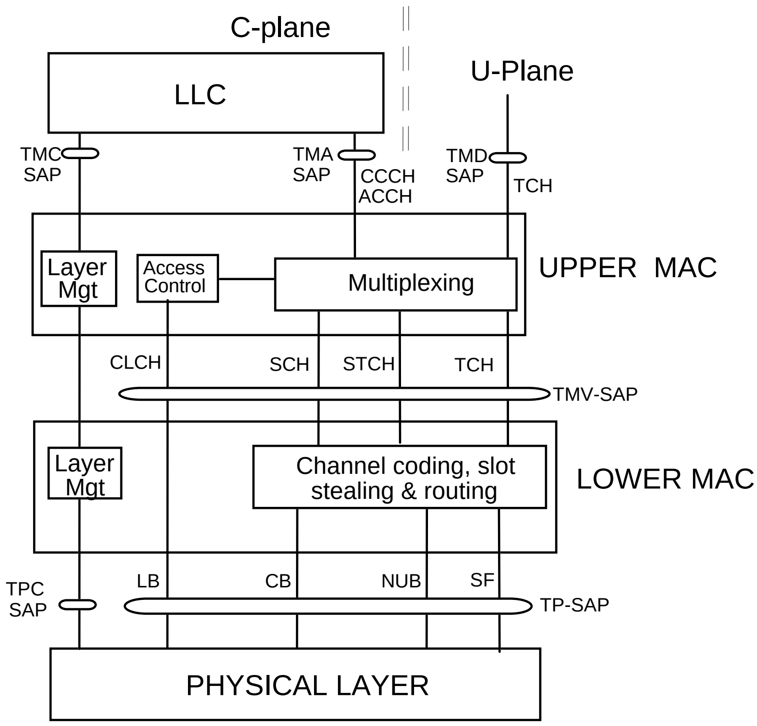


Figure13: MAC sub-layers and logical channels for MS uplink transmission (i.e. MS transmit)

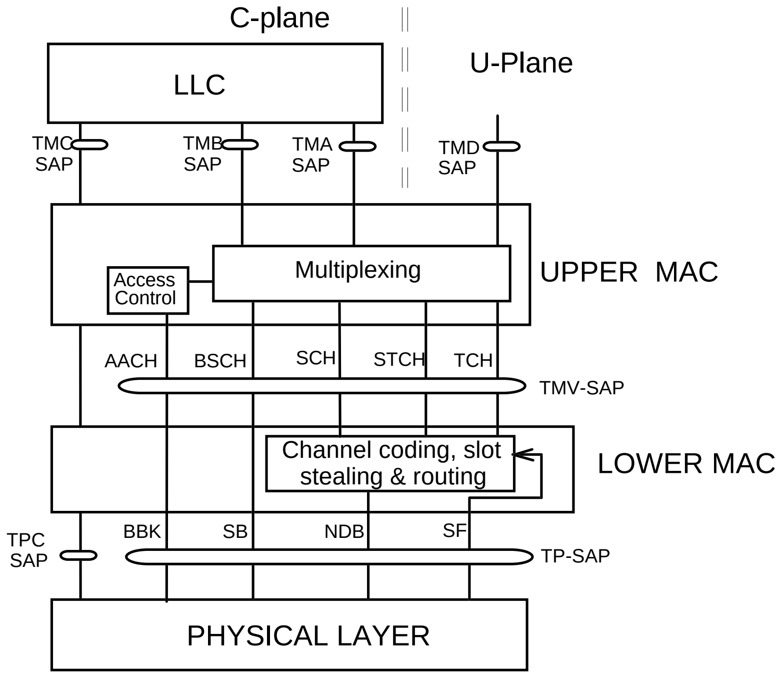


Figure 14: MAC sub-layers and logical channels for MS downlink transmissions (i.e. MS receive)

To put these figures in context the lower MAC shown in figure 14 should be compared with the more detailed representation given in figure 12. These indicative mappings between logical channels in different layers will now be described in more detail, starting from the top of layer 2.

5.6.1 Broadcast channel

The TMB-SAP is responsible for supplying/receiving the broadcast information on the present serving BS. The BSCH has to be mapped on to a special physical synchronization burst. The BNCH is mapped onto the MAC SCH and then on to a Normal Downlink Burst (NDB) at the physical level.

The broadcast channel information is mainly broadcast in frame 18 (see figure 7) following a defined sequence but this information can also be transmitted in any other frame if there is spare signalling capacity. This is an option that will be different in different systems.

The DWRK-BROADCAST, which provides information on adjacent BSs, is routed to the TMA-SAP.

5.6.2 Signalling channel

There are two categories of signalling channel:

- the common control channels deal with control of MSs which are not involved in a circuit mode call. They may also be used for communicating packet mode data to these MSs;

  The associated control channels deal with control of MSs which are involved in a circuit mode call. The MAC knows when it is involved in a circuit mode call, since it will have been assigned to a particular physical channel. Once the assignment has taken place MSs on the assigned channel have three varieties of associated control channel at their disposal; the FACCH, the SACCH, and the STealing CHannel (STCH). Depending on the state of the MS, i.e. transmitting or receiving, and activity on the channel, one or several of these signalling channels will be available as shown in table 1.

Table 1: Availability of control channels to BS and MS entities

Activity on channel	MS		BS
	Transmitting	Receiving	
During conversation	STCH, SACCH	SACCH	STCH
During signalling - message trunking or quasi-transmission trunking	FACCH, SACCH	FACCH, SACCH	FACCH, SACCH - no need to steal
During signalling - transmission trunking	MCCH	MCCH	MCCH - ordinary control channel signalling

When a traffic channel is first assigned, the assigned MSs arrive on channel to find the channel, by default, in signalling mode. This is the FACCH when the resources in frames 1 to 17 are all allocated for signalling on the assigned channel. Normally, there is a small amount of control signalling at the start of a call, e.g. the BS allocating transmit permission to a particular MS, and then the assigned channel is used for traffic, i.e. it becomes a TCH. At the end of a call, capacity is stolen from the circuit mode TCH to pass control signalling to the system and the assigned channel reverts to a FACCH, able to support further control signalling. It is clear from this description that the FACCH and TCH are mutually exclusive; the assigned resources are one or the other, they can not be used for both at the same time.

On the other hand the STCH can exist at the same time as the TCH. On the uplink it corresponds to the transmitting MS only, taking some of the TCH capacity for signalling either to the infrastructure or to the end user. On the downlink the system can steal capacity to signal to either the transmitting MS or to any member of the ongoing call (this may for instance be used to signal an urgent call waiting message to an individual member of the group). In minimum mode (see subclause 5.9.3) the system may steal capacity from the TCH using the MCCH resources to update the waiting MSs or to contact specific MSs.

Similarly the SACCH exists at the same time as the TCH or FACCH. Physically the SACCH corresponds to use of the normal uplink or downlink blocks in frame 18, thus explaining the compatibility with TCH and FACCH which run in frames 1 to 17. All MSs on the assigned channel have access rights to their same numbered slot in frame 18, subject to the normal restrictions imposed by the access assign field (see subclause 5.7.1).

5.6.3 Traffic channels

The traffic channels carry the circuit mode voice or circuit mode data traffic information. They exist only in physical frames 1 to 17 and are carried in the normal uplink and downlink bursts at the physical level.

5.6.4 Logical channels supporting operation of the physical layer

There are a number of logical channels present in the MAC which are needed just to support correct action of the physical layer. Amongst these are:

- AACH which indicates access rights on control channels and usage markers on traffic channels. This is carried on the broadcast block, present in every downlink slot;

- Common Linearization CHannel (CLCH) which is an opportunity, offered by the system, for MSs to linearize their power amplifiers after switching frequency (for instance at a channel assignment). At the physical level this corresponds to the linearization burst;

- SF which corresponds to one of two synchronization training sequences used at the physical level to indicate whether one or two logical channels are present in the burst (it only applies to normal uplink or downlink bursts).

5.7 MAC functionality

5.7.1 Random access procedures

The MS MAC layer uses a random access protocol to initiate information transfer to the BS. The random access protocol is used for unsolicited MS messages, whereas messages solicited by the BS are generally sent in a slot reserved by the BS for the response, called a reserved access.

NOTE 1: Reserved access is also used for other services in which pre-arrangements have been made with the BS, such as packet data transfer.

The random access protocol is based on slotted ALOHA procedures, with a superimposed access framing structure. By a suitable choice of access parameters, it is possible for the BS to:

- control the collision of access requests from different MSs;
- minimize access delay and traffic loss for a particular traffic loading;
- maintain peak throughput for a particular traffic loading;
- avoid protocol instability;
- dynamically restrict random access to different access priorities, and to selected groups and subscriber classes;
- provide simultaneously, independent access grades of service for different groups and subscriber classes.

Generally, the same random access procedures are suitable for use on all types of control channel, i.e. MCCH, FACCH, SACCH, although the access parameters, waiting time and the number of re-tries, may be different.

A basic concept to grasp about the TETRA random access procedures is that radio access to the system is only by invitation. A MS wishing to access has to wait until an access opportunity is presented by the infrastructure. The MS will be continuously monitoring the downlink broadcasts looking for a message addressed to it, so that it can respond to accept the message. The MS will also be continuously monitoring the access rights to the system so that if it requires to send a message then it can respond rapidly.

The BS offers random access opportunities to sets of MSs in turn by using different access codes on the AACH. There is a maximum of four possible access codes (denoted A, B, C and D) active at any one time and the BS marks each access opportunity with the appropriate access code.

TETRA differs from other Private Mobile Radio (PMR) and cellular air interface protocols in that it is able to simultaneously support these four different access codes and hence provide a range of grades of service to different subscribers.

The way that the access codes are defined is a network operator option. The process of grouping together group subscriber identity, subscriber class and priority is called binding. The definition of the binding parameters is broadcast periodically in an access define message.

The binding of MSs to access codes is dynamic. The binding defines the minimum valid priority for an access code. It may also restrict use of the access code to a set of subscriber classes, or to a group of MSs. An MS may use a sub-slot designated for a particular access code only if the message priority and the subscriber class or MS identity, conform to the current binding.

For a particular access code, the MSs must randomize their response within access frames consisting of a number of access opportunities (uplink sub-slots). This is to spread out the access attempts within the access frame and so minimize collisions.

The random access procedures rely on two types of message broadcast by the BS. These messages are:

1) the ACCESS-DEFINE message:

- this message is transmitted at intervals, the frequency being an operator option. It contains slowly changing information about the random access parameters for an access code:

    - the priority and MS binding to the access code;
    - a parameter (IMM) defining when immediate access is permitted for the first transmission;
    - the waiting time (WT) before deciding to retry;
    - the permitted number of random access retries;
    - a frame length multiplying factor;
    - the uplink channel configuration;

2) the ACCESS-ASSIGN message:

- the ACCESS-ASSIGN message is transmitted in every downlink slot on the AACH, in the broadcast block. The ACCESS-ASSIGN message conveys information about the downlink slot in which it appears, and also access rights for the corresponding, i.e. same-numbered, uplink timeslot of that TDMA frame. If the uplink channel is in use for control signalling, the ACCESS-ASSIGN message may contain two access fields which convey independent access rights for each of the two uplink sub-slots in the uplink slot. The access field will define the allowed access code for the uplink sub-slot. Otherwise, it may indicate that the uplink sub-slot is reserved (for use by one MS, whose identity does not appear in the ACCESS-ASSIGN message) and is therefore not available for random access, or it may assign the sub-slot for common linearization.

    NOTE 2: The reservation will have been separately indicated to the relevant MS.

The BS may optimize system performance by varying the access code bindings, the frame length and the other access parameters. The choice of parameters will depend on the type of system and the traffic mix.

The basic format for the access procedures is illustrated in figure 15.

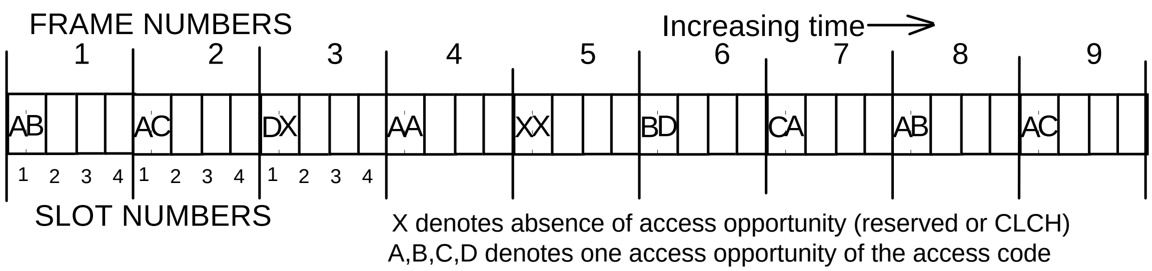


Figure 15: Structure of the uplink access sub-slots

Figure 15 shows the location of uplink access slots defined by the BS. All MSs have to monitor the downlink broadcasts, and in particular the ACCESS-DEFINE and ACCESS-ASSIGN messages before attempting access.

The uplink slot structure exactly mirrors the downlink structure but is offset in time by two slots. The uplink slot numbering is identical to the downlink number. Information concerning uplink access rights is conveyed in the corresponding downlink slot e.g. frame 1, slot 1 (first and second half slots) access rights data is sent in the ACCESS-ASSIGN message of the downlink frame 1, slot 1.

The accessing MSs can only belong to one access set at a time and so need only to consider the sub-slots relevant to their particular access code. Considering only these sub-slots, the MSs have to organize their requests within ALOHA access frames. The access field in the ACCESS-ASSIGN message indicates the number of following uplink sub-slots which make up an ALOHA access frame for this access code. A special value ("ongoing frame") is used when the field does not mark the start of a new ALOHA access frame.

When a user access request is initiated, e.g. a valid request for access code A, the MS-MAC is permitted to send a first random access request in the next available code A sub-slot, provided that this occurs within a designated time.

NOTE 3: The characteristic of the slotted ALOHA protocol requires access requests to be made slot synchronous (i.e. only at the start of a slot, not part way through a slot).

If an immediate first access attempt is not made then the MS-MAC has to wait for an ACCESS-ASSIGN PDU containing a frame marker for its access code, and then choose a sub-slot randomly from that access frame for its random access request. An MS-MAC wishing to send a repeat transmission after an unsuccessful access attempt has to wait for a new frame marker and choose another sub-slot randomly from that frame.

The access procedure is illustrated in figures 16 and 17, in which the sub-slots shown are only those control sub-slots marked for random access by code A. WT is the retry time after which the MS-MAC decides that its access request has failed.

In figure 16, the BS chooses to mark rolling access frames with a new access frame marker in every sub-slot, clearly showing that the access frames sizes and the resulting frame overlap.

In figure 17, the BS chooses to mark discrete access frames, by using the "ongoing frame" value (here denoted by *) to indicate on-going frame continuation.

It should be emphasized that the MS access procedures (i.e. the MS response) will operate independently of the BS offered choice of access opportunities.

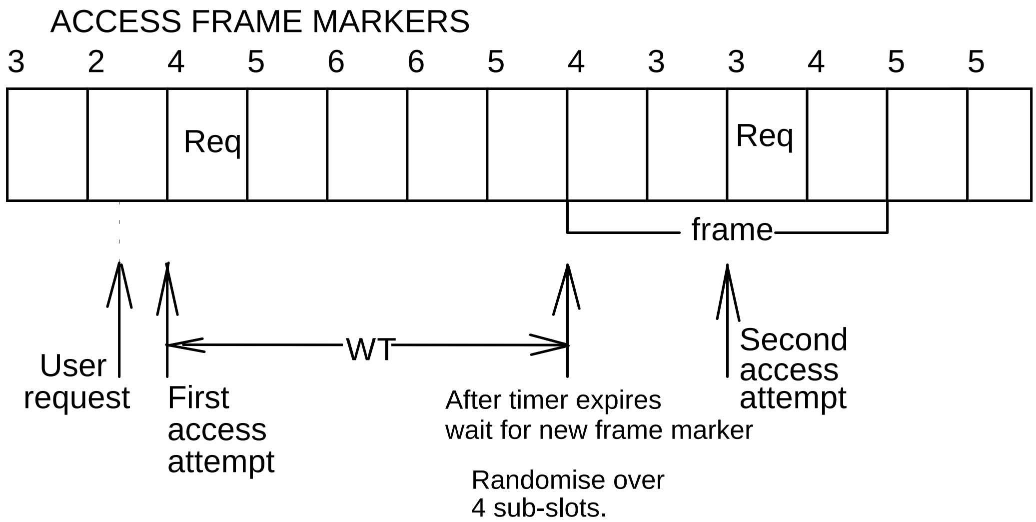


Figure 16: Example of random access procedure with the BS using rolling access frames

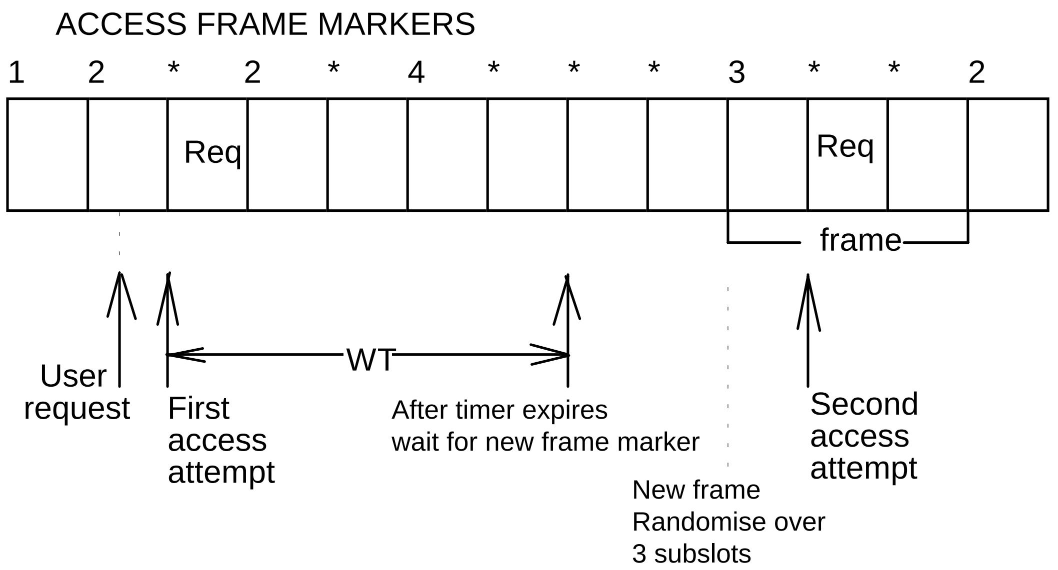


Figure 17: Example of random access procedure with the BS using discrete access frames

The choice between the rolling access frame and the discrete access frame procedures is a manufacturer/operator option. It is expected that they will have different characteristics in various traffic densities and traffic mixes. This will be examined further in part 2 of this ETR [3].

5.7.2 Reserved access procedures

Once the initial random access to the system has been performed all subsequent accesses can use reserved accesses. In other words, all subsequent information exchanges between the MS and the BS can be planned, unlike the initial access. Thus when an MS is required to respond to the BS or when it has further signalling to send after the initial access, the BS may reserve slots for that particular MS, possibly on request from the MS.

The ACCESS-ASSIGN message (on the AACH) indicates which sub-slots are reserved and therefore not available for random access by other MSs. The MS for which a sub-slot or slot(s) are reserved is informed separately on the downlink signalling channel.

5.7.3 Call set-up procedures

The basic message exchanges for an individual call and a group call are described below. When initiated from a MS both types of call start with a random access followed by a number of reserved accesses. The basic format for both procedures are similar, the difference being that an individual call may perform a presence check on the called party before assigning the traffic channel. The group call, being a multi-party call can not easily perform a presence check on the called party before assigning the channel (there would be a collision of the responses giving a garbled message). However TETRA supports a tele-service called "acknowledged group call" in which the group call is assigned a traffic channel and then an individual poll performed to check presence, before proceeding with or soon after the start of the group call.

NOTE 1: The LLC and MAC protocol have been designed to support a network service relying on using a power measurement to indicate presence of members of a group on a particular base site.

The power measurement can be based on CLCH transmissions at the start of the call or on transmissions invited by polling the group. The motivation behind this network service is to ensure that in multi-site group calls only those base sites with group members present are allocated resources.

These optional procedures supported by the standard would allow the group call to be set-up on the site but cleared down soon after if power measurements indicated that a member of the group is not present on the site. This procedure enhances the efficiency of setting up wide area group calls.

It is envisaged that for the duration of the group call a late entry message would be regularly transmitted on the site to notify members of the group switching on or entering the BS coverage area that a group call is in progress.

The precise signalling channels (physical or logical) to be used for setting up the acknowledged group call are not defined in the standard but will be chosen by the system designer from those described previously.

TETRA differs from many other radio air interface protocols in that for the majority of basic calls all the information necessary to establish the call is transferred on the initial random access. This property produces rapid and reliable call set-ups.

Only calls to subscribers in other TETRA networks (in which the full 48 bit ITSI has to be sent) or calls involving some of the less commonly used supplementary services, need to transfer more information than fits into the access slot (92 bits net).

In the message sequences illustrated below we will use the actual layer 3 PDU names for the messages.

NOTE 2: Some of the message sequences shown are optional.

5.7.3.1 Individual calls

An example of the message sequence for an individual call set-up is shown in figure 18. This corresponds to MSs under the coverage of the same BS and with no processing delay in the infrastructure. The message sequence starts with the calling MS M1 making a random access attempt (u-set-up). The BS acknowledges the request in its next slot 1 (d-call-proceeding) and at the same time pages the called MS M2 (d-set-up).

Assuming that direct signalling is used (i.e. the called radio responds rather than the called user) then the response is returned in the subsequent slot 1 (u-connect). The BS then proceeds to assign a channel for traffic (this is a MAC message) at the same time as informing the calling party of the response from the called party (d-connect) and acknowledging the called party (d-connect ack). The assigned channel is slot 2 on another frequency. It could have been any of slots 1, 2, 3 or 4 on another frequency duplex channel or in fact it could have been slots 2, 3, or 4 of the same frequency pair. If slot 2 of the same frequency was allocated it could not be used until the next frame due to the switching time of the synthesizer.

NOTE: See definitions of direct signalling and on/off hook signalling.

The first MS action on the new frequency is to linearize the transmitter. If called and calling party are on the same site then the called party may (as instructed by the BS) proceed to indicate presence on the assigned frequency with the layer 2 message MAC-access. If the MSs are on separate sites then they can both indicate presence in the second half slot after linearization. The BS next announces to the calling party that a connection has been established and grants transmit permission (all with the d-connect message). The calling MS then proceeds to transfer coded voice frames.

It will be seen that the time between first random access and first voice frame transferred to the called party is about 200 to 250 ms depending on the allocated traffic channel. This assumes perfect radio transmission. In a realistic scenario the elapsed time will be greater. This is a topic for investigation in part 2 of this ETR [3].

5.7.3.2 Group calls

The group call message sequence is similar to the individual call but is shorter because the BS immediately assigns a traffic channel in response to the u-set-up (see figure 19).

5.8 Layer 3 functionality

The three layer 3 entities, MM (Mobility Management), CMCE (Circuit Mode Call Entity), and PD (Packet Data comprising CONS and CLNS) control all the functionality of the radio system in delivering service to the application. As explained previously layer 1 runs semi-autonomously, whilst layer 2 performs the control and mapping between the layer 3 discrete events and the layer 1 continuous events.

So far most explanation has been concerned with layers 1 and 2 since these are the layers that largely characterize the TETRA protocol. In this subclause we will seek to briefly outline some layer 3 procedures that are important for system operation.

5.8.1 Cell selection and re-selection

The TETRA air interface protocol supports five types of cell re-selection depending on:

a) whether a call is presently in progress, and if so whether it is a group call or individual call and whether the transferring MS is the transmit MS or a receive MS;

b) the circumstances of the MS, whether it has had time to gain information on the new cell;

c) the grade of service of call re-establishment supported by the infrastructure, whether the infrastructure supports any planned call re-establishment and if so whether the channel allocation is negotiated by the MS with the new cell or transferred to the MS via the present serving cell.

An important aspect of the TETRA air interface protocol is that it is the MS which makes the call re-establishment decisions, not the infrastructure. This has important repercussions on the support of group calls since the workload for deciding on call re-establishment is transferred to the MSs, although the infrastructure must of course endorse any requests made by MSs.

The different call re-establishment procedures supported by the TETRA standard are an implementation option for the network operators. The chosen option must be supported by the MSs to gain the benefit of the call re-establishment facilities. This does not impose too great a burden on the MS manufacturers since the call re-establishment procedures are a generic process, placing most differentiating features in the infrastructure.

From the network operator perspective, all aspects of call establishment and re-establishment except the decision when to do it, are controlled by system broadcasts. Thus a network operator can install a system with minimal re-establishment capability and subsequently upgrade the re-establishment capability, perhaps piecemeal in parts of the system.

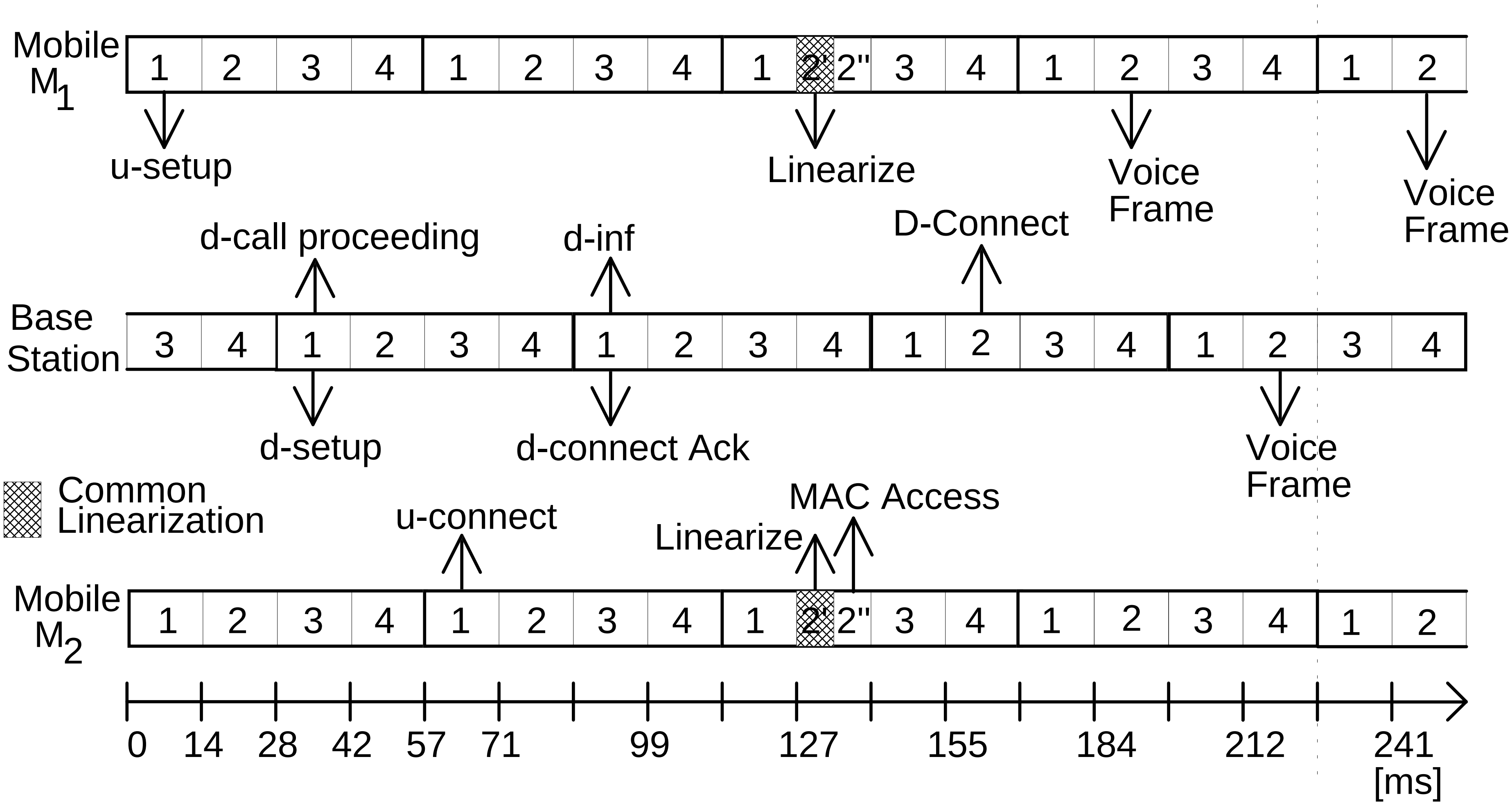


Figure 18: Timing sequence for individual call set-up

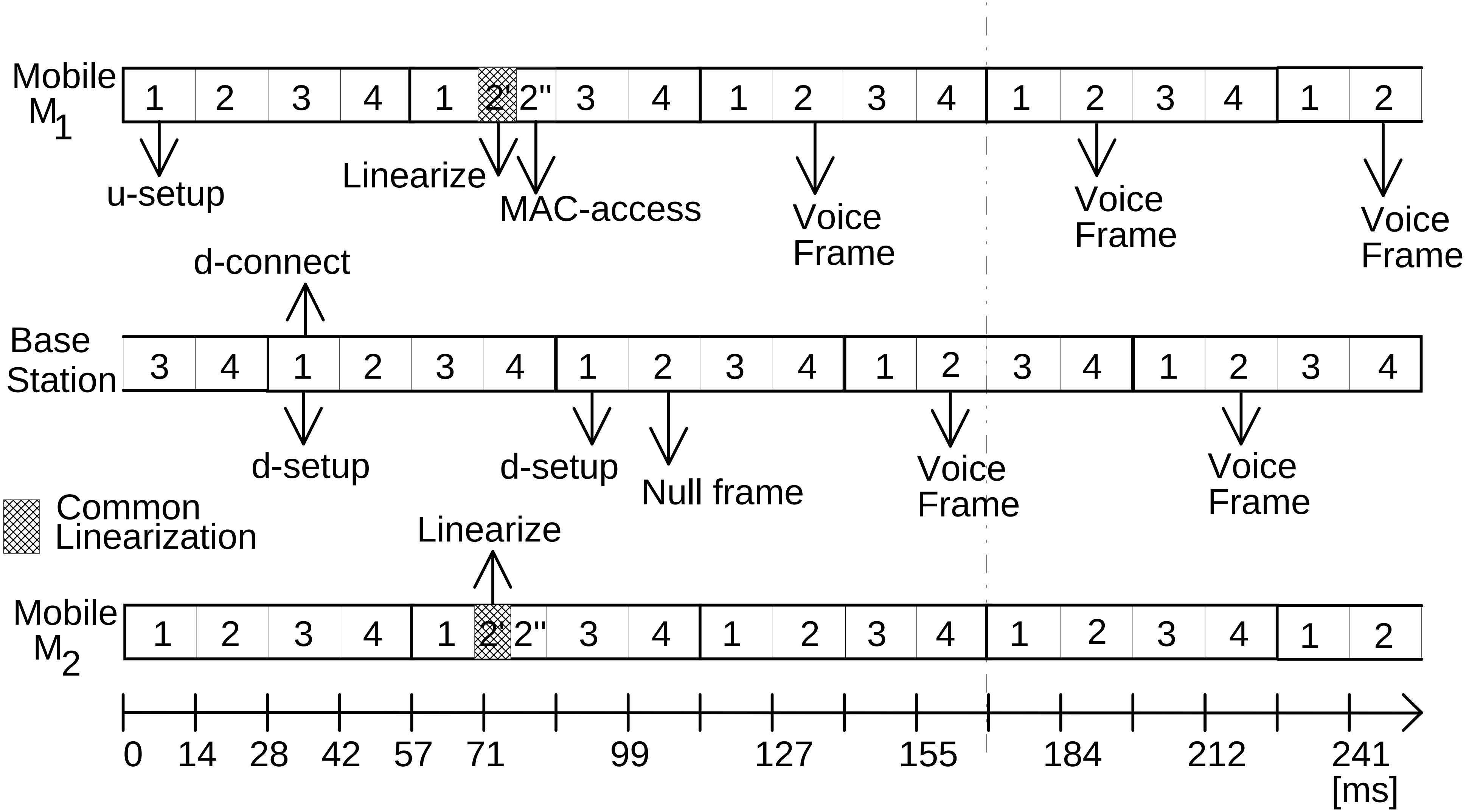


Figure 19: Timing sequence for group call set-up

The categories of cell re-selection supported by the protocol are as follows:

a) undeclared; when an MS is not currently engaged in a circuit mode call;

b) unannounced; when an MS is currently engaged in a circuit mode call but does not have the opportunity to inform the infrastructure of its intention to find service on another BS;

c) announced type 3; when an MS is currently engaged in a circuit mode call but does have the opportunity to inform the infrastructure of its intention to find service on another BS e.g. when listening in a group call;

d) announced type 2; when an MS is currently engaged in a circuit mode call, informs the present serving cell of its intention to find service on another cell and negotiates directly with the new serving cell on its MCCH;

e) announced type 1: when an MS is currently engaged in a circuit mode call, informs the present serving cell of its intention to find service on another cell and the details of its preferred new serving cell. Negotiations for access to the new serving cell are performed via the present serving cell and the infrastructure. Channel allocations on the new serving cell are issued via the present serving cell. This procedure amounts to seamless handover.

In the following subclauses the basis for each of these procedures will be established and the criteria for call establishment and re-establishment examined.

5.8.1.1 Establishing service

5.8.1.1.1 Acquiring cell synchronization

An MS must first gain frequency synchronization with the synchronization training sequence contained in the SYNC burst (BSCH) of any frequency used on the cell. On acquiring synchronization, the MS then decodes the contents of the SYNC message also contained in the synchronization burst. The SYNC message contains the colour code, which is used by the MS to de-scramble the contents of all other bursts transmitted by that BS, and the system code, which indicates whether the system is a TETRA V+D or PDO system. The SYNC message also contains the slot, frame and multi-frame number for this downlink slot thus giving the MS full frame synchronization with this BS. The SYNC message also contains information about the system mode of operation (time shared etc.).

Having synchronized with a cell, the MS continues to decode subsequent SYNC messages transmitted by that BS but only those with the correct colour code to prevent an MS decoding the BSCH transmitted by an adjacent cell. (The BSCH is not scrambled and so there is no co-channel interference protection on this logical channel). The MS stores the information received in the SYNC message and updates this information on receiving subsequent SYNC messages.

5.8.1.1.2 Acquiring network information

An MS, having acquired cell synchronization by receiving and decoding the BSCH information, is now able to decode all downlink bursts transmitted by the BS. The MS next searches for the BNCH on the acquired frequency channel in order to receive and decode the system information for this cell contained in the SYSINFO message. The SYSINFO message contains information about the frequency of the main carrier, the number of SCCHs in operation on the main carrier, information used for power control and cell (re)selection and some random access parameters.

Having decoded the SYNC and SYSINFO messages, the MS may locate the MCCH on slot 1 of the main carrier) or the relevant common SCCH. The MS has all of the information needed to communicate with the system and may now receive downlink messages and transmit uplink messages.

5.8.1.2 Cell selection and re-selection

The standard defines various thresholds which the MS can use to select a BS to provide service. Basically the thresholds define three service regions:

a) a good service region where the MS is not allowed to re-select any other BS;

b) a reasonable service region where the MS can change BS if it wishes;

c) a poor service region where the MS must change if it can find a better serving BS.

5.9 System modes of operation

A distinguishing feature of the TETRA protocol is the wide range of system modes of operation that are supported. Each system mode of operation is aimed at a different operational scenario such as lightly loaded, heavily loaded, predominantly packet data traffic etc.

5.9.1 Normal mode

Normal mode of operation is intended to cope with the majority of radio BS installations where there is normal system load, typically 4 or 5 radio frequency pairs present on a site (i.e. 16 to 20 voice channels). In the normal mode of operation, the common control channel on the main carrier is the MCCH and is present in timeslot 1 of all frames 1 to 18. This common control channel is used for all common control signalling. All MSs not involved in a call listen to the downlink transmissions of the MCCH. The BS transmits on all the downlink slots of the main carrier during normal mode.

5.9.2 Extended mode

In larger installations it may be necessary to have more than one common control channel operational at a time in order to attain a required call set-up grade of service or to support high levels of packet data. With more than one common control channel operational the system is said to be in extended mode. The extra control channels may be operated in the following manner:

- a common SCCH with the same functionality as the MCCH is put up but to be used only by a sub-set of the user population;

- an assigned SCCH is put up for use only to continue control signalling after the initial random access (uplink) or paging (downlink) message.

The MCCH is always a single slot width. However, the BS may, in addition, operate ECCHs with more than one timeslot per TDMA frame. The ways to use this may be as follow:

- an extended random access channel available on the uplink of the main carrier, allowing additional random access opportunities;

- multi-slot SCCHs used to provide a higher transfer rate. A multi-slot SCCH would only be used as directed by the BS after an initial access or paging message.

  NOTE: The MCCH and any SCCHs having the same functionality as the MCCH cannot be extended to more than one timeslot per TDMA frame.

Extended mode of operation, by definition, must have the MCCH present on slot one of every frame. In addition it will have one or more of the following: a common SCCH, an assigned SCCH or and ECCH.

5.9.3 Minimum mode

Minimum mode is intended for use in low traffic density areas. It is envisaged that minimum mode system operation would usually be associated with a single frequency pair per BS (4 voice channels or 3 voice channels plus 1 control) but in theory there is no correlation between BS size and use of minimum mode.

Minimum mode operation allows a BS to allocate all timeslots on the main control carrier for traffic or dedicated control purpose. Therefore in this mode of system operation, only frame 18 would be available for common control.

By definition, a BS enters minimum mode when all four timeslots on the main carrier are assigned to traffic so that there is no common control channel available in timeslot 1.

It is anticipated that a BS may enter and leave minimum mode several times per multi-frame as calls are cleared down and new ones set-up.

MSs are required to continuously monitor the MCCH and be aware of when the system enters and leaves minimum mode. When the system enters minimum mode and common control broadcasts on slot 1 are interrupted, the MS is required to await resumption of these broadcasts and not seek an alternative BS.

5.9.4 Discontinuous downlink transmissions - time sharing mode

The TETRA protocol supports BS discontinuous transmissions to allow an RF carrier to be shared among a number of distributed base sites. This mode of operation is only suitable for low density traffic areas or where the allocated radio spectrum is very limited.

This system mode of operation should be clearly distinguished from MS discontinuous transmissions, which is happening all the time since MSs will usually be allocated just one uplink slot per frame.

NOTE: There is another discontinuous mode of operation associated with the vocoder. During periods when the pressel is pressed but there is no voice activity the vocoder may issue a message indicating "no activity". This optional message is transferred to the destination receiver(s) where it causes comfort noise to be generated. No further transmissions are sent from the source MS (other than periodic contact messages with the BS) until voice activity is continued or the call is cleared.

There are basically two aspects to discontinuous BS transmissions. One is where common control operation relies on the MCCH being shared around a number of sites and the other is where the traffic channels are shared between sites. Clearly this all has to be carefully planned on a site co-ordinated basis.

For MCCH sharing there will be a degraded access time to the system but this may be acceptable for the sake of spectral efficiency. Besides the need for extra system co-ordination the other major disadvantage of discontinuous BS transmissions is the reduced opportunity for synchronization and received RF power measurements available to the MSs. In continuous BS transmissions there is a synchronization burst mid-slot of every slot (also used as the slot flag) and in addition there is a separate synchronization burst between each slot (where the transmitting MSs are ramping up or ramping down). Discontinuous transmissions lose the training sequence between slots. This will reduce the reliability of MS synchronization, affecting reliability at edge of coverage and in fast moving vehicles.

It would be possible to operate time sharing common control channels and traffic channels together on the same site or there may be a combination of continuous and discontinuous modes of operation.

5.9.4.1 MCCH sharing mode

In MCCH sharing mode the MCCH may be shared by up to 36 cells under the control of the infrastructure.

5.9.4.2 Carrier sharing mode

In carrier sharing mode, one carrier frequency pair may be shared by up to four cells, each cell being allocated a timeslot of the TDMA frame as required to support its traffic. This technique provides an efficient use of spectrum which may find use in low traffic areas.

5.10 MS modes of operation

5.10.1 Idle mode

The "idle" mode is the state of a registered MS not actively in communication with a BS. It is continuously listening to the MCCH or to any of the other common control signalling channels. All MSs must be capable of monitoring adjacent cell signal strength in this mode.

5.10.2 Common signalling and packet mode

The CCCH supports all common control signalling (including transport of user packet data) for an MS. In a system, there may in addition to the MCCH be one or more SCCH or an ECCH as described under the system modes of operation. By default, the MS must listen to the MCCH for all signalling.

5.10.3 Traffic mode

Traffic mode is the MS state when it has been assigned to a traffic channel and user speech or circuit mode data is being transferred.

5.10.3.1 Stealing mechanism

When in traffic mode (either circuit mode speech or data), capacity may be stolen by a transmitting party for signalling purposes. This leaves the current mode of operation unchanged. The appearance of the slot flag set to 1 (SF = 1) in the transmission indicates that stealing has occurred. The slot flag information is indicated by the appropriate training sequence as described in subclause 6.2.5.

The header of the first half of the slot indicates whether the other half slot has also been stolen or if it belongs to the normal traffic circuit. The header also contains information on the intended destination of the signalling message, either C-plane or U-plane signalling. Stealing occurrence is locally reported to the U-plane application at the TMD-SAP.

This mechanism applies to both BS and MS transmissions.

5.10.3.1.1 Uplink stealing

Transmission on the uplink STCH can only be performed by an MS that has been authorized to transmit. No other MS has permission to transmit so stealing would not be feasible.

The traffic channel may be stolen for a number of different purposes:

a) for an MS layer 3 entity to pass service information to the SwMI (e.g. end of transmission);

NOTE 1: The layer 3 message may be the trigger but it is the MAC that makes the decision to steal.

b) for an MS layer 3 entity to pass information to its peer entity at the destination;

c) for user-to-user signalling (e.g. to support end-to-end encryption synchronization) during a call.

NOTE 2: This special case in item c) has not been standardized and hence is left totally to implementation.

The infrastructure is able to distinguish these cases and to route the stolen slots accordingly. It is important to realize the significance of this process in switching from traffic mode to signalling mode at the end of every circuit mode transmission.

5.10.3.1.2 Criteria for uplink stealing

When an MS is authorized to transmit traffic, the MAC may steal from the traffic capacity to send C-plane signalling. The MAC discards the U-plane data it would have sent (since it is a circuit connection with constant delay characteristics).

The MAC reports C-plane stealing to the U-plane application, enabling the application to revise the intended use of subsequent half slots, or to re-transmit any U-plane signalling (such as end-to-end encryption information) that has been overwritten by the MAC.

Frequent stealing would degrade the quality of the circuit, therefore, suitable criteria should be used for deciding when the MAC may steal, based on the priority of the C-plane message, the half slot importance and the time since the last stealing occurrence.

5.10.3.1.3 Downlink stealing

The BS may steal from a traffic channel at any time to send C-plane signalling messages on the downlink. A possible application would be to send an urgent call waiting indication to a member of the group (with a reserved access for the response either on the SACCH i.e. frame 18, or the MCCH). However, the BS designer should note that frequent stealing would degrade the quality of the circuit. Also, it is recommended that, when the BS needs to steal, it should not overwrite U-plane end-to-end signalling (which has already been stolen from speech).

C-plane stealing does not really exist since a message to any MS can be inserted in the signalling channel data stream without disrupting the flow of messages.

5.10.3.1.4 Reception of downlink transmissions

All MSs that are receiving the common or associated signalling channel need to check whether the C-plane messages are addressed to itself and, if so, process the message and deliver PDUs to higher layers.

The training sequence (slot flag) in each slot indicates whether stealing has occurred. If the slot flag is set to SF =O, the receiving MS may assume that the slot contains only TCH.

If the slot flag is set to SF = l, the first half slot may be assumed to be STCH. Then the MAC PDU type indicates whether the first half slot was stolen for C-plane (TMA-SAP/TMB-SAP) or for U-plane (TMD-SAP) signalling. The receiving MAC inspects the MAC message to discover whether the second half slot is also stolen.

5.10.4 Energy economy mode

Energy economy mode is an MS mode of operation which allows the MS to sleep an agreed number of TDMA frames before awakening to monitor the next control slot. Clearly the MS has to inform the BS of its precise intentions else the BS would be paging the MS in vain or would possibly be paging in the wrong slots.

Energy economy mode is initiated by MS request to the BS. The position of the energy economy period is indicated by the BS. The MS then follows a regular cycle of N timeslots in energy economy for 1 timeslot in reception. During energy economy mode it is expected that the MS remains synchronized to the BS transmission. Seven sleep ratios are supported ranging from 1:1 to 1:359.

Energy economy mode is only applicable in idle mode. An energy economy mode request is usually valid in all cells within a location area. If an MS changes cell within the location area, it may maintain the same energy economy mode and follow the same energy economy pattern after acquiring slot and frame synchronization on the new cell. All energy economy groups have a cyclic energy economy pattern and so, given a start point and energy group, the MS may calculate the absolute frame and multiframe numbers it must monitor.

It is not expected that an MS in energy saving mode would have to modify its monitoring behaviour if the system entered minimum mode. However the infrastructure would need to take account of the monitoring pattern of energy economy groups and may need to page MSs by using the stealing channel.

Although the sleeping MS can not be contacted from the SwMI during its sleep period, it can be locally aroused by the application to initiate a call or data transaction.

The MS may terminate energy economy mode by re-defining the sleep period. Alternatively, as an implementation issue, energy economy mode may be implicitly terminated by making a call.

5.10.5 Independent allocation of uplink and downlinks

The system may allocate uplink and downlink channels on the same frequency pair for different purposes. This can apply to channels which are assigned for use as a traffic channel or control channel. For example, a traffic channel may be allocated in the downlink direction (only) when the transmit MS is on another cell and there are only receiving MSs on cell. The corresponding uplink channel may be allocated for a call which only requires an uplink channel. The allowed combinations of uplink and downlink channels are listed below:

a) circuit mode call X on downlink channel;
circuit mode call Y on uplink channel; i.e. different MSs;

b) circuit mode call on downlink channel;
assigned SCCH on uplink channel;

c) assigned SCCH on downlink channel;
circuit mode call on uplink channel;

d) common control on downlink MCCH (slot 1);
uplink slot 1 of main carrier allocated for a circuit mode call;

e) downlink slot 1 of main carrier allocated for a circuit mode call;
uplink slot l of main carrier available for common control.

The allocation of uplink and downlink slots is indicated by the Access Assignment channel which is broadcast by the BS on every downlink slot. All of the above examples can be accommodated within the available combinations in the Access Assignment PDU.

5.11 Classes of MS

Classification of MSs is based on several attributes such as:

a) power class;

b) class A, B or E equalizer;

c) frequency full duplex operation;

d) capable of operation in multiple slots;

e) support of end-to-end encryption.

5.11.1 MS power classes

There are four MS power classes as follows:

Power class	Nominal Power
1 (30 watts)	45 dBm
2 (10 watts)	40 dBm
3 (3 watts)	35 dBm
4 (1 watt)	30 dBm

5.11.2 MS receiver classes

The TETRA standard defines three receiver classes, distinguishing their intended operating environments and test conditions. Class A equipment is optimized for use in urban areas and in areas with hilly or mountainous terrain. Class B equipment is optimized for use in built-up and urban areas. Class E equipment is intended to meet the more stringent requirements of quasi-synchronous systems.

5.11.3 MS duplex capability

All MSs are required to support frequency half duplex operation. An MS may optionally also support frequency full duplex operation.

5.11.3.1 Frequency half duplex operation

A frequency half duplex MS can either transmit on an uplink frequency or receive on a downlink frequency at any time. It is not able to transmit and receive at the same time. This type of MS requires time to switch from its transmit to receive frequency. In TETRA this must be less than a timeslot duration. Figure 10 shows the uplink and downlink TDMA slot and frame arrangements.

NOTE: If both the uplink and downlink slot in figure 10 are used by a single MS, time division duplex operation can be realized allowing a frequency half duplex MS to support single slot duplex call services.

5.11.3.2 Frequency full duplex operation

A frequency duplex MS has the ability to transmit on an uplink frequency and receive on a downlink frequency at the same time. Therefore, this type of MS can use all four uplink time slots and all four downlink timeslots in a TDMA frame. Any combination of these slots may be used for a single call or for multiple calls.

5.11.4 Support of air-interface encryption

MS support of air interface encryption is optional. If this facility is supported, the MAC encrypts signalling messages on a message by message basis. Encrypted messages are indicated in the MAC header in order to instruct the receiving end to decrypt the message content. Only the message content at the TMA-SAP is encrypted. The MAC header information remains clear.

Any end-to-end U-plane encryption is in addition to air interface encryption.

5.11.5 Support of concurrent calls

Depending on the capability of the MS (especially full duplex operation as outlined above) concurrent calls may be supported.

Thus we could have up to four simultaneous duplex voice circuits to different remote users, each with a different vocoder and a different encryption algorithm. We could equally have a combination of voice and data tele-services to the same or different remote end points.

An MS transmitting on multiple slots per frame without full duplex or fast switching capability would have difficulty receiving signalling in the downlink between transmitted bursts. It is expected that the infrastructure would take this into account when attempting to contact the MS. It may be that such a transmitting MS can only be contacted by the infrastructure during frame 18.

It is expected that MSs wishing to transmit or receive in more than one slot per frame will need to have full RF duplex capability so that they can transmit and receive on adjacent slots or even simultaneously on the same slot. This is to satisfy the TETRA requirement to decode and check whether the usage marker on every downlink slot is applicable. As a consequence it appears that simply going from one slot per frame to two slots per frame is a large increase in MS complexity that may inhibit service enhancements for some time.

5.12 Data services in Voice plus Data

TETRA offers three types of data services to the user; their suitability depends on the intended application:

- short data service;

- circuit mode data;

- packet mode data.

TETRA does not offer standardized messaging applications.

5.12.1 Short data service

The short data service is offered by the SDS entity in the Circuit Mode Control Entity (CMCE). The short data entity supports the following MS originated and MS terminated services:

- user defined and pre-defined reception and transmission for:
    - individual message;
    - group message.

5.12.2 Circuit mode data

In the circuit mode data services an end-to-end circuit is established. This end-to-end circuit can be used unprotected, or have low or high forward error protection added. Optionally, the data may be encrypted by the standardized mechanisms of TETRA on the air interface or end-to-end as described in the security section.

The data rates offered are:

- unprotected data: 7,2; 14,4; 21,6; 28,8 kbit/s;
- protected data low: 4,8; 9,6; 14,4; 19,2 kbit/s;
- protected data high: 2,4; 4,8; 7,2; 9,6 kbit/s.

5.12.3 Packet mode data

The Packet mode services offered to the user are divided in two categories:

- connection oriented packet data services;
- connectionless packet data services.

A connection oriented packet data service is a service which transfers X.25 packets of data from one source node to one destination node using a multiphase protocol that establishes and releases logical connections or virtual circuits between end users.

A connectionless packet data service is a service which transfers a single packet of data from one source node to one or more destination nodes in a single phase without establishing a virtual circuit.

Two alternative points of attachment are defined for both services, fixed point of attachment or MS point of attachment but identical applications may be supported. The wired connections correspond to those used in X.25 packet data networks.

5.12.3.1 X.25 connection mode packet data

On the protocol stack of V+D this corresponds to the Connection Oriented Network Protocol (CONP) which is included in the PD entity of the layer 3 (see figure 22).

The user can run:

- a standard X.25 packet user application following ISO8348/8878/8208 (see figure 20); or
- a standard character mode MS with integrated Packet Assembler and Dissembler (PAD) (see figure 21).

Figure 21 shows the positioning of the Application in the TETRA protocol stack of the TE and MTU in the case of a MS, LS and a PAD, other examples are given in ETS 300 393-1 [8].

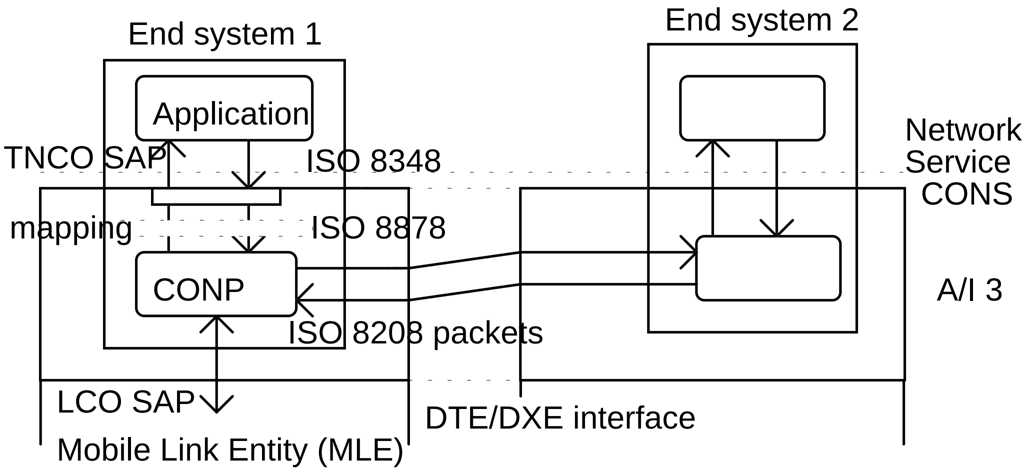


Figure 20: CONP and ISO

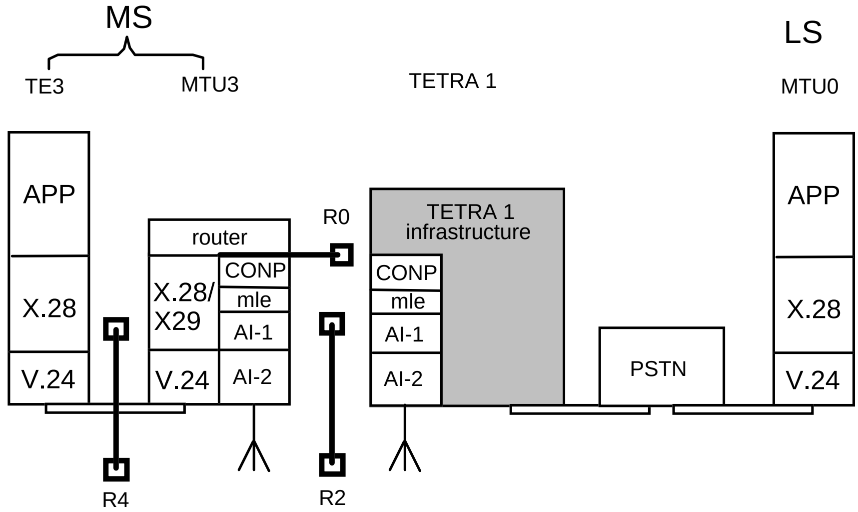


Figure 21: Character mode MS with integrated PAD (MTU3) connected to a character mode LS via PSTN

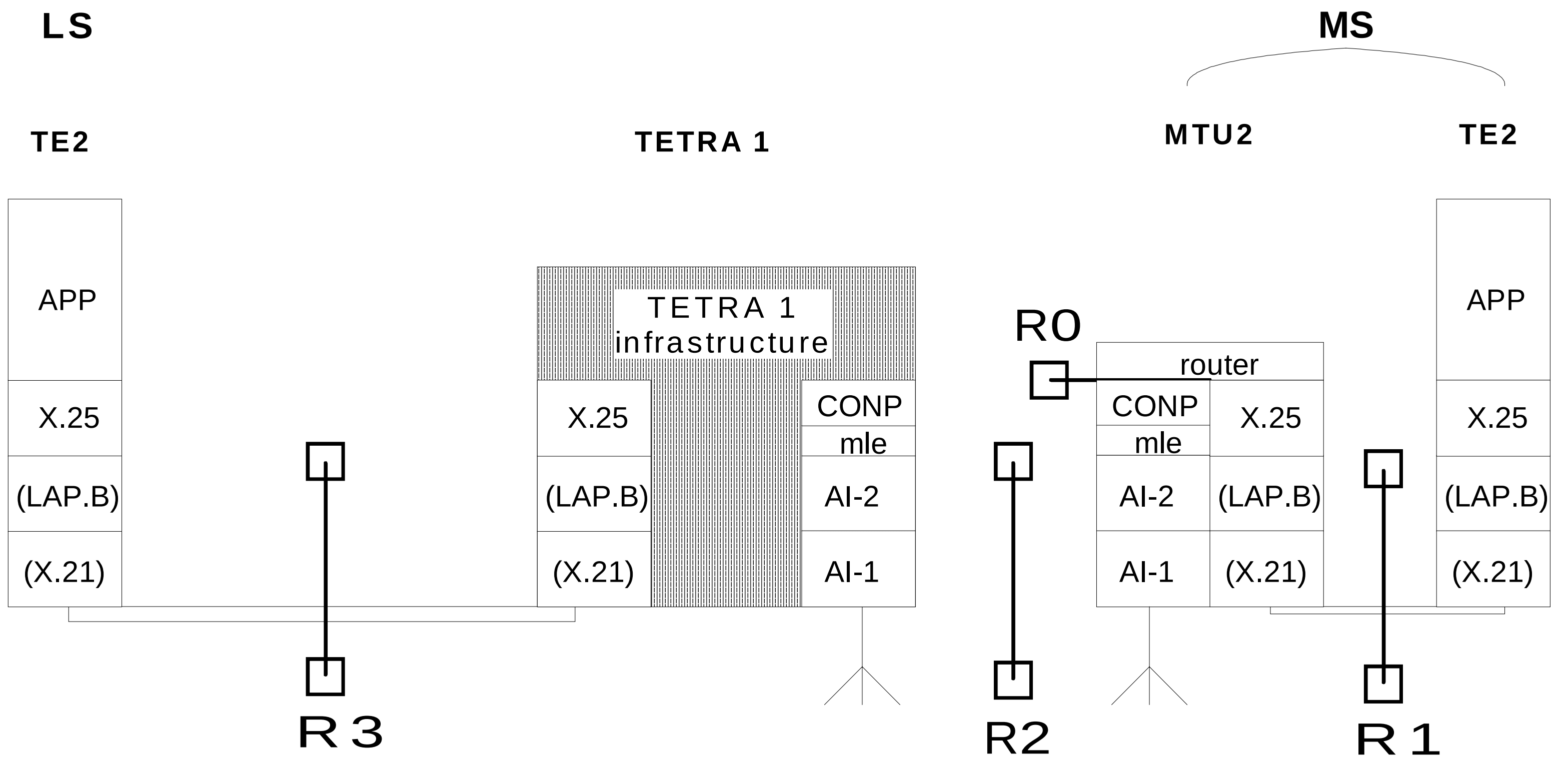


Figure 22: LS to MS through one TETRA network

The facilities offered by the X.25 packet application are listed in table 2:

Table 2: Packet data optional user facilities

Optional User Facility	Classification (note 1) VC*	PVC*	Agree For Period Of Time?	Applies Per Call?	Applies to DTE/DTE Operation? (note 6)
On-line Facility Registration	A	A	Yes	No	Yes (note 2)
Extended Packet Sequence Numbering	A	A	Yes	No	Yes
D-bit Modification	A	A	Yes	No	No
Packet Retransmission	A	A	Yes	No	Yes (note 2)
Incoming Calls Barred	E	-	Yes	No	No (note 3)
Outgoing Calls Barred	E	-	Yes	No	No (note 3)
One-way Logical Channel Outgoing	E	-	Yes	No	Yes
One-way Logical Channel Incoming	A	-	Yes	No	Yes
Non-standard Default Packet Sizes	A	A	Yes	No	Yes
Non-standard Default Window Sizes	A	A	Yes	No	Yes
Default Throughput Classes Assignment	A	A	Yes	No	Yes
Flow Control Parameter Negotiation	E	-	Yes	Yes (note 4)	Yes
Throughput Class Negotiation	E	-	Yes	Yes (note 4)	Yes
Closed User Group related facilities:					
-Closed User Group	E	-	Yes	No	No
-Closed User Group With Outgoing Access	A	-	Yes	No	No
-Closed User Group With Incoming Access	A	-	Yes	No	No
-Incoming Calls Barred Within a Closed User Group	A	-	Yes	No	No
-Outgoing Calls Barred Within a Closed User Group	A	-	Yes	No	No
-Closed User Group Selection	E	-	No	Yes (note 4)	No
-Closed User Group With Outgoing Access Selection	A	-	No	Yes (note 4)	No
Bilateral Closed User Group related facilities:					
-Bilateral Closed User Group	A	-	Yes	No	No
-Bilateral Closed User Group With Outgoing Access	A	-	Yes	No	No
-Bilateral Closed User Group Selection	A	-	No	Yes (note 4)	No
Fast Select	E	-	No	Yes	Yes (note 5)
Fast Select Acceptance	E	-	Yes	No	No (note 3)
Reverse Charging	A	-	No	Yes	No
Reverse Charging Acceptance	A	-	Yes	No	No
Local Charging Prevention	A	-	Yes	No	No
Network User Identification related facilities					
- NUI Subscription	A	-	Yes	No	No
- NUI Override	A	-	Yes	No	No
- NUI Selection	A	-	No	Yes (note 4)	No
Charging Information	A	-	Yes	Yes	No
RPOA related facilities					
- RPOA Subscription	A	-	Yes	No	No
- RPOA Selection	A	-	No	Yes	No
Hunt Group	A	-	Yes	No	No
Call Redirection and Call Deflection related facilities					
-Call Redirection	A	-	Yes	No	No
-Call Deflection Subscription	A	-	Yes	No	No
- Call Deflection Selection	A	-	No	Yes (note 4)	No
- Call Redirection or Call Deflection Notification	A	-	No	Yes	No
Called Line Address Modified Notification	A	-	No	Yes	No
Transit Delay Selection and indication	E	-	No	Yes	No

(continued)

Table 2 (concluded): Packet data optional user facilities

VC = Virtual Call; PVC = Permanent Virtual Call. NOTE 1: The classification indicates whether the facility should be provided by an X.25 network (an E-Essential facility), may optionally be provided by an X.25 network (an A-Additional facility), or does not apply (shown as a dash) as given in ITU-T Recommendation X.2. NOTE 2: In a DTE/DTE environment, use of these facilities is agreed separately for each direction of transmission. NOTE 3: In a DTE/DTE environment, these facilities may apply only through the use of the On-Line Facility Registration (OLFR) facility. NOTE 4: These VC facilities cannot be used unless the corresponding facility has been agreed to for a period of time. NOTE 5: In a DTE/DTE environment, use of this facility requires agreement by both DTEs for a period of time. NOTE 6: Annex A of ISO/IEC 8208 and ISO/IEC TR 10029 apply in lieu of this column for DTE to DTE operation in the case where one DTE is acting as an intermediate system for exporting packet network facilities to other DTEs.

An Interrupt transfer of 1 to 32 octets may be done without the flow control procedures.

The throughput may range from 75 to 19 200 bits/s (using SCH with 2/3 FEC) depending on the control mode (extended) and depending on the slots available between Voice and Data. The packet size is between 16 and 4 096 bytes.

The control and user packet data are sent through the control plane so they may be encrypted on the air interface in a similar manner to control channels. End-to-end encryption is a supported application option but not specified in the standard.

5.12.3.2 Connectionless mode

In the protocol stack the connectionless data mode corresponds to the SCLNP (TETRA Specific Connectionless Network Protocol) SAP (Service Access Point) see figure 23. It is called specific, as it offers different facilities from the standard ISO 8473 connectionless network protocol.

Figure 23 shows the position of the Application in the MS and LS protocol stacks with SCLNP connection.

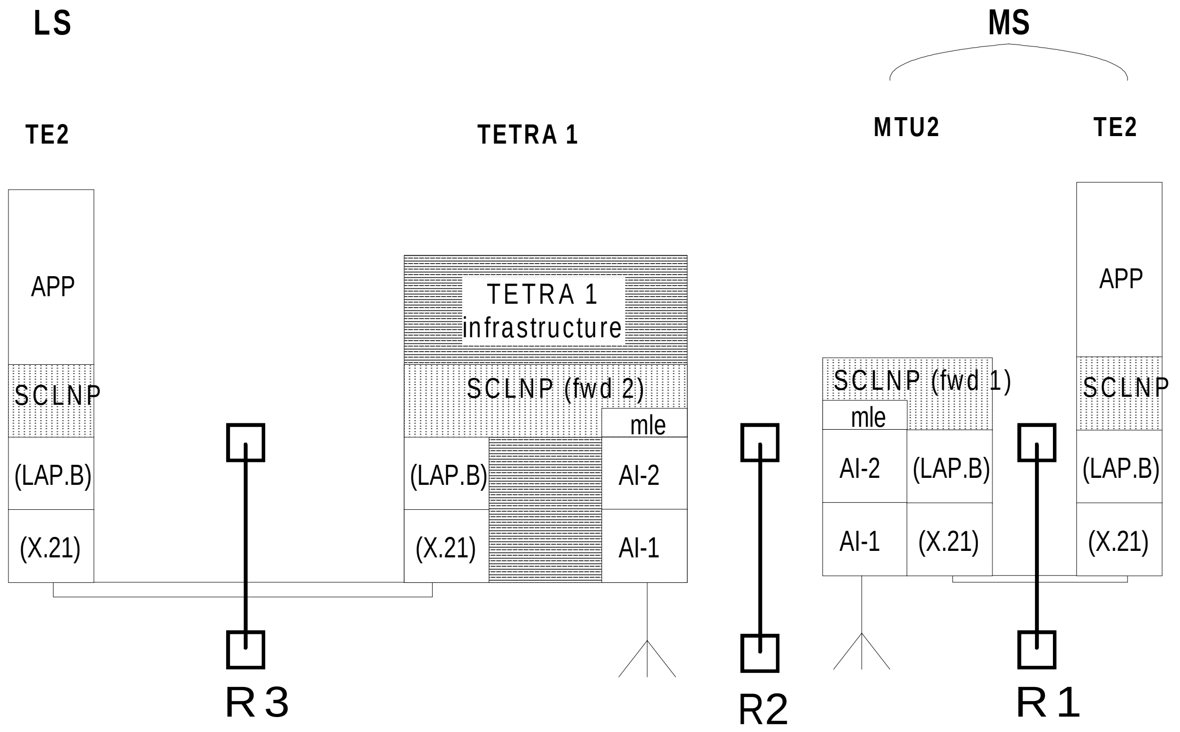


Figure 22: LS to MS through one TETRA network (SCLNP Connection)

A user can run :

- a TETRA specific SCLNP user application;
- a standard CLNP user application conforming to ISO 8473 with a convergence protocol.

The facilities offered by the Specific Connectionless include the full service:

- delivery disposition;
- priority;
- multicast;
- area selection;
- time stamping;
- packet storage;
- sub-addressing.

If the user chooses the "slim service" no specific facilities are offered, except priority and sub-addressing, this optimizes the length of messages and allows support of ISO 8473 CLNP operation.

Figure 24 shows the support of ISO CLNP using a convergence protocol to write.

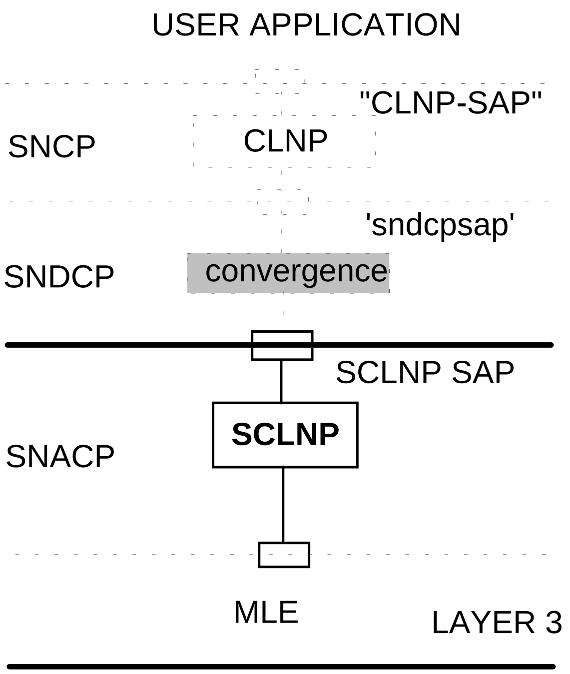


Figure 24: Support of CLNP with SCLNS

Internet Protocol can be supported using a convergence protocol to write as shown in figure 25.

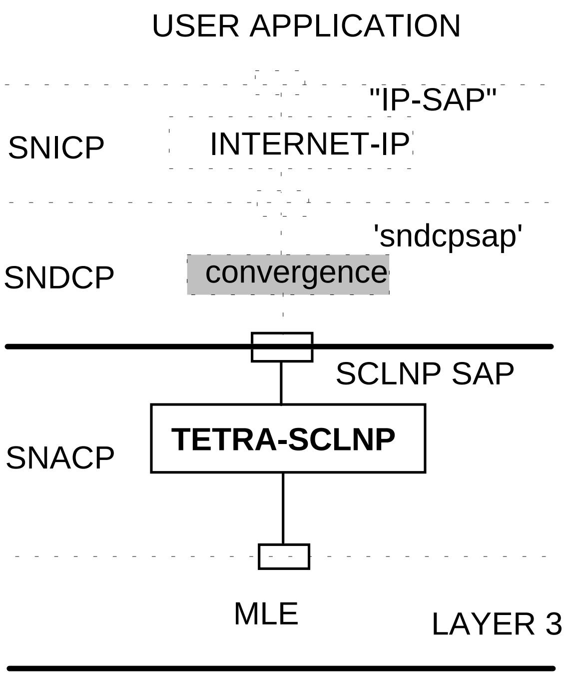


Figure 24: Support of INTERNET protocol

5.12.4 Network interconnection

A user can run an application on a TETRA MS, a fixed terminal LS, with eventually a PAD, which can then access in connection mode to data bases through eventually a standard X25 PDN public data network.

6 Radio aspects

The area covered by a network depends on several parameters and starting points. For example there will be a different range for handheld equipment and vehicle mounted equipment. Handheld equipment in general will have a lower transmit power and a lower antenna efficiency than vehicle mounted MSs. There are different techniques to obtain handheld coverage.

Other aspects are the availability and efficiency of radio channels.

6.1 Area coverage techniques

6.1.1 Single site wide area coverage

A simple radio system may consist of a single site serving a large geographic area. The disadvantage of this approach is that to provide the required capacity more channels may need to be provided on this site. The re-use distance of these radio channels by other systems will be limited by interference.

6.1.2 Cellular channel re-use

Commonly a cellular channel re-use strategy is foreseen for frequency allocation in land mobile bands. The cell size depends on the projected link budget. The acceptable path loss depends on the power class of the BS and its height as well as the MS class (HH or MS).

The cell size also has a substantial influence on the traffic capacity and switching capacity (see part 2 of this ETR [3]).

In medium to higher traffic capacity networks the cellular approach will often be used.

6.1.3 Quasi-synchronous transmission

Quasi-synchronous transmission will be used in areas that cannot be covered by one site and where a limited number of radio channels are available. These areas could, for example, be rural areas with a low traffic density. The use of one radio channel quasi-synchronously on several overlapping sites makes special synchronization arrangements necessary for the BSs and the interconnection.

Quasi-synchronous operation requires a special class of MS (possibly class E) to be used in areas with relatively large propagation delay differences between the sites.

Besides low traffic rural areas, quasi-synchronous transmission is often used in urban areas to provide more reliable coverage.

6.1.4 Time sharing transmission

In areas with a very low traffic density a radio resource (i.e. one uplink frequency and one downlink frequency) can be shared in time. This avoids the complexity of quasi-synchronous BSs and MSs. With the time slot structure of TETRA it is possible to rotate a control channel (i.e. uplink and downlink slot) between several sites. The traffic channels will then be assigned at the sites where they are needed.

6.1.5 Antenna diversity

TETRA receiver performance can be enhanced by the use of multiple antennas in a form of antenna diversity. Antenna diversity at the BS will allow the range (and reliability of coverage) to be increased for low power MS operation. Alternatively antenna diversity at the MS will enhance reliability of MS reception.

Methods of obtaining diversity are not defined in the standard. So far as the network or the MS are concerned a diversity receiver acts as a normal receiver.

6.1.6 Site diversity

Networks, because of the frequency assignments and economic factors, can be dimensioned for MS use. Radio coverage performance can subsequently be enhanced by the use of receive only sites placed between transmit/receive sites. This technique is often used to improve the coverage for low power handheld stations. Use of receive only sites will entail some selection (coherent addition, voting etc.) process to be performed at the combining switch but that is outside the scope of the standard.

6.1.7 Direct Mode (DM) / trunked gateway

A DM / trunked gateway makes it possible for the TETRA infrastructure to communicate with a MS in DM. The DM / trunked gateway must of course be within the network coverage area. The DM-MS must on the other hand be within the DM / trunked gateway coverage area.

DM can, among other uses, be programmed in the MSs as a fallback mode. If a MS cannot find the infrastructure it goes to a predefined DM channel.

Networks that are projected for MS use only, could give a virtual hand held coverage if a DM / trunked gateway is mounted in the vehicle and the user always operates in the vicinity of this vehicle.

A DM / trunked gateway can also be used as fixed gap-filler for difficult coverage areas in the infrastructure. These areas could for example be tunnels, road underpasses and parking facilities. MSs that enter these areas will (if they go out of range of the infrastructure) go into the fall-back mode. The MS can in that situation communicate via the DM channel over the DM / trunked gateway with the users in the infrastructure.

NOTE 1: A reduced set of services and facilities is supported in DM operation.

NOTE 2: Further information on the DM / trunked gateway will appear in the part 3 of this ETR [4].

6.1.8 On-frequency repeaters

In difficult coverage areas of the infrastructure network independent gap-fillers may be used. The difficult coverage areas could for example be tunnels, road underpasses and parking facilities. The gap-fillers could be on-frequency repeaters. A directional antenna outside would be directed to the nearest site of the infrastructure. This antenna would then be connected to an antenna inside the obscured space. Depending on the physical situation, connection could be done with or without amplification (active or passive).

NOTE: On-frequency repeaters are outside the scope of the TETRA standard.

6.1.9 Comparison of some area coverage techniques

6.1.9.1 Small active cells versus passive receive only cells

Compared to a solution with several small active cells (to support hand held use), a cell design strategy that supports MS use with additional passive (diversity) receivers to give hand held coverage could be less complex and hence less costly. A fully active (i.e. transmit and receive) small cell architecture will generate substantial handover between cells and so need more switching and control channel capacity.

With the same number of radio channels per site the site diversity system traffic capacity will be smaller than with a fully active small cell hand held system. With the same overall number of radio channels used for a diversity system as for the comparable coverage small cell configuration, the diversity system traffic capacity will be larger.

6.1.9.2 Cellular versus quasi-synchronous

In a cellular network MSs may generate many handovers in urban areas because of shadowing and fading. In a quasi-synchronous network the handovers are made "naturally" and seamlessly without generating any load on the radio control channels nor requiring infrastructure switching or control capacity.

However, with the same number of BSs per site a cellular network will have a substantially higher traffic capacity since the quasi-synchronous technique effectively stretches a single site.

Quasi-synchronous BSs are more complex (more costly) and need a special interconnection to maintain quasi-synchronous operation. Also the quasi-synchronous MS receivers have to be of a special class.

6.1.9.3 Quasi-synchronous versus time-shared transmission

The mode of operation entailing time-shared transmission enables a single TDMA time slot to be used at one site at a time. A time shared traffic channel system would, for instance, allow the four TDMA slots of a single channel to support four independent voice calls on four separate sites (which would otherwise produce co-channel interference). A time shared control channel system will allow the control channel to be shared by up to 32 base sites (with the corresponding increase in call set-up times). A combination of time shared control and traffic channels allows very economical use of the radio spectrum.

Quasi-synchronous transmission makes the TDMA time slots available at the same time at all base sites to provide four channels per RF frequency pair. A time shared transmission system separates the four TDMA time slots and uses them on four geographically separated BSs.

Quasi-synchronous thus provides better wide area coverage than time shared transmission (since the four channels are supported at all sites) but requires a special interconnection to maintain quasi-synchronous operation. In low traffic density areas requiring point-to-point transmission time shared operation can be more spectrally efficiency than quasi-synchronous.

On the negative side quasi-synchronous transmission will ask for a class of equalized MSs and needs special hardware in the BSs and the interconnection. On the positive side the quasi-synchronous switch will be less complex, the quasi-synchronous BSs behave like one normal BS.

6.1.9.4 DM / trunked gateway versus on-frequency repeaters

On-frequency repeaters will provide all the services and facilities within the area that is not directly covered by the infrastructure. However, there could remain an area where there is no direct coverage by the infrastructure and no indirect coverage by the on - frequency repeater.

The use of a DM / trunked gateway can give coverage in the same area where the infrastructure is also present. However, it is foreseen that the services and facilities supplied by direct mode operation will be very limited.

6.2 Radio parameters

6.2.1 Frequency allocation

Frequency allocations for TETRA are still under discussion. The CEPT recommended bands are listed in subclause 5.2.1.

6.2.2 Propagation models

6.2.2.1 Introduction

Radio wave propagation in the mobile radio environment is described by a dispersive multipath model containing reflection, diffraction and scattering. Different paths may exist between a BS and a MS due to large distant reflectors and/or scatterers and due to scattering in the vicinity of the MS, giving rise to a number of partial waves arriving with different amplitudes and delays. Since the MS will be moving, a Doppler shift is associated with each partial wave, depending on the MS's velocity and the angle of incidence. The delayed and Doppler shifted partial waves interfere at the receiver causing frequency and time selective fading on the transmitted signal.

When system bandwidth and propagation path lengths are sufficiently small (which is the case for TETRA), the resulting frequency and time selective fading process may be simulated by a simplified propagation model. Such a model exhibits only a few discrete paths which are independently fading. For practical channel simulation, stationary Gaussian processes with a power density spectrum equal to the classical Doppler spectrum (Clarke's model) are commonly assumed. This spectrum may be considered as the average over a large number of situations.

Based on extensive investigations (COST207) some tapped delay line models (figure 26) which are typical for propagation conditions in urban or rural areas have been derived for GSM. In principle these models have been adopted for TETRA, however, with a reduced number of taps (paths) taking into account the much smaller system bandwidth of TETRA. It can be shown that the propagation models defined for TETRA are almost equivalent to the corresponding GSM models when applied to a TETRA system.

The TETRA standard specifies five different propagation models to be used for simulation or radio conformance testing. The models are defined in ETS 300 392-2 [2] by:

- the number of discrete taps;
- the relative tap delay;
- the average relative tap-gain;
- the type of tap-gain process to be applied.

The vehicle speed in km/h denoted by x is the only selectable model parameter. The TETRA standard assumes a maximum vehicle speed of 50 km/h in urban areas and 200 km/h in rural areas and in a quasi-synchronous environment.

NOTE: The standard does not take care of the average gain of the models in an absolute sense. For any implementation, however, the adjustment of the average gain is essential in order to achieve the correct average receiver input signal level.

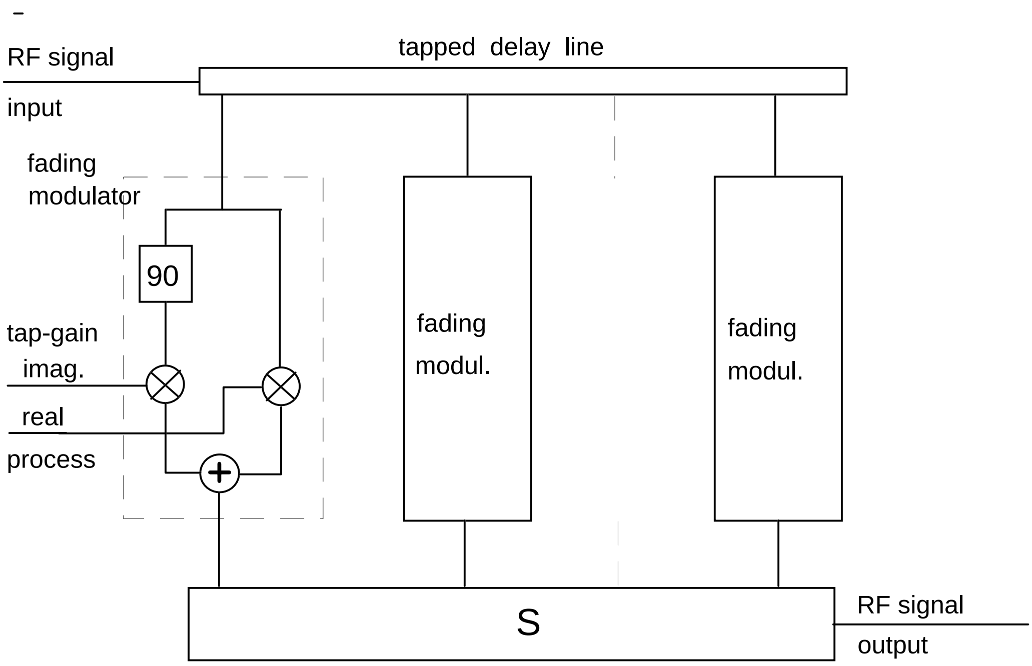


Figure 26: Tapped delay line propagation model

6.2.2.2 Static

This models refers to ideal conditions without multipath and for a non-moving MS. It is a one tap model and the constant tap-gain process STATIC(fs) with parameter fs = 0 is applied.

6.2.2.3 Rural Area (RAx)

This model is typical for flat rural areas where there is often a line-of-sight path (dominant component), no distant reflectors but scattering in the vicinity of the MS. In this case the different propagation paths are not resolvable with respect to the TETRA system bandwidth. The model defines only one tap introducing Rician fading. This is achieved by applying a tap-gain process (RICE) which is the sum of a complex component (STATIC(fs)) with a constant magnitude and a constant Doppler shift fs and a complex random component (CLASS) with a Rayleigh distributed magnitude and with a power density spectrum according to the classical Doppler spectrum.

6.2.2.4 Hilly Terrain (HTx)

This model is typical for hilly areas where there is normally no line-of-sight path and where reflections at distant hills are likely to occur. The model defines two taps with a ratio of the average gain of -8,6 dB and a delay difference of approximately one quarter of the duration of a TETRA symbol. For both taps a complex process CLASS is applied. The two processes are mutually statistically independent. The HT model introduces frequency and time selective Rayleigh fading.

6.2.2.5 Typical Urban (TUx) and Bad Urban (BUx)

These models are typical of built-up areas for situations where there is no line-of-sight path but some reflections from large, distant buildings. Both TUx and BUx are two tap models with identical delay difference (about 1/10 of a symbol duration) between the first and the second tap but with a different average gain in the second tap. The TU model introduces almost flat Rayleigh fading, that means, no significant inter-symbol interference will occur in a TETRA receiver.

6.2.2.6 Equalizer testing model (EQx)

This model is intended to test class E equipment which employs channel equalization. The model defines four independent Rayleigh-fading taps spread over an interval of roughly two TETRA symbol durations (100 µs). It represents a severe propagation case which might be found in a quasi-synchronous system or in mountainous terrain.

NOTE: The EQ model is relevant for the downlink only.

6.2.3 Sensitivity, interference rejection and nominal performance

6.2.3.1 Definition of sensitivity

For analogue speech systems, receiver sensitivity is defined as the required RF input signal level to provide a certain signal-to-noise ratio (measured as SINAD) at the receiver audio output. In digital speech systems using low rate codecs, distortion of the audio output signal is not additive noise like. Thus SINAD is not an appropriate measure of speech intelligibility as it is the case for analogue systems. In digital systems the raw Bit Error Ratio (BER) at the speech decoder input may be used as an indication of speech quality.

Demonstrations of applying typical propagation error patterns to the TETRA voice codec show that it will cope with raw BERs up to 4% without severe speech quality loss. The sensitivity for TETRA receivers may therefore be defined as the signal input level required to provide an uncoded BER of 4% in the speech traffic channel.

6.2.3.2 Reference sensitivity levels and reference sensitivity performance

In ETS 300 392-2 [2] the minimum required performance in terms of BER or Message Erasure Rate (MER) whichever is appropriate, is specified at a given receiver input level, called reference sensitivity level. Different reference sensitivity levels are defined for BS and MS for static and dynamic (multipath fading) conditions as shown in table 2.

Table 2: Reference sensitivity levels and assumed receiver noise figures

equipment type	static conditions	dynamic conditions	noise figure
BS	-115 dBm	-106 dBm	6,4 dB
MS	-112 dBm	-103 dBm	9,4 dB

These sensitivity levels and the corresponding sensitivity performance specification are based on calculations and simulation results assuming a state of the art receiver design and different noise figures for BS and MS (see table 2). The sensitivity levels have been determined such that the TCH uncoded BER does not exceed 4% in the most common propagation conditions considered. The defined BER value is only exceeded for EQ200 propagation conditions as can be seen from table 3.

The TETRA standard specifies the minimum required sensitivity performance for static, TU50, HT200 and EQ200 conditions only. Further simulation results for HT50, BU50, and RA200 are given in table 3. These results are only informative but not normative. They have been obtained from a receiver implementation that meets the Class B and A performance specification given in ETS 300 392-2 [2] which is also represented in table 3.

The BER/MER performance of the different equipment classes (see subclause 6.1.1) are specified at the same reference sensitivity level but might differ depending on the logical channel and propagation conditions. Class A equipment is not specified in EQ conditions, and class B equipment is not specified in HT or EQ conditions.

NOTE: Particular equipment may perform better than these specification limits and it may also be that lower speech quality obtained at lower receive levels is acceptable in some applications.

Table 3: Reference sensitivity performance

Downlink (continuous mode)

Logical channel	**Performance meas.**	Static **class A/B**	TU50 **class B/A**	HT200 **class A**	EQ200 **class E**	HT50 ******	BU50 ******	RA200 ******
AACH	MER	28 %, 38 %	11 %, 10 %	17 %	16 %	13 %	11 %	10 %
BSCH	MER	3 %	8 %	11 %	22 %	10 %	8 %	7 %
SCH/F	MER	4,5 %, 9 %	8 %	11 %	22 %	12 %	8 %	2 %
SCH/HD	MER	2,5 %, 5 %	8 %	11 %	21 %	12 %	10 %	5 %
TCH/7,2	BER	3,5 %, 4 %	2,2 %, 2,5 %	4 %	4,5 %	2,7 %	2 %	1,5 %
TCH/4,8 N=1	BER	0,3 %	2 %	4 %	6,4 %	3,2 %	2,2 %	1,3 %
TCH/4,8 N=4	BER	0,2 %	0,4 %	3,3 %	2,7 %	0,9 %	0,4 %	0,05 %
TCH/4,8 N=8	BER	0,15 %	0,06 %	3 %	1,5 %	0,2 %	0,05 %	0,01 %
TCH/2,4 N=1	BER	0,01 %	0,35 %	1,1 %	0,82 %	0,5 %	0,3 %	0,01 %
TCH/2,4 N=4	BER	0,01 %	0,01 %	0,4 %	0,02 %	0,01 %	0,01 %	0,01 %
TCH/2,4 N=8	BER	0,01 %	0,01 %	0,13 %	0,01 %	0,01 %	0,01 %	0,01 %
NOTE 1: SCH/HD, BNCH, STCH have equal performance. The uncoded BER of TCH/S is equal to the BER of TCH/7,2.								
NOTE 2: ****** means the specification is informative.								

Uplink

Logical channel	**Performance meas.**	Static **class A/B**	TU50 **class B/A**	HT200 **class A**	EQ200 **class E**	HT50 ******	BU50 ******	RA200 ******
SCH/F	MER	10 %	8 % 11%	11 %	no spec.	12 %	8,2 %	1,7 %
SCH/HU	MER	3 %	8 %	9,5 %	no spec.	11 %	8,3 %	3,5 %
STCH	MER	8 %, 5 %	8 %, 9 %	11 %	no spec.	12 %	10 %	5 %
TCH/7,2	BER	3 %, 4 %	2,2 %, 2,5 %	4 %	no spec.	3 %	2,3 %	1,8 %
TCH/4,8 N=1	BER	3,3 % 0,3 %	2 % 4 %	4 %	no spec.	3,5 %	2,4 %	0,5 %
TCH/4,8 N=4	BER	1 % 0,2 %	0,4 % 1,2 %	4 %	no spec.	1,7 %	1,3 %	0,9 %
TCH/4,8 N=8	BER	0,4 % 0,2 %	0,06 % 0,4 %	4 %	no spec.	0,75 %	0,5 %	1,1 %
TCH/2,4 N=1	BER	0,2 % 0,01 %	0,35 % 1,2 %	1,3 %	no spec.	1 %	0,6 %	0,4 %
TCH/2,4 N=4	BER	0,01 %	0,01 % 0,02 %	0,3 %	no spec.	0,04 %	0,02 %	0,2 %
TCH/2,4 N=8	BER	0,01 %	0,01 %	0,15 %	no spec.	0,01 %	0,01 %	0,05 %
NOTE 1: The un-coded BER of TCH/S is equal to the BER of TCH/7,2. NOTE 2: ****** means the specification is informative.								

Table 4: Nominal performance

Down- and uplink

Logical channel	**Perform. measure.**	Static **all class.**	TU50 **all class.**	HT200 **class A**	EQ200 **class E**	HT50 ******	BU50 ******	RA200 ******
TCH/7,2	BER	0,01 %	0,4 %	3 %	2 %	2,6 %	0,8 %	0,3 %
NOTE: ****** means the specification is informative.								

6.2.3.3 Equivalent signal-to-noise ratio

For the assumed noise figures, a symbol energy-to-noise density ratio (Es/No) of 10 dB for static and 19 dB for dynamic conditions results at the reference sensitivity level. The ratio Es/No is equal to the ratio of the signal power to the noise power measured in 18 kHz bandwidth.

NOTE: The actual Es/No used for simulations was 8 dB and 17 dB respectively for all equipment types. Thus the specified reference sensitivity BER/MER performance includes a 2 dB margin for implementation losses.

6.2.3.4 Interference rejection

Interference rejection is a measure of the capability of the receiver to receive a wanted signal in the presence of an unwanted signal. The TETRA standard considers both co-channel and adjacent channel interference rejection for the case where the unwanted signal is a continuous TETRA modulated signal subjected to the same propagation conditions as the wanted signal.

In line with subclause 6.2.3.1 the interference rejection may be defined as the required ratio of wanted and interfering input signal providing an un-coded BER of 4%.

In ETS 300 392-2 [2] the minimum required interference performance in terms of BER or MER is specified at a given interference ratio, called the reference interference ratio. The following reference interference ratios are defined for all types of equipment (BS, MS) and for dynamic conditions:

Reference co-channel interference ratio: C/Ic = 19 dB;

Reference adjacent channel interference ratio: C/Ia = -45 dB.

These interference ratios and the corresponding interference performance specification are based on simulation results assuming state of the art receiver design. The specified BER/MER performance applies for co-channel and adjacent channel interference. The interference ratios have been determined such that the un-coded BER does not exceed 4% in all propagation conditions to be considered. The ratio C/Ic was chosen to be equal to the assumed Es/No at the reference sensitivity level, since the simulated interference performance is similar to that in table 3. This shows the AWGN-like character of a TETRA co-channel interference.

In case of co-channel interference the performance specification applies for a wanted input signal at -85 dBm, and in case of adjacent channel interference for a wanted input signal 3 dB above the dynamic reference sensitivity level.

NOTE 1: The actual C/Ic used for co-channel interference simulation was 17 dB. The performance values obtained for co-channel interference have been adopted for adjacent channel interference specification. It has been shown by simulation that this specification can be met with reasonable IF filtering. Adjacent channel interference simulations have to be performed at C/Ia = -45 dB and at a signal-to-noise ratio Es/No = 20 dB (AWGN has to be included).

NOTE 2: The TETRA standard defines no reference interference ratios for static conditions.

For static conditions a C/Ic = 10 dB and a C/Ia = -54 dB with a wanted input signal 3 dB above the static reference sensitivity level is recommended. Simulations may be performed at C/Ic = 8 dB for co-channel interference and at C/Ia = 54 dB, Es/No = 11 dB for adjacent channel interference.

6.2.3.5 Nominal performance

The TETRA standard specifies a minimum performance at a receive level of -85 dBm for the un-coded BER (only). This is called the nominal performance. It has to be met up to -40 dBm in all propagation conditions considered. All nominal performance specifications are based on simulation results obtained at Es/No = 36 dB and include an implementation margin factor of 2 in the BER values.

The standard also specifies a BER limit for high receiver input levels up to -20 dBm however in static conditions only.

6.2.3.6 Sensitivity comparison of TETRA with analogue FM systems

According to ETS 300 086 [6] the maximum usable sensitivity of an analogue FM receiver is defined as the input signal level providing a psophometrically weighted (p.w.) SINAD (S+N+D)/(N+D) of 20 dB in static conditions using the normal test modulation.

Pre-emphasis and de-emphasis processing of the audio signal resulting in partial phase modulation is applied in most of today's FM systems to improve the signal-to-noise ratio. The maximum usable sensitivity at 20 dB p.w. SINAD of such an FM receiver at 400 MHz to 500 MHz is typically in the range of:

-118...-114 dBm (-5...-1 dBμV e.m.f.) for 25 kHz channel spacing;

-116...-113 dBm (-3...0 dBμV e.m.f.) for 12,5 kHz channel spacing.

The scattering of the sensitivities is mainly due to different receiver noise figures. A performance comparison of the different transmission schemes based on the assumption of equal receiver noise figures therefore seems to be more adequate. The table below shows the sensitivity of FM relative to the reference sensitivity of TETRA. It also shows the carrier-to-noise ratios (C/N) after the IF filter which is typically required to provide a 20 dB p.w. SINAD for 25 kHz and 12,5 kHz FM receivers (an equivalent noise bandwidth of 15 kHz and 7,5 kHz, respectively, is assumed).

Table 5: Carrier-to-noise ratio and relative sensitivity of FM

	25 kHz	**12,5 kHz**
C/N after IF-filter	9 dB	14 dB
relative FM sensitivity	2 dB better	equal

In some countries a non-weighted SINAD of 12 dB is also used as the FM performance criterion. This would result in a 3 dB better sensitivity of FM compared to TETRA for both 25 kHz and 12,5 kHz channel spacing (C/N = 8 dB and 11 dB, respectively).

NOTE: The sensitivity levels as specified for TETRA refer to the receive power during the burst. The average received power per speech channel of TETRA however is 4 times lower. Thus the digital transmission scheme of TETRA has an advantage of 6dB in energy efficiency over analogue FM.

The ETSI standards for land mobile services specify the following maximum usable sensitivities for FM systems in static conditions:

- for voice ETS 300 086 [6]: -107 dBm (6 dBμV e.m.f.) at 20 dB p.w. SINAD;

- for data ETS 300 113 [7]: -110 dBm (3 dBμV e.m.f.) at BER = 1 %.

These reference sensitivity values are significantly higher than those specified for TETRA.

For dynamic conditions the comparison of TETRA with FM is difficult because no adequate performance definition for FM exists. It is however common practice to increase the minimum required carrier-to-noise ratio by 10 dB in order to take into account the deteriorating effects of short term Rayleigh fading. Although this would result in similar reference sensitivities for TETRA and analogue FM, TETRA may provide on average better speech quality.

6.2.3.7 Comparison of co-channel interference rejection of TETRA with analogue FM

The standards ETS 300 086 [6] and ETS 300 113 [7] define the co-channel interference rejection ratio (C/Ic) of FM receivers at 14 dB p.w. SINAD and at 1 % BER, respectively, for static conditions as follows:

- C/Ic = 8 dB for 25 kHz channel spacing;

- C/Ic = 12 dB for 12,5 kHz channel spacing.

Although the interference rejection is measured at a low wanted signal level of -107 dBm, noise normally does not affect the resulting SINAD significantly. Thus similar interference rejection ratios may be expected at -85 dBm where TETRA is to be tested. According to subclause 6.2.3.4 an interference ratio of 10 dB may be assumed for TETRA in static conditions.

It is reasonable to assume an increase in the required C/Ic for FM by 10 dB in dynamic conditions. The specified limit for TETRA is 19 dB.

6.2.4 Path loss model

Path loss due to propagation effects is usually predicted on the basis of the local area median path loss, L (dB measured between isotropic antennas), measured at a distance (BS-MS) of R (km). This means that L represents the path loss attained or exceeded at 50 % of locations at a distance R, after the signal has been averaged over the short term fading component, which usually involves an averaging window corresponding to distances of some 10's of metres.

The rate at which L increases as a function of R depends on the type of environment in which the system operates. In a given environment, however, L may be characterized by the following parameters:

h_b BS antenna height above local ground level, (m);

h_m MS antenna height above local ground level, (m);

f_c Carrier frequency, (MHz).

As a reference, values of h_m = 1,5 m and f_c = 400 MHz will be used throughout this ETR.

A precise calculation of L requires a very detailed knowledge of the environment. For general calculations, therefore, the environment is usually classified into one of a number of general categories and an empirical model is used, which gives L in terms of h_b, h_m, f_c and R only. A commonly used, well-proven example, is the Hata model. This model is used in this ETR to estimate the path loss in two types of environment, rural and suburban areas.

6.2.4.1 Rural Area

The Hata model defines path loss for an open area as:

$$\begin{aligned} L_{OA} = {} & 69{,}55 + 26{,}16 \log_{10}(f_c) - 13{,}82 \log_{10}(h_b) - (1{,}1 \log_{10} f_c - 0{,}7)\, h_m \\ & + (1{,}56 \log_{10}(f_c) - 0{,}8) + \left(44{,}9 - 6{,}55 \log_{10}(h_b)\right) \log_{10}(R) \\ & - 4{,}78 \left(\log_{10}(f_c)\right)^2 + 18{,}33 \log_{10}(f_c) - 40{,}94 \text{ [dB]} \end{aligned}$$

In rural areas, clutter such as isolated buildings and trees acts to increase *L*. A margin of 10dB is taken here to account for this clutter. Thus rural area path loss, L_{RA} is defined as:

$$L_{RA} = L_{OA} + 10 \text{ (dB)}$$

The graph (figure 27) shows L_{RA} versus *R* for h_b = 30, 50, 100 m.

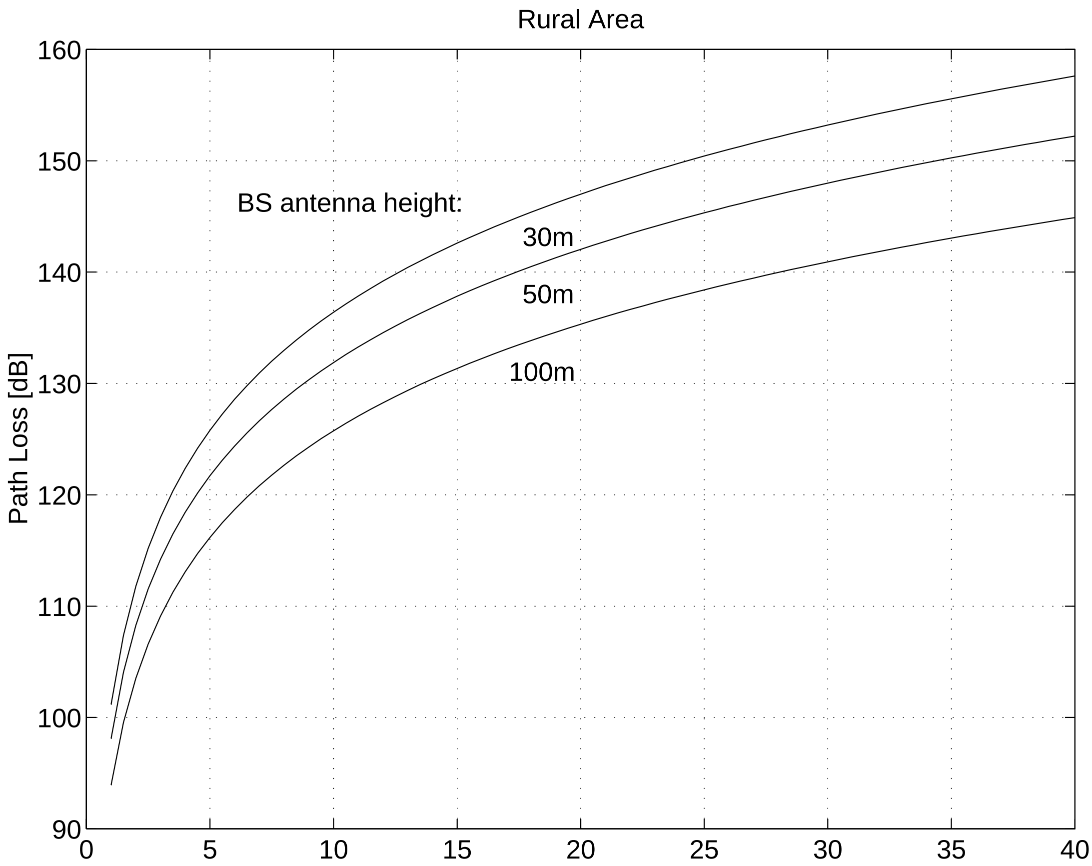


Figure 27: Graph showing path loss variation for typical rural area

6.2.4.2 Suburban area

For suburban areas the Hata suburban model may be used directly to define the path loss, L_{SA}:

$$L_{SA} = 69{,}55 + 26{,}16\ \log_{10}(f_c) - 13{,}82\ \log_{10}(h_b) - (1{,}1\ \log f_c - 0{,}7)\, h_m \\ + (1{,}56\ \log_{10}(f_c) - 0{,}8) + \left(44{,}9 - 6{,}55\ \log_{10}(h_b)\right) \log_{10}(R) \\ - 2\left(\log_{10}(f_c / 28)\right)^2 - 5{,}4\ \text{[dB]}$$

The graph (figure 28) shows L_{SA} versus R for h_b = 30, 50, 100 m.

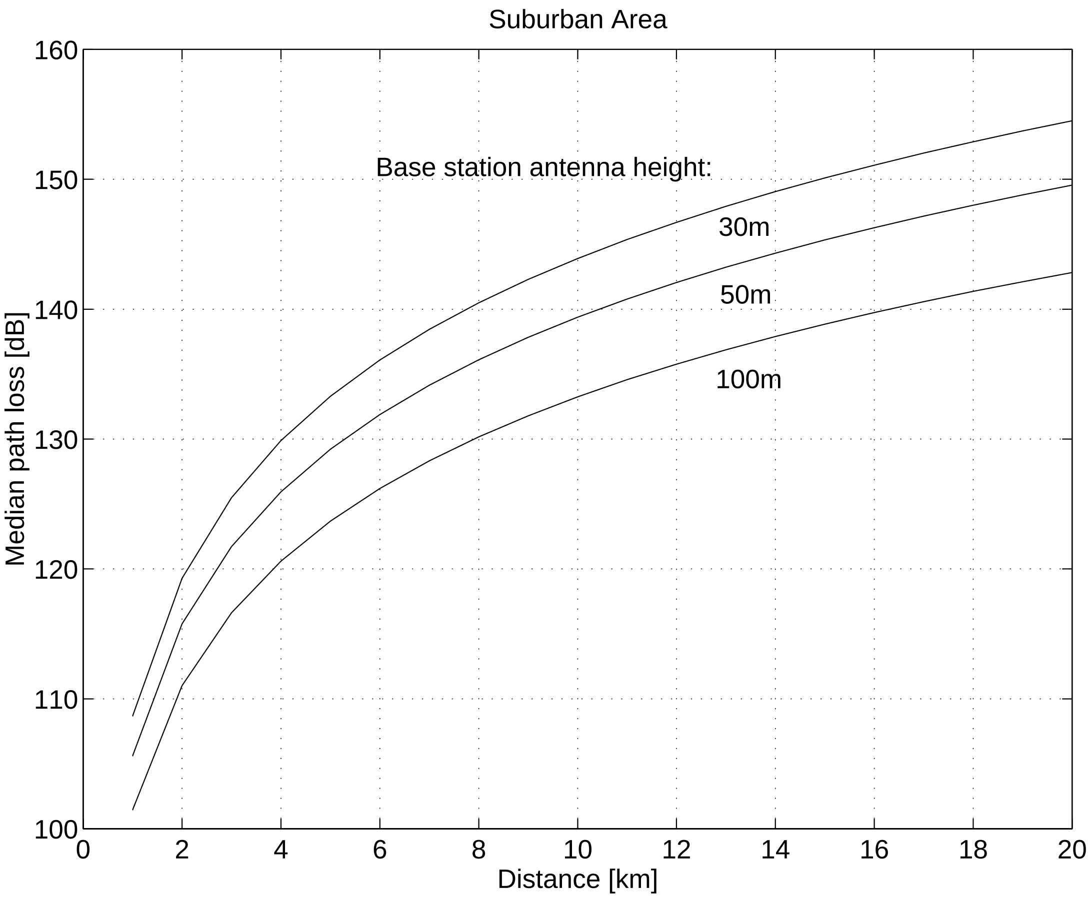


Figure 28: Graph showing path loss variation for typical suburban area

6.2.5 Link budget

To calculate the local mean power at the receiver input terminals at median locations, the path loss calculation is used in conjunction with a link budget calculation. Table 6 gives the link budgets in general terms.

Table 6: General link budget calculations

	Downlink	Uplink	Unit	Formula
TX Power	P_{BS}	P_{MS}	dBm	A
TX Cable and Filter Loss	B_{BS}	B_{MS}	dB	B
TX Antenna Gain	C_{BS}	C_{MS}	dBi	C
Peak Effective Isotropic Radiated Power	P_{BS} - B_{BS} + C_{BS}	P_{MS} - B_{MS} + C_{MS}	dBi	D = A - B + C
Propagation Loss	L	L	dB	E
Signal Level at RX Antenna	P_{BS} - B_{BS} + C_{BS} - L	P_{MS} - B_{MS} + C_{MS} - L	dBm	F = D - E
RX Antenna Gain	G_{MS}	G_{BS}	dBi	G
RX Cable Loss	H_{MS}	H_{BS}	dB	H
Receiver Input Power	R_{BS} = P_{BS} - B_{BS} + C_{BS} - L + G_{MS} - H_{MS}	R_{BS} = P_{MS} - B_{MS} + C_{MS} - L + G_{BS} - H_{BS}	dBm	F + G - H
NOTE: The BS antenna gain may be different for transmission and reception. This permits allowance to be made for techniques such as antenna diversity.				

Having calculated general expressions for the power at the receiver input terminals, the maximum acceptable path loss can be calculated when the minimum useful signal under varying channel conditions is known. This may, for instance, be the dynamic reference sensitivity of the receiver.

For the downlink:

$$L = P_{BS} - B_{BS} + C_{BS} - R_{MS} + G_{MS} - H_{MS}$$

For the uplink:

$$L = P_{MS} - B_{MS} + C_{MS} - R_{BS} + G_{BS} - H_{BS}$$

6.2.6 Signal variability

Measurement at the edge of coverage, where there is usually no line of sight component, have shown that signal strength fluctuations over a relatively small distance (in the order of a few tens of wavelength) are well-described by Rayleigh statistics. This is the short term (microscopic) Rayleigh fading caused by multipath propagation in the immediate vicinity of the receiver.

Superimposed on this Rayleigh fading is the long term (macroscopic) fading, caused by large scale variations in the terrain profile (shadowing) and by changes in the nature of the local topography. Long-term fading may be regarded as variations in the local mean and are found to be closely log-normal in urban areas.

The resulting probability distribution of the mixture of Rayleigh and log-normal statistics is termed the Suzuki distribution.

The location variability s (in dB), required for coverage area calculations, is defined to be the standard deviation of the normally distributed local mean (in dB), while the local mean itself is the RMS value (in dB) of the Rayleigh distribution. The mean value (in dB) of the local mean (in dB) is the signal strength which is predicted by the median path loss model. Measurements performed by Okumura in Tokyo at 400 MHz show a location variability of approximately 6 dB and 8 dB for urban and suburban areas, respectively. In subclause 6.3 a location variability of 8 dB is assumed to predict coverage in suburban and rural areas.

6.3 Area coverage

In calculating the coverage area of a TETRA system, two main cases are distinguished: noise limited and interference limited systems. Furthermore, for the noise limited case, the situations corresponding to stationary operation and MSs moving at speed higher than 50 km/h are distinguished.

6.3.1 Noise limited

The radio range is defined as the distance from the transmitter at which the location probability falls below a specified value (e.g. 90 %).

For stationary operation the location probability at distance R is defined as the probability that the receive signal level at distance R exceeds the static sensitivity level of the receiver. In this subclause the reference level will be the static reference sensitivity level specified for each type of equipment (see subclause 6.2.2.2).The range is therefore sensitivity limited which is also said to be noise limited. The location probability in the stationary case is given by the Suzuki distribution.

For moving vehicles, the short term spatial fading appears as fast time selective Rayleigh fading which requires an increased minimum average receive level (an increased local mean) in order to maintain acceptable speech quality. The location probability at distance R for this case will be defined here as the probability that the local mean exceeds the dynamic sensitivity of the receiver. In this subclause the reference level will be the dynamic reference sensitivity level specified for each type of equipment (see subclause 6.2.2.2). Strictly, it can only be used for MSs moving at speeds higher than 50 km/h. The location probability in the moving case is determined by a log-normal distribution.

Assumptions are made for the various elements of the link budget. The values are intended to be representative of real equipment, but do not prescribe any particular implementation. The resulting maximum acceptable path loss for the static and the dynamic cases is shown in table 7. Notice that the range for handheld portables will be set by the uplink, while the uplink and downlink budgets balance for MSs.

Table 7: Typical link budget for TETRA

	BS to MS	MS to BS	BS to HH	HH to BS	Unit
TX power	44	40	44	30	dBm
TX cable and filter loss	6	2	6	0	dB
TX antenna gain	8	2	8	-4	dBi
Peak effective isotropic radiated power	46	40	46	26	dBm
Propagation loss	L	L	L	L	dB
Signal level at RX antenna	46 - L	40 - L	46 - L	26 - L	dBm
RX antenna gain	2	8	-4	8	dB
RX cable loss	2	4	0	4	dB
RX input power	R_{BS} = 46 - L	R_{BS} = 44 - L	R_{BS} = 42 - L	R_{BS} = 30 - L	dBm
RX sensitivity static: dynamic:	 -112 -103	 -115 -106	 -112 -103	 -115 -106	 dBm dBm
Maximum acceptable median path loss static: dynamic:	 158 149	 159 150	 154 145	 145 136	 dB dB

6.3.1.1 Coverage for stationary operation

Under these assumptions, the range for 50 % location probability at the edge of coverage is given by taking the maximum acceptable median path loss for static conditions, subtracting a margin of 2 dB, and using the path loss models of subclause 6.2.4 to find the corresponding value of R, as given in table 8 for h_b = 50m, h_m = 1,5 m, and f = 400 MHz.

NOTE: The 2 dB margin is due to the difference between the median value of the receive level and the median value of the local mean predicted by the Hata model.

Table 8: Range calculations based on 50 % probability of exceeding reference sensitivity at edge of coverage (stationary operation)

	MS range (km)	HH range (km)
Rural area	53,8	20,7
Suburban area	32,2	12,4

These ranges yield coverage at approximately 75 % of locations within the coverage area. A margin has to be subtracted from the maximum acceptable median path loss in order to design for a higher location probability. For 90 % of locations at the edge of coverage, or approximately 95 % of locations within the coverage area, assuming the Suzuki distribution and a location variability of 8 dB this margin is 15 dB. This leads to the ranges given in table 9.

Table 9: Range calculations based on 90 % probability of exceeding reference sensitivity at edge of coverage (stationary operation)

	MS range (km)	HH range (km)
Rural Area	22,2	8,5
Suburban Area	13,3	5,1

6.3.1.2 Coverage for moving MSs

The range for 50 % location probability at the edge of coverage for moving MSs is determined in the same way, however, by taking the maximum acceptable path loss for dynamic conditions. The corresponding value of R is given in table 10 for h_b = 50 m, h_m = 1,5 m, and f = 400 MHz. No margin has to be subtracted.

Table 10: Range calculations based on 50 % probability of exceeding reference sensitivity at edge of coverage (moving MSs)

	MS range [km]	HH range [km]
Rural Area	33,4	12,9
Suburban Area	20,0	7,7

These ranges yield coverage at approximately 75 % of locations within the coverage area. For 90 % of locations at the edge of coverage, or approximately 95 % of locations within the coverage area, assuming the log-normal distribution with a standard deviation of 8 dB the margin is 10 dB and leads to the ranges given in table 11.

Table 11: Range calculations based on 90 % probability of exceeding reference sensitivity at edge of coverage (moving MSs)

	MS range [km]	HH range [km]
Rural Area	16,9	6,5
Suburban Area	10,1	3,9

6.3.2 Interference limited

If several BSs in a given region are operating on the same frequency, there is some probability that the MS will suffer interference from BSs which are undesired, reducing the probability of successful communications with its own BS. If the system is designed such that the probability of such interference is considerably greater than the probability of the signal-to-noise ratio dropping below the MS receiver threshold, then the system is referred to as interference limited.

As an example of this effect, this subclause shows how interference probabilities may be calculated in the case of a single interfering BS. Figure 28 shows a single MS at position M, receiving a wanted BS, W a distance r_1 away from it. An interfering BS, I, is located a distance r_2 away.

For a moving MS (speed > 50 Km/hr) unacceptable interference then occurs whenever the ratio between the mean power of the wanted and interfering BS signals in the MS receiver is less than the reference co-channel interference ratio, C/I_c (in dB). For TETRA the reference co-channel interference ratio is defined as C/I_c = 19dB. This may occur even when $r_1 < r_2$, since shadowing (long-term fading) occurs which is only partially correlated for the propagation paths from the two BSs. The shadowing is usually assumed to be log-normally distributed, with an environment-dependent standard deviation, s_s (in dB), the location variability.

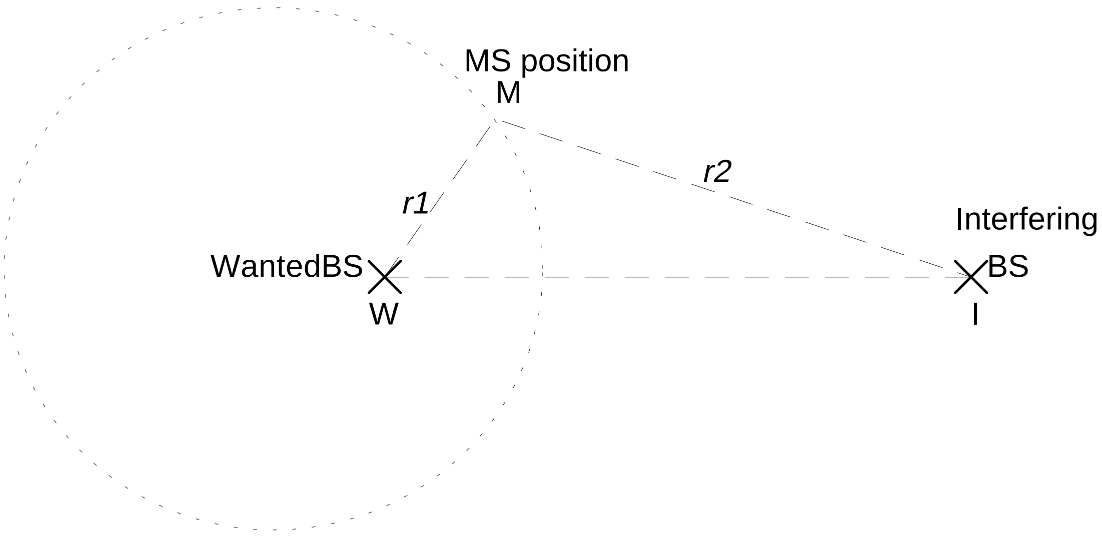


Figure 28: Interference limited coverage

For given values of r_1 and r_2 the probability of suffering interference also related to the path loss exponent, n, which is close to 4 for rural areas and slightly less for suburban areas. (see ETS 300 392-2 [2]).

The coverage of the wanted BS is most strongly affected by interference when the MS is on the line joining W and I. We therefore calculate the ratio of the total distance between the BSs (r_1+r_2) to the coverage radius of the wanted BS (r_1), assuming that the shadowing is completely uncorrelated - this gives the worst case re-use factor:

$$\text{Re-use factor} = \frac{r1 + r2}{r1} = 1 + 10^{\left(C/Ic + \sqrt{2\sigma^2}\,Q^{-1}(p)\right)/10n}$$

where p is the probability of suffering interference, and $Q^{-1}(p)$ is the inverse of the function Q(a), defined in terms of the complementary error function as:

$$Q(\alpha) = \frac{1}{2}\operatorname{erfc}\left(\frac{\alpha}{\sqrt{2}}\right)$$

Some useful values are $Q^{-1}(0,05)$ = 1,6 corresponding to a 5 % probability of interference, and $Q^{-1}(0,1)$ = 1,3, corresponding to a 10 % probability of interference. Some values for the re-use factor are given in table 12 below, assuming n = 4 and C/I_C = 19dB.

NOTE: The "Re-use factor" defined here is sometimes alternatively called the "Normalized Re-use Distance". It does not directly indicate the associated cellular cluster size for frequency re-use.

Table 12: Re-use factor for different location variability

Location Variability, σ	**Probability of suffering interference, p**	
	5 %	10 %
6 dB	7,7	6,6
8 dB	9,7	7,9
10 dB	12,4	9,5

These values for the re-use factor can be used when planning re-use of a particular frequency and for evaluating best cellular cluster sizes.

6.3.3 Quasi-synchronous operation

In quasi-synchronous operation several BSs at different sites are synchronized together in both time and frequency with all of them transmitting the same information. This has the effect of filling in any coverage nulls at the MS receiver.

In the uplink, the signals from all the sites are combined, usually relying on some form of (non-standard) voting technique so that the effective cell radius is increased. The quasi-synchronous technique is particularly useful in cases where the volume of traffic is low and there is such a shortage of spectrum as to preclude cellular frequency re-use techniques.

Even when the synchronization is perfect, the differing path lengths between the BSs and the MSs leads to the delay spread being increased which can degrade performance significantly for a class A or class B MS. A special class of MS, a class E, has therefore been included in the TETRA standard. Class E MSs achieve at least reference performance in a special propagation model (EQx), which is more severe than the hilly terrain model and is intended to represent the severity of multipath dispersion which will often be encountered in a realistic quasi-synchronous system.

Design of a quasi-synchronous system involves trade-offs in two main areas as explained below:

a) BS spacing and error rate performance:

   if BS spacing is increased excessively, the dispersion may exceed the capabilities of the MS to meet acceptable performance;

b) frequency synchronization and maximum mobile speed:

   any mismatch in carrier frequency between the BSs will be seen at the MS as an increase in the fading rate, limiting the maximum speed at which acceptable performance is achieved.

NOTE: The levels of time synchronization and frequency synchronization required to support quasi-synchronous are very difficult to achieve at the high data rates used in TETRA.

6.4 Direct mode

Link budget calculations for direct mode will be covered in part 3 of this ETR [4].

6.5 Co-existence aspects of TETRA

6.5.1 Introduction

This subclause studies aspects of co-existence of different TETRA systems with each other as well as the co-existence of TETRA systems with other systems.

In general, we can distinguish between two aspects of co-existence:

- the impact of unwanted emissions near the carrier on the coexistence of a TETRA system with other analogue or digital systems;

- the impact of unwanted emissions far from the carrier on the coexistence of a TETRA system with other systems.

The first item concentrates on the interference in the channel(s) adjacent to the active channel. The second item looks at the interference due to wide-band noise-like emissions which have a much lower level than the adjacent channel power but potentially affect a larger number of channels.

Both items are studied further in the following subclauses.

6.5.2 Impact of unwanted emissions near the carrier

The TETRA standard limits emissions in the channels adjacent to the active transmit channel to the values given in the table 13 below.

Table 13: Unwanted emissions close to the carrier

Frequency offset	Maximum level
25 kHz	-60 dBc
50 kHz	-70 dBc
75 kHz	-70 dBc

For analogue PMR systems (see ETS 300 086 [6] and ETS 300 113 [7]) a power of -60 dBc is allowed in the adjacent channel for a channel spacing of 12,5 kHz and -70 dBc for 25 kHz. The -60 dBc limit is met by TETRA in all adjacent channels, thereby ensuring coexistence with analogue PMR systems with a channel spacing of 12,5 kHz. The limit for 25 kHz spacing is met by TETRA in the second and third adjacent channel. One 25 kHz channel should therefore be left unused between channels of a TETRA system and those of an analogue PMR system with 25 kHz spacing unless other measures are taken to reduce the impact of the adjacent channel interference.

Concerning TETRA to TETRA interference in the adjacent channel the allowed level of unwanted emissions close to the carrier as well as the other system parameters lead to a reference adjacent channel interference ratio of:

- C/I_a = -45 dB for dynamic conditions; and
- C/I_a = -54 dB for static conditions.

C/I_a determines the required minimum ratio between the power of the signal on the active carrier (C) and the power of an interferer in the directly adjacent channel (I_a).

The adjacent channel interference ratio has to be respected when adjacent channels are used in the same area.

Concerning the co-existence of TETRA and other digital systems an assessment has to be made on a case-by-case basis since there are no uniform limits for the tolerable unwanted emissions near the carrier.

6.5.3 Impact of unwanted emissions far from the carrier

The TETRA system uses the π/4-DQPSK modulation scheme which has a non-constant envelope in contrast to analogue FM and some other less bandwidth efficient digital modulations.

Due to this property of the modulation scheme a highly linear transmitter is required in order to avoid non-linear distortions. Non-linear distortions would cause an intolerable broadening of the frequency spectrum.

Imperfections in the linearized transmitter can, however, cause low-level wide-band noise-like emissions outside the wanted channel. In order to ensure that the interference caused by this effect is limited, the TETRA specification requires that such emissions do not exceed specified limits. The limits apply to emissions within the transmit band of the TETRA transmitter, within the TETRA receive bands and beyond the TETRA allocation. These limits have been arrived at by probabilistic rather than by worst case analysis of several potential interference scenarios.

The specified limits are given in table 14.

Table 14: Specified wideband noise levels

Frequency offset	Maximum level		
	MS class 4 (1W)	MS class 3 (3W)	MS class 2 (10W) MS class 1 (30W) BS (all classes)
100 kHz - 250 kHz	-75 dBc	-78 dBc	-80 dBc
250 kHz - 500 kHz	-80 dBc	-83 dBc	-85 dBc
500 kHz - f_{rb}	-80 dBc	-85 dBc	-90 dBc
$>f_{rb}$	-100 dBc	-100 dBc	-100 dBc

f_{rb} denotes the frequency offset corresponding to the near edge of the receive band. All levels are expressed in dBc relative to the actual transmitted power level, and in any case no limit tighter than -70dBm apply.

Since the levels are given in dBc, the unwanted emissions produced by equipment of lower power classes are anticipated to be proportionately lower. It can also be expected that emissions will be further reduced by the application of power control.

6.5.4 Military systems

ETSI and ARFA have investigated possible interference from military frequency hopping systems to TETRA and vice versa in the frequency range 380-400 MHz. The following conclusions were obtained.

Interference from military frequency hopping systems like HAVE QUICK II and SATURN lead to very seldom but long (of the order of a second) interruptions or more frequent but very short interruptions. Both types of interruptions are quite well comparable to natural interruptions due to fading and shadowing. The short term interruptions are combated by the error coding scheme of TETRA and the longer but infrequent interruptions are handled by the appropriate link protocols. Moreover, it can be stated that under realistic assumptions neither the BER caused by the interferer nor the interruption probability alters remarkably the availability of TETRA links under natural propagation conditions. Hence interference from military systems are considered negligible.

The first analytical estimations of possible interference from TETRA systems on the military frequency hopping systems like HAVE QUICK II and SATURN came to the conclusion that such interference should be negligible in all cases.

Annex A: Services supported

A.1 Summary of basic services supported

Tele-services:

clear speech or encrypted speech in each of the following:

individual call (point-to-point);
group call (point-to-multipoint);
acknowledged group call;
broadcast call (point-to-multipoint one way).

Bearer services:

individual call, group call, acknowledged group call, broadcast call for each of the following:

circuit mode unprotected data 7,2; 14,4; 21,6; 28,8 kbit/s;
circuit mode protected data 4,8; 9,6; 14,4; 19,2 kbit/s;
circuit mode protected data 2,4; 4,8; 7,2; 9,6 kbit/s;
packet connection oriented data;
packet connectionless data.

A.2 Supplementary services supported

PMR type supplementary services:

- access priority, pre-emptive priority, priority call;
- include call, transfer of control, late entry;
- call authorized by despatcher, ambience listening, discreet listening;
- area selection;
- short number addressing;
- talking party identification;
- dynamic group number assignment.

Telephone type supplementary services:

- list search call;
- call forwarding - unconditional/busy/no reply/not reachable;
- call barring - incoming/outgoing calls;
- call report;
- call waiting;
- call hold;
- calling/connected line identity presentation;
- calling/connected line identity restriction;
- call completion to busy subscriber/on no reply;
- advice of charge;
- call retention.

Annex B: Speech coding and TDMA frame structure intrinsic delays

End-to-end delay is defined as the time that circuit mode speech or data remains within the transmission system. In this annex a brief description will be given of contributions to the single base site end-to-end delay due to the TDMA framing structure and the encoding, buffering and decoding of speech data.

An inherent property of the TETRA TDMA frame structure is that the 18th frame in every multi-frame (see figure 6) is reserved for control purposes. Freeing up of the 18th frame for control signalling is achieved by uniformly sampling the speech, slightly compressing the speech data (in the ratio 18/17) over that needed to send 60 ms of speech in a 15 ms slot and then sending the 18 frames of data in 17 physical frames. This entails buffering of the speech at the transmit end and also some buffering and expansion of the speech data at the receive end to ensure that continuous speech is presented to the user. The is process is shown in figure 29.

At the transmit end the speech is sampled at a uniform rate of 8 kHz but the relation between the input speech frames and the transmitter frame structure is arranged such the transmit speech buffers are exhausted just prior to frame 18 (when no speech data is sent) and the speech samples taken over the 18th frame period are buffered and gradually sent in the following 17 frame periods (this is to achieve minimum overall delay). Note the characteristic feature of the TDMA frame that the downlink frames precede the uplink frames by 2 slots. Thus speech data sent in the uplink slot 1 is transmitted (single site) in slot 1 of the following frame except in frame 17 when the uplink data is transmitted in frame 1.

At the receive end the decoded speech frames are synchronized to the downlink TDMA frames and buffered so that a continuous speech stream is presented to the user.

The result is a variable delay between encoding the speech and transmitting it on a physical RF burst and also a variable delay between receiving the RF burst and presenting it to the user. However buffering in the encoding and decoding processes compensate for each other so that overall there is a fixed end-to-end delay within the system.

The typical end-to-end delay of 207,2 ms (as shown in figure B.1) is made up of the following elements:

t_{dsp} time required to encode one 30 ms frame of speech data (say 30 ms);

t_{window} a 5 ms window required around the speech frame;

t_2 time required to demodulate a received burst, say <10 ms;

t_3 time required to decode a speech data frame , say <3 ms.

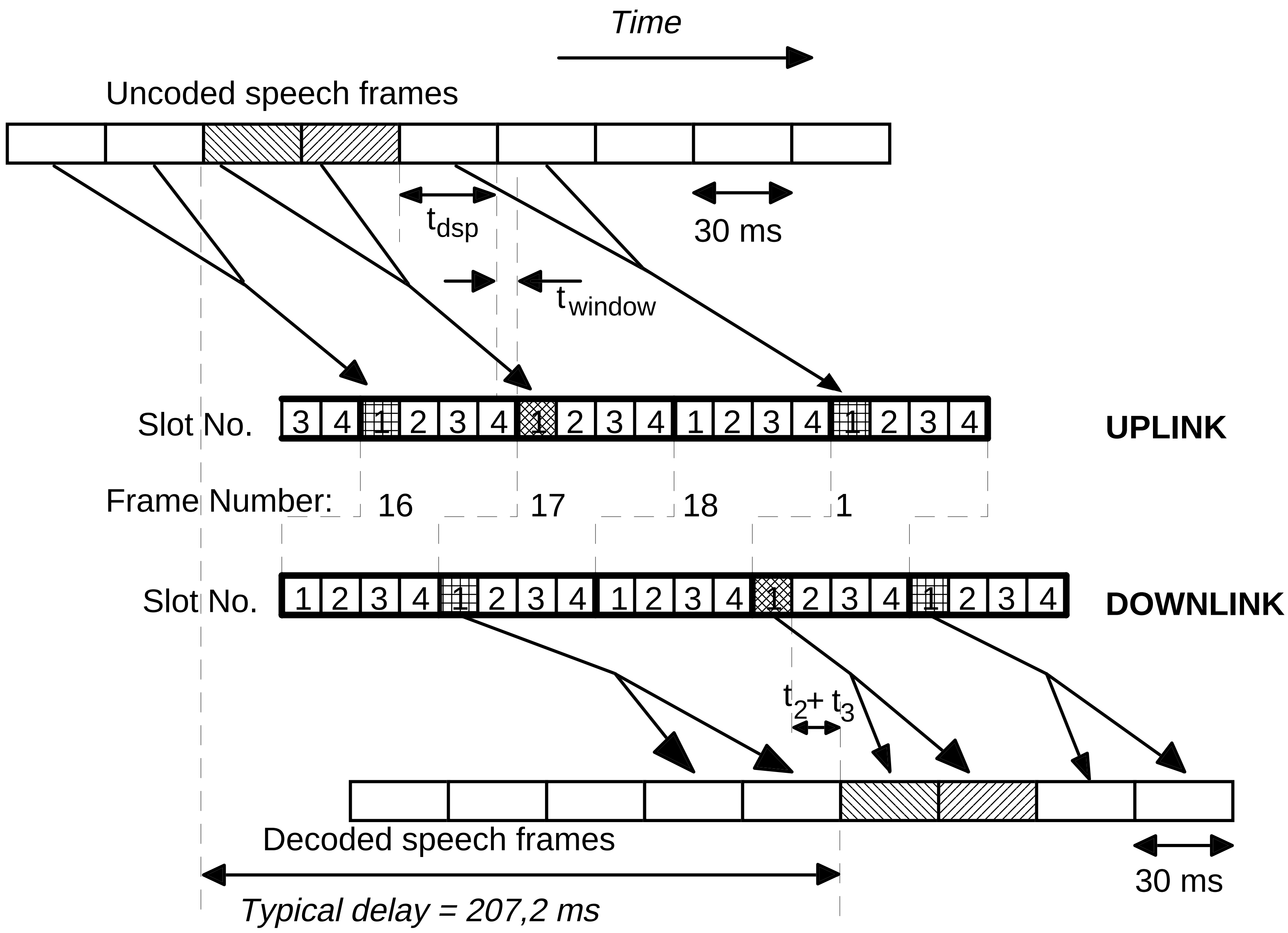
The encoding process is time limited by the time to encode a speech frame. The minimum delay is 2xspeech_frame_length + t_{dsp} + t_{window} = 95 ms.

The decoding process is time limited when decoding data from frame 1. The minimum delay is equal to t_2 + t_3 = 13 ms.

The TDMA frame structure is time limited at the frame 17 uplink to frame 1 downlink junction, introducing an extra frame delay over the usual 2 slot delay, due to the non availability of frame 18. Thus the limiting TDMA frame delay for single site operation is 1,5 x 56,667 = 85,0.

To allow for the data compression/expansion arrangements, the overall delay for the marked speech burst can be calculated by considering that it is decoded 2 speech frames before the speech in downlink frame 2 (i.e. uplink frame 1). Thus the typical MS to MS overall delay is:

95 + 7 x 14,1667 + 13 = 207,2 ms.


Time
Uncoded speech frames
t_{dsp}
30 ms
t_{window}
Slot No.
3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
UPLINK
Frame Number:
16
17
18
1
Slot No.
1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
DOWNLINK
$t_2 + t_3$
Decoded speech frames
30 ms
Typical delay = 207,2 ms

Annex C: Bibliography

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