Evaluation of Two Wireless Communication Standards for Public Safety and Security (PSS) Networks

By

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ABSTRACT

Law enforcement agencies in many countries have been using analogue wireless transmission networks based on an international standard known as MPT-1327 to support their operation. Recently, there is a significant move towards digital communication standards, such as Terrestrial Trunked Radio (TETRA) and TETRA Police (TETRAPOL). In this thesis, a study was conducted to compare the performance of these two standards when employed in a realistic network environment.

Selection of a realistic network environment was based on two criteria, namely the availability of data and the presence of a topology that represents urban and suburban settings. The City of Abu Dhabi, U.A.E. met these two criteria and was selected for this study. The methodology applied, however, is quite general and can be applied to typical environments in which law enforcement agencies wish to deploy Public Safety and Security (PSS) networks.

Both TETRA and TETRAPOL standards were evaluated by comparing their area coverage requirements and traffic capacity. The TETRAPOL standard was found to provide better coverage for the same number of base stations while the TETRA standard was found to provide a slight capacity cost advantage.

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1. INTRODUCTION

1.1. Background

Most countries, including the United Arab Emirates (UAE), are using telecommunication systems for public safety and security (PSS) in order to protect and guard their borders against different threats. The PSS network is a dedicated radio communication system for emergency services including police forces, fire brigades, ambulance services, transport police, maritime and coastguard services, and other related public services and organizations. These organizations also provide individual and professional responses to incidents and disastrous situations. They operate in an environment of ever increasing demands of fast, secure, and versatile communication between individual units, groups, and command and control centres. Over the years, the nature of emergency service operations has changed. Increased threats and changing mission critical requirements have added additional responsibilities to these organizations [1]. It is therefore necessary that the emergency services should have efficient, resilient, and highly reliable mobile communication infrastructures in place to support their needs as well as the needs of the public. Essential requirements for this mobile communication infrastructure are described in the following:

1.1.1. Resilience

The mobile communication network infrastructure should have a maximum resilience with sufficient level of redundancy such that no single failure would cause a major network outage. The communication systems must be able to accommodate power failures under normal, and more importantly, critical failure conditions. Following the general trend in other wireless networks, a move from the use of analogue communications by PSS was made towards a digital trunked system, such as TETRA and TETRAPOL, in order to make full use of the digital technology. TETRA standard has been developed specifically to solve the communication problems of the earlier analogue technology. The adoption of a digital standard by U.A.E.'s police forces can solve many communication problems of the MPT 1327 analogue standard. However, an examination and identification of the benefits from the switch to the TETRA or TETRAPOL standard require a deep research and understanding of the factors involved, particularly the area of coverage and available capacity of the system. A thorough evaluation and comparison of the TETRA and TETRAPOL should be conducted to determine which of them is more beneficial and suitable to replace the MPT 1327 system in the U.A.E.

1.1.2. Coverage

Coverage is one of the most important characteristics of a radio system. The emergency services require high levels of geographical coverage for mobile communications. It is important that the communication network provides extensive, reliable, and seamless radio coverage throughout the whole served area, including guaranteed availability of coverage under exceptional conditions such as remote rural locations and mountainous regions. Poor coverage will reduce the operational efficiency and hence, the effectiveness of any response to emergencies, and may jeopardize the personal safety of the emergency service officers who rely heavily on the radio communication in high-risk areas.

As Global System Mobile (GSM) private network must cover all places where subscribers need the service, users of the PSS network necessitate the coverage of the network since it is the backbone for emergency services and rescue scenarios. Hence, high level of topographical coverage must be considered for mobile communications in PSS networks. It is very important to cover all areas from urban to rural environments, from offshore to desert, and from inside the building to airborne atmosphere as emergencies or disasters can occur in any of these areas. Therefore, the coverage should be comprehensive and reliable at all places particularly, underground railway networks, shopping centers, and tunnels.

Furthermore, additional coverage may be required at some areas, which were not initially covered by the PSS network when emergencies take place and need of coverage arise such as training exercises or disastrous events outside of coverage area. This provision network coverage should be ready to install and use all the time.

On the other hand, missing coverage in some places will impact on the responsibility of the people who build the PSS network infrastructure in case of emergencies or disasters. In addition, it may jeopardize the user of the PSS network communication who relies on the radio communication.

1.1.3. Access and Capacity

Another key requirement for the emergency services personnel is to gain access to voice and data services with an agreed, and operationally acceptable, grade of service. The grade of service provided by the mobile communication system must be sufficient to manage the anticipated busy hour traffic and yet be flexible enough in its functional design to also support the communications during 'surge' conditions which exceed the anticipated busy hour traffic. For example, the need for a radio capacity increases during major accidents and incidents and this capacity must be guaranteed to the rescue and law enforcement personnel.

Capacity is one of the most important characteristics of a radio system. The PSS network requires high grade of services for the capacity to be able to handle unexpected usage of the network and to manage the busy traffic. Grade of service of the PSS network must be flexible enough to control the exceeded traffic in the network in addition to the normal daily usage. This flexibility should lead to controlling the system design and reconstruct the capacity by applying some mechanisms such as:

1. Pre-emption which gives the user the ability to initiate a call if the system is busy by giving him the authority of clearing down and free up network resources necessary to establish the priority call.
2. Ejecting some users by moving them to the direct mode operation (DMO) for local areas where there is no need for radio stations to save the network capacity.

1.1.4. Security

Security and confidentiality of information is fundamental to the operation of the emergency services. Although advances in technology provide immeasurable benefits to the emergency services, they also expose the radio systems to security vulnerabilities. Networks must have protection against corruption of, or unauthorized access to traffic and control including expanded encryption techniques and user authentication as appropriate.

1.1.5. Regulation

Procured public safety communication systems, both wired and wireless, must adhere to strict, Government imposed, regulations and standards rather than be formed from localized, ad hoc, solutions.

1.1.6. Group Communication

The emergency services usually involve a large number of personnel and often require significant logistic efforts. The efficient and safe co-ordination of these personnel necessitates the requirement for staff to be in constant communication with each other. It is necessary that an individual, both static and on the move, be able to initiate a call to all users who have been set-up as part of a pre-defined group or team.

1.1.7. Fast Call Set-up

Support for mission critical communications for the emergency services requires immediate call set-up. The mobile communication system should support a guaranteed call set-up time that takes no more than 300 msecs when communicating in the same 'cell' or localized area.

1.1.8. Priority

Mobile communication systems should provide a network priority service to authorized organizations conducting emergency services during disasters or when the network becomes congested. For example, during a fire incident, the priority should be given to the police and fire services to guarantee the required communications and ensure effective and efficient management of the incident.

1.1.9. Direct Mode Gateways and Repeaters

In a situation where the BSs providing communication to emergency services in a particular area are not available, the radio terminals must be able to work in Direct Mode to communicate with each other without the need for the core radio infrastructure. Direct Mode is also ideal for working in areas where the network coverage is uncertain, such as the basement of a building, the tunnels and other confined areas. The use of devices such as Direct Mode Gateways and Repeaters helps to enhance set-to-set operations and to extend infrastructure coverage into buildings, tunnels, cliffs, etc. These devices provide a 'bridge' between the infrastructure and those users operating out of infrastructure coverage but within a Direct Mode range of the Gateway. Repeaters can be used to provide extended Direct Mode coverage for group communications out of range of the network infrastructure.

1.1.10. Integration with Control Room

Communication Control Rooms are fundamental to meeting the requirements for both day-to-day operational duties and emergency situations. Operators can take calls from the public or from staff within their own organization and then dispatch them, via the mobile radio system, to the appropriate resources. Information Technology (IT) systems and databases are used to record incidents, provide mapping information, and to provide information for managing and allocating resources. Integration of these systems and databases with mobile communication systems is a growing requirement, especially with the increase of data communication in the mobile environment.

1.1.11. Voice Quality

Quality of voice communication is a priority requirement for the emergency services during times of critical operations. In an emergency scenario, the noise levels in voice calls are likely to be high which may lead to poor communication that can result in severely serious consequences. Uncompromized voice quality allowing the listener to recognize the speaker, even under excessive background noise, is necessary for emergency services. Therefore, the environment in which users are required to work and communicate should be considered in determining the standards for the private mobile radio (PMR) operations. The integrity of the call has to be preserved in order to successfully transfer the required information from one point to another.

1.2. Telecommunication Standards

The European Telecommunications Standardization Institute (ETSI) has approved different system standards for PSS applications. These systems are the British Ministry of Post and Telecommunications MPT 1327 and the TErrestrial Trunked RAdio (TETRA). Each system can structure constant national network. Descriptions of these systems are given below. The TETRAPOL standard was not approved by the ETSI, yet it is being used in many of the European countries.

1.2.1. MPT 1327

The MPT 1327 system is an open protocol and an international standard. It became the most widely used trunked radio protocol in the world for radio share multiple channels with queuing and channel assignment being handled dynamically by the system infrastructure. When the radio user places a call, the trunked radio system automatically allocates an available free channel, which resulted in the increase of quality of service and reduction of infrastructure and operating costs. This protocol is ideally suited for providing individual or group calls, and offers fast call set-up time along with a wide range of advanced features and functionality to support the field units such as emergency and priority call management, status messaging, dynamic regrouping of users, and data/text messaging. It uses a digital control channel with analogue voice channels, which provides a data gateway that allows for supporting enhanced features including security and subscriber verification, mobile data communications, system administration, and seamless multi-site roaming.

1.2.2. TErrestrial Trunked RAdio (TETRA)

TETRA is a powerful multi-function mobile radio standard that provides a system tool kit from which system planners may choose in order to satisfy their requirements. Its 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. It meets the need of most professional mobile radio market including the PMR systems, Military and Public Safety organizations, and Public Access Mobile Radio Systems for public services [2]. TETRA uses time division multiple access (TDMA) technology with 4 time slots at a bandwidth of 25 kHz per carrier. The architecture within the system infrastructure is not standardized. There are various manufacturers supplying the network equipment, terminals, applications and mobiles such as Motorola, Nokia, and Rhode & Schwarz. However, the proper interoperability between mobiles and infrastructure of different manufacturers is guaranteed by the so-called TIP specifications (TETRA Interoperability Profiles) that are published by the TETRA MoU and represents the user organizations and manufacturers.

The TETRA standard utilizes a CODEC specifically designed to eliminate background noise and ensure delivery of a high level of voice quality from within a very noisy environment to maximize message intelligibility. This is very important to the emergency services in ensuring rapid and successful information transfer. In addition, the advanced digital coding used in TETRA allows users to make group calls, scan groups, send emergency calls, and communicate in push-to-talk mode with a very fast call set-up. Many data applications can effectively be built on these capabilities.

1.2.3. TETRAPOL

TETRALPOL is a label that combines the two words "TETRA" and "Police" since the French Ministry of Home Affairs has chosen this standard for its police force. It was one of the proposals that could have been the final ETSI standard, but was not chosen despite the fact that many of the ETSI participants preferred it to TETRA [3]. Several suppliers, particularly the French supplier Matra, continued developing the TETRAPOL standards and its specifications became available as Public Available Specifications (PAS).

TETRAPOL has the same features like TETRA but can cover larger areas than TETRA coverage, therefore, fewer BSs are needed and may result in lower maintenance and operating costs. It is now being used in many European countries such as France, Switzerland, Spain, and Romania.

1.3. Problem Definition and Research Needs

The police forces in the U.A.E provide Emergency Services to their citizens. A highly resilient and secure mobile communication infrastructure with high geographical coverage is necessary for these forces to accomplish their mission critical demands. In addition, it is crucial that they have terminal and peripheral equipments designed specifically to meet their needs and support features essential in delivering their operational requirements.

During the last decade, the U.A.E.'s police forces have adopted the MPT 1327 standard, a complex analogue trunking system, to support their operations. Even though the system has helped in increasing their mobility and effectiveness during emergencies, many communication problems have emerged, particularly due to the topographic nature and the increasing specific requirements of these forces. Today, there is a significant move towards the digital trunked PMR systems, such as TETRA and TETRAPOL, which make fullest use of the digital technology. TETRA standard have been developed specifically to solve those communication problems of the analogue technology. The adoption of a digital standard by U.A.E.'s police forces can solve many communication problems of the MPT 1327 analogue standard. However, an examination and identification of the benefits from the switch to the TETRA or TETRAPOL standard require a deep research and understanding of the factors involved, particularly the area of coverage and available capacity of the system. A thorough evaluation and comparison of the TETRA and TETRAPOL should be conducted to determine which of them is more beneficial and suitable to replace the MPT 1327 system in the U.A.E. It should be noted that the TETRA and TETRAPOL have been approved by ETSI and for that reason they gained international acceptance.

1.4. Research Objectives and Scope

The objectives of this thesis are to compare and evaluate the TETRA and TETRAPOL digital standards and to identify their benefits and shortcomings when operating in urban, suburban and rural settings. The U.A.E. environment was selected to provide a proper context for the comparison because of its topography and the availability of data required for the analysis. The methodology, however, is quite general and can be applied to any national environment provided that data is available. Therefore, the results of this research can have strong influence on selecting which technology is suitable for PSS in different countries.

Providing recommendations as to which of the two standards is beneficial to the U.A.E.'s police forces will follow. The evaluation of the standards will be undertaken based on the following performance measures:

1. Comparing the signal performance of the two standards by using the ICS Telecom software with two different propagation coverage models of radio-electronic signals and digital maps of a number of sites. These models can simulate fairly accurate signals from 80 MHz and above, over rough paths when the obstructions are primarily due to real variations in the topography rather that earth curve. These conditions are consistent with those exist in the U.A.E.
2. Examining the capacity and support for classes of applications of both standards and identifying which standard is more suitable for the U.A.E.'s police forces. In comparing the performance of different standards, we define a "capacity-cost" measure as the maximum traffic carried by the network for a given infrastructure configuration when a standard is implemented over that infrastructure.

1.5. Thesis Contribution

The use of ICS Telecom tool to simulate the capacity and coverage of a realistic wireless communication network can be beneficial in planning and implementing different technologies, therefore, resulting in enormous time and cost savings.

This research has shown that Akmura-Hatta propagation model is more conservative than the ITU 525 model. It also concluded that the TETRAPOL standard has wider area coverage than the TETRA for Abu Dhabi city and that the TETRA standard has a slight capacity cost advantage over the TETRAPOL standard.

Finally, the TETRA standard is shown to be more ideal for applications requiring more capacity whereas TETRAPOL could be more suitable for applications in which capacity is not a major concern.

1.6. Thesis Organization

Chapter 1 presents an introduction to the TETRA and TETRAPOL standards. It also defines the problem under consideration as well as the objectives and scope of this research. Chapter 2 review the technical specifications of the TETRA and TETRAPOL standards.

Chapter 3 discusses a literature review of previous research, while Chapter 4 presents the methodology used to compare the TETRA and TETRAPOL standards.

Chapter 5 presents and discusses the area coverage and capacity simulations and the analyses. Finally, Chapter 6 presents the conclusions of this study and provides some recommendations for future research.

2. TECHNICAL BACKGROUND

2.1. The TETRA

The TETRA is an ETSI standard for the digital land mobile radio designed for the both Public and private networks such as the PMR system and the safety and security organizations. It comprises a variety of features tailored for professional user requirements. It exploits the advantages of the digital transmission and makes best possible use of the radio spectrum through sharing of radio resources among users. Its users have the ability of encompassing trunked, non-trunked and direct mobile-to-mobile communication with a range of facilities including speech, short data messages, circuit mode data, and packet mode data services. TETRA is capable of handling multimedia transmissions and can provide secured, reliable and cost effective means of communication for professional user groups such as police forces and emergency services.

2.1.1. TETRA Network Architecture

The TETRA has no constraints on the form of the radio network architecture. The TETRA standard refers to the infrastructure as the Switching and Management Infrastructure (SwMI). The infrastructure is defined only in terms of six specified interfaces, which are required to ensure interoperability, inter-working and network management [4]. The six interfaces are:

1. Radio Air Interface (I1): It is considered the most important interface as it ensures the interoperability of mobile terminal equipment over the air interface.

2. Line station interface (I2): It connects the TETRA system with the Line Station (LS) over the wire-line connection.
3. Inter-system Interface (I3): It allows for the interconnection of TETRA networks supplied by different manufactures.
4. Terminal equipment interface (I4): It connects the mobile station (MS) and the terminal equipment (TE).

   Terminal equipment interface (I4)': It connects the line station (LS) and the terminal equipment (TE).
5. Network management interface (I5): It supplies the network management equipment inter-working with TETRA system network.
6. Direct mode radio air interface (I6): It allows the mobile stations to communicate with each other directly through a direct mode repeater.

A number of defined system entities can be identified in the functional TETRA network diagram (Figure 2.1):

1. An individual TETRA system 1 comprising base stations (BS), switches, operations and management center and associated control and management facilities.
2. The Mobile Station (MS) comprising the mobile termination unit (MTU) and the associated terminal equipment (TE), which is connected via the defined interface I4. The MS can be classified based on attributes such as its capability for a given mode of operation and power class.

MS receiver classes

The TETRA standard defines the following three receiver classes, distinguishing their intended operating environments and test conditions:

a. Class A equipment is optimum for use in urban areas and in areas with hilly or mountainous terrain.

b. Class B equipment is optimum for use in built-up and urban areas.

c. Class E equipment is intended to meet the more stringent requirements of quasi-synchronous system.

MS transmit power

The TETRA standard has four power classes:

a. Class 1: 30 watt with nominal power of 45 dBm.

b. Class 2: 10 watt with nominal power of 40 dBm.

c. Class 3: 3 watt with nominal power of 35 dBm.

d. Class 4: 1 watt with nominal power of 30 dBm.

3. The line station (LS) comprising the line terminal unit (LTU) and its associated TE, which are connected via the defined interface I4.

4. The central network management unit connected via the defined interface I5. It provides local and remote network management, which is now becoming the standard in a complex network system such as TETRA. This entity manages the fault, configuration, accounting, planning, and performance of the TETRA system.

5. Gateway entity enables the set-up of calls between users of a TETRA network and a non-TETRA network such as Public Switched Telephone Network (PSTN),

ISDN, Packet Data Network (PDN), and Private Telephone Network (PTN). For examples, the gateway component is required when setting-up a call between the analogue PSTN and digital TETRA network since this inter-connection involves signal coding and formats.

6. The MSs communicate with each other directly via a direct mode repeater (DM-REP) using the defined DM air interface I6. They communicate with the TETRTA 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.

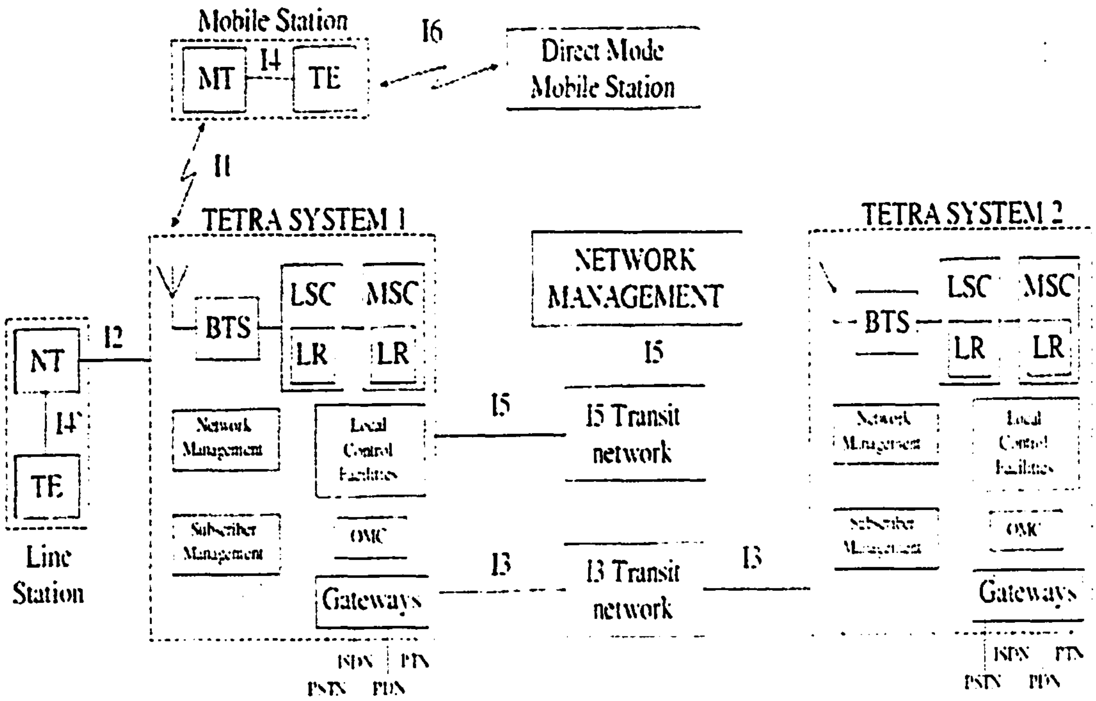

Figure 2.1: The TETRA network architecture with defined interfaces (Source: reference [4])

where,

BTS = Base Transceiver Station,

LSC = Local Switching Centre,

MSC = Main Switching Centre,

LR = Location Register,

OMC = Operations & Maintenance Centre,

PDN = Packet Data Network,

PSTN = Public Switched Telephone Network,

PTN = Private Telephone Network, and

ISDN = Integrated Services Digital Network.

The system entities shown in Figure 2.1 are all within the TETRA domain i.e. they are all in the same address space. The following three choices to expand the basic mode of operation have been specified by TETRA standards:

a. Direct mode repeater MS: to expand the range beyond two DMO mobiles.
b. Dual mode switchable MS: to support both TETRA DMO and trunked TETRA voice + data (V+D) in dual watch mode.
c. Direct mode gateway: to enable a link between TETRA DMO and TETRA V+D.

2.1.2. TETRA Network Functions

TETRA has a number of standard network procedures for call handling, which are required in order to provide an acceptable grade of service to users. These procedures are:

2.1.2.a. Establishing Service

When the mobile system is powered up, a channel acquisition in the TETRA V+D system is activated automatically. In the V+D operation (as opposed to DMO), the user does not need to manually select the channels. The relevant channel is contained in the MS memory or a search is performed to find a channel.

2.1.2.b. Location Registration

The coverage area of a TETRA network is divided into a number of location Areas (LAs). Each LA corresponds to a single cell or a to number of cells depending on the size of the coverage area. In order for a mobile to be called within a particular LA, it must be registered within that LA. Implicit registration is the network functionality that registers the location of the MS without a need for an explicit registration message and this can be performed by any system message that conveys the identity of the MS.

2.1.2.c. Connection Restoration

Connection restoration is one of the TETRA's best network functions. The responsibility for initiating the connection restoration procedures can rest with the BS or with the MS, depending on the situation of propagation effect, traffic load, or other reasons of restoration. For example, the BS may choose to move the MS to another channel on the same serving cell if interference on the uplink is encountered or force it to an adjacent channel if the loading becomes too high on a particular site.

2.1.2.d. Call Re-establishment

The TETRA air interface standard provides a range of re-establishment procedures of different quality that can be implemented by a network operator for subscribing users. The range of procedures varies from a totally unprepared call re-establishment taking typically 15 to 20 seconds during which time the connection is broken, to a seamless handover with unnoticeable break in the service to the user.

2.1.3. Call Set-up Procedures in TETRA

An example of the message sequence for an individual call set-up between MSs under the coverage of the same BS and with no delay in the infrastructure is presented in Figure 2.2 [4].

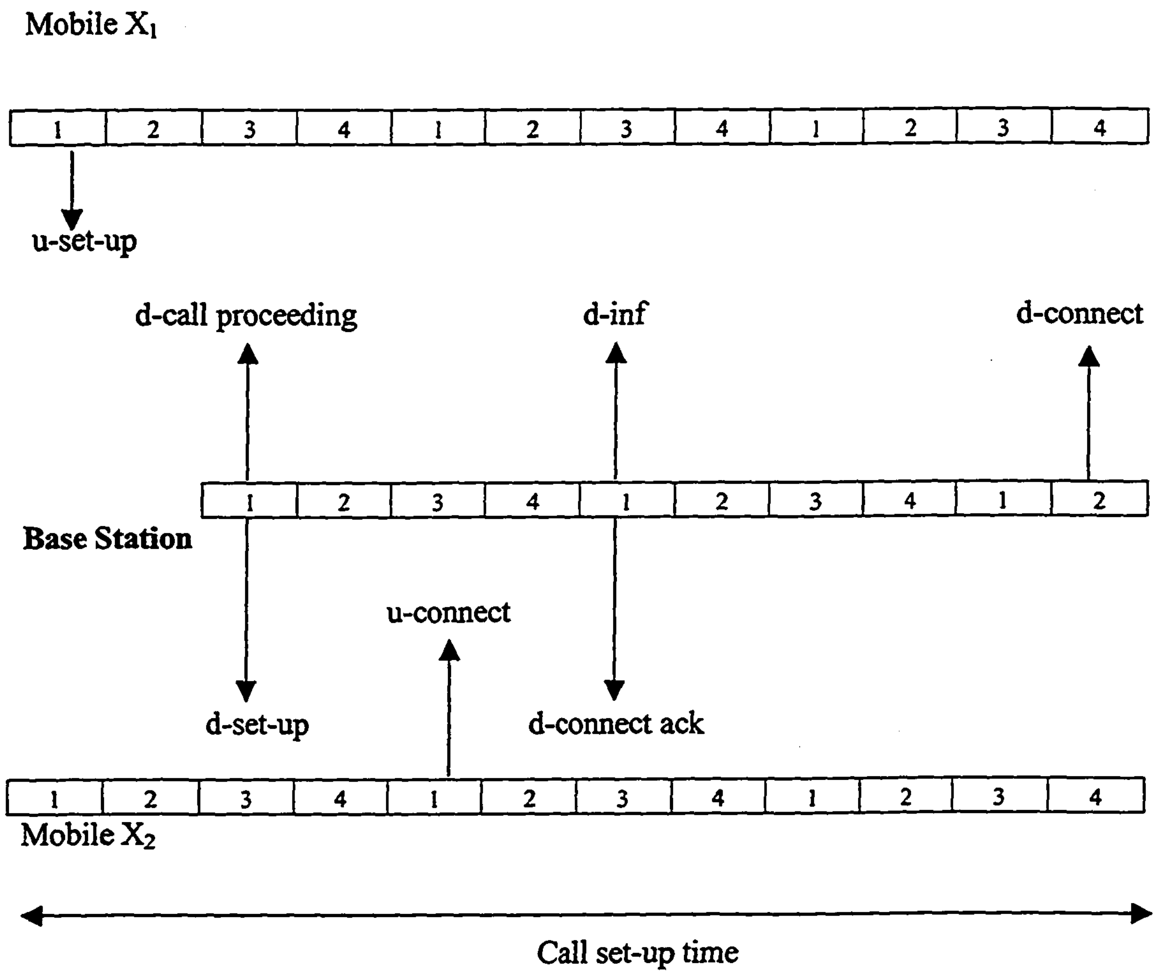

Figure 2.2: Call set-up in TETRA standard (Source: reference [4])

When a calling mobile MS X_1 wants to communicate with another mobile MS X_2 via a BS, the call 'set-up' has a message sequence that starts by X_1 making a random access attempt 'u-set-up' in X_1's time slots. This message must contain sufficient information to establish the service and it is sent in a shape of a single burst. The BS acknowledges the request in its next slot 1 with a 'd-call' proceeding message to X_1 and at the same time pages MS X_2 with a 'd-set-up' message. Both messages; d-call proceeding to X_1 and d-set-up to X_2 have to be from the same BS's next slot 1. The called mobile X_2 then responds with a 'u-connect' message in the subsequent slot 1. Then, the BS assigns a channel by for traffic and at the same time informing X_1 of the response from X_2 with a d-connect message to and acknowledging X_2 with a 'd-connect ack' massage.

2.1.4. Technical Specifications

2.1.4.a. Voice Coding in TETRA

The coding and decoding speech algorithms of TETRA are based on Algebraic Code Exited Linear Predictive (ACELP) coder. The data rate achieved is 4.567 kb/s.

2.1.4.b. Radio Characteristic

- A modulation of $\pi/4$-differential quaternary phase shift keying ($\pi/4$-DQPSK) has been adopted for the TETRA standards. The $\pi/4$-DQPSK modulation technique represents a compromise solution between the conventional or coincident transition QPSK and offset-keyed QPSK (O-PSK) methods. The most advantage of this modulation is that the signal can easily be differentially demodulated. Thus, it has also been adopted for the digital cellular system that is using time division multiple access (TDMA) technology in countries such as Japan and the USA.

- A gross channel rate of 36 kbit/s (18k symbols/s).
- A net channel rate of 2.4 kbit/s for high-protected data, 4.8 kb/s for low protected data, and 7.2 kbit/s for unprotected data.
- Duplex spacing of 10 MHz (45 MHz in 900 MHz band).
- RF carrier spacing of 25 kHz.
- The TETRA V+D has been designed to be work in the frequency range from VHF (150 MHz) to UHF (900 MHz). For public safety users, the recommended frequency range was from 380 MHz to 400 MHz.
- CEPT has made additional recommendations for use in the following frequency bands:

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

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

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

2.1.5. TETRA Frame Structure

The TETRA frame structure consists of four 510-bit time slots per TDMA frame as shown in Figure 2.3 [4]. This is further organized as 18 TDMA frames per multiframe and 60 multiframe per hyperframe, which represent the largest time unit and takes approximately one minute. In circuit mode V+D operation traffic from an 18 frame multi-frame length of time is compressed and conveyed with 17 TDMA frames, thus allowing the 18th frame to be used for control signalling without interrupting the flow of data. Each time slot contains 510 bit periods and since TETRA uses π/4-DQPSK modulation, a modulation symbol has duration of two-255 symbol periods.

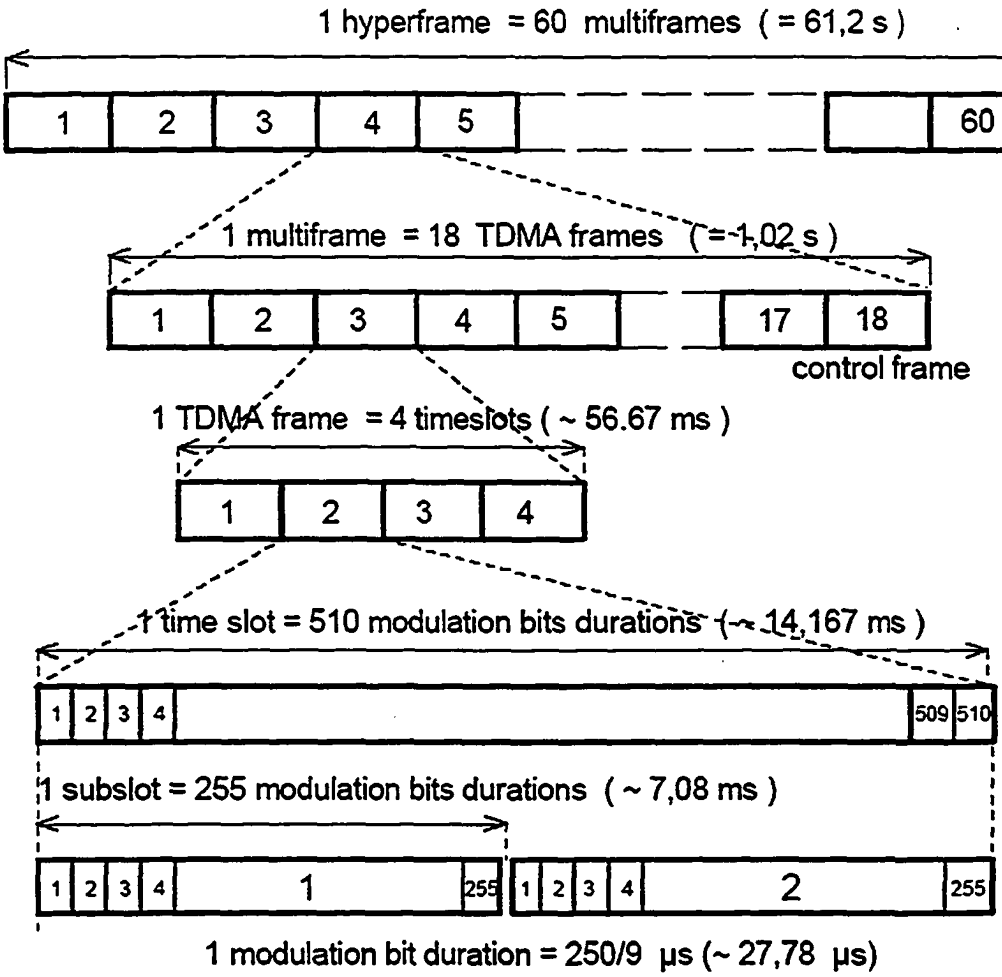

Figure 2.3: TETRA TDMA frame structure (Source: reference [4])

2.1.6. Slot Structure

The TETRA places powerful constraints on the slot structure due to the nature of the anticipated traffic. For example, 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, the downlink transmission capacity is greater than the uplink capacity. The extra downlink capacity has been used to transmit low layer MAC information.

Figure 2.4 presents three basic slot structures, uplink half slots, uplink full slot, and downlink full slot.

2.1.7. Radio Transmission Burst Structure

A transmission burst is a period of RF carrier that is modulated by a data stream. The TETRA protocol standardizes the radio transmission burst structure as shown in Figure 2.4 [4]. From the three basic slot structures in Figure 2.4, the following five basic types of physical bursts can be derived for use by the air interface protocol:

a. Control uplink, which consists of half slots to be used for random and reserved access.

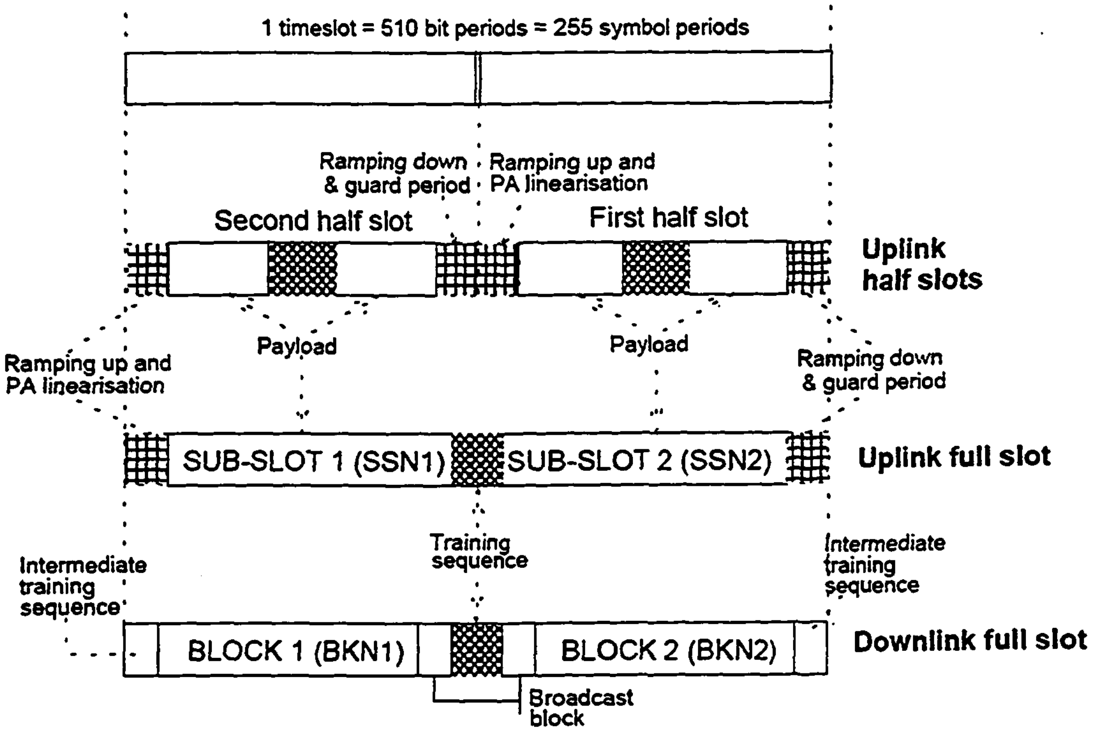

Figure 2.4: Basic slot structure seen at the physical layer (Source: reference [4])

b. Normal uplink, which consists of full slot format to be used by the MSs after their initial access to the system.
c. Linearization uplink.
d. Normal downlink.
e. Synchronization downlink.

Both the normal uplink and downlink bursts contain 216 scrambled bits gross for higher layer information exchange (124 bits net). The broadcast block contains 30 scrambled bits gross (14 information bits net) and is used exclusively for the Access Assignment Channel (AACH). Uplink half slots each convey 168 bits gross (92 information bits net).

2.1.8. Propagation models

The TETRA standard specifies five different propagation models to be used for simulation or radio conformance testing. These models are defined by the number of discrete taps, the relative tap delay, the average relative tap-gain, and the type of applied tap-gain process. The five models are:

2.1.8.a. Static Model

The static model refers to ideal conditions without multipath and for a non-moving MS.

2.1.8.b. Rural area (RAx) Model

This model is typical for flat rural areas where there is often a line-of-sight path, 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.

2.1.8.c. Hilly terrain (HTx) Model

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. It is suitable for class A mobile station environment.

2.1.8.d. Typical Urban (TUx) and Bad Urban (BUx) Models

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. They are suitable for class A, B, and E mobile station environments.

2.1.8.e. Equalizer testing (EQx) model

This model is intended to test class E equipment that employs channel equalization. It represents a severe propagation case, which might be found in a quasi-synchronous system or in mountainous terrain and is relevant for downlink only.

2.1.9. TETRA Data Services in Voice plus Data

TETRA network services follow the ISDN model of groupings as bearer services, teleservices, and supplementary services.

2.1.9.a. Bearer Services in TETRA:

Bearer services are the basic communication facilities provided by the network at layers 1 to 3 of OSI protocol stack. It is concerned with how the data is transported from one point to another irrespective of the type of data being transported. TETRA supports three type of bearer Services:

Short data service

The short data entity supports the MS originated and MS terminated services of user defined and pre-defined reception and transmission for individual and group messages.

Circuit mode data

An end-to-end circuit is established in the circuit mode data services, which can be used unprotected, or has 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. The data rates offered are 7.2, 14.4, 21.6, and 28.8 kbit/s for unprotected data, 4.8, 9.6, 14.4, and 19.2 kbits/s for protected data low, and 2.4, 4.8, 7.2, and 9.6 kbits/s for protected data high.

Packet mode data

The packet mode services are divided in two categories; connection oriented packet data services and connectionless packet data services. The first is a service that transfers X.25 packet 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. The second is a service that 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.

2.1.9.b. Teleservices

Teleservices are those services that are visible for the user from the man-machine interface of the terminal. It is a clear speech or encrypted speech communication with the following categories:

Individual call (point-to-point)

It is a call established between two parties and the calling party receives acknowledgement of the call progress.

Group call (point-to-multipoint)

It is a call established from one user to more than one individual. The call is established immediately and the calling party does not receive acknowledgement from any of the called individuals as to whether or not they are ready to communicate.

Acknowledged group call

It is the same as the group call but the call is not established unless acknowledgement is received from a defined number of the called parties that they are ready to communicate.

Broadcast call (one-way, point-to-multi point)

It is a call from one party to more than one individual. It established immediately and called parties are not permitted to respond.

2.1.9.c. Supplementary Services

Supplementary services are those services, which are used to modify or supplement the basic services. The TETRA standard defines the supplementary services in Annex A: Services supported in 300-1 ETSI Technical report. The following are supplementary services under PMR style capability and telephone style services:

PMR style supplementary capability

- Access priority, pre-emptive priority, and priority call.
- Include call, transfer of control, and late entry.
- Call authorized by dispatcher, ambience listening, and discrete listening.
- Area selection allows the user to choose a geographic area for outgoing individual calls. For incoming call area selection, this restricts the reception of incoming group calls to only those received when the user is in the defined area.
- Short number addressing.
- Talking party identification.
- Dynamic group number assignment.

Telephone style supplementary services

- List search call allows the user to define one or more alternative numbers to which the infrastructure will attempt to route unsuccessful incoming calls.
- 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 probability of having the network connection resources pre-empted network connection resources pre-empted.

2.1.10. Security

The TETRA supports two levels of security:

a. A basic level that employs air interface encryption for users require security level comparable with the fixed telephone network or GSM.
b. A higher level that employs end-to-end encryption for users who are ready to undertake the cost and burden involved with end-to-end key management.

The air interface encryption provides the first line of security for TETRA's users, which protects not only the user data from eavesdropping over air interface but also the user's ID and signalling data of the communicating parties. Similar to the GSM system, the air interface encryption protects just the air interface and not the information passing between the BS and the rest of the infrastructure. In the DMO and class 2 systems, a set of Static Cipher Keys (SCKs) is used to protect traffic in both directions. These keys can be distributed either manually or by a standardized mechanism over the air. The TETRA MoU specifies three different security classes, depending on different categories of authentication, encryption, terminal diabling, and identity inscription. Class 3 system is the most secure and is the choice of large public safety network. It uses four traffic keys encryption:

2.1.10.a. Derived Cipher Keys (DCKs)

The DCKs are derived during the authentication procedure, thus providing an extended implicit authentication during the call, and can be used for encryption of uplink communications.

2.1.10.b. Common Cipher Keys (CCKs)

The CCKs are generated by the SwMI and encrypted and distributed to the MS. These keys are encrypted with the DCK and are competent to be used for encryption of messages, which are directed to a certain Location Area (Murgatroyd, 2003).

2.1.10.c. Group Cipher Keys (GCK)

The GCK are linked to a specific user group. These keys are generated by the SwMI and distributed to the MS of a group. They are used either in their "raw" state or modified by the CCK, for encryption of calls for this user group.

2.1.10.d. Static Cipher Keys (SCK)

The SCK are preset keys, which can be used without prior authentication. They are not changed by an authentication exchange and that is why they are called "static". Alternatively, those who regard their transmission as particularly sensitive, such as security policy, require following traffic keys, which involve end-to-end encryption:

- The traffic encryption keys (TEK) with three editions used in terminal to give key overlap.
- The group encryption keys (GEK) used to protect the TEK during Over The Air Rekeying (OTAR).
- The unique KEK (long life) used to protect the GEK during OTAR.

- The signalling encryption keys (SEK) used optionally for control traffic.

2.1.11. Radio parameters in TETRA

All parameters, which the MSs or BSs may operate, are defined according to a certain numbers in this section.

2.1.11.a. Nominal power for BS

Table 2.1: Nominal power of BS transmitters

Power class	Nominal power per carrier
1 (40 W)	46 dBm
2 (25 W)	44 dBm
3 (15 W)	42 dBm
4 (10 W)	40 dBm
5 (6.3 W)	38 dBm
6 (4 W)	36 dBm
7 (2.5 W)	34 dBm
8 (1.6 W)	32 dBm
9 (1 W)	30 dBm
10 (0.6 W)	28 dBm

2.1.11.b. Nominal power for MS

Table 2.2: Nominal power for MS transmitters

Power class	Nominal power per carrier
1 (30 W)	45 dBm
1L (17.5 W)	42.5 dBm
2 (10 W)	40 dBm
2L (5.6 W)	37.5 dBm
3 (3 W)	35 dBm
3L (1.8 W)	32.5 dBm
4 (1 W)	30 dBm
4L (0.56 W)	27.5 dBm

2.1.11.c. *Maximum adjacent power level*

The level that will not be accessed at the listed frequency offsets from the nominal carrier frequency is presented in Table 2.3.

Table 2.3: Maximum adjacent power levels for frequencies below 700 MHz

Frequency offset	Maximum level for MS power classes 4 and 4L	Maximum level for other power classes
25 kHz	- 55 dBc	- 60 dBc
50 kHz	- 70 dBc	- 70 dBc
75 kHz	- 70 dBc	- 70 dBc

2.1.11.d. *Wideband noise limits*

Table 2.4 presents the wideband noise levels, which should not exceed the stated limits for the nominal power levels and the listed offsets of the nominal carrier frequencies.

Table 2.4: Wideband noise limits for frequencies below 700 MHzs

Frequency offset	Maximum wideband noise level		
	MS Nominal power level $\leq$ 1W (class 4)	MS Nominal power level = 1.8 W or 3 W (class 4)	MS Nominal power level $\geq$ 5.6 W (class 2L) 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 of 5 MHz (10 MHz for frequencies above 520 MHz) whichever is greater.

2.1.11.e. Blocking level

Table 2.5 gives the blocking performance specifications, which must be applied at all frequencies except those at which spurious responses occur.

Table 2.5: Blocking levels of the receiver

Offset from nominal Rx frequency	Level if interfering signal
50 kHz to 100 kHz	- 40 dBm
100 kHz to 200 kHz	- 35 dBm
200 kHz to 500 kHz	- 30 dBm
> 500 kHz	- 25 dBm

2.1.11.f. Dynamic reference sensitivity performance

The minimum required dynamic reference sensitivity performance is specified according to the logical channel, the propagation condition and the receiver class at the dynamic reference sensitivity level. The dynamic reference sensitivity level is -103 dBm for the MS and -106 dBm for the BS.

2.1.11.g. Receiver performance at reference interference ratios

The minimum required reference interference performance (for co-channel, C/Ic, or adjacent channel, C/Ia) is specified according to the logical channel, the propagation condition and the receiver class at the reference interference ratio. For the BS and all types of MS, the reference interference ratio shall be:

- C/Ic = 19 dBm for co-channel interference, and
- C/Ia = - 40 dBm for the MS and C/Ia = -45 dBm for the BS for adjacent channel interference below 700MHz.

- C/Ia = - 40 dBm for adjacent channel interference above 700MHz.

2.1.11.h. Static reference sensitivity performance

The minimum required static reference sensitivity performance is specified according to the logical channel and the receiver class at the static reference sensitivity level. The static reference sensitivity level shall be -112 dBm for the MS and -115 dBm for the BS.

2.1.11.i. Transmitter intermodulation attenuation

The intermodulation attenuation is the ratio between the power level of the wanted signal and the power level of an intermodulation component. It is a measure of the capability of the transmitter to inhibit the generation of signals in its non-linear elements caused by the presence of the useful carrier and an interfering signal reaching the transmitter via its antenna.

The transmitter intermodulation attenuation for any intermodulation component when measured in 30 KHz bandwidth is at least 70 dB for the BS equipment and at least 60 dB for the MS equipment.

2.2. The TETRAPOL

The TETRAPOL is a digital FDMA PMR system. It belongs to the same generation as GSM. It was developed in Europe and has its origins in the opening of propriety standard developed by the French company Matra [5]. The Publicly Available Specifications (PAS) comprise 3000 pages of technical specifications of open interfaces. The documents are managed by the TETRAPOL Forum's technical committee and are written in compliance with the rules defined by ETSI.

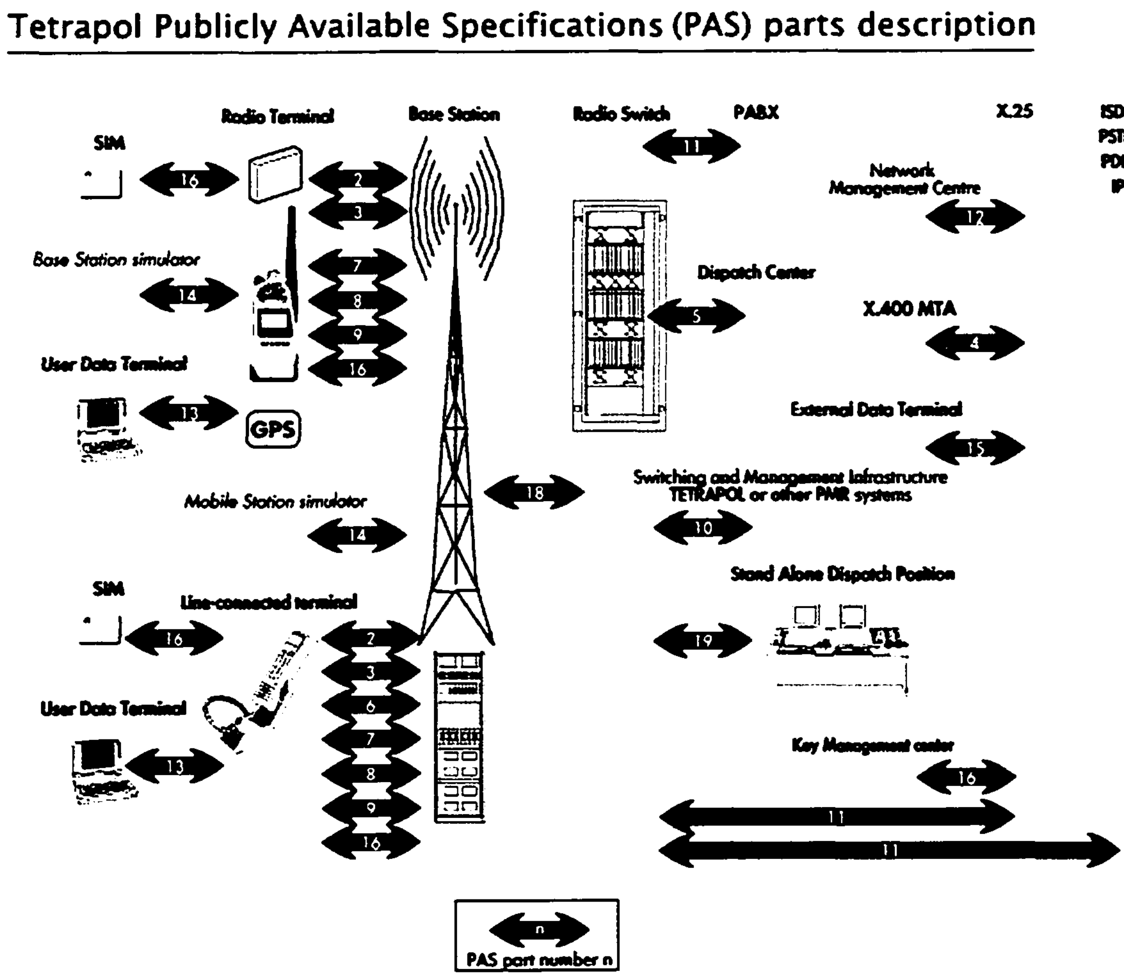

Figure 2.5: The TETRAPOL network reference model (Source: reference [5])

2.2.1. Network structure

The TETRAPOL channel access is based on Frequency Division Multiple Access (FDMA) with channel spacing of 12.5 kHz. The radio transmissions between radio stations and mobile stations are done by duplex channel, which carries two radio links in opposite directions supporting bi-directional transmission. A TETRAPOL BS can handle up to 24 radio channels, one of which supports the Control Channel (CCH). All the clocks of the BS are derived from a unique pilot, in phase on the n channels [5]. The radio terminal acquires the synchronization at physical level: pilot frequency, bit synchronization, and Time Interval synchronization by using the Control Channel, then, it is synchronized on the n downlink channels, and maintains this synchronization on the uplink channels, and when changing between Traffic Channel and CCH.

Since TETRAPOL using FDMA technology, frames are organized in superframes, with a 4 second period (or 200 frames). The MS extracts the superframe synchronization from the CCH, by recognizing the paging channel (PCH) and broadcast channel (BCH) frames. Transmission is organized in Frames of 160 bits, each Frame being transmitted during a 20 ms time Interval (equivalent to 160 modulation symbols) in both directions. Then, the mobile station can transmit during time interval allocated by BS [6]. There are five types of frames in TETRAPOL:

a. Voice Frame: transmitted in 20 ms Time Intervals in both direction uplink and downlink.
b. Data Frame: transmitted in 20 ms Time Intervals in both direction uplink and downlink.
c. Random Access Frames: transmitted in 20 ms Time Intervals in uplink direction only.
d. Training Frame: deterministic frame which shall carry no varying information in uplink direction only.
e. SCH/TI Frames: carry only 5-bit information in downlink direction only.

All MS transmissions in the uplink direction start with a training frame except random access frame. The random access frame is only sent in the uplink direction, at precise time intervals in a superframe defined by the network.

Since TETRAPOL using FDMA technology where each communication channel is given its own frequency, there are two links in opposite directions supporting bi-directional (full duplex) transmissions: the downlink connection, which connects the SwMI to the Station Terminal (ST) and the uplink connection which connects the ST to the SwMI. A multiplex of different logical channels is mapped on each radio channel (traffic Channel or Control Channel) depending on the performed function such as signaling and data, paging, broadcasting, and traffic.

Frames are organized in superframes, with a 4 second period (or a set of 200 consecutive frames). Each radio link of a radio channel is a succession of 160-bit frames transmitted during 20 ms time intervals. Therefore, the gross bit rate is 8 kbit/s (Figure 2.6).

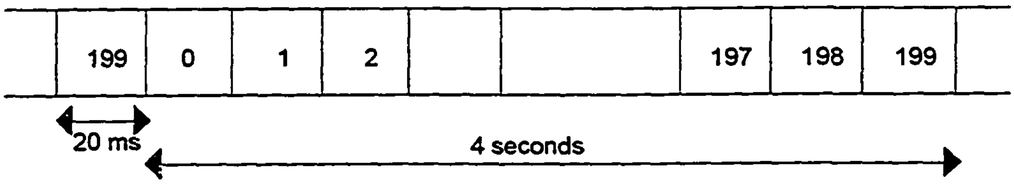

Figure 2.6: TETRAPOL superframe.

2.2.2. Technical Specifications

2.2.2.a. Voice coding in TETRAPOL

Coding and decoding speech algorithms of TETRAPOL are based on the Regular Pulse Code Excited Linear Predictive (RPCELP) technology, which is a very low-based band algorithm CELP. The RPCELP algorithm provides a good communication quality at 6 kb/s even over noisy transmission because it involves only 20 multiply-odds per sample instead of 4000 for a basic CELP scheme [7].

2.2.2.b. *TETRAPOL Modulation*

A binary Gaussian Minimum Shift Keying (GMSK) modulation with gross modulation rate of 8 bit/s has been adopted by the TETRAPOL standard. The GMSK modulation is classified as FM modulation and is related to Minimum Shift Keying (MSK). The GMSK is created from the MSK by applying a Gaussian pulse shape instead of a half sinusoid. It is used in several mobile systems around the world such as the Global system mobile (GSM), Cellular Digital Packet Data (CDPD), Digital Cordless Telephone (DECT). The TETRAPOL standard is a PMR system and does not use a frequency planning and therefore, the bandwidth of its signal must adhere to strict limits. The signal is being constrained within a narrow band by reducing the modulation rate. The carrier rate is limited to 8 kb/s, giving either 0.8 b/s/Hz or 0.64 b/s/Hz. The TETRAPOL signal fits into a 12.5 kHz band completely (adjacent channel interface less than -60 dB to the carrier), and can fit into a 10 kHz band sufficiently well to allow adjacent TETRAPOL carrier to operate (adjacent channel interface less than -42dB to the carrier). Moreover, TETRAPOL system can fit in a 25 kHz band as well. The GMSK is a constant envelope scheme, and so it does not need linear amplification, but it has poor bandwidth efficiency [8].

The TETRAPOL standard uses the GMSK modulation instead of the $\pi/4$-QDPSK used by TETRA. This results in a much less amplitude modulation on the RF carrier. TETRAPOL is closely aligned with the RF modulation techniques used in the worldwide proven technology GSM, which provides a further support to the TETRAPOL as a robust and low-risk option for digital technology. This technique provides a significant benefit in receiver performance at low signal levels, which in turn, results in a wide-coverage footprint design that requires fewer sites to cover a given area.

2.2.2.c. Radio characteristic

- TETRAPOL standard system can operate in 2 bands, Very High Frequency (VHF) version < 150 MHz and Ultra High Frequency (UHF) version > 150 MHz.
- Channel spacing is 12.5 kHz, or 10kHz.
- Without half-channel offset, the recommended duplex frequency 10 MHz for UHF.
- Channel bit rate is 8 kbit/s.
- Radios normally operate in half duplex mode.
- Duplex separation is 5 MHz to 15 MHz.

2.2.3. TETRAPOL Voice and Data Services and Support

TETRAPOL adopted the same names as those chosen in the TETRA standard; thus, TETRAPOL has services and classes of application similar to those in TETRA. It supports voice, data, and supplementary services.

2.2.3.a. Voice teleservices

The teleservices are those services that are visible for the user from the man-machine interface of the terminal. It is a clear speech communication or encrypted speech communication with following categories:

Individual call (point-to-point)

This is a two way communication call established between a calling party and a called party for dispatching or interconnection purposes.

Group call (point-to-multipoint)

This is a call initiated by one user to one or more individuals, which belong to the same group that may be different from the calling party. The call is established immediately and the calling party does not receive acknowledgement from any of the called individuals as to whether or not they are ready to communicate. The normal end of the call corresponds to the on hook of the call owner and resources are made free. Group composition can be modified dynamically; the call may be in clear or encrypted and may be trunked.

Acknowledged group calls

This is the same as the group call but the call is not established unless acknowledgement is received from a defined number of called parties that they are ready to communicate.

Broadcast open channel calls

This is a call from one-way point to multipoint voice and data communication within a selectable predefined area. The selected area and all of the called parties shall be previously defined. There is no acknowledgement of called parties' presence in the communication.

Emergency call and emergency open channel

On a user action, the terminal will send a status. Two options for the operator will then be possible:

- Automatic call set-up of a pre-emptive open channel; or
- Using a pre-emptive priority, a predefined user will establish a call chosen on an operational basis.

Multi-site open channel and multi-site trunked open channel

This is a communication identified by a number, between several terminals located within a predefined area. The open channel is established and released by authorized terminals. Resources may be allocated permanently during the call or trunked between users.

Talk group

This is a point-to-multipoint group addressed communication established within a selectable predefined area. The coverage is associated to the group number and may be different of the total coverage. Resources are allocated all the time. Any concerned user may enter or leave the talk group at any time.

2.2.3.b. Data teleservices

Broadcast without acknowledgment

This service provides one-way point-to-multipoint data communication without acknowledgement.

Short data messaging

This message service will be optimized for a quick service enabling the user to exchange a short user message.

Status transmission

This service allows for sending or broadcasting upward or downward a very short predefined message.

TCP/IP access

This service permits access to fixed networks (such as Internet) and to the corresponding computers conforming to the TCP/IP protocols.

2.2.3.c. Data support services

Circuit data services

This service offers a permanent or switched circuit between 2 terminals or between a terminal and a gateway at a standardised data rate.

Connected packet data service

This service transfers a single packet of data from one BS to one or more radio terminals in a single phase.

Connectionless packet data service

This service offers a X.25 connection between two terminals. It shall also offer an X.25 access to an external PDN or to a computer directly linked with the TETRAPOL network.

2.2.3.d. Data applications

External application messaging

This service offers a communication tool for customer-tailored interactive applications between the network terminals and one or several external computers.

Fast local messaging

This service provides a fast non-acknowledged message transmission.

Interpersonal messaging (X.400)

This service allows a user to send messages to one or several other users. The message transmission will be secured in terms of acknowledgement, non-delivery and storage. The service will also allow sending messages to subscribers of non-compatible interface with other networks.

Paging

This service complements local messaging and allows sending the same type of messages from dispatch positions to classical pagers.

2.2.3.e. Supplementary services

Supplementary services can modify or supplement the basic services. As in TETRA standard, TETRAPOL has the following supplementary services under the PMR style capability and telephone style services:

Access priority

This supplementary service gives specified users preferential access to the system in the event of radio link congestion. Preferential treatment will apply to the uplink access only.

Adaptive area selection

This service allows the selection area to be a function of the radio terminal movement.

Ambience listening

This service enables a dispatch position to place user equipment into a special type of individual call so that the called terminal is transmitting without any action from or indication to the called user. Ambience listening is set-up only if the called terminal is not already engaged in a call.

Area selection

This service allows a user to select on a call-by-call basis a predefined area to be used by the network for call set-up. For a group call or a talk group this means that called users will not be alerted if they are outside of the selected Area.

Automatic call back

This service allows a calling party encountering a busy network to have the call automatically redialled when the network resource(s) becomes free.

Call completion to busy subscriber

This service allows a calling party encountering a busy called party to have the call automatically redialled when the called party becomes free.

Call barring

This service prevents all or certain types of calls or calling identities to be issued or received by a user or a terminal. Barring could also inhibit the use of supplementary services.

Call authorized by dispatcher

This service provides call set-up mode where calls between third parties have to be authorized by dispatcher. This is a call authorization service as intercepted by a dispatcher. Concerning telephony access the dispatcher or the operator can intercept either incoming or outgoing calls and grant authority for the call to be completed. The same service can offer interception between terminals.

Call forwarding

This service enables a call intended for one terminal to be diverted to another terminal.

Calling (/Called) party identification

This service makes it possible to store and/or to display at terminal level calling parties identities at call set-up.

Call-me-back

This service enables a calling party to leave his identity to a called party for a subsequent call back. This voice facility shall operate as a prompt for the party to call back.

Call transfer

This service enables a user to transfer the ongoing call to another user in the System.

Call waiting

This service enables a user to be notified of an incoming voice call while the terminal is already engaged in another call.

Dual watch

This service prompts a terminal in the network mode when it is called in direct mode.

Discreet listening

This supplementary service makes it possible for a Dispatcher to listen to a voice call.

Digital Tone Multi Frequency (DTMF)

This service makes it possible to transmit DTMF signalling to an external network from the keypad of a terminal.

Dynamic Group Number Assignment

This service allows a served user or an authorized user to create, modify and delete a group (Dynamic regrouping/Group merging).

Intrusion

This service allows an authorized user to intervene in an ongoing call.

Include call

This service allows addition of one or more users to an existing communication.

Interconnect access

This service allows connection to other networks like ISDN, PSTN and PABX.

Late entry

This service enables the Network to send, during a group communication, late entry indications related to this call, and shall allow latecomer users to join the ongoing call.

Listening restriction

This service prevents mobiles communicating in a point-to-multipoint call from hearing each other. Only the dispatcher can communicate with them.

List search call

This service allows a user to define a search list. When providing this service the network starts sending the message or the call request to the first address in the list. If the call succeeds no further action is taken, otherwise it is sent to the next address in the list.

This continues until an acknowledgement is received or until the end of the list is reached.

Priority call

This service allows a call to proceed before any other call with lower priority. The priority level can be assigned according to various criteria.

Priority scanning

A user can belong to several groups. In case of concurrent calls, the terminal can switch automatically to the call.

Pre-emptive priority call

This service makes it possible to release the necessary resources if needed to set up the communication.

Short number addressing

This service allows a user (radio or line connected) or an operator to define and use short numbers. These may be stored in the network and the network may do the necessary address conversion.

Shortened numbering

This service allows entering only the last digits at call set-up. The lacking digits are implicitly equal to the calling party ones.

Stroke signal

This service makes it possible for the user, simply by depressing a function key on the terminal, to transmit simultaneously a tone received by all users in the same group.

Talking party identification

This service enables all connected parties of a call/or a dispatcher to be aware of the talking party identity.

2.2.4. TETRAPOL Security

The following security features are implemented in the TETRAPOL system:

Detection of Intrusion

TETRAPOL contains a feature allowing for access control and reporting of incidents to an operator.

End-to-end encryption

The encrypted transmission from sender to receiver is performed without intermediate decryption.

Login/Logout

It is a PIN code procedure executed by the user on the radio terminal.

Mutual authentication (network-terminal)

TETRAPOL protocol provides for a mutual proof of identity between a system terminal and the network based on confidential elements known only to the other party.

Secured key management

It is an encrypted way to record and to transmit keys automatically on the air interface (over the air).

Security fallback modes

These are additions of particular procedures in case of technical incident to ensure security function.

Temporary terminal identity generation

The system generates a subscriber identity after registration.

Terminal disabling

This feature allows for inhibition of radio terminal operation.

Terminal identity control

This feature allows for the verification of existence and consistency of radio terminal parameters.

Total inhibition of radio terminal

This feature allows for the inhibition and erasure of sensible information in the radio terminal.

2.2.5. Transmitter characteristics (Output Power)

Power is defined as the average power, measured in 10kHz over the transmitted bits. The power at which BSs or MSs may operate is specified below.

2.2.5.a. *Nominal power for BS*

The BS transmitter nominal power is shown in Table 2.6 according to its power class. It has to be declared by the manufacturer within a range of +2 dB and –2 dB centred on the power class as defined in Table 2.6.

Table 2.6: Nominal power of BS transmitters

Power class	Nominal power per carrier
1 (25 W)	44 dBm
2 (16 W)	42 dBm
3 (6 W)	38 dBm
4 (2.5 W)	34 dBm
5 (1 W)	30 dBm

2.2.5.b. *Nominal power for MS*

The MS transmitter nominal power is shown in Table 2.7 according to its power class. The power levels needed for adaptive power control should have values starting from the minimum power control level up to the nominal power level corresponding to the class of the particular MS as given in Table 2.7. The MS output power should be able to reduce continuously, down to a minimum level of 19 dBm for power class 1 and 21 dBm for power classes 2 and 3.

Table 2.7: Nominal power of BS transmitters

Power class	Nominal power per carrier
1 (10 W)	40 dBm
2 (2 W)	33 dBm
3 (1 W)	30 dBm

2.2.5.c. *Maximum adjacent power level*

Table 2.8 gives the power levels, which should not be exceeded at the listed frequency offsets from the actual carrier frequency.

Table 2.8: Maximum adjacent power levels

Frequency offset	Maximum level	
	P = 10 kHz	P = 12.5 kHz
P	-36 dBc	- 60 dBc
2 x p	- 60 dBc	- 70 dBc

2.2.5.d. *Wideband noise limits*

Table 2.9 gives the wideband noise levels, which should not exceed the limits at frequencies corresponding to the listed offsets from the nominal carrier frequency.

Table 2.9: Wideband noise limits

Frequency offset	Maximum level	
	MS	BS
25 kHz – 40 kHz	- 70 dBc	- 70 dBc
40 kHz – 100 kHz	- 75 dBc	- 75 dBc
100 kHz – 150 kHz	- 85 dBc	- 85 dBc
150 kHz – 500 kHz	- 90 dBc	- 95 dBc
500 kHz – 10 MHz	- 100 dBc	- 105 dBc
10 MHz and in the receive band	- 80 dBc	- 100 dBc

2.2.5.e. *Dynamic reference sensitivity performance*

The minimum required dynamic reference sensitivity performance is specified according to the propagation condition at the dynamic reference sensitivity level. The dynamic reference sensitivity level shall be - 111 dBm for the MS and - 113 dBm for the BS.

2.2.5.f. Reference interference performance

The minimum required reference interference performance (for co-channel, C/Ic, or adjacent channel, C/Ia) is specified according to the propagation condition at the reference interference ratio. The dynamic reference interference ratio for the BS and all types of MS are:

- C/Ic = 15 dB for co-channel interference, and
- C/Ia = - 45 dB (for p=12.5 kHz) for adjacent channel interference.

2.2.5.g. Static reference sensitivity performance

The static reference sensitivity level is - 119 dBm for the MS and - 121 dBm for the BS.

2.3. Advantages of TETRA services and support over TETRAPOL

All basic services are supported on TETRA and TETRAPOL but there are different supplementary services in each standard. The TETRA provides for call retention. That is that during the busy period, in progress high priority calls could be pre-emptively disconnected during the emergency call. This service is not supported in TETRAPOL.

2.4. Advantages of TETRAPOL services and support over TETRA

The TETRAPOL supports the following services while TETRA does not:

Adaptive area selection

This service allows the selection area to be a function of a mobile terminal movement. It is provided as a function of site registration and deregistration as a mobile terminal is roaming from one to another.

Listening restriction

This service prevents the mobile terminal in a group call from listening to each other. The dispatcher is the only user who can communicate with the group during this restriction.

Priority scanning

This service allows a radio user to scan a number if groups. In case of concurrent group calls, the terminal switches automatically to the priority group.

Digital tone Multi-frequency

The radio terminal can transmit a DTMF signal for telephone interconnecting to the PABX or PSTN using the digital tone multi-frequency. It is unlikely that DTMF signalling will be digitally encoded and decoded using CODEC. Instead, the digital signalling from the radio terminals is likely to be converted at central network equipment into DTMF for telephone interconnecting purposes after being used.

Multiparty call

This service allows the user to set-up a call to several radio terminals, either by entering numeric keypad or by predefined user list. This can be done for TETRA but requires a pre-programmed group call for the radio terminal or by a quest from the dispatcher officer.

3. LITERATURE REVIEW

In [2], Riesen discussed the use of mainstream technologies for Public Safety and Security (PSS) networks. He compared the functionalities of the two ETSI-standardized standards, TETRA and GSM with ASCI, by using hierarchical process consisting of a technical and economic comparisons depending on multiple criteria decision-making [9]. For technical comparison, the analyses focused on the functionality of the group calls. Each analysis has a different issue based on the air interface specifications and points out whether or not certain functionalities are supported by the technology. The capacity requirements have been calculated based on a typical user profile and a countrywide network for Germany. The technical analysis also discussed how the end-users and the network operators perceive the different functionalities. The analysis was divided into three parts:

1. The network functions which reflect the available services for the end user, including dispatchers and mobile users such as the dynamic group number allocation (DGNA), short data messaging, and call priorities. The normalized sum of the weighted grades of the network functionalities was 0.675 for the TETRA as compared to 0.168 for the GSM ASCI.
2. The factors that affect the network capacity such as cell size, shifting area group and the requirement of calls and the end-users for call set-up time. The normalized sum of the weighted grades of the network capacity was 0.541 for the TETRA as compared to 0.225 for the GSM ASCI.
3. Network security consisting of authentication, air interface encryption, and end-to-end encryption. The normalized sum of the weighted grades of the network

security was 0.476 for the TETRA as compared to 0.262 for the GSM ASCI. The normalized sum of the weighted grades of all technical analyses was 0.569 for the TETRA as compared to 0.217 for the GSM ASCI.

On the other hand, the economic analysis took into consideration the network's capital expenses, operating expenses, and the technology risk of each solution. The CAPEX compared the network infrastructure and end-user equipment for the TETRA and GSM ASCI. The normalized sum of the weighted grade was 0.343 for the TETRA as compared to 0.286 for the GSM ASCI.

The OPEX compared frequency licenses, transmission, site cost, and operating and maintenance and found out that the normalized sum of the weighted grades was 0.462 for the TETRA as compared to 0.264 for the GSM ASCI.

The risk was taken into consideration by evaluating the network infrastructure, mobile terminals, and dispatching stations. The normalized sum of the weighted grades of the network risk was 0.517 for the TETRA as compared to 0.242 for the GSM ASCI. The normalized sum of the weighted grades of the economic analysis was 0.425 for the TETRA as compared to 0.268 for the GSM ASCI. Finally, The normalized sum of the weighted grades for the technical and economic analyses was 0.497 for the TETRA as compared to 0.243 for the GSM ASCI.

The study concluded the TETRA standard has showed stronger performance than the GSM standard in almost all areas. The main reason could be seen not only in the technical maturity of the TETRA standard, but also in the capacity requirements which are based on TETRA's low bandwidth, large cells, shifting area group call, and fast call set-up times [2]. Although shifting group calls and fast call set-up times are possible for

GSM ASCI, they would require major changes in the core network infrastructure, which are unlikely to be implemented in commercial GSM networks.

Some European countries, such as Britain, Finland, Belgian, and the Nederland have chosen the TETRA standard for their public safety networks. Others, such as France, Spain, Switzerland, and Eastern Europe, have chosen the TETRAPOL standard. Germany, Norway, and Sweden, however, have not yet decided which standard they would choose. In [10], Clemons reported that the GSM did not fulfil the essential user requirements and therefore, it is suitable to be used as a public safety and security network. The study looked at the TETRA and TETRAPOL standards as alternatives to the GSM and compared their grade of service according to the user requirements and the standard supporting and developing view. It concluded that TETRA was the best choice since it is the first-generation hierarchical solution and expected to be replaced by a more flexible and cost effective IP-based solutions.

Different organizations such as the Police forces, armed forces, and the fire brigades, need to communicate fast, efficiently, and securely to ensure the security of their citizens. Digital communication systems such as TETRA and TETRAPOL are capable of providing these services. Therefore, most of the European countries have adopted digital systems for their PSS networks. Only Albania and Germany are still using the analogue radio networks. Major problems with using the analogue networks are that criminals can bug the conversations through these networks and that spare parts of these systems became rare and expensive.

In [3], Bretschneider compared four types of requirements among the TETRA, TETRAPOL and GSM/UMTS. First, the radio coverage, cell change and handover, capacity, quality of speech, and pre-emption. Secondly is a service requirement, which includes group call, direct call, telephone call, emergency call, and encryption. Thirdly is the gateway requirement such as Gateways to other radio networks with the same technique, Gateways to other radio networks with a different technique, Gateways to public telephone networks, Gateway to data networks, and Gateways between analogue and digital networks. Finally is the organizational requirement for uniform network, independent network, property and legal form of carrier, controlling, and frequencies.

Bretschneider concluded that the TETRA and TETRAPOL standards have fulfilled the requirements almost equally but the GSMASCI standard did not support same functionality supported by the two digital standards such as long call set-up time, limited group call, and no gateway to analogue network [3]. Although the TETRA standard was already developed and is more commonly used while the development of TETRAPOL was still underway, the economic considerations concluded that TETRAPOL was the least expensive alternative mostly because fewer BSs are needed. The study recommended that TETRAPOL was the favourable standard for a digital PSS network in Germany.

In [11], Stelacon investigated the functional and financial requirements of alternative communication technologies for the Swedish police force. Specifically, the study investigated the extent of public safety requirements that can be met by the different technologies using a joint radio network. In cases where specified user requirements were not met, the investigation examined the possibility and time required to develop the processes of fulfilling these requirements. If these requirements could not be met, alternative requirement levels have been suggested. The investigation was limited to those mobile telephone network technologies that were already in use and the different types of technologies, which could be adopted for future development. The study is divided into three main parts:

1. General questions presented the importance of the possibility of the implementation of TETRA standard in the public safety functions and customer groups.
2. Functional analysis, which explained each of the alternative technologies that were dealt with in their own right. A clarification is given of both the ability of the technologies to meet the requirements made by the user and the functionalities, which the alternative technologies can achieve.
3. Financial analysis, which contained a model for the analysis using a range of different scenarios along with the associated limitations and assumptions. For each technology cost, calculations were based on the specifically presented scenarios. Finally, a sensitivity analysis was carried out to identify uncertainties and the extent to which the investment cost has been estimated.

The study used a questionnaire to identify the frame of reference for the user and functionality requirements by interviewing the user representatives including the Swedish police force, the local councils association and the emergency services in Sweden. Then interviews with five system manufacturers, seven telecommunication operators and a service supplier using the preliminary results of the RFI, were conducted. Civil servants at the Ministry of Industry, Employment and Communications were consulted to choose the mentioned system manufacturers and telecommunication operators based on operators, system manufacturers and service suppliers currently active in the Swedish market.

The companies interviewed were also asked to provide written answers to whether or not the current technology meets present and/or future user requirements. They were also asked to provide estimates to the cost of development and implementation of different technologies. The documents required for the financial analysis were collected at the same time of the initial interviews, written answers to questionnaires and follow-up interviews and the financial analysis was adapted to reflect the financial information supplied.

The study concluded that until to-date, none of the available technologies has fulfilled all the functionality requirements; just basic requirements were only partially met. Furthermore, due to the inter-dependency between the operators and the system manufacturers, equipment of new technologies has to be standardized. The equipment standardization and development require a long period of time, and therefore, operators would have a little or no interest to investigate and implement the functionalities of the public network.

The City of Waco, Texas undertook another study in which two important goals have been identified in its master plan.

1. To provide a proactive and efficient network of wireless infrastructure to its residents and businesses.
2. To provide a system of wireless support structures that meet location, site, and design guidelines.

To achieve these two goals, the city identified the following steps:

a. Need collocation on wireless communication structures as a means to reduce the large number of towers.

b. Assign acceptable sites for future locations of wireless support structures, thus minimizing the number of facilities and acquiring the maximum number of carriers per facility.

c. Minimizing visual obtrusions by discourage wireless communication structures in residential neighborhoods and other visually sensitive areas to the extent necessary.

d. Assuring compatibility with surrounding land uses by screen wireless communication structures at the ground level.

e. Encouraging and supporting the development of an advanced wireless service infrastructure in the city.

The process of developing the plan required four phases:

1. Tower inventory:

   Have a mobilized team of site development professionals to help the city staff in listing the existing tower inventory and locations and enter this information in the Geographic Information System (GIS).

2. Analyzing collocation availability:

   Identifying the sites via visual inspection including the apparent structural suitability, ground space availability, and the availability of space for additional carrier antennas and equipment.

3. Analyzing coverage deficiency:

   A 2-mile radius of coverage for each existing antenna or tower was used to identify the current coverage areas. Potential coverage deficiencies were identified as those areas without carrier coverage that lack of collectable towers.

4. Identifying the possibility of future wireless tower locations.

In [12], Chapman compared the TETRA and TETRAPOL standards using different simulations under specific scenarios. They evaluated the traffic performance of both standards by means of stochastic simulation using a prototypic implementation of the German public safety organizations such as the police forces, fire brigades, and customs. They compared the TETRA and TETRAPOL standards and their protocol stacks at the air interface and concluded that they were very similar. They also provided technical data consisting of type of modulation and gross modulation rate in each of standard. The simulation was based on creating a mobile station and a base stations, then assigns traffic generators to create a specific traffic loads at the individual mobile stations depending on the ten different scenarios defined for the comparison of the TETRA standard in RES06 [13].

For performance analysis, the study chose scenario 10 with error free transmission since it defines the maximum offered load per terminal and discusses the parameters of public and private networks such as police, customs, and fire bridges. The simulation concept used the following principles:

1. The protocol stacks of the trunked radio systems have been specified with the help of Formal Description Techniques (FDT), to guarantee syntactically and semantically unambiguous formal descriptions of the communication protocols and to ensure the interoperable and compatible implementations of communication protocols independent of their implementers.
2. The mobile and BS protocol stacks has been embedded in the C++ simulation environment.

3. The C++ implementations are based on the SDL Performance Evaluation Tool Class Library (SPEETCL), which provides generic C++ classes as well as a simulation library with strength in the random number generation, statistics evaluation, and event-driven simulation control models.

To conduct the simulation, a communication between the mobile and BS has been established in both ways, uplink and downlink, by exchanging bursts and different types of application such as speech, video, FTP, and WAP. Because of the limited signalling capacity on the TETRAPOL Random Access Channel (RACH), a configuration with 2 signalling and 22 traffic channels has been chosen for the performance analysis. The performance measurement, which is the duration between the creation of connection set-up request and the reception of the acknowledgment of a successful connection set-up set by the BS, was recorded for both the TETRA and TETRAPOL standards. The probability of a connection set-up time exceeding 300 ms in the TETRA standard is between 0.07 and 0.30, depending on the traffic load offered. The TETRAPOL connection set-up time is mainly determined by the RACH access delay, which can be reduced by assigning more control channels. The probability of a connection set-up time exceeding 300 ms in the TETRAPOL standard is about 0.90. The connection set-up time in both systems has met the ETSI requirements of 4 or less. The study recommended that further research is needed to evaluate the performance of the TETRA and TETRAPOL standards under different traffic load conditions without error free transmission.

4. METHODOLOGY

4.1. Comparison of TETRA and TETRAPOL

The area coverage and system capacity of the TETRA and TETRAPOL standards were compared to examine their suitability for replacing the MPT 1327 analogue system currently being used by the police force at the U.A.E. The coverage area was simulated under two scenarios for each standard. For the two scenarios of each of TETRA and TETRAPOL, one scenario assumed the Omni directional antenna with gain of 2 dBi from Katherine Company while the other assumed the three directional antennas with gain of 11 dBi, also from Katherine Company. Figure 4.1 presents a satellite image of Abu Dhabi city with 10m resolution and Figure 4.2 shows the clutters in the city, also with 10m resolutions. The height of the receiving antenna is 1.5m. The coverage area in the City of Abu Dhabi, U.A.E. was simulated under each scenario using two propagation models from the ICS Telecom software. These models are the ITU 525 and the Akamura-Hatta propagation models. The ICS tool was selected for the following reasons:

1. It is comprehensive in terms of the calculation of propagation models for 3D terrain maps.
2. It is widely used by wireless planners around the world, which means that its accuracy has been verified.
3. It is commercially available and is well supported by the vendor.

Figure 4.1: Satellite Image of Abu Dhabi city with 10m resolution

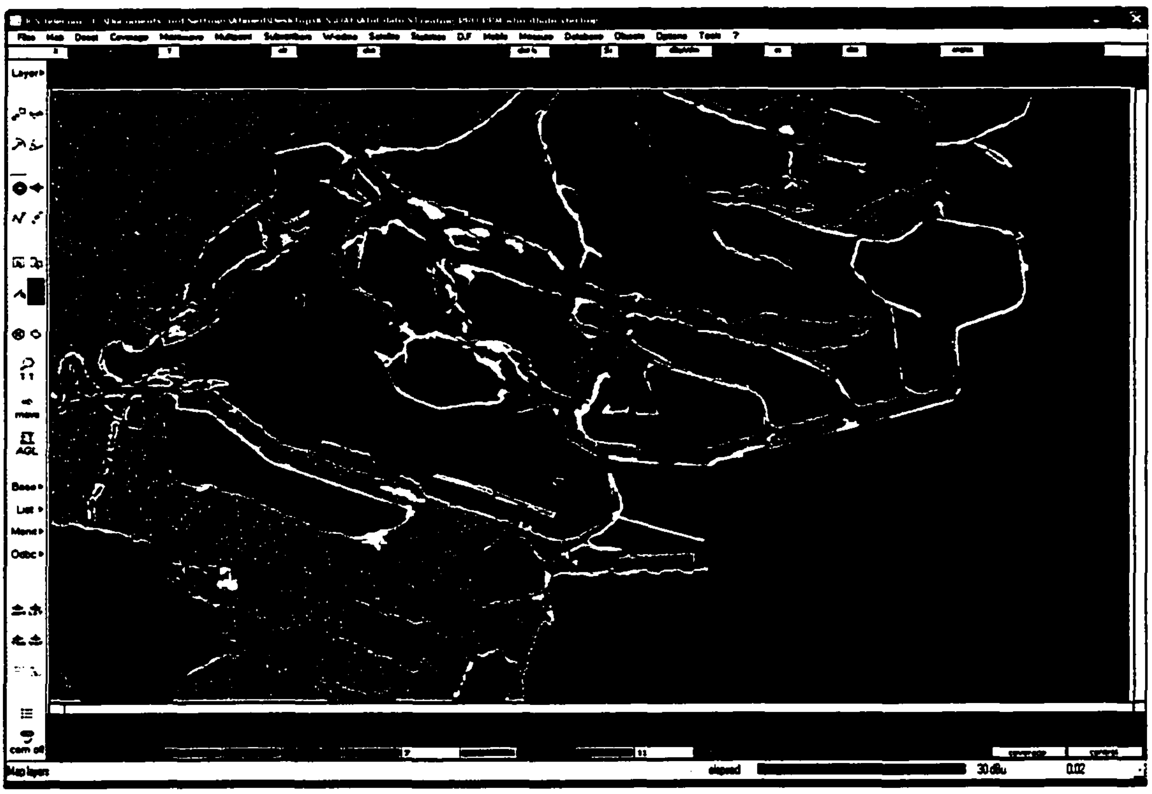

Figure 4.2: Clutter with 10m resolution

Clutter code	Name
0	rural
1	suburban
2	urban 8 m
3	urban 15 m
4	urban 30 m
5	forest
6	hydro
7	urban 50 m
8	wood
9	road or roof
10	user 1

Figure 4.3: Clutter code legend for areas

Two sets of parameters were considered in these simulations, constant parameters and variable parameters. The values of these parameters used in this thesis are given in Tables 4.1 and 4.2 respectively. The parameters used in each scenario are listed in the corresponding section dealing with that scenario. The coverage analysis examines the percentage of the same area to be covered by each of these standards under a specific scenario. The output of each simulation produces a coverage map and a table giving the coverage area and its percentage in the total assumed area.

Table 4.1: Constant parameters for the TETRA and TETRAPOL

Station parameters	TETRAPOL	TETRA
Units Nominal power	50.00 Watts	40.00 Watts
Tx losses	4.75dB	4.75dB
Rx losses	4.75 dB	4.75 dB
Frequency	400.00 MHz	400.00 MHz
Bandwidth	12.5 KHz	25 KHz
Rx bandwidth	12.5 KHz	25 KHz
Height of antenna	30.00-90.00 m	30.00-90.00 m
Antenna aperture	0.00 °	0.00 °
Azimuth	0.00 °	0.00 °
Tilt	0.00 °	0.00 °
Polarization (Tx)	V	V
Polarization (Rx)	V	V

Table 4.2: Variable parameters for the TETRA and TETRAPOL

	TETRAPOL	**TETRA**
Tx gain	2.0 and 11.0 dBi	2.0 and 11.0 dBi
Rx gain	2.0 and 11.0 dBi	2.0 and 11.0 dBi
Radiated power	219.77 & 27.67 W	175.81 & 22.13 W

The Flow Chart in Figure 4.4 explains the process of the coverage simulation. Finally, the capacity analysis uses the Erlang C method to evaluate the grade of services (GOS) offered by each standard was undertaken.

4.2. The Simulation Tool

ICS Telecom is software dedicated to all kind of radio-planning simulations. ICS Telecom is used to simulate, validate and analyze broadcast (FM, TV, DVB...), Point-to-Multipoint (LMDS, DECT...), mobile (GSM, Tetra...) and Point-to-Point (Microwave links) networks.

ICS software systems design to meet the planning and administration requirements of civilian and military radio networks. These various tools can be used both as operational mobile tools in the field and for analysis purposes. It runs under Microsoft Windows and designed to operate in frequency range between 10 kHz and 450 GHz. The software supports all the needs of Radio Engineers in the field of radio network design, spectrum administration, and cartographic data management. It has an electromagnetic compatibility (EMC) calculation module which is a computer-based tool used to produce accurate calculations.

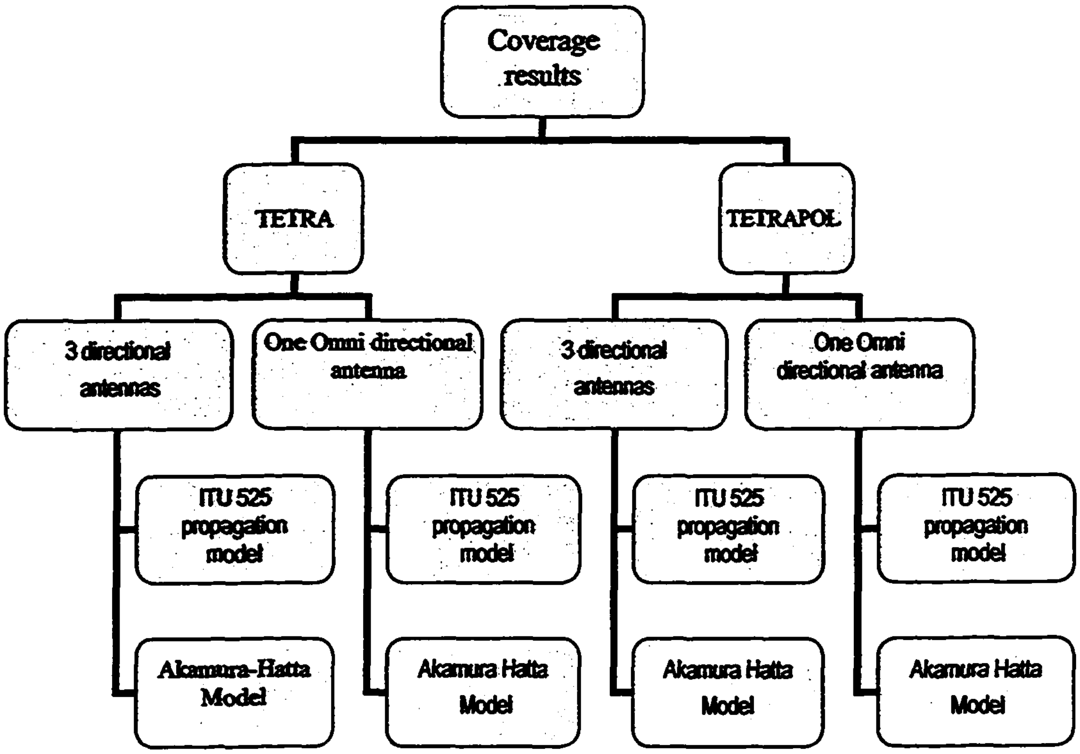

Figure 4.4: The TETRAPOL and TETRA coverage simulation process

There are several categories of propagation models available in the ICS Telecom, which can be divided into geometrical models, statistical models and mixed models. Two of these models are selected to simulate the coverage using Abu Dhabi City:

1. The ITU525 Geometrical (or deterministic) model to simulate the coverage using the Deygout Method for multiple knife-edge diffraction. Standard free space attenuation is used when the ITU525 model is selected.
2. A statistical model to simulate the coverage using Akamura-Hatta method, which is suitable for distances between 1 km and 100 km, mostly for urban or suburban areas. This model is recommended, particularly for mobiles, using frequencies between 150 MHz and 1,500 MHz.

The ICS tool supports the mathematical formulas currently used by Industry Canada to perform the EMC calculations. The propagation models used in the ICS Telecom follow the technical conventions discussed below.

4.2.1. Path radio calculation mode for propagation

The path radio calculation mode for propagation is used in the ICS Telecom software simulation. This mode takes into account the modelling steps that contribute to field strength or power received calculation. In the path radio mode, it is possible to compute either the field strength at the receiving antenna location Rx or the power received.

4.2.2. Calculation of the field strength

The field strength is computed from the basic field strength propagation equation:

$$F_{rec} = P_{rad} + R - L_{prop} \qquad (4.1)$$

where

F_{rec} = received field at the antenna R_x location,

P_{rad} = radiated power by the transmitter T_x,

L_{prop} = propagation loss, and

R = field strength offset due to the electromagnetic impedance of vacuum (=120π Ω).

$$R = 10\log(120\pi/4\pi) = 10\log(30) = 14.8 \text{ dB} \tag{4.2}$$

The quantity

$$R' = R + 60 = 74.8 \text{ dB} \tag{4.3}$$

is more frequently used in order to express distances in km and field in dBμV/m (in L_{prop}). The radiated power can be expressed as:

$$P_{rad} = P_{Tx} + G_{Txma} - D_{Txoa} - L_{Tx} \tag{4.4}$$

Where,

P_{Tx} = Tx nominal power,

G_{Txma} = Tx main axis antenna gain,

D_{Txoa} = Tx off-axis pattern loss, and

L_{Tx} = Tx internal losses.

The propagation loss is given by:

$$L_{prop} = L_{fsd} + L_d + L_{sp} + L_{gas} + L_{rain} + L_{clut} + L_{model} \tag{4.5}$$

Where,

L_{fsd} = free space distance loss,

L_d = diffraction loss,

L_{sp} = sub path loss,

L_{gas} = attenuation caused by atmospheric gas,

L_{rain} = attenuation caused by hydrometeor scatter,

L_{clut} = clutter attenuation, and

L_{model} = specific unclassified attenuation deriving from model selection in the model dialog box.

4.2.3. Calculation of the received power

For the calculation of the power received, the above mentioned field strength offset R must be replaced by the power received offset C minus the free space frequency loss term Φ defined by:

$$C = -20 \log(4\pi/c) = +147.6 \text{ dB} \tag{4.6}$$

and

$$\Phi = 20 \log(f) \tag{4.7}$$

where C is the propagation speed of electromagnetic energy and f is the frequency. In order to introduce distances in km and frequencies in MHz, the offset C is often replaced by

$$C' = C - 180 = -32.4 \text{ dB} \tag{4.8}$$

In addition, the Rx antenna gain must be added so that the basic power propagation equation reads so that

$$P_{rec} = P_{rad} + C - \Phi - L_{prop} + G_{Rx} \tag{4.9}$$

Substituting from Equation (4.1) into Equation (4.9),

$$P_{rec} = F_{rec} + C - R - \Phi + G_{Rx} \tag{4.10}$$

Which is a conversion filter from field strength to power received. Similar to the Tx antenna gain, the Rx antenna gain can be subdivided into:

$$G_{Rx} = G_{Rxma} - D_{Rxoa} - L_{Rx} \tag{4.11}$$

Where,

G_{Rxma} = Rx main axis antenna gain,

D_{Rxoa} = Rx off-axis pattern loss, and

L_{Rx} = Rx internal losses.

4.2.4. Basic transmission loss conversion formulas

Many propagation formulas in the literature (e.g. ITU recommendations) are expressed through the basic transmission loss L_b. Since L_b is different from L_{prop}, a specific care must be given to the integration and interpretation. In fact, the received power P_{rec} is the sum of every loss component except P_{rad} and G_{Rx}, i.e.

$$P_{rec} = P_{rad} - L_b + G_{Rx} \tag{4.12}$$

Substituting from Equation (4.12) into Equations (4.9) and (4.10) respectively,

$$L_b = -C + L_{prop} + \Phi \tag{4.13}$$

and

$$F_{rec} = P_{rad} + R - L_b - C + \Phi. \tag{4.14}$$

5. ANALYSIS OF TETRA AND TETRAPOL STANDARDS

5.1. TETRAPOL Area Coverage Simulations

Simulation of the area covered in Abu Dhabi city. U.A.E., using TETRAPOL standard was undertaken for two different scenarios. Both scenarios use the fixed and variable parameters given in second column of Tables 4.1 and 4.2. The ITU 525 and Akamura-Hatta propagation models were used to simulate the area coverage and the output of each simulation was presented.

5.1.1. Scenario #1 (Omni directional antenna)

The parameters used in the TETRAPOL's simulations #1 and #2 are given in Table 5.1 below.

Table 5.1: Station parameters used in simulations #1 and #2

Station parameters	
Units Nominal power	50.00 Watts
Tx gain	2.0 dBi
Rx gain	2.0 dBi
Tx losses	4.75dB
Tx losses (additional)	0.00 dB
Rx losses	4.75 dB
Radiated power	27.67 Watts
Frequency	400.00 MHz
Bandwidth	12.5 KHz
Rx bandwidth	12.5 KHz
Height of antenna	30.00-90.00 m
Antenna aperture	0.00 °
Azimuth	0.00 °
Tilt	0.000 °
Polarization (Tx)	V
Polarization (Rx)	V
Polar discrimination	0.00 dB
KTBF	-130 dBm
Noise floor	-131 dBm
Dynamic receiver sensitivity BS	-113 dBm

5.1.1.a. Simulation #1 (Using the ITU 525 simulation model)

The area assumed for the simulation in Abu Dhabi city is shown in Figure 5.1. The ITU 525 model was used to simulate the coverage area and percentage using the parameters specified in Table 5.1. The colour code legend is given in Figure 5.2.

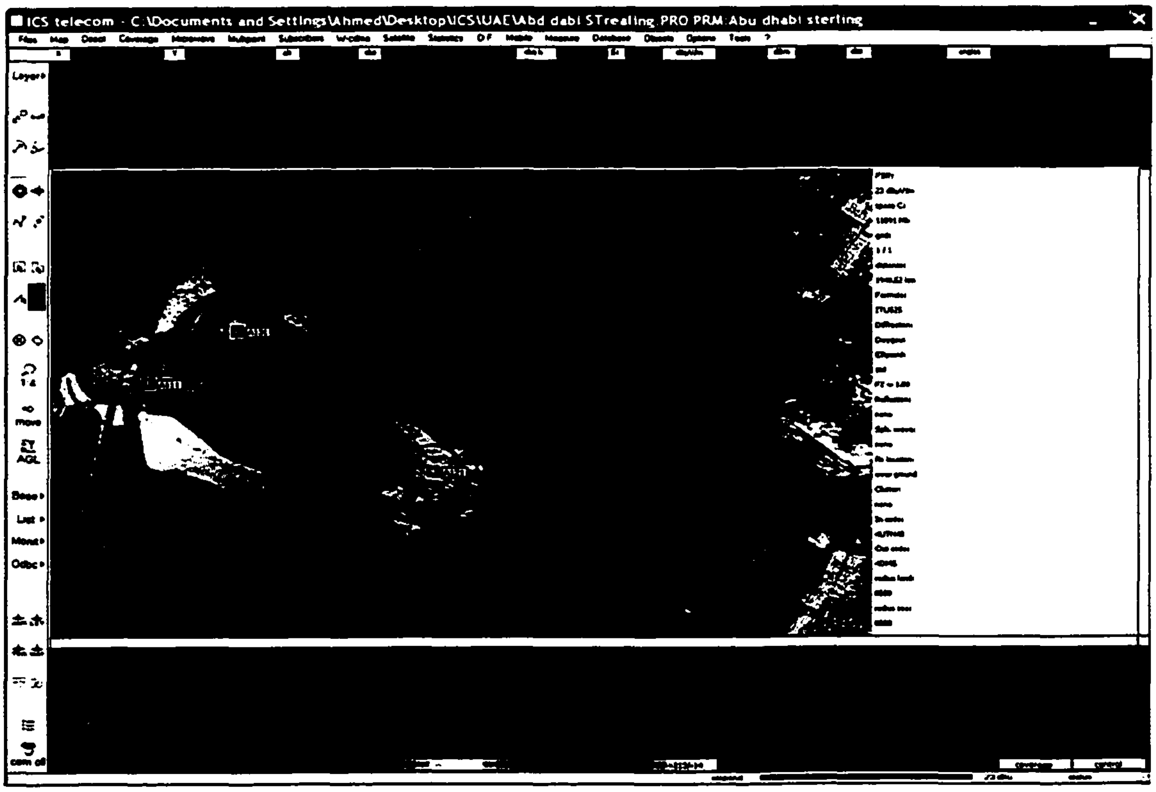

Figure 5.1: Area covered in simulation #1 – TETRAPOL omni directional antenna – ITU 525 Model

The simulation output in Table 5.2 gives the covered area and its percentage in the total area assumed for the simulation. These are:

Table 5.2: Output of simulation #1

Area covered (%)	97.8529
Area covered (km^2)	897.8940
Total area (km^2)	917.5959

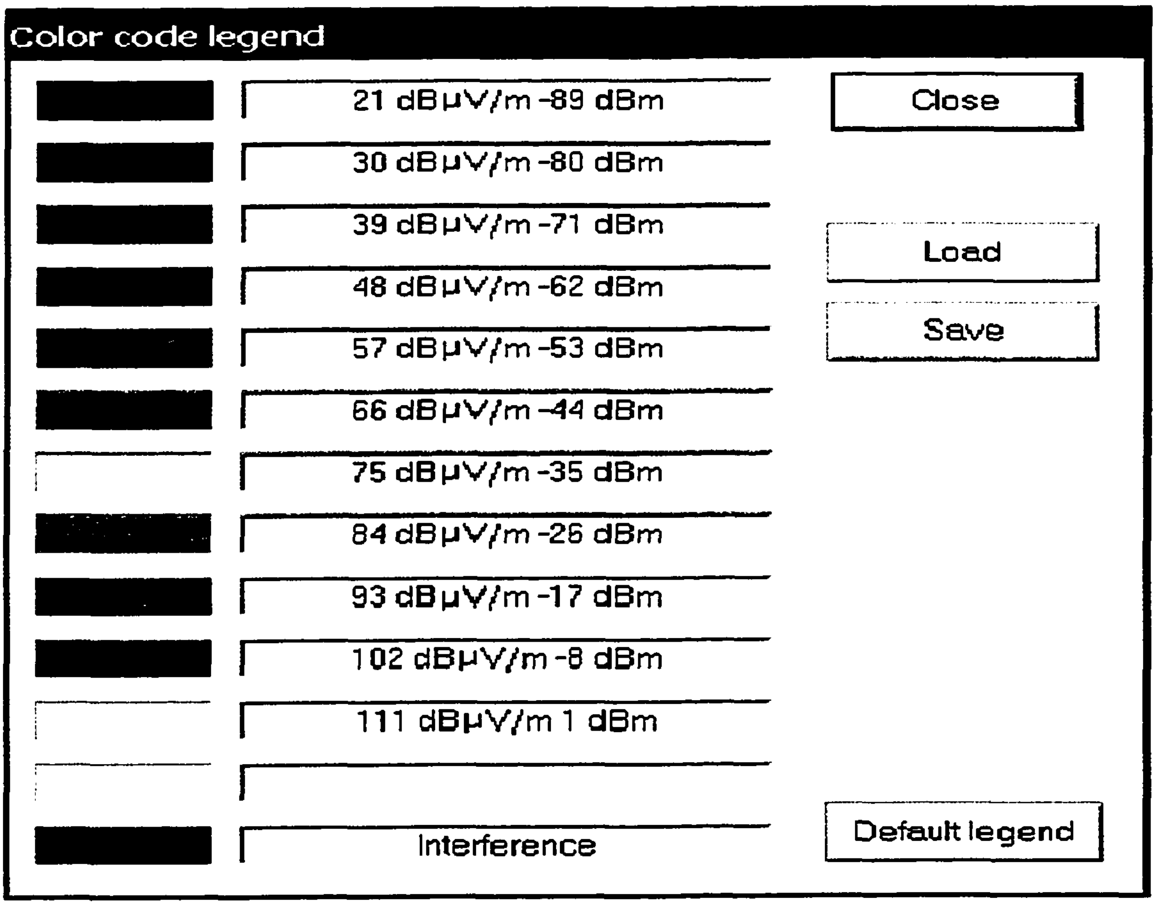

Figure 5.2: The color code legend for field strength (Coverage)

5.1.1.b. Simulation #2 (Using the Akamura-Hatta simulation model)

The area assumed for the simulation in Abu Dhabi city is shown in Figure 5.3. The Akamura-Hatta model was used to simulate the coverage area and percentage using the parameters specified in Table 5.1.

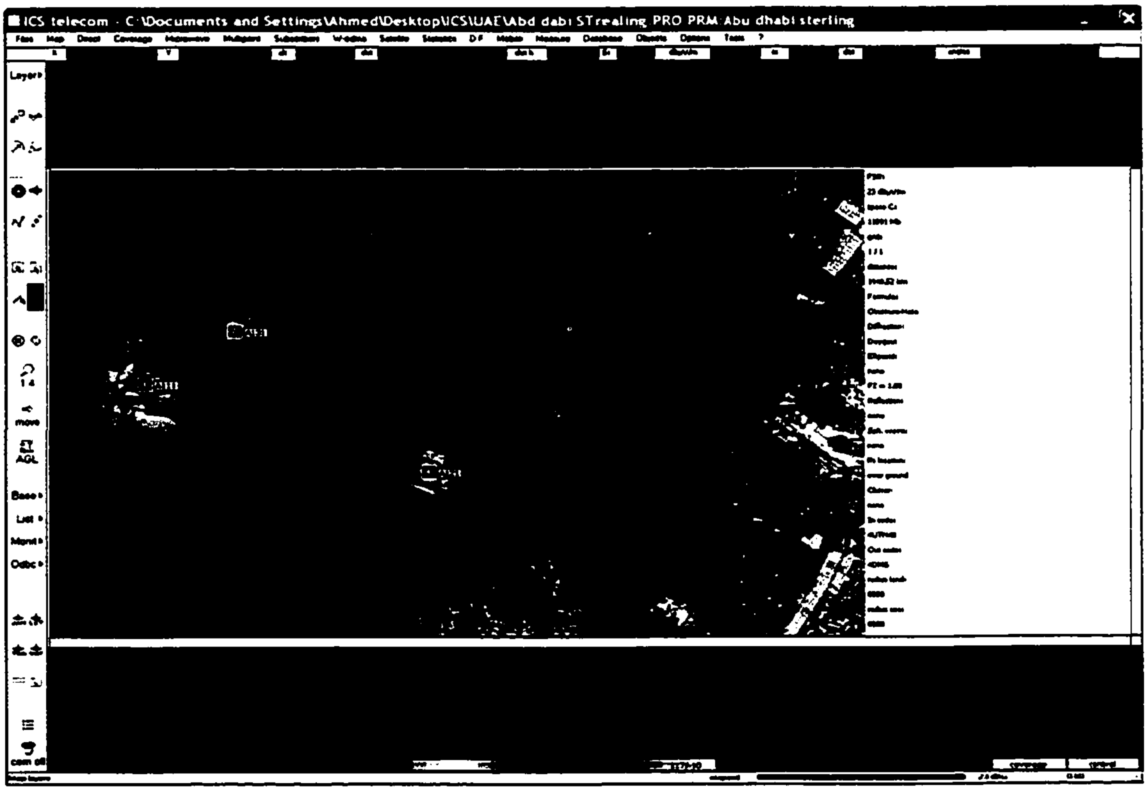

Figure 5.3: Area covered in simulation #2 – TETRAPOL omni directional antenna – Akamura-Hatta Model

The simulation output in Table 5.3 gives the covered area and its percentage in the total area assumed for the simulation. These are:

Table 5.3: Output of simulation #2

Area covered (%)	96.9577
Area covered (km^2)	889.6797
Total area (km^2)	917.5959

5.1.1.c. Output analysis of scenario #1

If the TETRAPOL standard was adopted with three Omni directional antennas, the ITU 525 propagation model shows that 19.75 km^2 of the assumed area in the City of Abu Dhabi would not be covered. On the other hand, the Akamura-Hatta propagation model shows that 27.92 km^2 of the assumed area would not be covered. These area which is not covered is an intense area in east part of the city and therefore, an additional BS would be required if the TETRAPOL standard with Omni directional antennas were used.

The difference between the two areas which are not covered in simulation #1 and simulation #2 is about 8.17 km^2, or 0.89% of the total assumed area.

5.1.2. Scenario #2 (Three directional antennas)

The parameters used in the TETRAPOL's simulations # 3 and #4 are given in Table 5.4 below.

Table 5.4: Station parameters used in simulations #3 and #4

Station parameters	
Units Nominal power	50.00 Watts
Tx gain	11.0 dBi
Rx gain	11.0 dBi
Tx losses	4.75dB
Tx losses (additional)	0.00 dB
Rx losses	4.75 dB
Radiated power	219.77 Watts
Frequency	400.00 MHz
Bandwidth	12.5 KHz
Rx bandwidth	12.5 KHz
Height of antenna	30.00-90.00 m
Antenna aperture	0.00 °
Azimuth	0°-259 °
Tilt	0.000 °
Polarization (Tx)	V
Polarization (Rx)	V
Polar discrimination	0.00 dB
KTBF	-130 dBm
Noise floor	-131 dBm
Dynamic receiver sensitivity BS	-113 dBm

5.1.2.a. Simulation #3 (Using the ITU 525 simulation model)

The area assumed for the simulation in Abu Dhabi city is shown in Figure 5.4. The ITU 525 model was used to simulate the coverage area and percentage using the parameters specified in Table 5.4.

Figure 5.4: Area covered in simulation #3 – TETRAPOL three directional antenna – ITU 525 Model

The simulation output in Table 5.5 gives the covered area and its percentage in the total area assumed for the simulation.

Table 5.5: Output of simulation #3

Area covered (%)	100.0000
Area covered (km^2)	917.5959
Total area (km^2)	917.5959

5.1.2.b. Simulation #4 (Using the Akamura-Hatta simulation model)

The area assumed for the simulation in Abu Dhabi city is shown in Figure 5.5. The Akamura-Hatta model was used to simulate the coverage area and percentage using the parameters specified in Table 5.4.

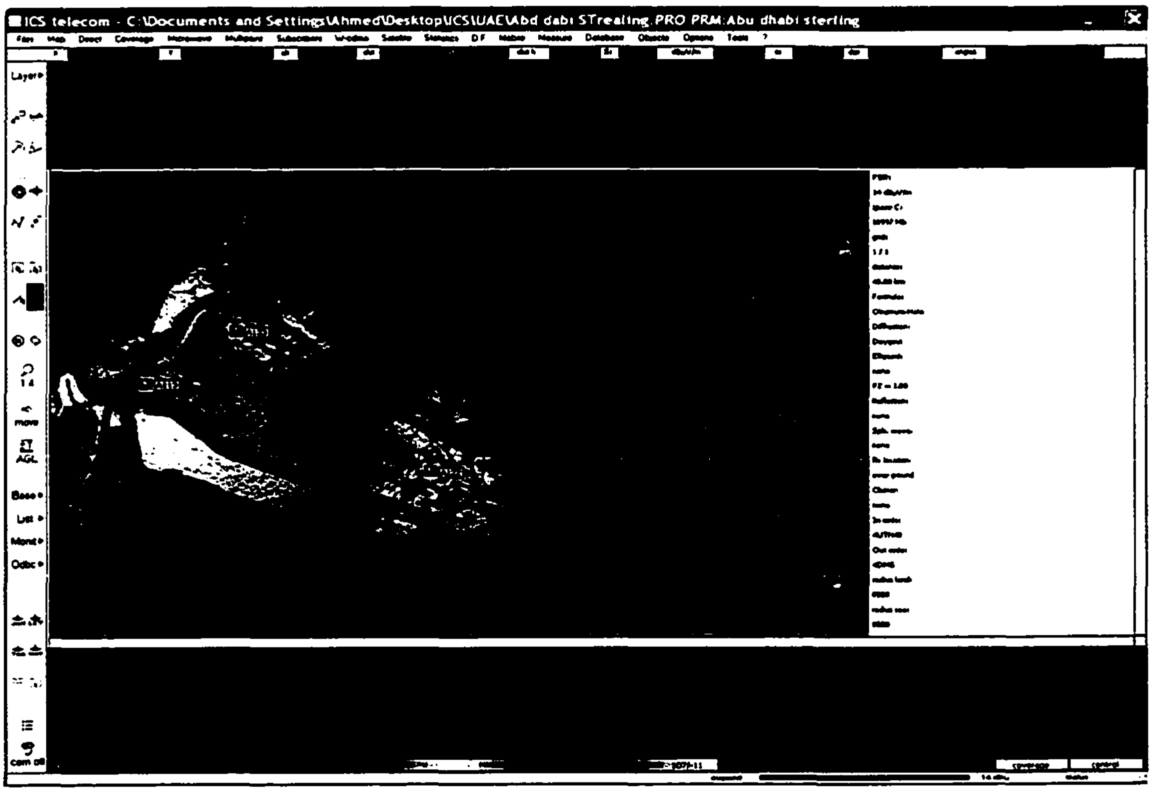

Figure 5.5: Area covered in simulation #4 – TETRAPOL three directional antenna – Akamura-Hatta Model

The simulation output in Table 5.6 gives the covered area and its percentage in the total area assumed for the simulation. These are:

Table 5.6: Output of simulation #4

Area covered (%)	99.9465
Area covered (km^2)	917.1054
Total area (km^2)	917.5959

5.1.2.c. Output analysis of scenario #2

If the TETRAPOL standard with three directional antennas was adopted in each station, the ITU 525 propagation model shows that 100% of the assumed would be covered. On the other hand, the Akamura-Hatta propagation model shows that 0.49 km^2 of the assumed would not be covered. The difference between the two uncovered areas is about 0.49 km^2, or 0.05% of the total assumed area.

5.2. TETRA Area Coverage Simulations

Simulation of the area covered in Abu Dhabi city. U.A.E., using TETRA standard was undertaken for two different scenarios. Both scenarios use the fixed and variable parameters given in third column of Tables 4.1 and 4.2. The ITU 525 and Akamura-Hatta propagation models were used to simulate the area coverage and the output of each simulation was presented.

5.2.1. Scenario #3 (Omni directional antenna)

The parameters used in the TETRA's simulations #5 and #6 are given in Table 5.7 below.

5.2.1.a. Simulation #5 (Using the ITU 525 simulation model)

The area assumed for the simulation in Abu Dhabi city is shown in Figure 5.6. The ITU 525 model was used to simulate the coverage area and percentage using the parameters specified in Table 5.7.

Table 5.7: Station parameters used in simulations #5 and #6

Station parameters	
Units Nominal power	40.00 Watts
Tx gain	2.0 dBi
Rx gain	2.0 dBi
Tx losses	4.75dB
Tx losses (additional)	0.00 dB
Rx losses	4.75 dB
Radiated power	22.13 Watts
Frequency	400.00 MHz
Bandwidth	25.00 KHz
Rx bandwidth	25.00 KHz
Height of antenna	30.00-90.00 m
Antenna aperture	0.00 °
Azimuth	0.00 °
Tilt	0.000 °
Polarization (Tx)	V
Polarization (Rx)	V
Polar discrimination	0.00 dB
KTBF	-130 dBm
Noise floor	-131 dBm
Dynamic receiver sensitivity BS	-106 dBm

The simulation output in Table 5.8 gives the covered area and its percentage in the total area assumed for the simulation. These are:

Table 5.8: Output of simulation #5

Area covered (%)	94.6050
Area covered (km^2)	868.0914
Total area (km^2)	917.5959

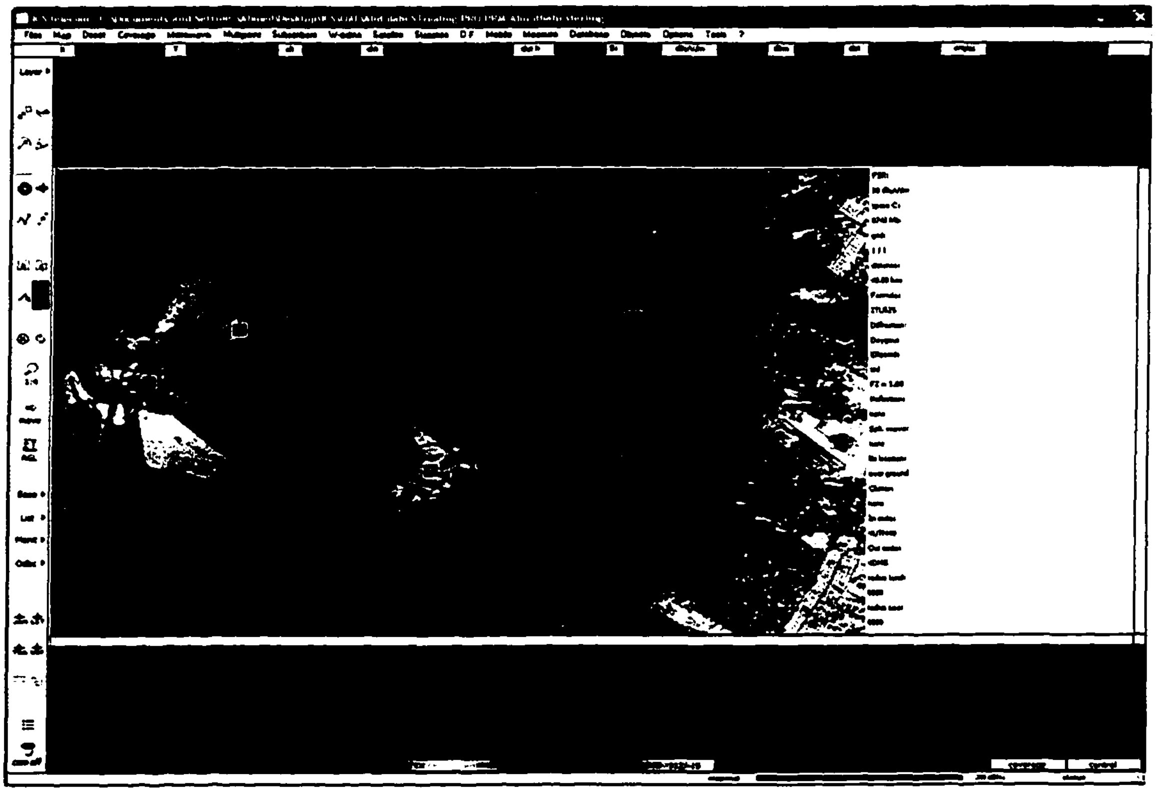

Figure 5.6: Area covered in simulation #5 – TETRA omni directional antenna – ITU 525 Model

5.2.1.b. Simulation #6 (Using the Akamura-Hatta simulation model)

The area assumed for the simulation in Abu Dhabi city is shown in Figure 5.7. The Akamura-Hatta model was used to simulate the coverage area and percentage using the parameters specified in Table 5.7.

The simulation output in Table 5.9 gives the covered area and its percentage in the total area assumed for the simulation. These are:

Table 5.9: Output of simulation #6

Area covered (%)	78.9631
Area covered (km^2)	724.5621
Total area (km^2)	917.5959

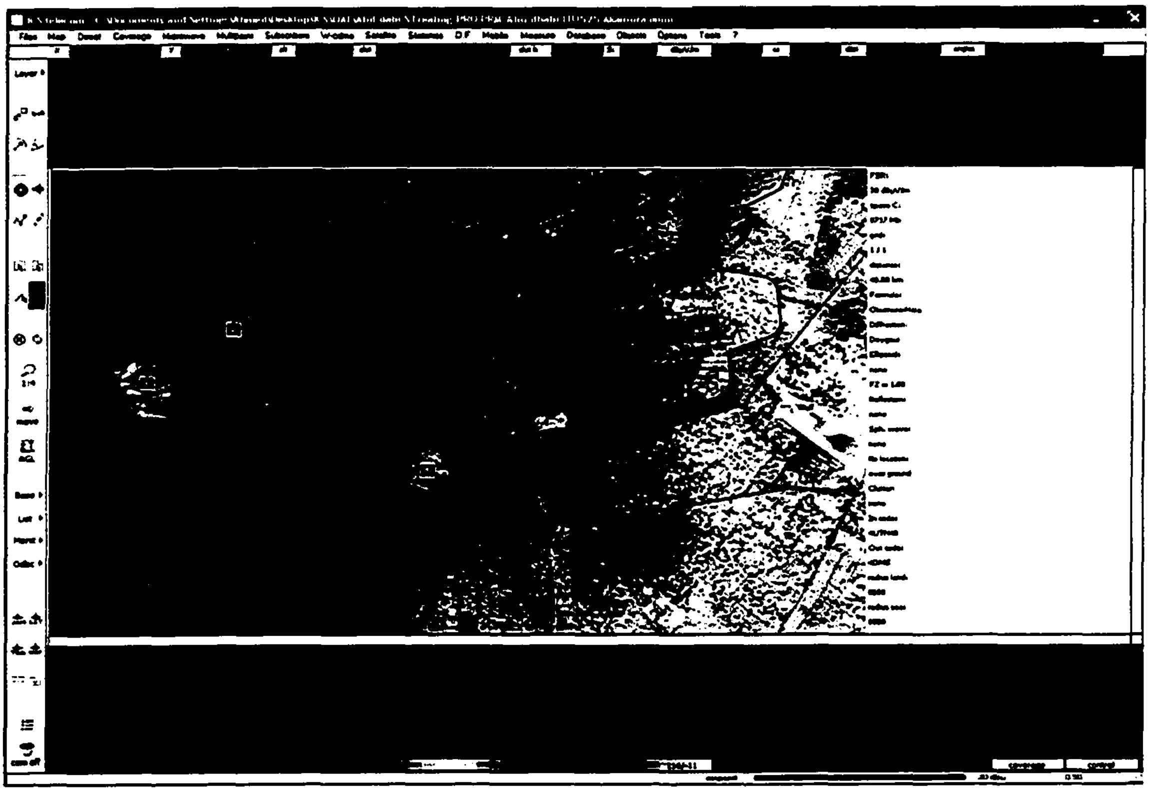

Figure 5.7: Area covered in simulation #6 – TETRA omni directional antenna – Akamura-Hatta Model

5.2.1.c. Output analysis of scenario #3

If the TETRA standard with three Omni directional antennas was adopted, the ITU 525 propagation model shows that 49.51 km^2 of the assumed would not be covered. On the other hand, the Akamura-Hatta propagation model shows that 193.04 km^2 of the assumed would not be covered. The difference between the two uncovered areas is about 143.53 km^2, or 15.64% of the total assumed area.

5.2.2. Scenario #4 (Three directional antennas)

The parameters used in the TETRA's simulations #7 and #8 are given in Table 5.10 below.

Table 5.10: Station parameters used in simulations #7 and #8

Station parameters	
Units Nominal power	40.00 Watts
Tx gain	11.0 dBi
Rx gain	11.0 dBi
Tx losses	4.75dB
Tx losses (additional)	0.00 dB
Rx losses	4.75 dB
Radiated power	175.82 Watts
Frequency	400.00 MHz
Bandwidth	25.00 KHz
Rx bandwidth	25.00KHz
Height of antenna	30.00-90.00 m
Antenna aperture	0.00 °
Azimuth	0°-259 °
Tilt	0.000 °
Polarization (Tx)	V
Polarization (Rx)	V
Polar discrimination	0.00 dB
KTBF	-130 dBm
Noise floor	-131 dBm
Dynamic receiver sensitivity BS	-106 dBm

5.2.2.a. Simulation #7 (Using the ITU 525 simulation model)

The area assumed for the simulation in Abu Dhabi city is shown in Figure 5.8. The ITU 525 model was used to simulate the coverage area and percentage using the parameters specified in Table 5.10.

The simulation output in Table 5.11 gives the covered area and its percentage in the total area assumed for the simulation. These are:

Table 5.11: Output of simulation #7

Area covered (%)	99.9919
Area covered (km^2)	917.5212
Total area (km^2)	917.5959

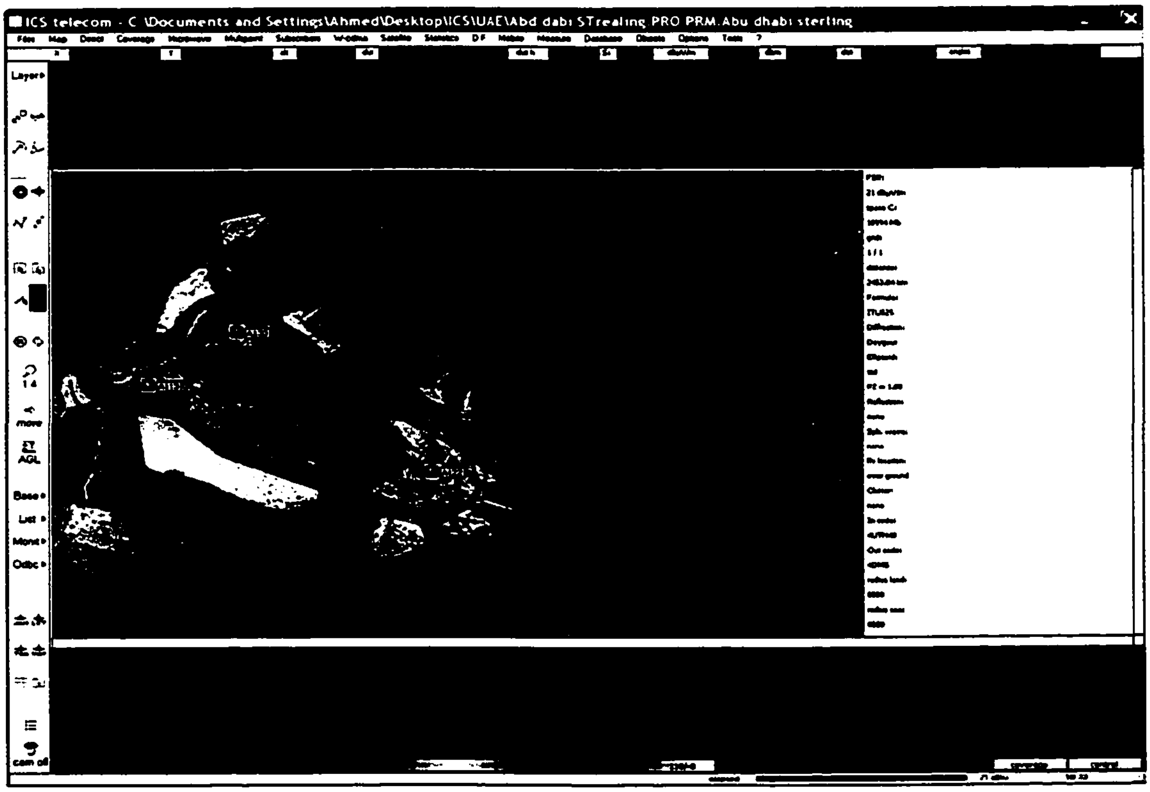

Figure 5.8: Area covered in simulation #7 – TETRA three directional antenna – ITU 525 Model

5.2.2.b. Simulation #8 (Using the Akamura-Hatta simulation model)

The area assumed for the simulation in Abu Dhabi city is shown in Figure 5.9. The Akamura-Hatta model was used to simulate the coverage area and percentage using the parameters specified in Table 5.10.

The simulation output in Table 5.12 gives the covered area and its percentage in the total area assumed for the simulation. These are:

Table 5.12: Output of simulation #8

Area covered (%)	99.2597
Area covered (km^2)	910.8027
Total area (km^2)	917.5959

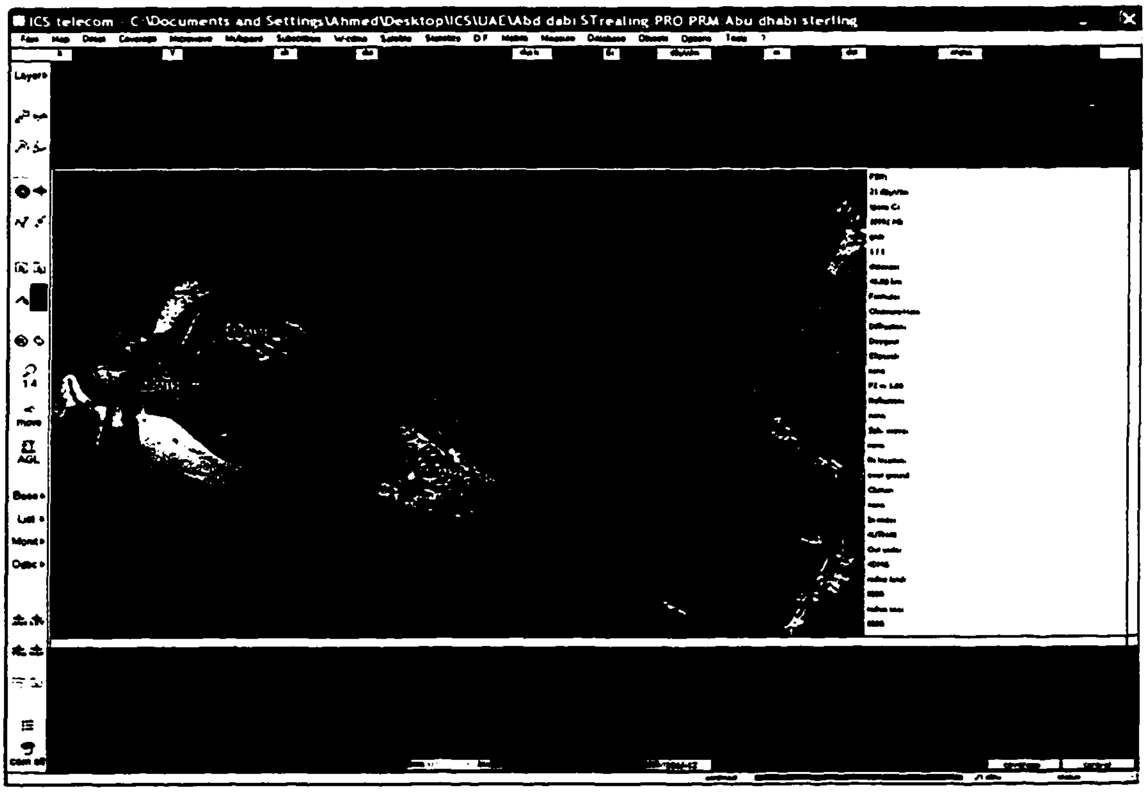

Figure 5.9: Area covered in simulation #8 – TETRA three directional antenna – Akamura-Hatta Model

5.2.2.c. Output analysis of scenario #4

If the TETRA standard with three directional antennas was adopted in each station, the ITU525 propagation model shows that 0.08 km^2 of the assumed would not be covered. On the other hand, the Akamura-Hatta propagation model shows that 6.80 km^2 of the assumed would not be covered. The difference between the two uncovered areas is about 6.52 km^2, or 0.73% of the total assumed area.

5.2.3. Coverage analysis

Figure 5.10 shows that the coverage areas produced by Akamura-Hatta propagation model were consistently smaller than those produced by the ITU 525 propagation model. The difference was, in general, very small and less than 1% (except in scenario #3 where the difference was over 15%). Therefore, it is advisable to use the Akamura-Hatta model for the simulations since it produces more conservative percentage of area coverage than the ITU 525 model.

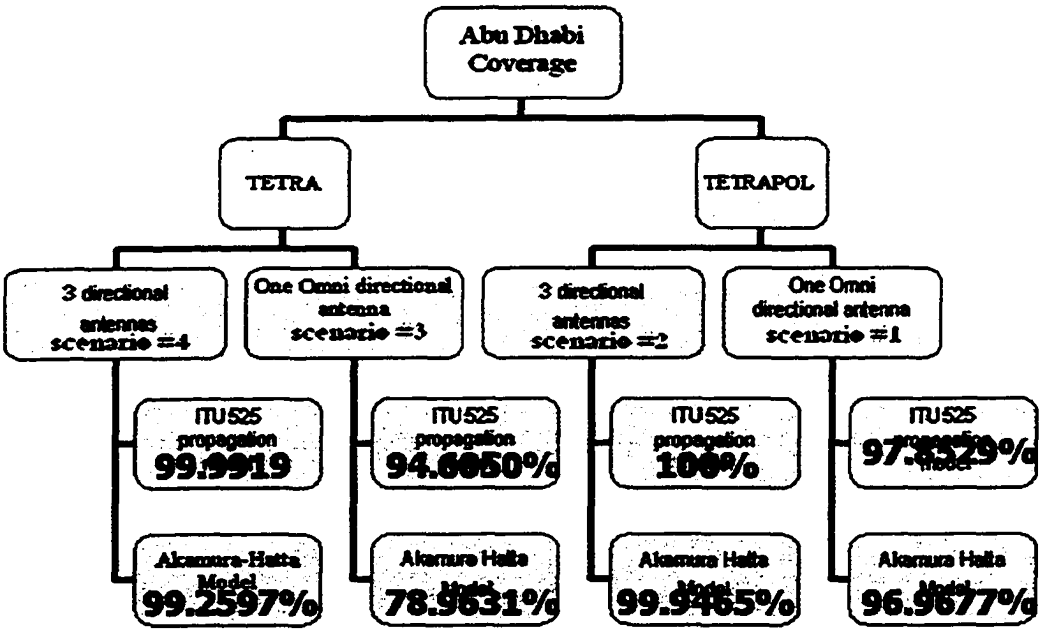

Figure 5.10: Coverage areas using the ITU 525 and Akamura-Hatta propagation models for omni and 3-sector directional antenna

It is noted that there is a substantial difference in the coverage between ITU 525 and Akamure-Hatta models when an omni direction antenna is used (case of scenario #3). This can be explained by the fact that the Akamura-Hatta model tends to estimate higher attenuation for urban terrain when the single antenna is used.

The analysis of the effect of different factors on the achieved area coverage are discussed below:

First, to illustrate the effect of model use on the field strength, two positions of a transmitting point (Tx) and a receiving point (Rx) were used and the field strength path between them was calculated. Figure 5.11 represents the profile encountered between the transmitting point and the receiving point using the ITU 525 propagation model.

The legend for Figure 5.11 is:

- The straight teal/light blue line represents line of sight.
- The darker blue ellipse represents the Fresnel Zone.
- The light green line represents the field strength received.
- The Y-axis on the right is a reading of the field strength received values (in dBμV/m) at different points of elevation in meters (Y-axis on left) and distance in meters (X-axis) along the profile.
- The red line represents free space loss.
- The dark line with gray fill in represents the terrain elevation.
- The colored (orange, red, green) regions represent the clutter over the terrain.
- The scale on the lower right tells what each color means.
- ITU-525 is using the clutter data on the clutter layer provided by ICS tool. Using this model, the FSR is 48.2 dBμV/m or -62 dBm as summarized in the report.
- The PSO: probability of successful operation, margin corresponding to [field strength received - RX threshold] = 48.2 dBμV/m – 30 dBμV/m = 18.2 dBμV/m.

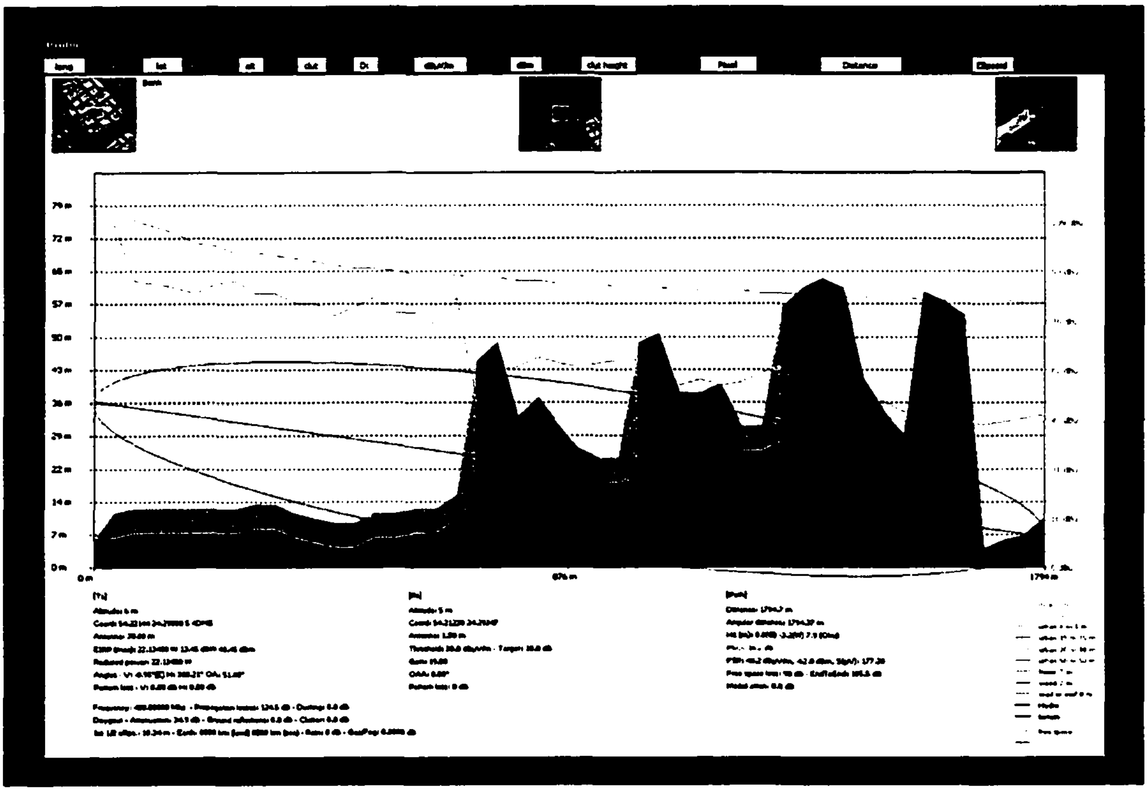

Figure 5.11: Profile encountered between the transmitting point (Tx) and the receiving point (Rx) using the ITU 525 propagation model

Figure 5.12 presents the profile encountered between the same Tx and Rx positions using the Akamura-Hatta model. The legend of Figure 5.12 is the same as in Figure 5.11 except for the following differences:

- The PSO: probability of successful operation, margin corresponding to [field strength received - RX threshold] = 35.8 dBμV/m – 30 dBμV/m = 5.8 dBμV/m.
- Akamura-Hatta model assumes certain clutter characteristics defined by the model rather than by the ICS clutter layer. With Akamura-Hatta, the reading is getting FSR 35.8 dBμV/m or -75.4 dBm.

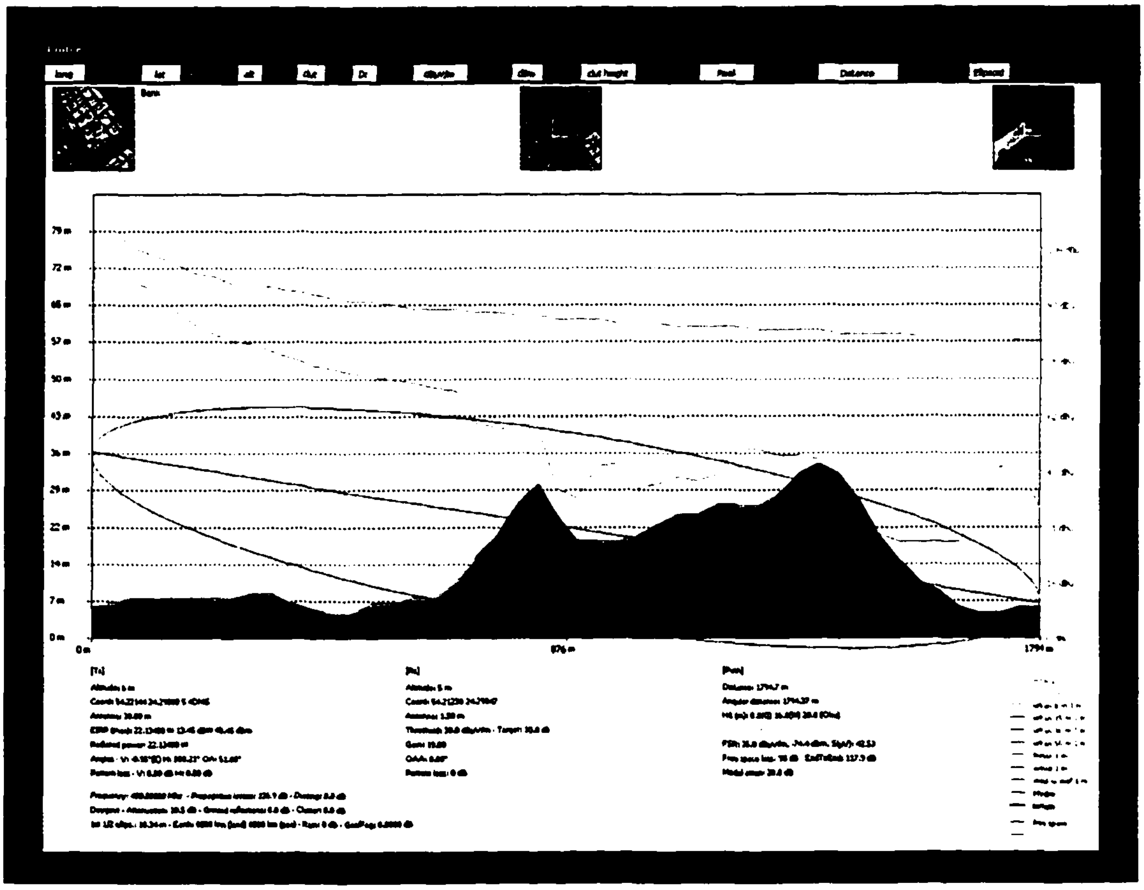

Figure 5.12: The profile encountered between the transmitting point (Tx) and the receiving point (Rx) using the Akamura-Hatta propagation model

The paths in Figures 5.11 and 5.12 illustrate more clearly that the area was not covered in Abu Dhabi city due to the very low level of field strength in that area. Therefore it was concluded that irrespective of the propagation model used, a field with enough strength was required to be able to cover that area.

Secondly, to examine the effect of the use of different types of antennas on the area of coverage, the outputs of simulations #1 and #2 in scenario #1 with the Omni directional antenna were compared to the outputs of simulations #3 and #4 in scenario #2 with the three directional antennas respectively. Also the outputs of simulations #5 and #6 in scenario #3 with the Omni directional antenna were compared to the outputs of simulations #7 and #8 in scenario #4 with the three directional antennas respectively. The areas coverage achieved by using the three directional antennas were higher than the areas coverage achieved by using the Omni directional antenna in all the comparisons. Therefore, it was concluded that the use of the three directional antennas with gain of 11dBi would achieve better area coverage than one omni directional antenna with 2 dBi irrespective of the propagation model used.

Thirdly, it clear from the appendix A that the field strength for the closest base station is less than the stations which are far so this base station is need to be changed or it has to be modified with some technical solutions like increasing the height of the antenna or redirect the antenna to met the proper coverage.

Finally, to examine the effect of different standards on the area of coverage, the outputs of simulations #1 and #2 in scenario #1 of the TETRAPOL were compared to the outputs of simulations #5 and #6 in scenario #3 of the TETRA respectively. Also the outputs of simulations #3 and #4 in scenario #2 of the TETRAPOL were compared to the outputs of simulations #7 and #8 in scenario #4 of the TETRA respectively. The TETRAPOL standard has achieved higher areas coverage than the TETRA standard in all the comparisons.

5.3. Capacity Simulation

The capacity simulation will be based on several values:

5.3.1. Traffic loading

Traffic loading is expressed in terms of the individual subscribers and the methods of determining the requirement can be fairly straightforward. If, for example, there are three BSs with a number of channels available to cover the 917.60 km² of Abu Dhabi city.

Assume that it is required to determine 6 clutters, each clutter will cover a certain area as given in Table 5.13.

Table 5.13: Specific areas covered by clutters

Clutter No.	Area type	Area coverage (km^2)
0	Rural	436.400
1	Suburban	97.170
2	Urban 8 m	3.008
3	Urban 15 m	1.966
4	Urban 30 m	1.233
6	Hydro	315.700
Total		855.477

The total covering area of these clutters is 855.477 km^2. It has a users density of 2 per km^2. Therefore, there are 416 users in Abu Dhabi area distributed according to Table 5.14.

Table 5.14: Number of users in Specific coverage areas

Clutter No.	Area type	Number of users
0	Rural	100
1	Suburban	200
2	Urban 8 m	30
3	Urban 15 m	26
4	Urban 30 m	30
6	Hydro	30
Total		416

A mobile user generates traffic of 0.012E in the uplink direction. The traffic density can then be calculated as:

Traffic density = 416 users x 0.01E = 4.16 Erlang.

Next, the Erlang value for each clutter per unit area is calculated according to the formula:

0.01 x Number of users in the clutter/area covered in the clutter.

Thus, the Erlang values for the above clutters are:

Clutter 0 = 0.01 * 100 / 436.4 = .0022914 E/km^2

Clutter 1 = 0.01 * 200 / 97.71 = 0.02046 E/km^2

Clutter 2 = 0.01 * 30 / 3.008 = 0.09973 E/km^2

Clutter 3 = 0.01 * 26 / 1.966 = 0.13224 E/km^2

Clutter 4 = 0.01 * 30 / 1.233 = 0.24330 E/km^2

Clutter 6 = 0.01 * 30 / 315.7 = 0.0009 E/km^2

The calculated Erlang values can then be entered in the clutter box marked Erlang/km^2 in the simulation program as shown in the Table 5.15.

The output of this model is the total traffic in each area served by best server and the grade of service, which is calculated as:

$$GOS = 1 - P(\text{delayed} > \text{objective}) = \mathrm{Exp}\{-T/H*(s-y)\}$$

where,

T = objective delay,

H = mean duration of a call,

s = number of communication lines, and

y = offered traffic.

Table 5.15: Clutter code with Erlang values

Clutter parameters

Clutter code	Name	Attenuation (dB)	Clutter height	Reflection factor (0-1)	Erlang/km² (1)
0	rural			0.300	0.0020
1	suburban			0.300	0.0200
2	urban 8 m			0.300	0.1000
3	urban 15 m			0.300	0.1400
4	urban 30 m			0.300	0.2500
5	forest			0.300	0.0000
6	hydro			0.300	0.0010
7	urban 50 m			0.300	0.0000
8	wood			0.300	0.0000
9	road or roof			0.300	0.0000

5.3.2. Existing sectorized stations (Simulations #4 and #8)

The same base stations and sectorized antennas together with the same clutter code that was used in the coverage simulation with the Akamura-Hatta propagation model will be used to calculate the traffic for the TETRAPOL simulation #4 and the TETRA simulation #8. Figures 5.13 And 5.14 Presents the optimum area served by the best server for TETRA standard with 21 dBm threshold and for the TETRAPOL standard with 14 dBm threshold.

5.3.3. TETRAPOL traffic capacity

A TETRAPOL BS can handle up to 24 radio channels. The capacity is calculated under the assumption that the maximum capacity of 24 channels for the TETRAPOL are used, with 50 seconds calls duration and a delay objective of 5 seconds.

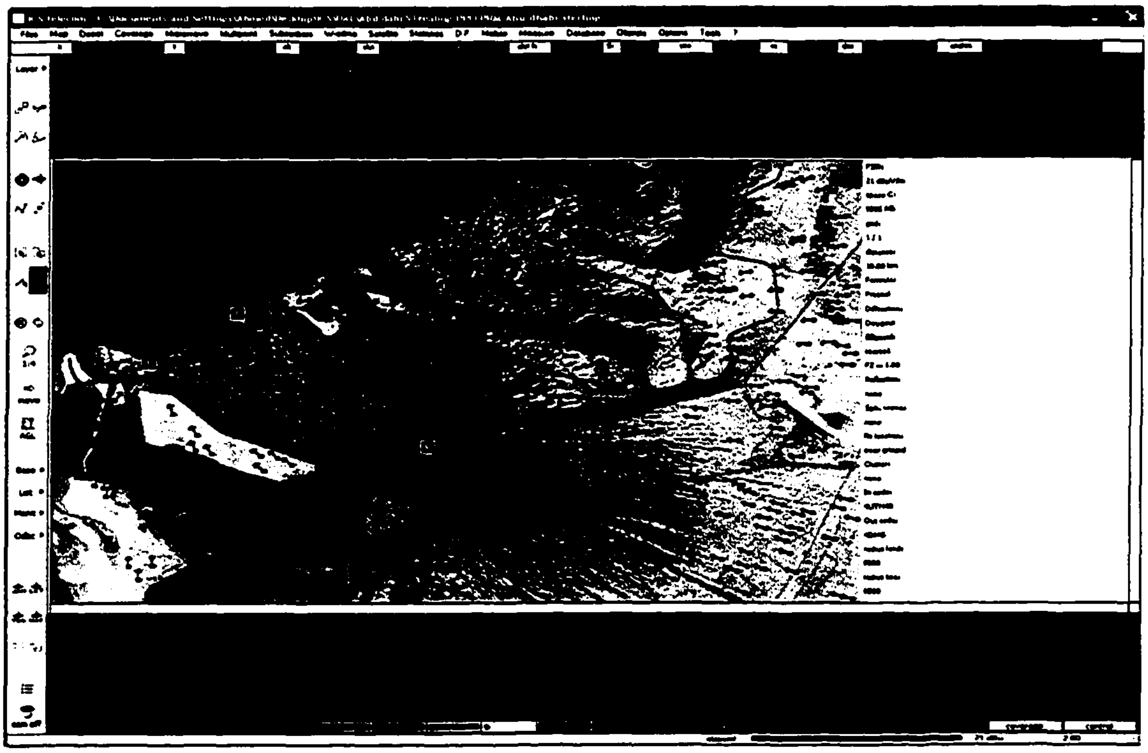

Figure 5.13: The optimum area served by the best server for TETRA standard with 21 dBm threshold

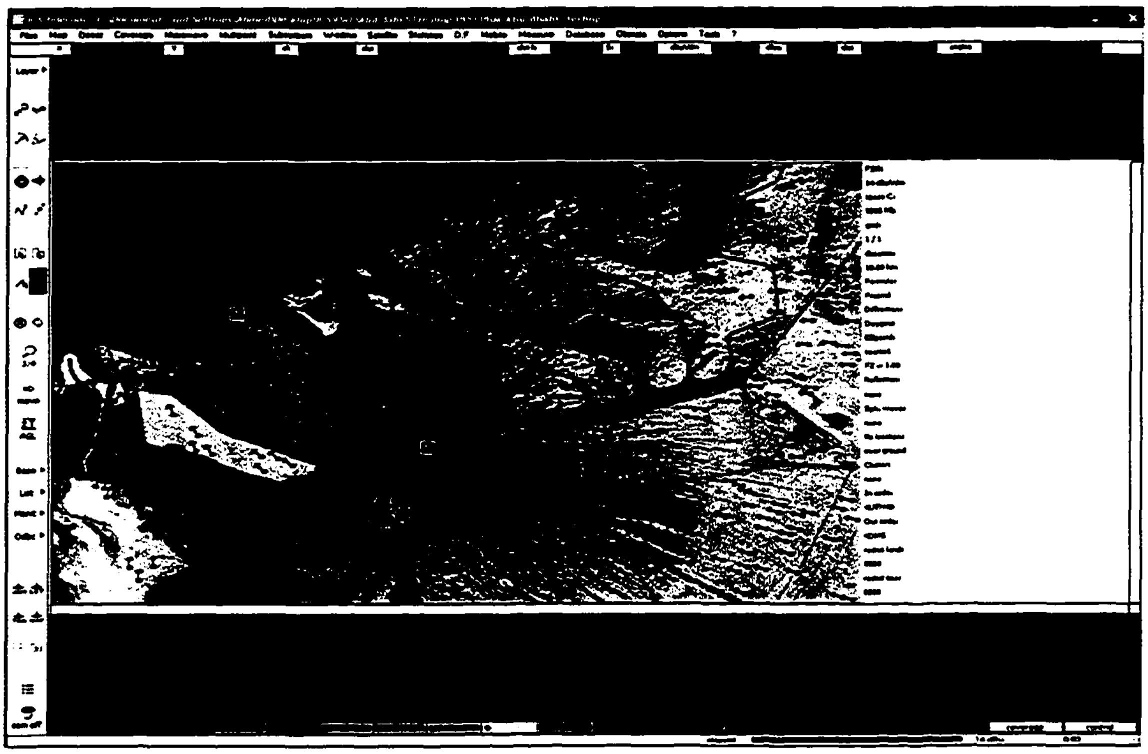

Figure 5.14: The optimum area served by the best server for TETRAPOL standard with 14 dBm threshold

The gross modulation bit rate for the TETRAPOL is 8 kbit/s with a channel spacing of 12.5 kHz. Each channel provides one bi-directional control or traffic channel and carries a set of logical channel. The resulting traffic grade of service (G.O.S.) is presented in Figures 5.15 and 5.16.

The area coverage percentages are displayed and give the G.O.S. at each point of the network where,

Device = number of communication line, and

Cx = Number of channels.

TRAFFIC G.O.S

Station	#	Call-sign	GOS %	Offered traffic (E)	Device	Cx
A.1.1	1	A111	100.00	0.39	5	5
A.1.2	2	A131	100.00	0.39	5	5
A.1.3	3	A123	100.00	0.28	5	5
A.1.3	4	A121	100.00	0.83	7	7
A.1.3	5	A122	100.00	0.16	4	4
A.1.2	6	A132	99.99	0.23	4	4
A.1.2	7	A133	100.00	0.18	4	4
A.1.1	8	A112	99.98	1.72	8	8
A.1.1	9	A113	99.99	0.09	3	3

Figure 5.15: Traffic grade of service for TETRAPOL standard

5.3.4. TETRA traffic capacity

A typical TETRA BS can handle up to 32 channels. The calculation of capacity assumed that the maximum BS site capacity of 32 channels for the TETRA with 50 seconds call duration and the delay objective of 5 seconds are used. Furthermore, four channels can share one frequency. The gross modulation bit rate for the TETRA is 36 kbit/s in a single 25 kHz channel spacing and four TDMA voice or data channels are available per carrier. The traffic G.O.S grade of service is presented in Figures 5.17 and

5.18. The area coverage percentages are displayed and give the GOS at each point of the network.

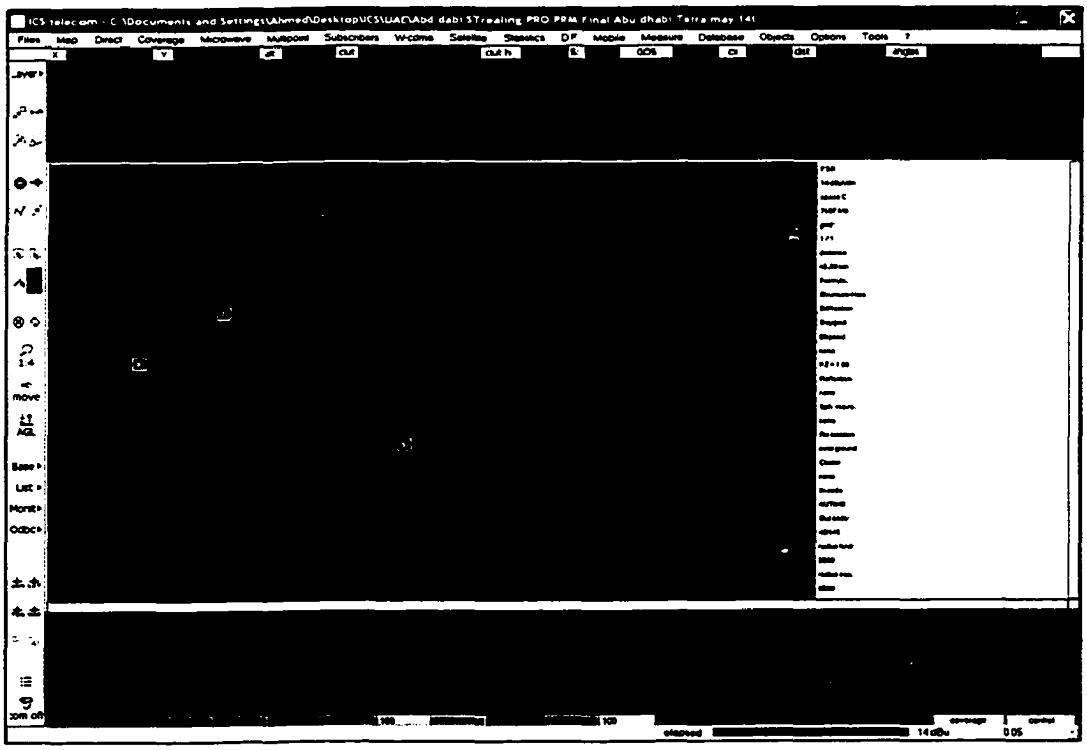

Figure 5.16: Area coverage percentage and G.O.S. at each point in the network.

TRAFFIC G.O.S

Station	#	Call-sign	GOS %	Offered traffic (E)	Device	Cx
A.1.1	1	A111	100.00	0.39	14	5
A.1.2	2	A131	100.00	0.39	14	5
A.1.3	3	A123	100.00	0.28	14	5
A.1.3	4	A121	100.00	0.83	17	6
A.1.3	5	A122	100.00	0.16	11	4
A.1.2	6	A132	100.00	0.23	14	5
A.1.2	7	A133	100.00	0.18	11	4
A.1.1	8	A112	100.00	1.62	23	8
A.1.1	9	A113	100.00	0.09	11	4

Figure 5.17: Traffic grade of service for TETRA standard

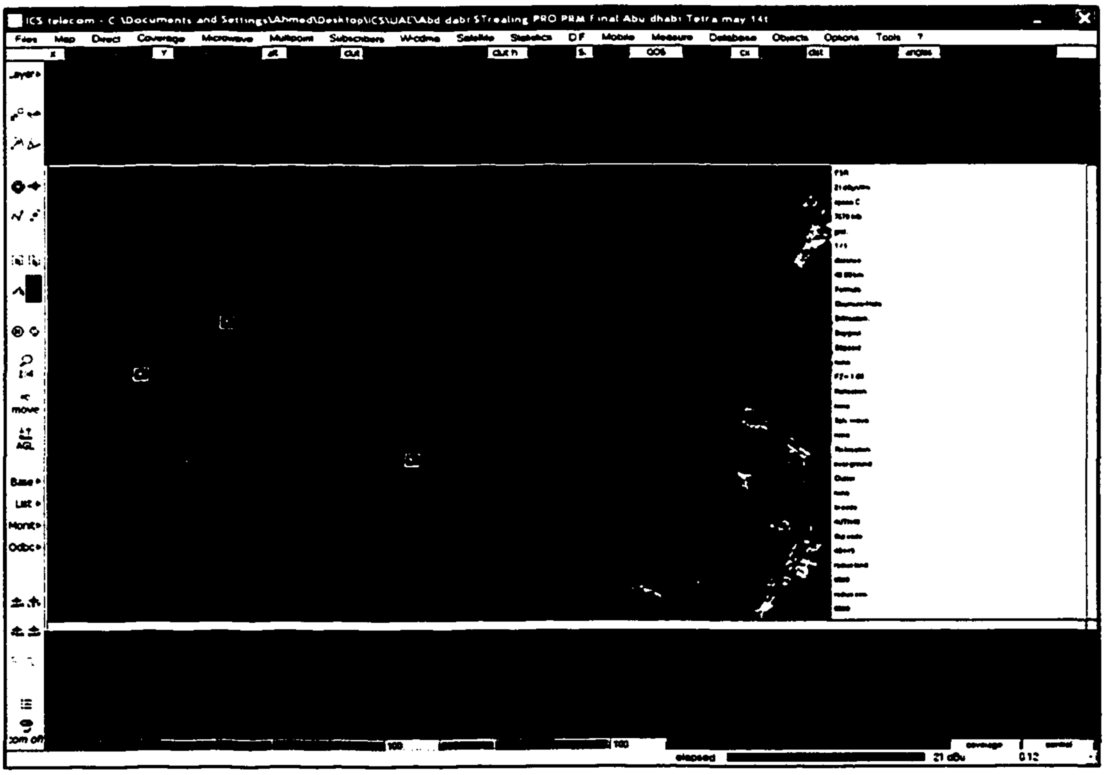

Figure 5.18: Area coverage percentage and G.O.S. at each point in the network

5.3.5. Capacity analysis

In general, the limiting factor affecting the capacity is the number of traffic channels that can be supported at the BS site. Since the TETRA BS can handle up to 32 channels and the TETRAPOL can only handle up to 24 channels, therefore TETRA supports more traffic channels per BS site than TETRAPOL, which is consistent with the capacity simulation results. Both standards offer a significantly high grade of service capacity according to the assumptions under consideration. Each BS will provide 100% grade of service in each of the two standards, the only 3 sectorized BS's (call sign) that cannot offer 100% are the A112, A113, and A132 using the TETRAPOL Standard. This means that if there was an increasing call duration and the delay objective, the percentage of grade of service will be less than those produced above.

On the other hand, the results of offered traffic by both standards are the same except for the sectorized BS (call sign) A112, which is offering 1.62 E/km^2 when the TETRA standard was used and it offers 1.72 E/ km^2 when TETRAPOL standard was used. This difference can increase if the call duration or the number of users increased. This analysis concludes that the TETRA standard achieves higher capacity performance and can serve more users than the TETRAPOL.

The TETRAPOL network can support up to 69 communication lines in addition to three control channels. Figure 5.15 shows that the optimum operations of the TETRAPOL network in Abu Dhabi city under the given assumptions requires 45 communication lines, each of which serves a group of users. On the other hand, the TETRA network can support up to 288 communication lines in addition to 96 control channels. Figure 5.17 shows that the optimum operations of the TETRA network in Abu Dhabi city under the given assumptions requires 129 communication lines, each of which serves one single user.

Comparing the above results with the spectrum efficiency calculations for both technologies, the following three performance specifications can be determined:

1. The number of channels per RF carrier.
2. The RF occupied bandwidth.
3. The Carrier to Interface (C/I) ratio.

Table 5.16 presents the relationship between frequency Re-use “N” and C/I faded values [14].

Table 5.16: Relationship between frequency Re-use “N” and C/I faded values

N	3	4	7	9	12	13	16	19	21	27	28
C/I	11.3	13.8	18.7	20.8	23.3	24.0	25.8	27.3	28.2	30.4	30.7

From Table 5.16, the spectrum efficiency at faded C/I of 19 dB for the TETRAPOL standard is

$$Spectrum\ efficiency = \frac{Number\ of\ communication\ channels}{Occupied\ RF\ channel\ bandwidth \times N}$$
$$= \frac{1}{12.5 \times 9} = 0.009$$

Similarly, the spectrum efficiency at the faded C/I of 25 for the TETRA standard is

$$Spectrum\ efficiency = \frac{Number\ of\ communication\ channels(Device)}{Occupied\ RF\ channel\ bandwidth \times N}$$
$$= \frac{4}{25 \times 16} = 0.010$$

Therefore, the TETRA standard has a slightly more capacity performance and frequency spectrum cost advantage over the TETRAPOL standard.

6. CONCLUSIONS AND FUTURE WORK

6.1. Conclusions

This study has examined the classes of applications supported by each of the TETRAPOL and TETRA Telecommunication standards. The coverage and the capacity provided by each standard were analysed using the ICS Telecom tool. Four simulations under two scenarios using the ITU 525 and Akamura-Hatta propagation models were conducted for each standard and the results were compared. The following conclusions were supported by the output results of these simulations:

6.1.1. Classes of application

The classes of applications of the TETRA and TETRAPOL standards are more or less similar as they were originally designed to serve the same PMR users and the PPS networks. Since the TETRAPOL standard has more features and supports more applications than the TETRA standard, it appears that the TETRAPOL has the potential to provide more services than the TETRA. This is because as TETRA manufactures were serving the PMR users, a wide range of new services and applications emerged and can be easily incorporated in future into TETRAPOL.

6.1.2. Area coverage

This study has examined four scenarios with 8 simulations of the area coverage analysis of Abu Dhabi city and has produced the following results:

- Using Akamura-Hatta propagation model for ICS Telecom is more realistic than using ITU 525 model.

- For testing a type of area and terrain, such as Abu Dhabi city, by using ICS Telecom tool, the results from all scenarios have shown that the Akamura-Hatta simulation model estimates less signal strength at the various positions than the ITU 525 model. As a result, the Akamura-Hatta model predicts a smaller coverage area than the ITU 525 model.
- The TETRAPOL standard has wider area coverage than the TETRA for Abu Dhabi city. It provided a larger area coverage percentage than the TETRA standard. A main reason is that the dynamic reference sensitivity for the TETRAPOL is -113 dBμV, compared to -106 dBμV for the TETRA. These two values are important for the noise floor and they also affect the threshold. Therefore, smaller reference sensitivity results in wider coverage.

6.1.3. Capacity

- Capacity analysis concluded that the TETRA standard has a slight capacity cost advantage as compared to the TETRAPOL standard since the former supports more traffic channels per BS site than the TETRAPOL. Therefore, TETRA is more ideal for applications requiring more capacity whereas TETRAPOL could be more suitable for applications in which capacity is not a major concern.
- Reaching a final decision on selecting the most suitable technology standard for PMR users and PPS network depends upon both area coverage and traffic analyses and their interaction. For example, large area coverage by few channels will result in a poor traffic performance. The converse would result in poor area coverage and an over-engineered solution for these areas. Therefore, it is

important that the final decision on which standard to deploy should be based on the objectives and evolving requirements.

6.2. Future Research Work

The following topics have been identified for future research.

- This study focused on narrow band wireless communications standards such as TETRA and TETRAPOL. The increasing demand for telecommunications by PSS agencies requires similar studies to compare broadband network standards that are currently being considered for applications such as WiMax and IEEE.16.3.
- The simulation should be expanded to include other types of data traffic such as low rate video and image transmission.
- Future studies should focus on alternative techniques and methods to reconfigure existing wireless networks in order to enhance coverage and increase capacity.

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APPENDIX A

Path balance analysis for a subscriber in a position where there is no enough coverage in the east of Abu Dhabi city with radiated power of 2.00 W, 1.5 m height of antenna, and 19 dBm Rx gain.

TETRAPOL: 3 stations with omni directional antenna

BST	Callsign	Freq MHz	FSR dB μV/m down	PR dBm down	FSR dB μV/m up	PR dBm up	Dist (km)	ToA (μsec)
1	A111	400.00000	32.1	-78.15	20.7	-111.13	32.83	109.45
2	A131	400.00000	25.9	-84.35	14.5	-117.33	28.83	96.09
4	A121	400.00000	45.1	-65.12	33.7	-98.10	19.11	63.71

TETRAOPL: 3 stations with 3 Directional antennas for each station

BST	Callsign	Freq MHz	FSR dB μV/m down	PR dBm down	FSR dB μV/m up	PR dBm up	Dist (km)	ToA (μsec)
1	A111	400.00000	32.7	-77.55	12.3	-110.53	32.83	109.45
2	A131	400.00000	25.7	-84.55	5.3	-117.53	28.83	96.09
3	A123	400.00000	46.1	-64.12	25.7	-97.10	19.11	63.71
4	A121	400.00000	50.0	-60.27	29.6	-93.25	19.11	63.71
5	A122	400.00000	36.9	-73.32	16.5	-106.30	19.11	63.71
6	A132	400.00000	28.5	-81.74	8.1	-114.72	28.83	96.09
7	A133	400.00000	15.5	-94.79	-4.9	-127.77	28.83	96.09
8	A112	400.00000	49.4	-60.83	29.0	-93.81	32.83	109.45
9	A113	400.00000	40.7	-69.55	20.3	-102.53	32.83	109.45

TETRA: 3 stations with omni directional antenna

BST	Callsign	Freq MHz	FSR dB μV/m down	PR dBm down	FSR dB μV/m up	PR dBm up	Dist (km)	ToA (μsec)
1	A111	400.00000	31.1	-79.12	20.7	-111.13	32.83	109.45
2	A131	400.00000	24.9	-85.32	14.5	-117.33	28.83	96.09
4	A121	400.00000	44.2	-66.09	33.7	-98.10	19.11	63.71

TETRA 3 stations with 3 Directional antennas for each station

BST	Callsign	Freq MHz	FSR dB μV/m down	PR dBm down	FSR dB μV/m up	PR dBm up	Dist (km)	ToA (μsec)
1	A111	400.00000	31.7	-78.56	12.3	-110.54	32.83	109.45
2	A131	400.05000	24.7	-85.53	5.3	-117.57	28.83	96.09
3	A123	400.10000	45.2	-65.09	25.7	-97.12	19.11	63.71
4	A121	400.15000	49.0	-61.26	29.5	-93.29	19.11	63.71
5	A122	400.20000	36.0	-74.31	16.5	-106.34	19.11	63.71
6	A132	400.25000	27.5	-82.72	8.1	-114.74	28.83	96.09
7	A133	400.30000	14.5	-95.77	-5.0	-127.79	28.83	96.09
8	A112	400.35000	48.4	-61.83	29.0	-93.81	32.83	109.45
9	A113	400.40000	39.7	-70.53	20.3	-102.55	32.83	109.45

APPENDIX B

List of Abbreviations and Symbols

AACH	Access Assignment CHannel
ACELP	Algebraic CELP
ASCI	Advanced Speech Call Items (GSM)
BCH	Broadcast CHannel
BS	Base station
BUx	Bad Urban
CAPEX	CAPtial EXpenses
CCH	Control CHannel
CCKs	Common cipher keys
CDPD	Cellular Digital Packet Data
C/Ia	Carrier to Interference (co-channel)
C/Ic	Carrier to Interference (adjacent channel)
Codec	Co der / dec oder
dB	Decibel
dBm	Decibel with reference to a milli-watt power
DCKs	Derived cipher keys
DGNA	Dynamic group number allocation
DM	Direct Mode
DMO	Direct Mode Operation
DM-REP	Direct Mode Repeater

DQPSK	Differential quaternary phase shift keying
DTMF	Dual tone multi-frequency
DVB	Digital video broadcasting
EMC	Electro Magnetic Compatibility
EQx	Equalizer testing
ETSI	European Telecommunications Standards Institute
FDMA	Frequency division multiple access
FDT	Format Descriptions Techniques
FM	Frequency modulation
FTP	File transfer protocol
GCK	Group cipher key
GIS	Geographic Information System
GMSK	Gaussian minimum shift keying
GoS	Grade of service
GSM	Global System for Mobile communications
GSM SCIA	GSM advanced Speech Call Item
HTx	Hilly Terrain
IEEE	The Institute of Electrical and Electronics Engineers
ISDN	Integrated services digital network
IT	Information Technology
ITU	International Telecommunication Union
Kb/s	Kilo bite per second
Kbit/s	Kilo bite per second

KHz	Kilo Hertz (103 cycles/s)
Km	Kilo meter
LA	Location area
LMDS	Local Multipoint Distribution System
LS	Line (-connected) station
LTU	Line termination unit
MAC	Medium access control
MHZ	Mega hertz (106 cycles/s)
MoU	Memorandum of Understanding
MPT	Ministry of Post and Telecommunications (standards, e.g., MPT1327)
MS	Mobile station
ms	Mille second
msec	Mille second
MSK	Minimum shift keying
MTU	Mobile termination unit
NDB	Normal Downlink Burst
NMU	Network management unit
NSAP	Network-layer Service Access Point
NT	Network termination
NUB	Normal Uplink Burst
OPEX	Operating EXpenses
OSI	Open systems interconnection
OTAR	Over The Air Re-keying

PABX	Private automatic branch exchange
PAS	Publicly Available Specifications
PCH	Paging CHannel
PDN	Public data network
PMR	Public mobile radio
PSS	Public safety and security
PSTN	Public switched telephone network
QPSK	Quaternary phase shift keying
RACH	Random Access CHannel
RAx	Rural area
RFI	Request for Information
RPCELP	Regular Pulse Code Excited Linear Prediction
Rx	Receiver
SCKs	Static cipher keys
SDL	Specification and Description Language
SEK	Signaling encryption keys
SwMI	Switching and Management Infrastructure
TDMA	Time division multiple access
TE	Terminal equipment
TEK	Traffic encryption key
TETRA	TErrestrial Trunked Radio
TIP	TETRA Interoperability Profiles
Tux	Typical Urban

TV	Television
Tx	Transmitter
UAE	United Arab Emirates
UHF	Ultra high frequency
UMTS	Universal Mobile Telecommunications Service
V+d	Voice plus data
VHF	Very high frequency
VAD	Voice activity detector
VDB	Visitor database
W	Watt
WAP	Wireless Application Protocol
WiMax	Worldwide Interoperability for Microwave Access