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Public Safety Radio Frequency Spectrum: A Comparison of Multiple Access Techniques

FINAL

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1. INTRODUCTION

As local, state, and federal governments plan and install radio networks supporting communications requirements, the success of these networks may be driven by the availability of the radio frequency spectrum. The radio frequency spectrum, a finite natural resource, has greater demands placed on it every day. In an effort to make the most efficient use of this resource, various technologies have been developed so that multiple, simultaneous users can be supported in a finite amount of spectrum. This concept is called "multiple access." The three most commonly used access methods are frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA).

To plan, design, procure, and use any kind of radio communications, a basic understanding of the technologies involved is essential. In the last 20 years, great strides have been made in this area of technology. Wireless communications technologies, which were virtually unheard of as recently as the late 1970s, are now prevalent throughout today's society and growing in demand. However, limited by the finite frequency spectrum, spectrally efficient technologies have not kept pace with today's high traffic demands. To ensure profit grows parallel with the demand for wireless technologies, manufacturers have had to develop methods of putting more users in the same spectrum space.

This report will discuss the functionality of each access method (FDMA, TDMA and CDMA), the advantages and disadvantages of each technology, and various forms of implementation for each technology. FDMA and TDMA are currently being used to support conventional and trunked radio systems, as well as commercial cellular systems. CDMA is being used primarily in cellular systems at this time. (See PSWN Report: *Comparisons of Conventional and Trunked Systems,* May 1999.) An easy to understand example is given to provide the reader a general overview of how each technology differs. Next, a comparison is made between the technologies followed by a discussion of the primary benefits each technology offers to wireless communication system. Finally, the report discusses how the TIA-102 (Project 25) and TETRA (TErrestrial Trunked Radio) standards can support public safety communications systems. This document is *not* intended to cover the tremendous amount of detailed technical information available on this subject.

General concepts to keep in mind: Each radio frequency or “channel” must consist of enough space to carry the intended signal to its destination. Therefore, when the terms “spectrum space,” “radio frequencies,” or “channels” are used, it should be understood that actual physical space is involved, albeit invisible to the human eye. (It should also be noted the terms “frequency” and “channel” can be used interchangeably, and “channel’ *may* refer to a set of two frequencies used to support one link, such as between a base station and a vehicle.) Radio signals vary in size depending on the type of “message” being carried. The size of the signal is referred to as “bandwidth.”

2. UNDERSTANDING FDMA, TDMA, AND CDMA: A NON-TECHNICAL EXAMPLE

The best way to describe the differences between FDMA, TDMA, and CDMA technologies is with an example of how they work. The following example is one of the best.

Picture a large room with a group of people divided up into pairs. Each pair would like to hold their own conversation with no interest in what is being said by the other pairs. For these conversations to take place without interruption from other conversations, it is necessary to define an isolated environment for each conversation. In this example, the room should be considered as a slice of the radio spectrum specifically allocated to be used by this group of people. Imagine each pair communicating through cellular telephones or radios.

Applying an FDMA system to this analogy, the single large room (slice of spectrum) would be partitioned with many dividing walls and creating a large number of smaller rooms. A single pair of people would enter each small room and hold their conversation. Each room is like a single frequency/channel. No one else could use the room (or frequency) until the conversation was complete, whether or not the parties were actually talking. When the conversation is completed, the first pair of people would leave and another pair would then be able to enter that small room.

In a TDMA environment, each of the small rooms would be able to accommodate multiple conversations "simultaneously." For example, with a three-slot TDMA system, each "room" would contain up to three pairs of people, with the different pairs taking turns talking. According to this system, each pair can speak for 20 seconds during each minute. Pair A would use 0:01 second through 0:20 second, pair B would use 0:21 second through 0:40 second, and pair C would use 0:41 second through 0:60 second. However, even if there were fewer than three pairs in the small room, each pair would still be limited to 20 seconds per minute.

Using the CDMA technology, all the little rooms would be eliminated. All pairs of people would enter the single large room (our spectrum space). Each pair would be holding their conversations in a different language and therefore they could use the air in the whole room to carry their voices while experiencing little interference from the other pairs. The air in the room is analogous to a wideband "carrier" and the languages represent the "codes" assigned by the CDMA system. In addition, language "filters" would be incorporated so that, for example, people speaking German would hear virtually nothing from those speaking another language. Additional pairs could be added, each speaking a unique language (as defined by the unique code) until the overall "background noise" (interference from other users) made it too difficult to hold a clear conversation. By controlling the voice volume (signal strength) of all users to a minimum, the number of conversations that could take place in the room could be maximized (i.e., maximize the number of users per carrier). Additional pairs can be easily added to the room without much interference to the other pairs.

3. FDMA—FREQUENCY DIVISION MULTIPLE ACCESS

A. Overview

Frequency division is the original multiple access technique. Currently, most legacy public safety wireless networks use FDMA to improve spectrum efficiency. FDMA is used throughout the commercial wireless industry. Legacy commercial telecommunication networks (analog networks based on Advanced Mobile Phone Service [AMPS] and Total Access Communications System [TACS] standards) are built on a backbone of cellular base stations, using the FDMA technology. However, due to increased spectrum efficiency of CDMA and TDMA systems, very few, if any, new cellular systems are using FDMA.

B. How it Works

FDMA systems separate a client's large frequency band into several smaller individual bands/channels. Each channel has the ability to support a user. Guardbands are used to separate channels to prevent interference. They are used to isolate channels from adjacent-channel interference.

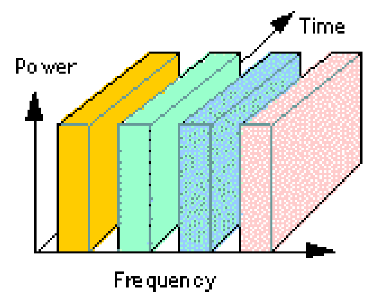

Figure 1: FDMA permits only one user per channel because it allows the user to use the channel 100 percent of the time. Therefore, only the frequency "dimension" is used to define channels. Each block represents a different user

When the FDMA technique is employed, each user is assigned a discrete slice of the radio frequency (RF) spectrum, a "channel" of spectrum space that will vary in size depending on the type of signal being transmitted. In a given amount of spectrum space, the user is granted access to a small sliver of the overall allocation. As long as the user is engaged in "conversation," no other user can access the same spectrum space. An example of this type of access is use of the spectrum by commercial radio broadcasters. In the commercial radio broadcast bands, 535–1705 kHz for amplitude modulation (AM) and 88–108 megahertz (MHz) for frequency modulation (FM), each local broadcast station (user) is assigned a specific slice of spectrum within the frequency band allocated for that purpose. As long as the station broadcasts, no other radio station in the same area can use that radio frequency bandwidth to send a signal. Another broadcast station can use that same bandwidth only when the distance between the stations is sufficient to reduce the risk of interference.

In a conventional two-frequency public safety radio system, one frequency is used to transmit and the other is used to receive. Each channel has its own center frequency and each channel has a bandwidth that is a fraction of the original allotted bandwidth. In this type of system, if an FDMA channel is in use, other users cannot use it until the "conversation" is complete. This is one of the inefficiencies of FDMA systems. Figure 2 graphically displays a two-frequency conventional system. The mobile and portable radio users transmit on frequency F1 to the repeater; the repeater then retransmits back to the users on frequency F2. In Figure 2, the F1 lightning symbol is an uplink to the repeater while the F2 lightning symbol is a downlink.

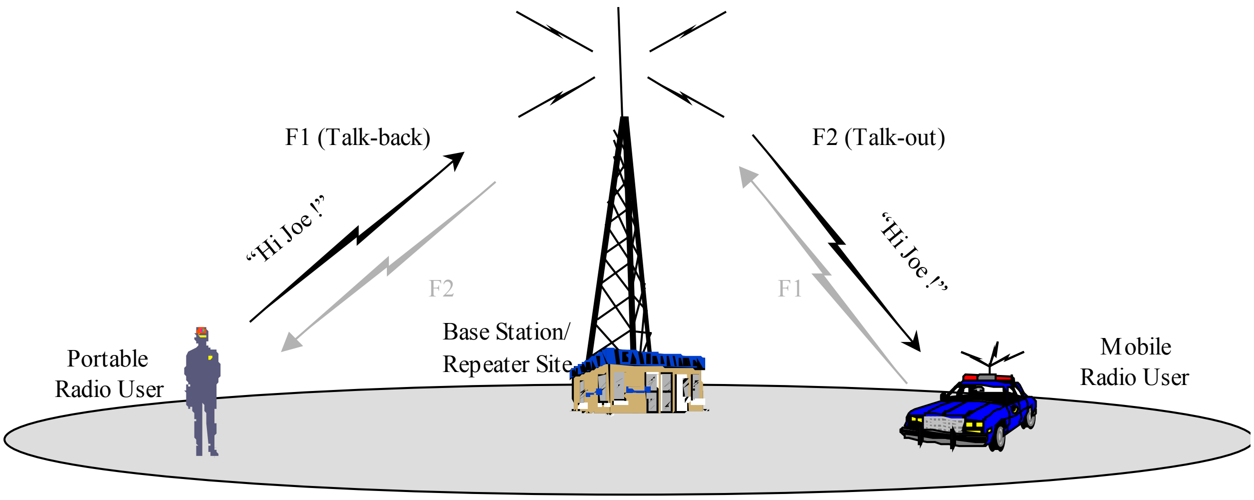

Figure 2: Single-Site Conventional System Configuration Operating in Half Duplex

Project 25's (P25) Phase I standard requires upgrades from standard analog technology with a 25 kHz bandwidth to digital technology with a narrower bandwidth of 12.5 kHz. Implementation of an FDMA system would give each user access to two separate frequency allotments, each with a 12.5 kHz bandwidth. Under P25, this newer equipment is also required to be "backward compatible" to the legacy 25 kHz analog equipment to allow a smooth transition.[3]

Because adjacent channel interference is an important factor in channel quality, frequency planning is a key consideration when selecting fixed or base station locations. Frequency planning is complicated and difficult. Available frequency bands must be researched and analyzed. Transceiver transmission strength affects fixed station range while antenna design affects its coverage patterns. These are also important factors in frequency planning. Figure 3 is a sample base station coverage scheme for a cellular system.

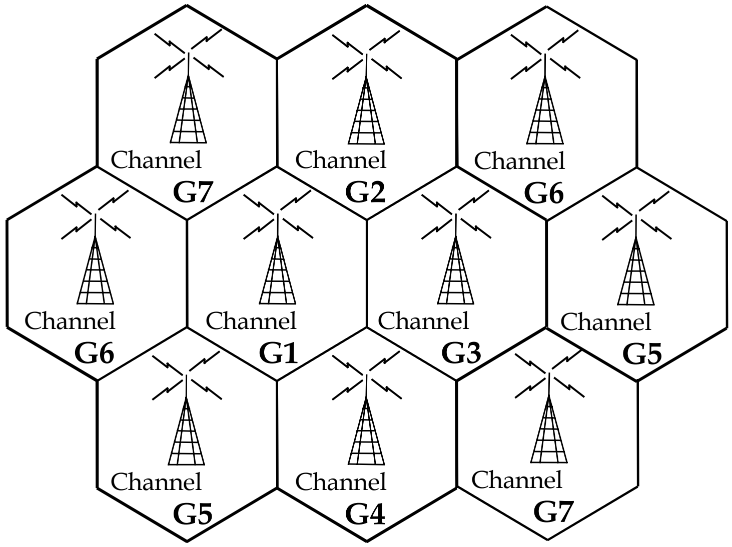

Figure 3: Channels F1-Fn are divided into 7 groups (G1-G7). Each site is assigned a frequency group different from adjacent sites to minimize co-channel interference.

C. Advantage / Disadvantages

Advantages

- Simple to implement, from a hardware standpoint
- Fairly efficient with a small base population and when traffic is constant
- P25 equipment is backward compatible to legacy 25 kHz analog radio equipment

Disadvantages

- Network and spectrum planning are intensive
- In a conventional system, because channels are allocated for one user, idle channels add to spectrum inefficiency
- Frequency planning is time-consuming

4. TDMA—TIME DIVISION MULTIPLE ACCESS

A. Overview

As the frequency spectrum experiences more traffic, spectrum efficiency becomes increasingly important. TDMA systems were developed as FDMA system spectrum efficiency became insufficient. Not only do TDMA systems split users into an available pair of channels, but they also assign each user an available time-slot/cell within that channel. TDMA systems have the capability to split users into time slots because they transfer digital data, instead of analog data commonly used in legacy FDMA systems. Each of the users takes turns transmitting and receiving in a round-robin fashion. Frequency division is still employed, but these frequencies are now further subdivided into a defined number of time slots per frequency. In reality, only one user is (actually) using the channel at any given moment. Each user is transmitting and receiving in short "bursts." Because TDMA systems do not transmit all of the time, their mobile phones have an extended battery life and talk time.

B. How it works

Similar to an FDMA trunked system, when a user depresses the Push-To-Talk (PTT) switch in a TDMA system, a control channel registers the radio to the closest base station. During registration, the base station assigns the user an available pair of channels, one to transmit and the other to receive. But, unlike an FDMA system registration, a TDMA system registration also assigns an available time-slot within the channel. The user can only send or receive information at that time, regardless of the availability of other time-slots. Information flow is not continuous for any user, but rather is sent and received in bursts. The bursts are re-assembled at the receiving end and appear to provide continuous sound because the process is very fast.

In Figure 4, each row of blocks represents a single channel divided into three time-slots. Calls in a TDMA system start in analog format and are sampled, transforming the call into a digital format. After the call is converted into digital format, the TDMA system places the call into an assigned time slot.

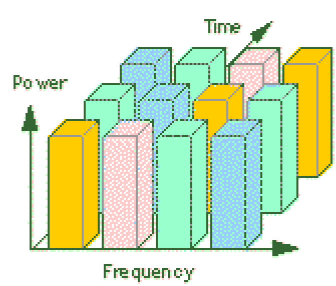

Figure 4: TDMA increases the number of users who have access to particular channel by dividing that channel into time-slots.

Figure 4 is also a graphical display of the efficiency of a TDMA system. The improved efficiency of TDMA over FDMA can be realized through a quick glance at Figures 1 and 4. In Figure 1, the FDMA system supports 4 users while in Figure 4, the TDMA system supports 12 users within the same bandwidth as the FDMA system. There are systems in place today that allow an increase of up to six times the capacity of FDMA alone.

Because TDMA systems also split an allotted portion of the frequency spectrum into smaller slots (channels), they require the same level of frequency planning as FDMA systems. The same careful steps in frequency planning must be taken in both FDMA and TDMA systems.

C. Advantage / Disadvantages

Advantages

- Extended battery life and talk time
- More efficient use of spectrum, compared to FDMA
- Will accommodate more users in the same spectrum space than an FDMA system which improves capacity in high traffic areas, such as large metropolitan areas
- Efficient utilization of hierarchical cell structures – pico, micro, and macro cells
- Can handle video and audio data efficiently

Disadvantages

- Network and spectrum planning are intensive
- Multipath interference affects call quality
- Dropped calls are possible when users switch in and out of different cells
- Frequency planning is time consuming
- Frequency guard bands add to spectrum inefficiency
- Too few users result in idle channels (rural versus urban environment)
- Higher costs due to greater equipment sophistication

5. CDMA—CODE DIVISION MULTIPLE ACCESS

A. Overview

CDMA is a spread spectrum technique used to increase spectrum efficiency over current FDMA and TDMA systems. Although spread spectrum's application to cellular telephony is relatively new, it is not a new technology. Spread spectrum has been used in many military applications, such as anti-jamming (because of the spread signal, it is difficult to interfere with or jam), ranging (measuring the distance of the transmission to determine when it will be received), and secure communications (the spread spectrum signal is very hard to detect).

B. How it works

With CDMA, unique digital codes (Walsh Codes), rather than separate radio frequencies/ channels, are used to differentiate users. The Walsh codes are shared by the mobile phone and the base station, and are called "pseudo-Random Code Sequences." All users access the entire spectrum allocation all of the time. That is, every user uses the entire block of allocated spectrum space to carry his/her message. A user's unique Walsh Code separates the call from all other calls. Figure 5 graphically shows each user simultaneously accessing the fully allotted frequency spectrum.

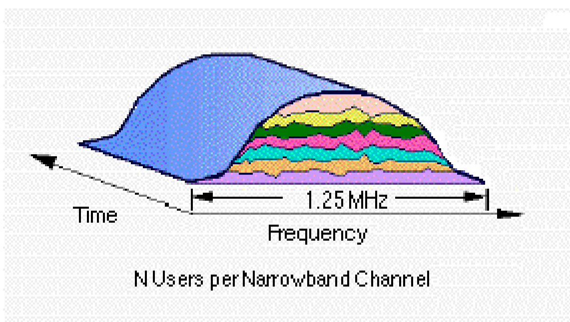

Figure 5[1]: CDMA allows all users access to their entire allocated spectrum.

CDMA, being a "spread-spectrum" technology, spreads the information contained in a signal over the entire available bandwidth and not simply through one frequency. Due to the wide bandwidth of a spread-spectrum signal, it is very difficult to cause jamming, difficult to interfere with, and difficult to identify. It appears as nothing more than a slight rise in the "noise floor" or interference level, unlike other technologies where the power of the signal is concentrated in a narrower band making it easier to detect. Therefore CDMA systems provide more privacy than FDMA or TDMA systems. These are great advantages over technologies using a narrower bandwidth.

CDMA channels can handle an unspecified number of users. There is not a fixed number. The capacity of the system depends on the quality of current calls. As more users are added, noise is added to the wideband frequency and therefore decreases the quality of current calls. Each user's transmission power increases the level of the frequency spectrum's "noise floor" and therefore decreases the overall call quality for all users. To help eliminate the "noise floor," CDMA mobile phones and base stations use the minimum amount of power required to communicate with each other. They use precise power control to decrease users' transmission power. By decreasing a user's transmission power, the mobile phone has added battery life, increased talk time, and smaller batteries.

Because CDMA is a spread spectrum technology, it requires less frequency planning. The full original spectrum is not divided into separate blocks/channels, like it is in FDMA and TDMA systems. Therefore, there is no need to plan for multiple frequency guardbands. Because all users have access to the entire spectrum at all times, frequency planning only needs to consider one frequency/channel. However, the channel requires relatively wide contiguous bandwidth.

C. Advantages / Disadvantages

Advantages

- Greatest spectrum efficiency: capacity increases of 8 to 10 times that of an analog system and 4 to 5 times that of other digital systems which makes it most useful in high traffic areas with a large number of users and limited spectrum
- CDMA improves call quality by filtering out background noise, cross-talk, and interference
- ”Soft handoffs”— Because of the multiple diversities in use, handoffs between cells are undetected by the user
- Simplified frequency planning - all users on a CDMA system use the same radio frequency spectrum.
  - Engineering detailed frequency plans are not necessary.
  - Frequency re-tunes for expansion are eliminated.
  - Fewer cells are required for quality coverage
- Random Walsh codes enhance user privacy; a spread-spectrum advantage
- Precise power control increases talk time and battery size for mobile phones

Disadvantages

- Backwards compatibility techniques are costly
- Currently, base station equipment is expensive
- Difficult to optimize to maximize performance
- Low traffic areas lead to inefficient use of spectrum and equipment resources

6. SYSTEM DESIGN FACTORS – TECHNOLOGY COMPARISON

Using five different performance metrics, the following table shows the differences between each of the technologies. Each technology is rated based on their performance with respect to the ideal performance level.

	FDMA	TDMA	CDMA
Capacity (Spectrum Efficiency)	1	2	3
Security	1	1	3
Ease of Network Planning	1	1	2
Ease of Implementation	4	4	2
Cost of Implementation	3	3	2
Backwards Compatibility	4	3	1

Excellent 4 3 2 1 0 Poor

Definitions for each performance metric is described below:

Capacity (Spectrum Efficiency): Measures the ability to handle heavy traffic.
Security: Measures the ability to keep information from being intercepted by others.
Ease of Network Planning: Measures the ease of creating and planning network structures.
Ease of Implementation: Measures the ease of carrying out a network system and equipment.
Cost of Implementation: Measures the financial requirements of carrying out a network system and equipment.
Backward Compatibility: Measures the ability to comply with existing systems.

7. PUBLIC SAFETY STANDARDS

A. Project 25/TIA 102

Project 25 is a joint effort of local, state, and federal governments, with support from the U.S. Telecommunications Industry Association (TIA). The primary objectives of the P25 standards process are to provide high quality digital, narrowband radios that meet public safety user needs, and to maximize interoperability. Additional objectives include obtaining maximum radio spectrum efficiency, ensuring competition throughout the life of systems, and ensuring that equipment meets the user needs. Although developed in the United States, Project 25 standards were designed for the global marketplace. P25 radios are produced for any VHF or UHF public safety band. The standards developed through Project 25 have been adopted and published by TIA and are referred to as TIA-102 standards.

Project 25 considered various access technologies in an attempt to make the best use of the available radio frequency spectrum. Under Phase I of P25, upgrades moved the existing equipment from standard analog technology with a 25 kHz bandwidth to digital technology with a narrower bandwidth of 12.5 kHz and FDMA capability. TIA-102 requires all new equipment to be "backward compatible" with the analog equipment to allow for a smooth transition.

In Phase II of P25, more spectrum-efficient equipment using FDMA and TDMA technologies will be implemented with a spectral efficiency equivalent to at least one voice channel within a 6.25 kHz bandwidth. This equipment must also be backward compatible to Phase I equipment. Phase II technologies will increase the user capacity up to four times that of conventional technology, depending on the type of equipment being used.

B. TETRA

TErrestrial Trunked RAdio (TETRA) is a modern digital Private Mobile Radio (PMR) and Public Access Mobile Radio (PAMR) standard being used in Europe to support public safety and other public services. With support of the European Commission (EC) and the European Telecommunications Standards Institute (ETSI) members, the TETRA standard has been developed over a number of years through the cooperation of manufacturers, users, operators and other experts, with emphasis on ensuring the standard will support the needs of emergency services thoughout Europe and beyond. The standard builds upon the lessons and techniques of previous analog trunked radio systems and the successful development of Global System for Mobile Communications (GSM) during the 1980s. The work started in 1990 and the first standards were ready in 1995. However, the TETRA standard is not yet mature so it is important to understand and identify the actual deliverables (functions and features) from each vendor before purchase since they may differ. Not all the standards have been completed, causing some proprietary designs to be implemented first or non-delivery of the function until the standards are complete. It is therefore important to understand the standard and to follow its progress.[13]

TETRA offers fast call set-up time, addressing the critical need for many user segments, excellent group communications support, direct mode operations between radios, packet data and circuit data transfer sevices, frequency economy, and excellent security features. TETRA uses

TDMA technology with 4 user channels on one radio carrier and 25 kHz spacing between carriers. This makes it inherently efficient in the way that it uses the frequency spectrum.

TETRA trunking facilities provide a pooling of all radio channels that are then allocated on demand to individual users, in both voice and data modes. By the provision of national and multi-national networks, national and international roaming can be supported. The user can be in continuous contact with his/her colleagues. TETRA supports point-to-point and point-to-multipoint communications both by the use of the TETRA infrastructure and the use of Direct Mode without infrastructure.

8. CONCLUSION

The access techniques discussed in this report are the latest technologies being used to expand the capacity and range of existing systems. FDMA was the first to be implemented in Phase I of P25 during the early 90's. Although difficult to plan, implementation was relatively simple and FDMA was the technology supported by the majority of the manufacturing community. To increase spectrum availability, Phase II of P25 is developing standards for TDMA technology as well as 6.25 kHz FDMA. Both of these technologies use digital technology but still provide the capability to interoperate with analog systems which provides interoperability between systems.

CDMA technology has many advantages and is the most recent multiple access technology to be considered. However, CDMA technology has not become a major player because it is more difficult and expensive to provide equipment that accommodates FDMA, TDMA, and CDMA systems. It is more difficult to provide backward compatibility, a primary objective of P25, if a CDMA system is implemented. The research conducted for this report did not reveal any plans to develop CDMA equipment for public safety radio equipment. However, the research did indicate that using a combination of CDMA and TDMA technologies could improve the quality of service and user capacity without loss of range in cellular telephone systems. As the demand for wireless services increase and technology advances, it is highly probable these techniques will continue to evolve within the public safety arena.

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Appendix A—Acronyms

AM	Amplitude Modulation
AMPS	Advanced Mobile Phone Service
APCO	Association Of Public-Safety Communications Officials International, Inc.
CDMA	Code Division Multiple Access
EC	European Commission
ETSI	European Telecommunications Standards Institute
FDMA	Frequency Division Multiple Access
FM	Frequency Modulation
GSM	Global System for Mobile Communications
kHz	kilohertz
MHz	Megahertz
P25	Project 25
PAMR	Public Access Mobile Radio
PMR	Private Mobile Radio
PTT	Push-to-talk
RF	Radio Frequency
TACS	Total Access Communications System
TDMA	Time Division Multiple Access
TETRA	Terrestrial Trunked Radio
TIA	Telecommunications Industry Association
UHF	Ultra High Frequency
VHF	Very High Frequency