PSWN

Public Safety Wireless Network

Comparisons of Conventional and Trunked Systems

May 1999

FOREWORD

Land mobile radio (LMR) networks are critical for public safety communications. In support of the Public Safety Wireless Network (PSWN) Program Management Office (PMO), Booz•Allen & Hamilton analyzed conventional, trunked, and hybrid system architectures to provide background information to public safety system planners on the different architecture alternatives.

Comparisons of Conventional and Trunked Radio Systems considers typical systems architectures. However, it does not analyze specific vendor systems, implementations, or technical requirements.

This report does not reflect a government position or endorse a particular type of LMR network architecture.

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1.0 INTRODUCTION

Increasing demands on frequency spectrum, a finite resource, force users create conditions force users to look for more spectrum-efficient systems, which the market is manufacturing along with increased features. Land mobile radio (LMR) systems are changing significantly. These changes include the introduction of narrowband digital LMR systems, the deployment of 800 megahertz (MHz) systems, the incorporation of advanced user services and features, and the development of alternative network architectures. Therefore, system planners may need to conduct a wide range of comparative analyses to determine the type of system that is most appropriate for their environment and requirements. Planners in public safety agencies need to consider, in addition, the special requirements imposed by their mission and operations.

An essential decision for LMR system planners is determining which system architecture should be implemented to meet technical, operational, and environmental requirements. In general, LMR systems are designed using one of three architectures: conventional, trunked, or a hybrid of the two. The selection of one architecture over the others is based on a range of factors, including spectrum, technical features, operational requirements, and cost considerations.

Comparisons of Conventional and Trunked Radio Systems is intended to provide background information for system planners, especially those in public safety agencies, to assist them in their evaluation of architecture options. Specifically the report—

- Informs system planners about the technical components and operational characteristics of LMR system architectures.
- Identifies essential technical and operational characteristics and considerations that relate to LMR performance and public safety communication requirements.
- Analyzes each architecture to highlight performance characteristics of, and the essential differences among, the alternatives.
- Provides system planners with descriptive information, analysis results, and operational considerations to foster decision making.

This document analyzes and compares conventional, trunked, and hybrid LMR systems. It provides high-level definitions of the architecture alternatives and analysis considerations. It then discusses each consideration as it applies to each of the architecture alternatives.

2.0 LMR TECHNOLOGY AND ARCHITECTURES

2.1 Brief History of LMR

Federal Communication Commission (FCC) rules define a land mobile radio system as a regularly interacting group of base, mobile, and associated control and fixed relay stations intended to provide land mobile radio communications service over a single area of operation. The term mobile refers to movement of the radio, rather than association with a vehicle; hence mobile radio encompasses handheld and portable radios.

The possibility of radio communications was established in 1864 by James Clerk Maxwell, then a professor of physics at Cambridge University. Maxwell showed theoretically that an electrical disturbance, propagating at the speed of light, could produce an effect at a distance. Theory was first put into practice by Hertz, who demonstrated spark-gap communications over distances of several feet in the 1880s. The distance was rapidly extended by Marconi, who by 1901 succeeded in transmitting Morse code across the Atlantic ocean. The vacuum tube made speech transmissions practical and by 1915 the American Telephone & Telegraph company had sent speech transmissions from Washington, D.C., to Paris and Honolulu.

The first practical land mobile communications occurred in 1928 when the Detroit Police Department finally succeeded in solving the instability and low sensitivity problems that had plagued their mobile receiver designs for 7 years. By 1933, a mobile transmitter had been developed, allowing the first two-way police system to operate in Bayonne, New Jersey. The 1939 success of a state-wide Connecticut highway patrol system using frequency modulation (FM) led to a nationwide phase-out of amplitude modulated equipment.

By 1933 the need for radio regulation was also apparent and the first operating rules were mandated by the Federal Radio Commission. The Federal Communications Commission was established one year later. Twenty-nine very high frequency (VHF) channels between 30 and 40 MHz (known today as low band) were allocated for police use. In 1946 the initial rules for the Domestic Public Land Mobile Radio Service were established and high band frequencies between 152 and 162 MHz were allocated. Small businesses could now purchase airtime from common carriers, thus avoiding the large startup costs of a private system. Previously only certain industries had access to mobile radio frequencies; for example, public safety, public utilities, transportation, and the media.

Since then, the rapid growth of the land mobile radio industry has been accompanied by substantial additional spectrum allocations in the ultra high frequency (UHF) band (406 to 512 MHz), and the 800- and 900-MHz bands. Nonetheless, it appears that practical mobile spectrum is unlikely to significantly increase because there is nothing left to allocate; hence, today's strong push toward more efficient use of the spectrum already allocated.

Increased efficiency can be achieved in a variety of ways. Technological advancements in frequency control have allowed the 900-MHz band to be channelized at 12.5 kHz. Major improvements have been occurring in speech coding and modulation efficiency. Trunking of groups of radio channels allows operation at much higher loading levels than single channels can handle with acceptable access delay. Finally, the cellular radio telephone service introduced in 1981 has boosted spectrum efficiency through geographic reuse of channels in the same metropolitan coverage area. [1]

These advances in technology have a profound effect on public safety communications infrastructure and operations described later in this study.

Typically, LMR systems are designed using one of three architectures: conventional, trunked, or hybrid, which is a combination of the two. This section briefly describes the architectures and principal differences between them.

2.2 Conventional Systems

2.2.1 Simplex

In simplex operation one terminal of the system transmits while the other terminal receives. Simultaneous transmission and reception at a terminal is not possible with simplex operation. The simplex dispatching system consists of a base station and mobile units, all operating on a single frequency.

Simplex operation is sometimes referred to as single-frequency simplex. [2]

2.2.2 Half Duplex

In half-duplex dispatching systems, the base station and the mobile transmit on two different frequencies. The base station transmits on the mobile's receive frequency and vice versa. However, the half-duplex terminal equipment does not allow simultaneous transmission and reception. Half-duplex operation is sometimes referred to as two-frequency simplex. [2]

Half-duplex configuration was designed to allow a repeater-type of operation, when a base station "repeats" and amplifies a mobile's signal on a different frequency (see Exhibit 1).

Half-duplex operation is used most commonly in public safety LMR systems.

2.2.3 Full Duplex

In full-duplex operations, radios can transmit and receive simultaneously. As in half duplex, this operation uses two frequencies, the difference is that transmitter and receiver can be both powered and active full time. Repeater base stations typically operated in full-duplex mode, receiving on one frequency and re-transmitting the signal on another frequency, using separate transmit and receive antennas. For full-duplex single-antenna configuration, additional equipment is required such as duplexer, which enables the receiver and transmitter to use the same antenna simultaneously. LMR systems rarely use this type of operation, since full-duplex subscriber units are typically much more expensive and, if battery-powered, consume more battery power.

2.3 Techniques for Improving and Extending Area Coverage

2.3.1 Single-Site Systems

In the beginning, LMR systems were built as single-site systems. A single-site system was designed to provide coverage for a small geographical area such as a factory, small town, or manufacturing facility. Single-site systems, which initially consisted of one simplex base station, evolved into the base station repeater which operated in a half-duplex fashion with a paired set of frequencies as shown in Exhibit 1. Mobile radio users communicate with a dispatch or other radio users by accessing the base station repeater, which retransmits the signal on the mobile receive frequency to all user radios. It also facilitates communicating with the dispatch console operator through the base station without using the repeater function. In all cases, the user radio must be within the range of coverage of the repeater, base station, or other radio asset.

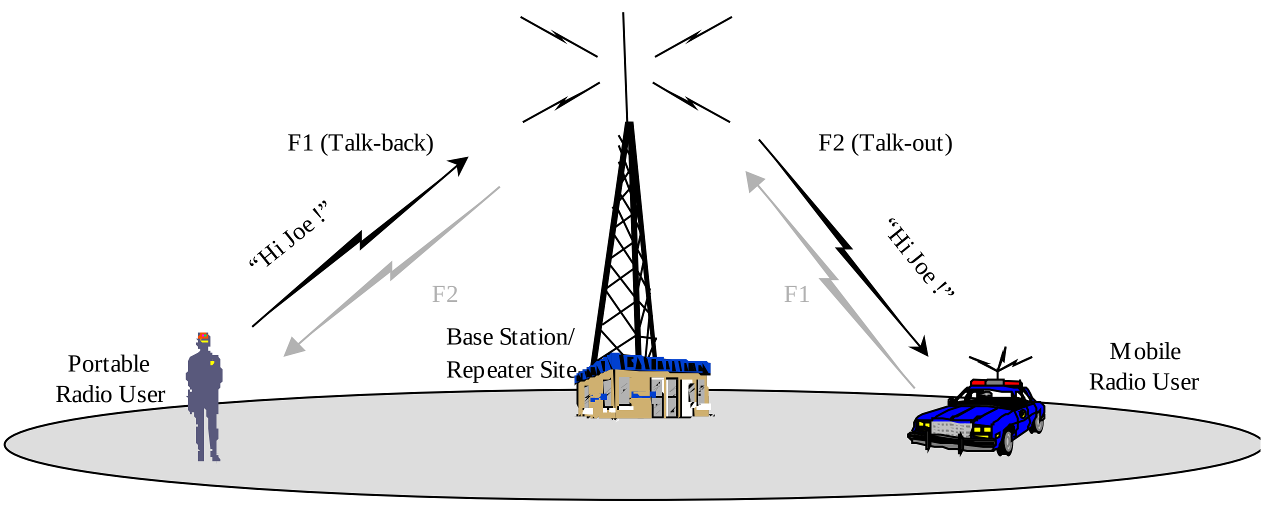


Exhibit 1 Single-Site Conventional System Configuration Operating in Half or Full Duplex

2.3.2 Receiver Voting Systems

The base transmitter in a LMR system typically has much more power than mobiles or portable radios. The base antenna is typically at a much higher elevation than mobile or portable radio antennas. For these reasons, mobiles and portables communications are limited by their talkback capability.

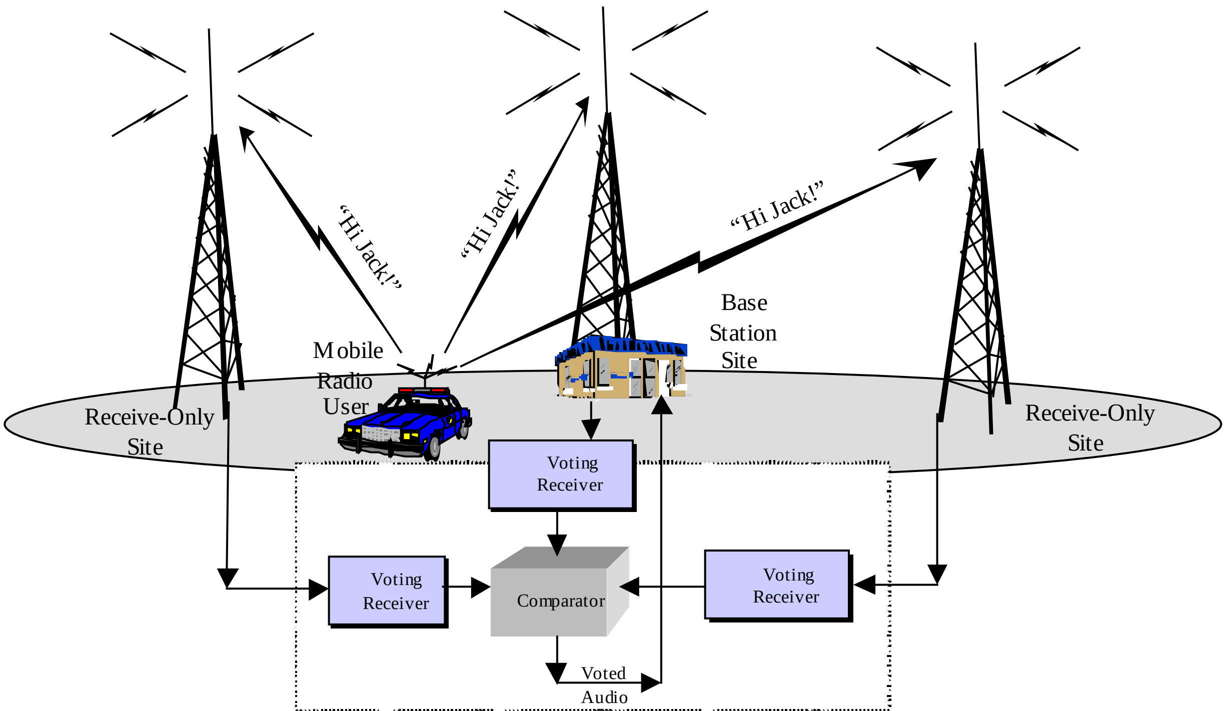


Exhibit 2 Receiver Voting System

One way to improve the talkback capability is to use a receiver voting system, as shown in Exhibit 2. A number of radio receivers located in strategic areas receive the RF signal from a mobile or portable unit. Receive-only sites act as "listening-only" base stations that receive the lower power signals of mobiles and portables and relay them back to a base station or repeater, usually via dedicated telephone or microwave links. By using one or more receive-only sites in conjunction with a high-power base station or repeater transceiver, the overall system talk back coverage can be expanded. A receiver voter or comparator is used to select the best receive signal. The comparator is usually located in a dispatching center. The "best" signal is voted in the comparator and the dispatcher hears that voted audio.

To provide a reliable talkback coverage when hand-held radios are used, the number of voting receivers must be increased considerably, compared to mobile-only talkback coverage, because of the lower transmitter power and antenna efficiency. [2]

2.3.3 Multi-Site Systems

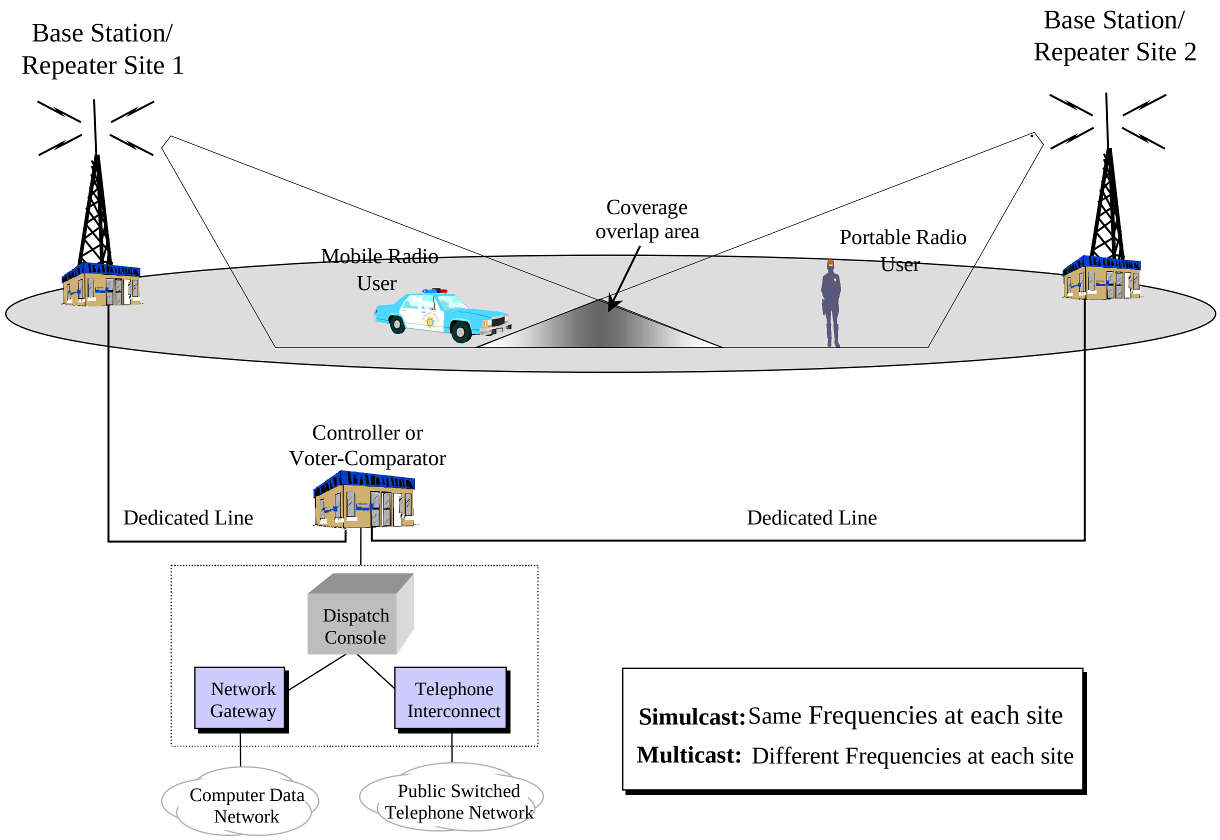


Exhibit 3 Typical System Configuration of a Two-Site Simulcast or Multicast System

If the service area calls for multiple transmitter sites and simultaneous coverage of that area, broadcast-type systems are used. The two major kinds of such systems are simulcast and multicast (Exhibit 3).

2.3.4 Simulcast Systems

Simulcast systems use several geographically separated base stations/repeaters that transmit on the same frequencies simultaneously (Exhibit 4). Through this type of a system deployment, a single radio channel can be radiated over a wider region than with a single-site transmitter. These networks require a timing system to synchronize each transmitter on the network to assure that transmissions on the same frequency are in phase thus reducing heterodyne interference. A simulcast system, when activated, performs a quasi-synchronous transmission, which means that the same message is transmitted at the same time on the same radio channel by two or more transmitters that are phase-locked to the same frequency.

Such systems are used where:

- A large service area must be covered by transmitters of moderate power, in which case there will be a small overlap in the coverage of the transmitters

- Intensive (high signal-to-noise ratio) coverage is needed throughout the area, in which case there will be a substantial overlap in the coverage of the transmitters that are used to provide diversity against shadowing (fading)
- Available spectrum is insufficient to implement a multicast or zone-type system.

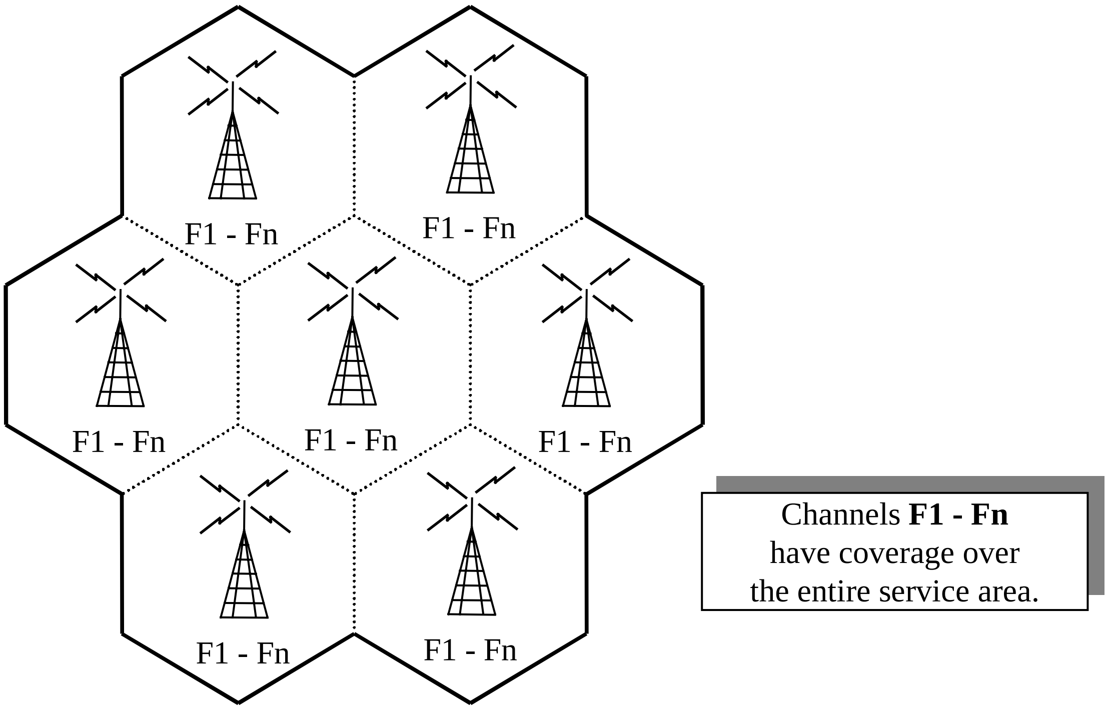
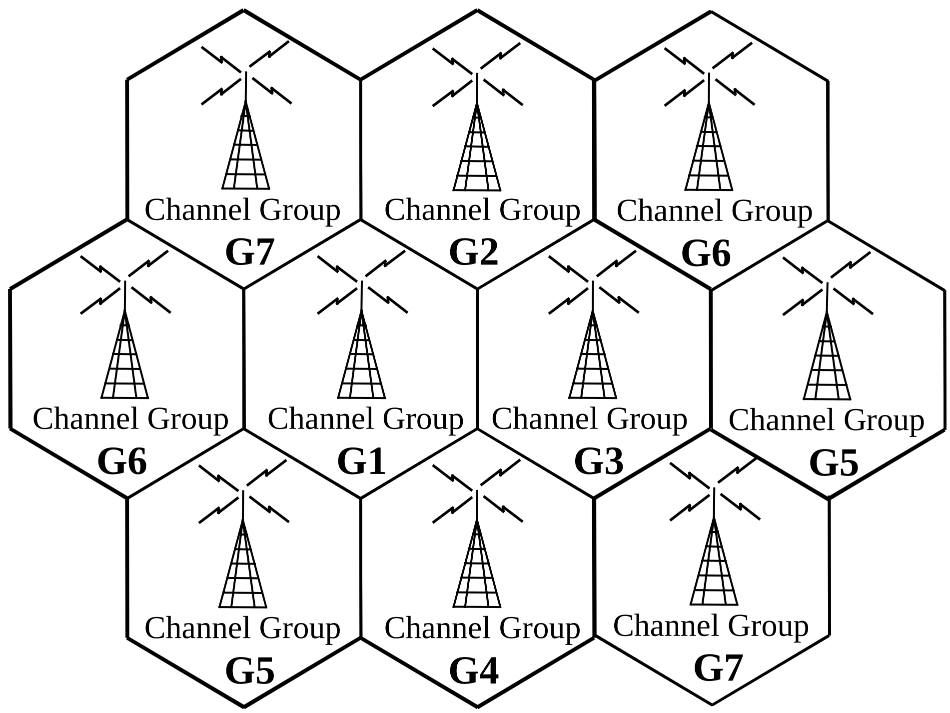


Exhibit 4 Frequency Layout of a Seven-Site Simulcast LMR System

2.3.5 Multicast Systems



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.

Exhibit 5 Frequency Layout of a Ten-Site Multicast or Zone-Type LMR System with Frequency Reuse Ratio of 7

Multicast systems are similar to simulcast systems with exception of the radio channels transmitted. While a simulcast system transmits on the same RF channels simultaneously from each base station/repeater, multicast systems use different RF channels at each site (Exhibit 5). Frequencies are reused in different cells, but the arrangement ensures the same frequency is never used in adjacent cells. This configuration offers the same coverage advantages of a simulcast system, eliminates the occurrence of co-channel interference from multiple sites, and allows smaller cell configuration which can allow greater RF penetration within the cell. However, multicast systems require multiple frequencies (limited available spectrum) and their users need to change mobile channels as they move between cells.

The main disadvantage of a broadcast-type architecture is that though it significantly expands coverage area compared with a single-site system, it does not increase capacity. For example, when two users occupy a channel at one site, that channel normally cannot be used at the same time by other users at different sites.

2.3.6 Zone-Type Systems

The disadvantage of lower user density is solved by applying zone approach and trunking logic. The coverage area is divided into zones served by different sites. The same channel can be used simultaneously by different groups of users at different sites thus enabling the system to handle a higher user density compared to broadcast-type systems. The frequency layout of zone-type systems is very similar to that of multicast LMR and cellular telephone systems. Frequencies are reused in different cells, but the arrangement ensures the same frequency is never used in adjacent cells (Exhibit 5). Frequency reuse patterns are defined by the ratio of the distance between identical frequency cells to the cell radius, which is a function of the desired carrier-to-interference ratio for the system design. The frequency reuse ratio is usually 4 or 7. A frequency layout for a system with a frequency reuse ratio of 7 is shown in Exhibit 5.

The main advantage of zone architecture is that it provides frequency reuse across the coverage area. The main disadvantage of the architecture is the high number of frequencies it needs. For example, if a frequency reuse ratio of 4 is chosen, a 10-channel system requires 40 frequency pairs, or 70 pairs if a reuse ratio of 7 is used. Zone architecture is used mainly in trunked systems, because it requires the use of a central control computer to operate.

2.4 Trunked Systems

At the present time the land mobile frequency spectrum is very crowded and additional frequencies are difficult to obtain. For this reason there has been a great deal of work in developing new techniques to conserve spectrum.

Trunking is one of these conservation systems. Trunking is the commonly accepted term for electronically controlled sharing of a relatively small number of communications channels among a relatively large number of users. In general terms, a trunk is a shared voice or data traffic path between two points. Trunked systems use access control schemes to share channel capacity among many users. The electronic control enables users to take advantage of the fact that some transmitted channels are idle at a particular time while others are busy. This results in a more balanced load sharing between trunks. This is in contrast to a non-trunked or conventional system, where the users exercise their own coordination regarding access to system resources, by listening for idle time and making manual channel selections, which may result in unbalanced channel loads. [2]

Trunked architectures differ by implementation of the system's control logic. There are two main types of trunking architectures: dedicated control channel (centralized trunking by FCC definition) and subaudible signaling control (decentralized trunking).[1] A combination of the two is also used in some systems.

In a dedicated control channel system (centralized trunked system), the system controller is the centralized logic of the system. It communicates with the units by way of the control

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1 *The trunking types listed may have a variety of names depending on the vendors; however the concepts remain the same.*

channel. All other channels act as repeaters for communications between user radios. When user radios are not communicating, they continuously monitor the control channel. When a user radio needs to communicate, it sends out a channel request on the control channel. This request includes the ID of the talk group with which the radio wants to communicate. The system controller checks whether a vacant channel is available or not, and sends instructions to units on the control channel.

This type of trunked architecture typically places blocked calls in a queue to wait for a vacant channel thus minimizing lost calls. Typically, a first-in-first-out queuing principle is used. As soon as a channel becomes available, a queued system signals it to the user radio. To assess traffic load performance of a system of this type, the Erlang C model is typically used, which calculates the average delay in queue.

The typical trunking system consists of some type of access control (whether in each mobile unit or centralized at a base station site), switching equipment, system management computer, control and voice channel repeaters, modems, and telephone interconnect as illustrated in Exhibit 6. Centralized trunking uses a microprocessor that governs all of the base station repeaters after receiving and processing service requests over the control channel. The switching equipment provides the interface between dispatch consoles and the central controller. The system computer allows computer access and monitoring of the central controller. In addition, trunking systems can be programmed to include specific options depending on the user's needs. Talk groups, encryption, emergency (e.g., man-down) operation, and telephone access are examples of some of the programming options.

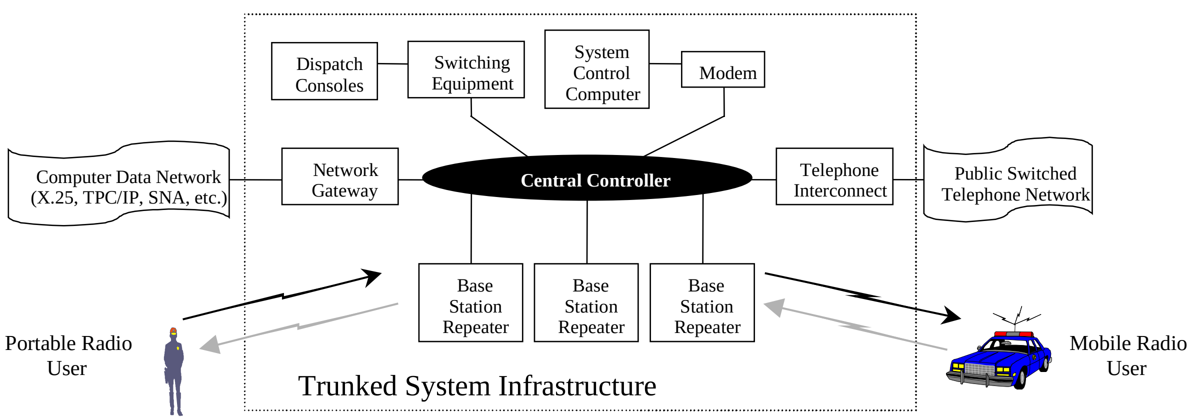

Exhibit 6 Typical Configuration of a Centralized Trunked System

A typical operational pattern of control channel trunking is as follows: User A wants to contact all of the units in his or her talk group. The Push-to-Talk (PTT) is keyed, which causes the radio to send a short burst of data to the control channel repeater. This data identifies the caller attributes and enters a channel request to the system controller. User A's radio then switches to receive mode to await a data response from the controller. Upon receipt of the request, the system controller attempts to select an available voice channel. If a voice channel is available, the system controller sends a data message over the control channel switching all units in User A's talk group to the available voice channel. Only units in this particular talk group are automatically switched to the assigned channel. When User A starts talking, all the members of the talk group will hear the conversation. This preempts any other use of that assigned channel for the duration of the call.

Trunked systems with subaudible control signaling, also known as scan-based or decentralized trunked systems, do not require a separate control channel and all channels can be used for communications between users. Each user radio monitors subaudible control data transmissions from its home channel continuously when it is not engaged in communications with other users. A home channel is one of the repeater transmit frequencies to which a particular user radio is assigned. The control information received subaudibly tells user radios what channel they should switch to if they need a channel to initiate communications or receive a call. It also tells them if all channels are busy. If a user attempts to initiate communications, he or she will hear a busy tone.

The logic in this system is distributed among each of the repeaters. A data bus connecting all of the sites updates the logic of individual sites to reflect which channels and sites are active and which are vacant. In this way, the system can operate without a system controller. The logic at each repeater can control those user radios for which it has a home channel. User radios are constantly advised of data relevant to the initiation and reception of communications. This design is usually limited to 15 channels.

In trunked systems with subaudible signaling, blocked calls are usually lost rather than being placed in a queue to await a vacant channel. The user must attempt to initiate communications later. To assess traffic load performance of a system of this type, the Erlang B traffic model is typically used, which calculates the probability of lost calls.

Modes of Trunking - Either type of trunked system architecture, control channel or subaudible control, has the capability to perform message or transmission trunking. Message-trunking mode, which is also called conversation trunking, uses a delay timer (hang time), which allows traffic an uninterrupted repeater (communication channel) for the entire conversation between several users. In a system operating in transmission-trunking mode, the repeater channel is relinquished immediately after each user releases the key of the radio during an ongoing conversation (no hang time). Subsequent transmissions within the same conversation are transferred to another repeater when the second party keys his or her radio. Message-trunking mode provides greater channel availability for the user, while transmission trunking provides a greater channel availability for the system.

A third mode of trunking is a technique called quasi-transmission trunking. This technique holds a channel open for about one second after the last user de-keys the microphone (short hang time). Quasi-transmission trunking mode does not hold the channel as long as message trunking after the microphone has been de-keyed. This should result in fewer times when the repeater is unavailable to other users. At the same time, the channel is held long enough for users to keep the channel if they respond quickly (in less than one second) to each other's transmissions.

Users do not manually select individual radio channels in a trunked system, unlike the procedure in a conventional system. Instead, they select talk groups, by performing essentially the same physical action of setting a knob to a different number. Each user radio is affiliated with at least one group and/or subgroup and has an individual ID. These groups may be called fleets and subfleets, or announcement groups and talk groups, depending on the manufacturer of the particular system. A talk group can be a subset of an announcement group as illustrated in Exhibit 7. When a member of a talk group initiates a conversation, the trunked system controller automatically allocates one of the free radio channels to that talk group. Each radio in the talk group is automatically tuned to the allocated channel for the duration of the transmission without the user's involvement.

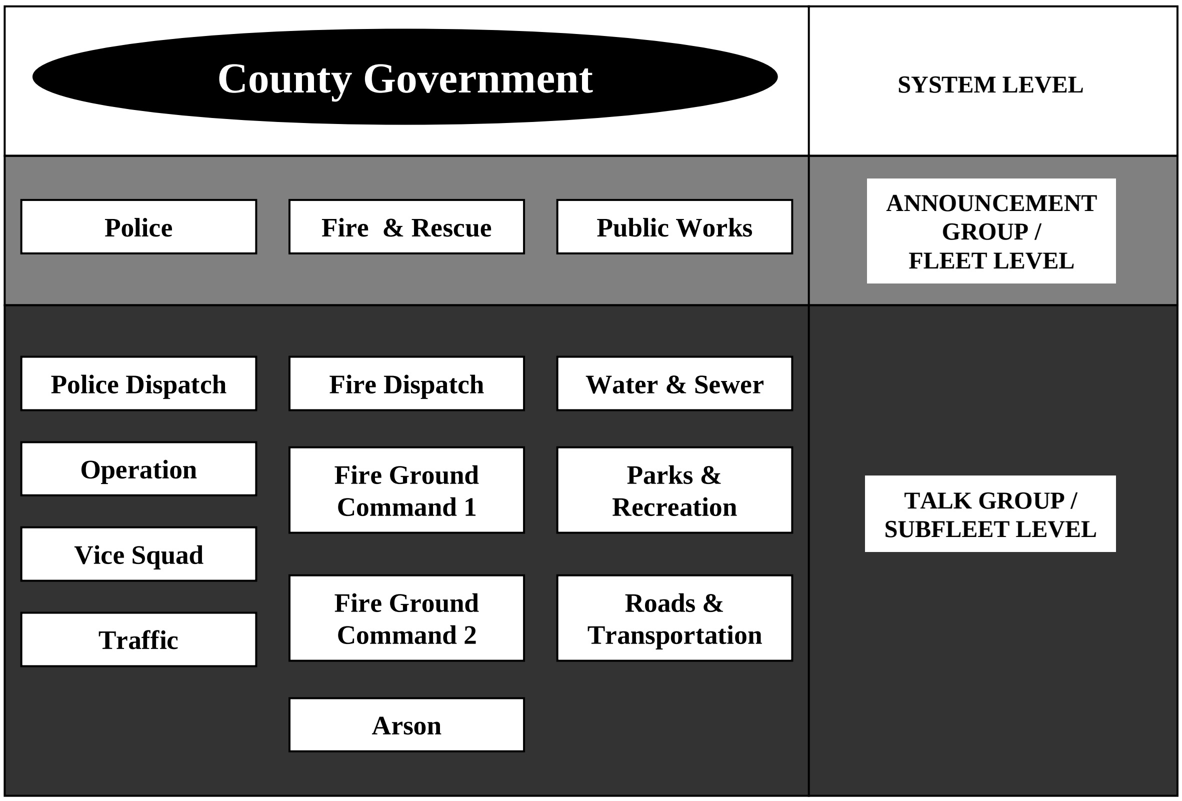

Exhibit 7 An Example of User Talk Groups in a Trunked System

Although initial trunked systems utilized the 800 and 900 MHz frequencies, in February 1997, the Commission adopted a Second Report and Order, which allows some centralized trunking in the shared private land mobile radio bands below 800 MHz.[2] the FCC now allows trunking on frequencies below 800 MHz if certain requirements are met (see Section 5.19), including the 150-162 (high VHF), 421-430 (UHF), 450-470 (UHF), and 470-512 (UHF-T) MHz bands. The rules adopted in the Report and Order became effective October 17, 1997. [5] For most government and private users in the VHF band, commonly referred to as the public safety pool and the industrial/business pool, trunking is not a common feature, since its implementation was only approved so recently.

2 *FCC Second Report and Order FCC 97-61*

2.5 Hybrid Systems

As its name indicates, hybrid systems are a combination of conventional and trunked systems. A hybrid system offers both conventional and trunked user groups and features within a single system. There are two major reasons for hybrid architectures. The first is cost. It may not be cost-effective to have a trunked site in an area with a few users; therefore, a conventional site would be a better alternative, but the conventional site would be part of a system with trunked portions serving areas with higher user density. The second reason is call setup delay. Because immediate communication is critical for user groups such as public safety agencies, conventional channels can be chosen to provide dedicated access with little or no call setup delay. However, large user organizations may include other user groups that are willing to accept the delay on trunked channels to take advantage of the capacity increase provided by trunking. Thus, a hybrid system architecture would provide conventional and trunked overlays in one system.

To provide trunked channels, a hybrid system needs the same system components as a trunked system. A hybrid system can be configured as an overlay of a trunked system by one or more conventional channels. In this case, a conventional channel would represent a talk group user to the trunked system logic.

User radios on a one-band hybrid system will be programmed to operate in either conventional only, trunked only, or conventional and trunked mode. Radios designated to operate in both modes would require the user to select conventional or trunked mode prior to establishing a call. When in conventional mode, a user would monitor the conventional channel and wait until it is free before attempting a call. This is the same procedure required of users on a conventional system. It differs from a trunked channel allocation where the user and that person's user group are automatically allocated a channel, if one is available. When in trunked mode, a user depresses the PTT button to make a call request, and the system controller handles the call as in a trunked system.

An example of channel and talk-group assignment in a hybrid system is presented in Exhibit 8. A conventional radio user can communicate with the trunked User Group B by selecting Channel 3 and vice versa: if a trunked user selects the trunked User Group B, he or she will also communicate with users of the conventional Channel 3.

USER GROUP	CHANNEL USED	ACCESS TYPE FOR USER GROUP
Not Applicable	Conventional Channel 1	Conventional Users Channel 1
Not Applicable	Conventional Channel 2	Conventional Users Channel 2
A	Any Available Trunked Channel	Trunked Users Talk Group 1
B	Conventional Channel 3 and Any Available Trunked Channel	Trunked Users Talk Group 1 and Conventional Users Channel 3
C	Any Available Trunked Channel	Trunked Users Talk Group 2
D	Any Available Trunked Channel	Trunked Users Talk Group 3
E	Any Available Trunked Channel	Trunked Users Talk Group 4
F	Any Available Trunked Channel	Trunked Users Talk Group 5
G	Any Available Trunked Channel	Trunked Users Talk Group 6

Exhibit 8 Example of a User Group Structure for a Hybrid System

3.0 ANALYSIS CONSIDERATIONS

This section lists and defines the considerations used to perform a comparative analysis of conventional, trunked, and hybrid LMR system types. To remain independent of specific vendors and to maintain as much consistency among systems as possible for comparative purposes, some assumptions and proxies were used. They are identified within the definitions below. The consideration definitions serves as metrics for the comparison.

3.1 List of Analysis Considerations

This subsection lists analysis considerations and includes high-level definitions.

CONSIDERATION	HIGH-LEVEL DEFINITION
Spectral efficiency	Measures frequency utilization in relation of total number of communications channels to total assigned bandwidth
Grade of service (GOS)	Measures percent of calls blocked during peak loading
Network capacity	Describes system performance under conditions of dense, moderate, and minimal user density for a similar geographic area
Call setup time	Measures average call setup time during normal and peak load conditions
Network architecture	Describes the hardware and systems needed to deploy the architecture
Network scalability	Describes the capability to seamlessly increase capacity, integrate new features, or support new communications applications
Network encryption	Describes the effect of user-based encryption on transmission and system performance
Network security	Describes the level of system vulnerability to transmission and computer-based electronic intrusion
Network robustness	Measures the capability to withstand single or multiple faults without service degradation and the time needed to recover from them
Multiorganizational interoperability	Describes the ability of each system to support interoperability between more than one user organization while providing a similar set of features
Ability to handle multiple voice and data applications	Describes system capability to seamlessly support voice and data traffic using common channels or user groups
Technology evolution	Describes the potential impact of technology evolution, including the introduction of system and user features
Policy impact	Describes the impact of FCC or legislative policies or actions that will affect the architecture
Compatibility with legacy systems	Describes system capability and interoperability needs to ensure compatibility with legacy analog systems
Required user discipline	Describes the level of user discipline needed to ensure that multiple parties can concurrently use a common set of channels
Network management	Describes the requirements for and the complexity of conducting network and system management
Network operator training	Describes the training needed to ensure system operators and technician can support network operations and resolve system faults or failures
Network cost effectiveness	Describes the optimal cost alternative using a set of potential user technical, operational, or environmental requirements
Migration to Trunking	Provides general information on the alternatives for migration to a trunked system

Exhibit 9 High-Level Definitions of Analysis Considerations

3.2 Analysis Considerations Definitions

This subsection provides detailed consideration definitions and comments on their relevance to public safety requirements and operations.

***Spectrum Efficiency* -** This is a measurement of the number of half-duplex radio communication channels, voice or data, provided by an LMR system versus the amount of spectrum required by that system. For the purposes of this analysis, spectrum efficiency is measured by the number of communications channels per 25 kHz of spectral bandwidth. Thus, a system occupying 25 kHz of spectral bandwidth and providing one half-duplex voice channel would be measured as 1channel/25 kHz.

***Grade of Service (GOS)* -** GOS is typically defined as the probability of an inbound communications call, i.e., a PTT, not being blocked in an attempt to reach a central traffic server. Depending upon the distribution model being used, this probability could be measured against a requirement either for immediate service or within a prescribed time delay.

***Network Capacity* -** This consideration analyzes the number of users that an LMR system can support within a specific geographic area. The number of users supported typically varies based on the number of channels available and the usage characteristics anticipated.

***Call Setup Time* -** Call setup time is an important system parameter showing how quickly a user can begin communicating over a particular system. Call setup time is defined as the time passed between the user's pushing the PTT button and the radio's response that the system is ready to accept the call. It measures the speed of network response to a user's request for communications. Call setup time typically consists of radio power on, propagation, call processing, time-in-queue, and synchronization delays and is usually measured in milliseconds (ms).

For systems that require synchronized operation of base and mobile radios and systems in an encrypted mode, a synchronization delay may significantly increase call setup time. Due to differences in protocol and operation, call setup times are different for conventional, trunked, clear, and encrypted systems.

Call setup time is affected by system architecture and configuration, the speed of switching equipment and software, the configuration of a particular call, as well as by the traffic load at that particular time. This analysis consideration describes the impact of trunking on call setup time.

***Network Architecture* -** This describes the amount and type of LMR specific hardware or related components required fielding a "typical" network configuration. Components may include but are not limited to the following network architecture elements:

- System Controllers

- Base stations/Repeaters
- Dispatch Consoles
- Switching Equipment
- System Control Computers
- Telephone Interconnects
- Satellite receivers (receive-only remote sites)
- Voter/comparators
- Data Network Gateways
- Scanners

These components include only the elements required to process or broadcast LMR transmissions in a typical configuration. Although communication transport mediums and related hardware, such as telephone lines, microwave links, and multiplexer/demultiplexers, are a part of network architecture, they are site specific and are not included in this analysis.

Network Scalability - This analysis consideration addresses the ability to seamlessly increase system capacity by adding communication voice or data channels:

- Ability to seamlessly add additional system features for system-wide users or individual user groups. Features include items such as tone codes, telephone patch capability, user ID, and over-the-air rekeying of the encryption key
- Ability to seamlessly support new communications applications in the form of new data features such as mobile data transmissions, SCADA (Supervisory Control and Data Acquisition) telemetry, short messaging, still frame video, etc.
- Ability to add additional sites (transmit, receive, or transmit and receive) to accommodate system growth.

Many specific equipment features affecting scalability are dependent on the vendor. To remain vendor-independent, this analysis does not compare individual features and applications available, but rather determines whether the systems are capable of expansion.

Network Encryption - The encryption of information at its origin and decryption at its intended destination without any intermediate decryption. The evolution of LMR technology toward digital provides a solid basis for encrypted communications. At the same time, encryption has some negative effects. These can include an increase in call setup time for both conventional and trunked systems, deterioration of voice quality, decrease in the throughput rate for data applications, and a reduced radio coverage area. The study quantifies these changes for each type of system.

Network Security - Network security consists of features that prevent unauthorized personnel from accessing system components or communications. Such actions include jamming, eavesdropping, spoofing, and physical sabotage. The analysis defines the areas of vulnerability, including physical, such as computer-based electronic intrusion, and RF transmission.

Network Robustness - A robust network degrades in such a manner that it continues to operate, but provides a reduced level of service rather than failing completely. In the comparison of conventional and trunked systems, it is necessary to compare systems of the same generation. This study focuses on advanced digital systems. Many specific equipment features affecting robustness are dependent on the standard and vendor used. The analysis compares the capability of conventional and trunked systems to withstand single or multiple faults.

Multiorganizational Interoperability - This analysis consideration evaluates the ability of each system to support interoperability between more than one user organization while providing a similar set of features.

Ability To Handle Multiple Voice and Data Applications - This analysis describes the system capability to seamlessly support voice and data traffic using common channels or user groups. It compares any existing inherent advantages/disadvantages of conventional or trunked systems for data voice/data integration.

Technology Evolution - This section analyzes the impact of technology evolution on existing and planned LMR systems and the risks assumed when selecting a conventional or trunked system type. It also gives a five-year forecast for LMR technology trends, as well as the impact of the emerging standards, such as TIA/EIA-102.

Policy Impact - This section analyzes the impact of Federal Communications Commission (FCC) and National Telecommunications & Information Administration (NTIA) policies on architecture selection.

Compatibility with Legacy Systems - This analysis determines whether the newer digital conventional/trunked systems or their components will interoperate with existing (legacy) analog conventional FM systems over the air interface. The analysis determines whether compatibility depends on system type (conventional or trunked). If interoperability cannot be achieved through little or no system re-configuration, such systems are considered incompatible.

Required User Discipline - This analyzes the network discipline required of users to ensure that multiple parties can easily share a common set of channels. For the purposes of this study, user discipline includes the discipline or control required on the part of users, so that they do not collide with other users' communications within the same channel.

Network Management - The analysis describes the requirements for and the complexity of conducting network and system management for conventional and trunked types of systems, including maintenance, radio and call group allocation, upgrading (software, hardware), optimizing performance, encryption key management, over-the-air features, and interoperability with other systems (if possible).

Network Operator Training - This analysis consideration describes the amount and types of training required by typical system operators and on-site radio technicians to assure they have the skills required to maintain day-to-day system operation. System operators include radio system managers employed by the user agency. Technicians are those individuals employed by the user agency to handle system maintenance, trouble-shooting, and repair.

Network Cost Effectiveness - This analysis provides general cost information on the different architecture alternatives to aid decision making regarding system cost, with a chart showing cost per user for different types of networks.

Considerations for Migration to Trunking - This analysis provides general information on the alternatives for migration to a trunked system.

4.0 SUMMARY OF RESULTS MATRIX

The matrix below summarizes results of the comparison analysis of conventional and trunked radio system architectures. The body of the analysis is given in Section 5.

Analysis Considerations	Conventional	Trunked	Hybrid
Spectrum Efficiency	– Similar between systems – Increases depending on type of technology used: wideband, narrowband, advanced digital modulation and multiple access schemes	– Similar between systems – Increases depending on type of technology used: wideband, narrowband, advanced digital modulation, multiple access schemes, number of users	– Similar between systems – Increases depending on type of technology used: wideband, narrowband, advanced digital modulation and multiple access schemes
Grade of Service (GOS)	– Call blocking at peak periods – Message colliding occurs unknown to caller, if gets no answer, the caller tries again – Manual call delay	– Call queuing during peak periods prevents call retries and message collision – Call delay occurs during queuing – Preemptive access limited – Call abandonment may occur, if queuing delay is significant	– Different for different overlays – Calculated as in conventional for the conventional overlay and as in trunked for the trunked overlay
Network Capacity	– High capacity and user density during low usage – Lower throughput/capacity at high usage	– Call queuing provides higher throughput and capacity at peak usage periods than in conventional architecture – In centralized trunked architecture typically one channel per site is dedicated to system control, therefore capacity per channel is lower than in decentralized trunked architecture	– Network capacity is a summation of capacities of the conventional and trunked overlays
Call Setup Time	– 15 ms typically – for legacy systems – 250 ms typically – for advanced digital systems with user authentication features. Also increases significantly if encryption is used	– 250 ms typically for both, analog and digital, technologies. Also increases substantially if encryption is used.	Typically: – 15 ms – for basic conventional overlay – 250 ms – for conventional overlays using advanced digital technology – 250 ms – for trunked overlay – 250 ms – for cross-calls (additional) – all times increase if encryption is used
Network Architecture	– No computer logic required for non-TIA/EIA-102 systems – No network required for direct user-to-user communications	– Interconnections needed for transmitter synchronization – Site and central controllers needed in centralized trunking systems – Control microprocessors in user radios required in decentralized trunking systems – More complex than conventional architecture	– A combination of conventional and trunked overlays – More complex than both conventional and trunked architectures
Network Scalability	– Allows for continued capacity expansion via additional channels and/or equipment	– Centralized trunking architecture allows for continued capacity expansion via additional channels – Channel addition limited in decentralized trunking architecture. (Can be expanded up to 15 channels per site with noticeable call setup delays) – Many cellular-like software-based features available	– Conventional overlay is as expandable as a conventional system – Trunked overlay scalability is also similar to trunked systems
Network Encryption	– Type 1 through 4 encryption products and algorithms are available on many types of LMR architectures	– Type 1 through 4 encryption products and algorithms are available on many types of LMR architectures	– Type 1 through 4 encryption products and algorithms are available on all types of LMR architectures

Continued

Analysis Considerations	Conventional	Trunked	Hybrid
Network Security	– Fewer architecture elements allows for fewer opportunities for intrusion – No form of dynamic frequency hopping is used, allowing for easy eavesdropping on one channel – Digital systems allow stronger encryption and may have user authentication feature	– User IDs and authentication prevents unauthorized access – Frequency hopping between conversations or messages makes eavesdropping more difficult – Digital systems allow stronger encryption and prevent unauthorized access	– Conventional overlay is as secure as a conventional system using the same technology – Trunked overlay is also as secure as a trunked system using the same technology – Combined security of a hybrid network is determined by the overlay with lower security
Network Robustness	– Sites capable of functioning independently in the event of outage at another site – Transceiver failures result in channel loss – Backup, stand-by equipment can limit outages	– In a networked configuration, inter-site calls cannot be provided during the failure of the central controller – Failure of a single traffic channel is usually unnoticeable by users except by increased delay in peak traffic periods – In centralized trunked systems, failure of a control channel may result in a shutdown of the site if backup or soft-fail features are not provided – Backup, stand-by equipment can limit outages	– Conventional overlay is as robust as a separate conventional system – Trunked overlay robustness is similar to trunked systems – The overall robustness of a system is determined by the robustness of its less robust overlay
Multiorganizational Interoperability	– Multiorganizational interoperability is limited over the air interface by the use of the same modulation type, mode, channelization, and encryption type and key – If interoperability not achievable over the air interface, it can be achieved with audio cross patches (either analog or digital)	– Is limited over the air interface by the use of the same modulation type, mode, channelization, and encryption type and key – If interoperability not achievable over the air interface, it can be achieved with audio cross patches (either analog or digital) – Some advantages for management of interoperability features. For example, creation of new groups or adding new members to a new group typically can be done in real time allowing formation of talk groups across organizational lines as needed.	– Interoperability may be achieved over conventional or trunked air interfaces as mentioned in respective systems – Has the advantages of trunked talk group management, which is available only to trunked users – As in other types of the systems, audio cross patches can be used (either analog or digital) – As in the other types of systems, if encryption is used, it should be of the same type and using the same key
Ability To Handle Multiple Voice and Data Applications	– Conventional architecture is well suited for packet-switched data on dedicated channels – Regular FDMA channels are unable to handle simultaneous voice and high to medium-rate data on one frequency channel	– Trunked architecture is less well suited for packet data, better suited for circuit-switched data – Regular FDMA channels are unable to handle simultaneous voice and high to medium-rate data on one frequency channel	– Hybrid architecture can use advantages of its conventional technology for packet-switched data transmissions and trunking for circuit-switched data – Regular FDMA channels are unable to handle simultaneous voice and high to medium-rate data on one frequency channel
Technology Evolution	– Conventional used in smaller systems with smaller user bases and few frequencies, where spectral efficiency of trunking cannot be realized – Digitalization – Increased set of user features – Strong encryption	– Trunked used in larger systems where larger pools of frequencies allow for full realization of trunking advantages supporting more users per frequency – Digitalization – Increased set of user features – Strong encryption	– Hybrid used on a case-by-case basis
Policy Impact	– The FCC National Plan Report and Order provided incentives for using trunking and requiring small entities with minimal requirements to join together in using a single system where possible, thus encouraging the use trunking in the 800-MHz band	– The FCC is encouraging the use of trunking as a spectrum-efficient technology – Decentralized trunking is allowed in all LMR bands – In addition to the 800-MHz band, the use of centralized trunking has now been permitted in lower LMR bands, subject to meeting certain licensing requirements	– Hybrid systems are not specifically defined and addressed by policy makers

Continued

Analysis Considerations	Conventional	Trunked	Hybrid
Compatibility with Legacy Systems	– Generally new analog conventional systems are compatible with legacy analog configurations – Compatibility between current digital conventional systems and legacy analog system is only via audio patches – TIA/EIA-102 systems are designed to be compatible with legacy analog systems over the air interface – Systems that are simultaneously analog and digital cannot interoperate over the air interface. The compatible digital system must be switched to analog mode to allow for simultaneous interoperation with an analog legacy system	– Digital trunked systems usually employ a gateway technique for migration from analog systems – Same issues of analog/digital compatibility apply as for conventional systems	– Since hybrid systems consist of conventional and trunked overlays, all compatibility considerations that apply to the two will be correct for the respective overlays of a hybrid system
Required User Discipline	– Conventional systems require a significant amount of user discipline on the part of each radio user to ensure that all the users on the system are able to share the channel	– Users on trunked systems do not have to monitor the system for an available channel to make a call – When communicating in their talk group, trunked users must obey by the user discipline rules applicable to conventional users	– Users of the conventional overlay of a hybrid system are required to abide by conventional user discipline – Trunked users do not have to monitor the system for an available channel to make a call. Nonetheless, when communicating in their talk group, trunked users must obey by the rules applicable to conventional users
Network Management	– Manual management required	– Many network management features are automated	– A combination of the two, requires manual management for conventional overlay – Management of trunked overlay is mostly automated
Network Operator Training	– Less training required – Some large conventional systems require a more detailed knowledge of system configuration from an operator/dispatcher than in trunked systems	– More training required for technicians and managers	– More training required for technicians and managers – Requires a good understanding of system configuration from an operator/dispatcher
Network Cost Effectiveness	– Less expensive than trunked – TIA/EIA-102 can be as expensive as trunked due to the use of user authentication equipment – Cost determined mostly by technology used, specific configuration, and user options selected, not by type of architecture	– More expensive than conventional – Cost determined mostly by technology used, specific configuration, and user options selected, not by type of architecture	– Cost determined mostly by specific configuration, technology used and user options selected – Some large hybrid systems can be more expensive than similar trunked due to conventional and trunked integration complexity

5.0 ARCHITECTURE ANALYSIS AND COMPARISON

This section analyzes and compares the alternatives using the analysis considerations. The subsections are organized by analysis consideration; each subsection includes an analysis of each architecture to allow system planners to compare analysis approaches, assumptions, and results.

5.1 Spectrum Efficiency

Spectrum efficiency is similar in different architecture types. It depends on channelization and type of multiple access used. Conventional and trunked systems are currently available in two channelizations: 25 kHz and 12.5 kHz. Each channelization, due to the bandwidth used, offers a different level of spectrum efficiency. Most systems in use today operate using 25 kHz half-duplex analog channels. Newer narrowband systems, however, operate in half the bandwidth, using 12.5 kHz half-duplex channels. For comparative purposes, spectrum efficiency is measured by the number of available traffic channels per 25 kHz of bandwidth. Exhibit 10 lists various spectrum efficiencies:

LMR SYSTEM MODE	NUMBER OF TRAFFIC CHANNELS PER 25 kHz	SPECTRUM EFFICIENCY
25 kHz Analog	1 channel	1 : 1
12.5 kHz Narrowband Analog	2 channels	2 : 1
12.5 kHz Narrowband Digital (current TIA/EIA-102 Phase 1)	2 channels	2 : 1
6.25 kHz Narrowband Digital (future TIA/EIA-102 Phase 2)	4 channels	4 : 1

Exhibit 10 Spectrum Efficiency

Narrowband systems provide higher spectrum efficiency due to the lower spectrum requirement for a single channel. However, the drawback of narrowbanding is a reduction in data capacity that can be accommodated by narrowband channels.

5.2 Grade of Service (GOS)

GOS is defined as the probability of an inbound communications call, i.e., a PTT, being blocked in an attempt to reach a central traffic server. There are essential differences in what causes blocking in conventional and hybrid systems.

In a conventional system where all users share and actively monitor a radio channel, blocking occurs when a user attempts to place a call (i.e., depresses the PTT button) at the same time that one or more other users attempt to place a call. In general, as a result of this user interference, neither user's message is received and both users must retry the call. Thus, during periods of peak usage when the chances of user interference are the greatest, users must continuously listen to a conventional channel and wait for a free moment to avoid colliding. This results in a manual delay of the call attempt. When free time is heard on the radio channel, users attempt to gain access, hoping not to conflict with a simultaneous request from another user. In certain cases, conventional user radios override and do interfere with other ongoing transmissions for necessary access (i.e., emergency or "man down" calls). However, in conventional systems, call delay is normally experienced by the user who is awaiting a free channel, and call-blocking results in no system throughput since both users must retry their transmission.

Centralized trunked systems make use of a set of shared channels. In this type of system, blocking occurs when a user attempts a call and no channels are available. At this moment, unlike conventional systems, a trunked system places the call attempt in a queue awaiting a free channel. As a result, the user experiences a queuing call delay and is notified of a free channel when it becomes available for his or her call. The use of a central controller in a trunked system prevents users from interfering with each other's conversations during peak usage periods. It results in a greater throughput of the number of calls per unit time than a conventional system, where users manually wait for a free channel and retry calls when call blocking occurs. Unless a priority feature is built into a trunked system, user radios are not able to override the controller for instant blocking-free access.

The essential difference in the concept of grade of service between conventional and trunked systems is as follows:

- Conventional systems involve manual call delay, require call retries if interference was created by another user
- Trunked systems involve queuing call delay, prevent collision of calls, thus reducing call retries.

5.3 Network Capacity

In LMR systems, channel capacity is a function of the user channel access protocol. To maximize capacity, users of a conventional system "listen then transmit." In an extreme situation, as the channel load increases, the chance of colliding messages increases. At that time, a greater number of messages are lost and effective channel throughput is reduced. Users that are more impatient will "transmit when ready," colliding with other messages and degrading the system performance. At this point, users typically abandon or do not attempt calls that are not essential, prioritizing their own calls based on the situation as they understand it, from monitoring the radio traffic.

Trunked LMR systems make use of electronically controlled access to multiple channels in the system. Users are prevented from causing a message collision since the system controls channel access. At peak usage periods when all channels are active, trunked systems are able to prevent message collisions and minimize retries. At those times, trunked systems provide greater network capacity than conventional systems because they provide a greater message throughput. At lower traffic periods, however, trunked systems inherently have a longer call setup delay. Appendix B illustrates the impact of using conventional and trunked systems on network capacity and call delay. Traffic modeling shows that the electronically controlled access capability of trunked systems provides less call delay, overall, and thus provides a greater throughput as traffic load in a typical system increases.

5.4 Call Setup Time

In a conventional system, a call attempt must simply seize the channel to which the radio is programmed or set. Call attempts do not require a central system controller channel assignment although a central controller is occasionally used to provide enhanced features. Thus, call setup times for conventional systems are shorter than for trunked when a free channel is available. Call setup time within a conventional system is a function of three processes: powering up of the user radio transmitter, radio signal propagation delay through the atmosphere to a repeater (typically 5 microseconds per mile), and repeater processing time. These three processes typically take 15 milliseconds after a user depresses the PTT button.

Call setup time within a trunked system is a function of many more processes than in a typically conventional system. In addition to the setup time typical of a conventional system (power of transmitter, propagation delay to repeater, and repeater processing time), several other processes occur when a call attempt is placed from a trunked user radio. Exhibit 11 identifies the call setup time typical for a trunked radio when a free channel is available.

PROCESS	SUBPROCESSES	TIME[3]
1. User radio call request time	• User presses PTT • Radio powers up transmitter on control channel • Radio encodes request message • Propagation delay of request message on control channel to controller occurs (minimal)	23 ms
2. Controller processing time	• Receipt and recognition of mobile request • Identification of available free channel • Establishment of instructions on channel assignment for all radios in talk-group	95 ms
3. Controller call request response time	• Controller transmits instructions to all talk group radios on control channel • Propagation delay occurs as instructions are transmitted over control channel (minimal)	23 ms
4. User radio processing time	• Requesting radio receives and processes instructions • Requesting radio switches to allocated channel	95 ms
5. Radio call establishment time	• Radio powers up transmitter on assigned channel • Propagation delay to repeater occurs (minimal) • Repeater retransmits audio on assigned channel (radio power up time)	20 ms
TOTAL TIME		**255 ms**

Exhibit 11 Trunked Radio Call Setup Time

Call setup time within a conventional digital system with user authentication feature is similar to that in a trunked system due to added computer processing. For example, the TIA/EIA-102 call setup time for conventional channels is stated as not to exceed 250 ms, which equals that of a trunked system.

Call setup times in hybrid systems differ greatly depending on the specific configuration employed. Calls executed over a conventional part of a hybrid system have a call setup time equal to that on a stand-alone conventional system with the same technology. Calls conducted over the trunked part of the hybrid system will have a setup time equal to that on a stand-alone trunked system. However, users making cross-calls (trunked to conventional or conventional to trunked) experience call setup delays similar to trunked.

5.5 Network Architecture

The basic architecture and configuration types of conventional systems are described in Section 2 of this report. Conventional systems can be single-site or multisite systems and offer receiver voting, single channel multicast, and multichannel multicast configurations. Components typically include base stations/repeaters, satellite receivers, and consoles. More complex multisite systems may require interconnection links between sites to facilitate time synchronization. In some cases, a conventional system may also include a system controller to provide enhanced features. Because a conventional system does not require a controller or processor to handle call requests and call group/channel management, the complexity of a conventional system is typically much less than that of a trunked or hybrid network. In fact, when users are operating in a simplex or mobile-to-mobile mode, no network architecture is needed to provide communications.

[3] *Approximate time (milliseconds) required to accomplish process*

Section 2 includes descriptions of architectures used for trunked radio network design. In addition, a component overview of a typical trunked system is displayed in Exhibit 6. These common components are relatively standard for either network. At a minimum, a multisite simulcast network needs some form of interconnect medium with constant latency for transmitter phase synchronization. Similarly, a zone system that needs to cover a large area has to deploy some form of frequency re-use pattern. All trunked systems require a central controller and interconnection links to that site. The need for this interconnection and the controller increases the network architecture complexity of a trunked LMR network.

5.6 Network Scalability

This analysis consideration discusses advanced digital systems to allow comparison of similar generation networks. Advanced digital conventional systems provide the ability to expand capacity, features, channels, and components over time as the need arises. Although different vendors offer different options and features for expandability, all vendors make their equipment scalable and offer that capability as a main selling point. Vendors have developed modular expandable digital conventional networks to enable users to increase services and features as their user base grows.

Each vendor offers different types of features, but in general, all conventional systems allow for continued expansion of capacity through the addition of channels and/or base stations/repeaters. Advanced digital conventional systems offer options for additional tone codes and telephone patch capabilities, if needed. Availability of other features varies by vendor.

Trunked radio communication system scalability is directly proportional to the manufacturer specifications. Some of today's more advanced LMR systems are comparable to cellular communication systems. They provide many, if not all, of the cellular features that have become popular such as person-to-person calls and short messaging, and also have the advantage of making group/dispatch calls.

The trunking controller and the portable and mobile radios are microprocessor-driven. This intelligence makes it possible to control the network equipment and the radios working in the system. Since the system' s computer is software driven, the capacity to accommodate upgrades is higher. Some of the scalable facilities include:

- Private individual-to-individual conversations
- Private group conversations
- Caller identification
- Priority for emergency calls
- Telephone/radio interconnect
- Ability to make status calls without voice transmission
- Conventional channel programming in user radio.

The underlying technology of a hybrid system combines conventional and trunked overlays. As a result, the scalability of the conventional overlay of a hybrid system is expected to be the same as in a conventional system. In the trunked overlay, as in a stand-alone trunked system, the control software and the intelligence it confers give it a greater flexibility to accommodate upgrades.

5.7 Network Encryption

Network encryption must be implemented if users require a heightened level of security against advanced interceptors. With the current technological advances, digital encryption is the standard. Digital voice encryption requires that the analog voice signal be sampled, digitized, encrypted, transmitted, and decrypted in real-time.

Standard network encryption schemes are available on all types of LMR systems. Encryption is independent of system type and architecture. Four types of encryption products and algorithms are deployed in the United States:

- Type 1 - A classified or controlled cryptographic item endorsed by the National Security Agency for securing classified and sensitive U.S. Government information. *Note:* The term refers only to products, and not to information, key, services, or controls. Type 1 products contain classified National Security Agency algorithms. They are available to U.S. Government users, their contractors, and federally sponsored non-U.S. Government activities subject to export restrictions in accordance with International Traffic in Arms Regulation. [7]
- Type 2 - Unclassified cryptographic equipment, assembly, or component, endorsed by the National Security Agency, for use in telecommunications and automated information systems for the protection of national security information. *Note:* The term refers only to products, and not to information, key, services, or controls. Type 2 products may not be used for classified information, but contain classified National Security Agency algorithms that distinguish them from products containing the unclassified data algorithm. Type 2 products are subject to export restrictions in accordance with the International Traffic in Arms Regulation. [7]
- Type 3 - A cryptographic algorithm that has been registered by the National Institute of Standards and Technology and published as a Federal Information Processing Standard for use in protecting unclassified sensitive information or commercial information. [7]
- Type 4 - An unclassified cryptographic algorithm that has been registered by the National Institute of Standards and Technology, but is not a Federal Information Processing Standard. [7]

There are potential drawbacks to using encryption on an analog LMR system. In analog systems, when portables or mobiles are used in encrypted mode, the radio coverage can be decreased compared to operation in clear or unencrypted mode due to quantization noise. Estimates by users indicate that an encrypted analog transmitter station’s range can be limited by as much as 30 percent. Because encrypted signals are digitally coded, strong error-free signals are needed to properly decrypt transmissions limiting radio reception at the edge of an analog system's coverage.

In addition, due to encryption in both analog and digital systems, the call setup time can increase because of the additional steps in the encryption process such as base-mobile synchronization, key exchange, and encryption/decryption delay. Voice quality may also degrade when encryption is used.

The management of encrypted radios would also affect the security profile of the system. The manner in which keys and key-loading devices are physically protected is important. The type of algorithm used and length of keys affect the strength of the encryption.

LMR network encryption can be configured as air interface-only or end-to-end encryption. Obviously, end-to-end encryption configuration is much more secure.

Encryption qualities of an LMR network are not affected by type of network architecture, conventional, trunked or hybrid. All four types of encryption products and algorithms are available on all types of LMR network architectures.

5.8 Network Security

Each physical component of the conventional architecture represents a potential security vulnerability: base stations/repeaters, consoles, satellite receivers, telephone patches, controllers, etc. A conventional network differs essentially from trunked and hybrid LMR architectures in its reduced network complexity and number of components (for similar capacity configurations). When similar security features are in place, a conventional network offers greater network security than other configurations due to the fewer points of potential electronic intrusion.

The RF link of a conventional network represents a second type of security risk. In a conventional network, radio channels are stable and not dynamically assigned. A radio user manually selects a radio channel and uses that channel for all conversations with a specific user community. Thus, transmission generally occurs on the same channel each time. For example, a maintenance user group assigned a maintenance channel always transmits on the same frequency. Without an encryption feature, an unauthorized intercept can tune in to that specific channel to gain access to each conversation.

Often described by vendors as an anti-eavesdropping security feature, the channel switching that occurs during trunking does not make eavesdropping more difficult due to the existence of trunking scanners designed to interpret trunking control signaling. Nonetheless, just as advanced conventional networks, advanced trunked networks typically offer a wide suite of features developed to strengthen defense from major communications security threats. Such features typically include the following:

- Equipment Electronic Serial Number and/or User Identity Module cards
- Provisions to prevent replay of messages

- Over-the-air rekeying (for systems utilizing encryption)
- Over-the-air deactivation of stolen radios
- User radio access denial.

The physical security of a hybrid network is similar to a trunked network. A hybrid network has most of all the components of a trunked network. The greater complexity and number of network components makes it more susceptible to intrusions than conventional networks. However, the use of a central controller also provides a hybrid network with the ability to increase the difficulty of unauthorized radio access through the use of user IDs.

The RF security of a hybrid network conventional overlay are similar to those of a stand-alone conventional network architecture. The security of a trunked overlay of a hybrid network is essentially similar to that of a stand-alone trunked network. The overall security of a network will be determined by the security of its least secure overlay.

5.9 Network Robustness

Graceful degradation, when system continues to operate but provides a reduced level of service rather than failing completely, is the key to determining robustness of a network. Conventional network configurations use independent base stations/repeaters to handle broadcasts to large geographic areas. Although multisite networks use interconnected and synchronized receivers and comparators to determine which received signal should be rebroadcast, each site is still capable of functioning independently in the event of a voter/comparator failure. Because each independent base station/repeater does not require interaction with a network controller to operate normally, conventional networks offer a high level of robustness. In the event of a failure of a particular network site (base station, diversity receiver, console, etc.), the remaining components are able to operate independently to provide service to users within range of operational components. Although coverage and services may decrease, the entire network does not suffer a service outage due to a single failure.

Adaptability is another key criterion to determining a network's robustness. Network robustness must take into account network architecture, network configuration, and manufacturer specifications.

Consider communicating on a particular channel in a conventional network when a channel fault occurs. The users on that channel should know in advance what channel to switch to, if another channel is available. This situation does not typically occur in trunked radio networks, since they are computer-controlled. If a repeater channel falls out, the controller registers the fault and does not assign the repeater channel as a traffic path until the malfunction is repaired or disappears. Since channels are allocated as needed and no user group is dependent on any one channel for communications, the failure of a single channel most likely is not noticeable to the users unless the network is under a heavy user load.

In a trunked simulcast network, all links between the simulcast sites (i.e., microwave) should have a backup. Should the system clock be lost, the transmission will loose synchronization and the network will fail with each site operating as a stand-alone site and overlap zones being extremely noisy.

Some trunked networks have been designed so that if the designated control channel is lost, then one of the other repeater channels assumes control channel responsibility. If this feature is not provided in a centralized trunked network, a loss of a control channel will typically make the whole site function in so called "soft-fail" mode meaning that the site operates in a conventional mode. If neither control channel reassignment, nor the soft-fail feature is available, the loss of a control channel will lead to a loss of the entire site.

The use of a central controller, creates a single point of failure for certain network functions in centralized trunked and hybrid network architectures. The controller is responsible for allocating channels to all user groups. If a redundant controller or other controller backup capability is not used, the failure of a controller can eliminate the network's ability to dynamically assign channels and can bring the network down. Depending upon manufacturer specifications, individual sites may be able to operate in stand-alone mode without a central controller, providing some communication ability to all or some users within range.

The robustness qualities of the hybrid network conventional overlay are similar to those of a stand-alone conventional network architecture. The network robustness of a trunked overlay of a hybrid network is essentially similar to that of a stand-alone trunked network. The overall robustness of a network is determined by the robustness of its least robust overlay.

5.10 Multiorganizational Interoperability

Conventional networks provide service to different user groups by frequency separation. Each user group can be provided its own half-duplex or full-duplex channel. In this way, both privacy and network sharing can be gained. Although each channel requires its own repeater/base station, other multichannel components such as consoles and radios can be shared by scanning or manually switching among all authorized channels. Authorized users may be able to access other groups on the same or nearby networks by programming their radio to access other channels/frequencies. Limitations to this ability arise if different channels use incompatible components made by different vendors or if networks operate in incompatible modes (25 kHz versus narrowband, FDMA versus TDMA, or analog versus digital, unless radios conform to interoperability standards such as TIA/EIA-102). In addition, if the components for each channel are fully compatible, similar features can be provided to all users of all groups. If air interface interoperability is not feasible, audio cross-patching between dispatch panels is widely used.

Trunked networks are not more or less interoperable than conventional networks of the same level of technology. As in case of conventional networks, users from trunked networks cannot access other networks if their radios do not operate on the other network's frequencies or use different technologies (e.g., digital versus analog, narrowband versus 25 kHz wideband). Networks with different trunking protocols cannot interoperate. Nonetheless, trunked networks have some advantages for management of interoperability features. For example, creation of new talk groups or adding new members to an existing talk group can be done in real time, allowing formation of talk groups across organizational lines on as-needed basis. As in conventional networks, if air interface interoperability between networks is not feasible, audio cross-patching between dispatch panels can be used.

Hybrid networks provide the same level of interoperability among organizations as trunked networks.

5.11 Ability To Handle Multiple Voice and Data Applications

Current conventional networks do not allow the ability to simultaneously transmit both voice and data signals on the same channel. At any one moment, a radio user may transmit only voice or data.

The technical features with the greatest effect on data transmission characteristics of a network the most are the channel's signal-to-noise ratio, available bandwidth, and modulation technique. The most important parameter for data transmission is the channel's signal-to-noise ratio. As a general rule, this ratio is low for LMR compared with other data transmission mediums and decreases with distance from the base station. Consequently, although some advanced applications can support rates as high as 19,200 bits per second (bps), data rates for LMR are typically low, averaging at around 2400 bps or less. In the case of analog conventional networks, data transmission capability is limited by the noisy medium and available bandwidth to very low speed (typically 2400 bps).

Sharing of a conventional channel for both voice and data is not typically performed because of the incompatibility of voice and data usage and bandwidth requirements. However, the use of dedicated conventional channels and packet-switched data format for wireless data transmissions, regardless whether the technology is analog or digital, is a common industry practice.

The technical features that affect data transmission characteristics of a network the most, such as the channel's signal-to-noise ratio, available bandwidth, and modulation technique, are not dependent on the choice of conventional or trunked architecture. Nonetheless, in certain network configurations, if transmission trunking is used as opposed to conversation trunking, the call setup delay time for re-establishing a trunked call between data bursts may negatively affect the data transfer rate. Therefore, in many cases, the use of circuit-switched data applications may be more efficient for trunked networks, since it requires only one call setup in the beginning of the call, but it can vary depending on a specific network configuration and data-handling protocols. Packet data applications such as CDPD can be implemented on trunked systems using dedicated data channels or idle channels as in AMPS application.

Among the three architecture types, the hybrid architecture is better suited for designing multiple voice and data applications because it gives the flexibility of placing data either on dedicated conventional channels (mostly for packet-switched applications) or on trunked infrastructure (mainly for circuit-switched data). Such a configuration allows for both groups of network requirements, the voice and the data, to be met more efficiently.

5.12 Technology Evolution

Technology is moving, in general, toward digital networks. Two of the most important public safety user communications requirements, better quality of audio and encryption, are advanced by the use of digital technology. Compared with their analog counterparts, digital networks give the advantage of more consistent toll-quality voice communications over a wider coverage area. They also accommodate encryption more easily, allowing encrypted communications be conducted over multiple cross-patches without degradation of voice quality. In addition, driven by increasingly scarce spectrum and higher spectrum efficiency requirements placed on vendors, networks with five or more channels will tend to be trunked in the future. Large conventional networks will not be as supported or available in the future as they are currently, because of the greater spectrum efficiency achieved through trunking. However, small conventional networks will still be available for smaller user organizations and networks.

Trunked LMR networks' evolution is driven by the same market demands, which include better audio quality, higher spectral efficiency, increased user and traffic capacity, enhanced data transmission capability, communications privacy, and ease of use and management. In an attempt to satisfy these demands, manufacturers are producing networks with digital voice, advanced digital modulation techniques, encryption, and over-the-air reprogramming.

The LMR technology is migrating towards more spectrum-efficient networks to serve more users with less spectrum. In the TIA/EIA-102 Phase I, spectral efficiency of 12.5 kHz per channel was achieved. The second phase of the TIA/EIA-102 suite of standards has two tracks: FDMA (frequency division multiple access) and TDMA (time division multiple access). To achieve a spectral efficiency equivalent to 6.25 kHz per channel, it is possible that Phase II of the TIA/EIA-102 may be a TDMA network.

Advances in cellular technology may make it a major competitor to traditional LMR networks. For example, one manufacturer is planning to introduce an LMR look-alike system that runs on existing GSM networks. The system is intended to allow GSM operators to sell LMR services as if on a private network. The new system needs no network-level alterations, except for a new dedicated server. At the client end, necessary additions may include new terminals incorporating LMR functions, as well as a dispatch console running on a PC to provide central control for companies subscribing to the service. Two major drawbacks of such systems would be an inherent, significant call delay resulting from consecutive dial-up of talk group members and unavailability of the repeater talk-around mode when mobiles communicate with each other directly (without a repeater).

5.13 Policy Impact

The Federal Communications Commission (FCC) regulates state and local public safety agency communications, and the National Telecommunications and Information Administration (NTIA) has jurisdiction over federal agency communications. Both have emphasized public safety spectrum allocation and efficient use and have historically supported the use of both conventional and trunked LMR technologies. Recent policy actions, however, indicate that as technology progresses and available spectrum becomes increasingly scarce, the FCC is encouraging public safety users to migrate to LMR networks using trunked technology [4]. Also, the FCC National Public Safety Plan Report and Order provides incentives for using trunking and requires small entities with minimal requirements to join together in using a single system where possible[4], thus endorsing trunking as a spectrum-efficient technology. FCC and NTIA regulations that impact network architecture considerations are explained below.

5.13.1 Development of a Public Safety National Plan

Until 1987, the FCC did not require public safety agencies to use one type of technology over another. In 1987, the FCC formulated a National Public Safety Plan Report and Order, allocating 821-824 MHz and 866-869 MHz for public safety use. Five channels in this band were designated for use only in mutual aid situations to facilitate interoperability, so-called "NPSPAC channels." These channels were designated solely for conventional LMR technology, which was chosen as the lowest common denominator.

4 *See 3 FCC Rcd at 911*

The national plan also specified that any public safety agency applying for four or fewer channels for their private network in the 821-824/866-869 MHz bands might choose to build conventional or trunked networks; however, agencies applying for more than four channels in that band were required to build trunked LMR networks without specifying a particular trunking standard or technology. Small agencies with minimal requirements were required to join together in using a single system where possible[5].

5.13.2 Spectrum Refarming

In October 1997, the FCC implemented new rules (PR Docket No. 92-235), termed the refarming rules, to improve spectrum efficiency standards for *non-federal* public safety LMR networks operating at frequencies below 800 MHz. The new rules consolidated seven categories of public safety services into one public safety pool and, as shown in Exhibit 12, created narrower channels. Manufacturers are to phase in new narrowband equipment that meets the new channeling guidelines, and use of dual mode (conventional/trunked) equipment is now permitted. Neither existing public safety licensees nor new applicants were required to replace their existing systems or to use any particular type of technology or operate in any particular frequency band. The rules ensure that narrowband equipment will be available by requiring that radio equipment type accepted by the FCC over a ten-year period meets increasingly efficient spectral requirements. Under this plan, non-federal public safety radio users have the freedom to choose equipment that best fulfills their needs while balancing technical capabilities and financial considerations. [5]

Frequency Band	Old Channel Plan	New Channel Plan
150–162 MHz (nationwide)	- 30 kHz channels spaced every 15 kHz, in general	- a new channel is added between each existing channel. - operation on the new channel is restricted to equipment designed to operate on channel bandwidths of 12.5 kHz or less
450–470 MHz (nationwide)	- 25 kHz primary channels spaced every 25 kHz, in general - 12.5 kHz low-power channels spaced 12.5 kHz and offset from primary channels	- three new channels are added, every 6.25 kHz, above each existing primary channel - operation on the new channels 6.25 kHz removed from a primary channel is restricted to equipment designed to operate on channel bandwidths of 6.25 kHz or less - operation on the new channels 12.5 kHz removed from a primary channels is restricted to equipment designed to operate on channel bandwidths of 12.5 kHz or less.
421–430/470–512 MHz (selected cities)	- 25 kHz channels, in general, spaced every 25 kHz	- three new channels are added, every 6.25 kHz, above each existing channel - operation on the new channels 6.25 kHz removed from an existing channel is restricted to equipment designed to operate on channel bandwidths of 6.25 kHz or less - operation on the new channels 12.5 kHz removed from an existing channel is restricted to equipment designed to operate on channel bandwidths of 12.5 kHz or less

Exhibit 12 Refarmed Frequency Bands

Prior to the implementation of the refarming rules, centralized trunking was not generally permitted on public safety LMR networks operating at frequencies below 800 MHz. The FCC

5 *See 3 FCC Rcd at 911*

believed that centralized trunking did not offer adequate interference protection. The refarming order amended the rules to permit public safety entities to build centralized trunked LMR networks below 800 MHz, provided that:

- The licensee had an exclusive license area (applicable only to users of the 470–512 MHz band)

- The licensee did not have an exclusive service area, but obtained consent from all licensees who had co-channel or adjacent channel operations.

As for *federal users*, the NTIA requires that after January 1, 1995, all new systems, and after January 1, 2005, all systems in the 162-174 MHz band must conform to narrowband standards. After January 1, 1995, all new systems and after January 1, 2008, all systems in the 406.1-420 MHz band must conform to narrowband standards. After January 1, 1997, all new systems and after January 1, 2008, all systems in the 138-150.8 MHz band must conform to narrowband standards. [12]

5.13.3 Allocation of Additional Public Safety Spectrum

In the Reallocation Report and Order[6], the FCC has allocated 24 MHz of spectrum in the 764–776/794–806 MHz bands to public safety use. The service rules for this spectrum have been released in First Report and Order and Third Notice of Proposed Rulemaking called "The Development of Operational, Technical, and Spectrum Requirements for Meeting Federal, State, and Local Public Safety Agency Communication Requirements through the Year 2010. Establishment of Rules and Requirements for Priority Access Service" (FCC 98-191). The FCC separated the spectrum into two categories: general use, which includes everyday operations in addition to mutual aid and emergency preparedness or task force operations; and interoperability, which is reserved for situations that require multiple agencies to communicate and amounts to approximately 10 percent of the new band. It also required all 700-MHz band equipment (general use, interoperability, and reserve) use digital modulation as its primary modulation mode.[7] The rules do not require a specific digital modulation standard, and public safety licensees are allowed to independently select the equipment and technologies that best meet their particular communications needs on general use or reserve channels. Of greatest impact to conventional and trunked network architectures is the FCC's decision to establish the Public Safety National Coordination Committee (NCC) to work on interoperability issues in the 700-MHz band and specifically evaluating the possible use of trunking technology on interoperability channels and the adoption of a trunking standard. The FCC "will strongly recommend to the NCC that it immediately consider the benefits of employing trunking on (at least) a portion of the nationwide interoperability spectrum,[8] and we (the FCC) will direct it to make a timely recommendation to us as to whether Commission action to require trunking on nationwide

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[6] *12 FCC Rcd 22,953*

[7] *The FCC allows mobile and portable units to have analog modulation capability as a secondary mode in addition to its primary digital mode.*

[8] *The FCC notes that 20 of 32 nationwide interoperability channels in each TV channel, which NPSTC had indicated would serve well for paired interoperability systems, could be used for trunked systems.*

interoperability spectrum is needed.[9]" In the event that a trunking standard for nationwide interoperability use is required, the FCC would prefer, instead of choosing one trunking technology on the market over another, to have a compatible trunking standard be developed by an American National Standards Institute-accredited standard setting body.

5.13.4 Federal Entities Seeking Authorization To Build Trunked Networks

Federal users seeking to build or expand LMR networks must define their needs, determine what type of system will meet their needs, and provide the required information to their agency to forward to the NTIA for review. Under the Interdepartment Radio Advisory Committee (IRAC) , the Spectrum Planning Subcommittee (SPS) reviews new and previously approved LMR trunking technologies. One of their responsibilities is to certify that the operation of the technology in the proposed environment will not cause harmful interference to other NTIA-approved communications networks. The process that agencies must follow and the corresponding data that users must compile for submission to the NTIA to receive a frequency assignment differ depending on whether the proposed LMR network is conventional or trunked.

Users proposing to build or modify a conventional LMR system must only submit frequency application data to the IRAC Frequency Assignment Subcommittee (FAS). No other review is usually required.

Users proposing to build or modify a trunked LMR system must submit data to the SPS for a system review and approval. This is followed by frequency application to the FAS frequency application review. The purpose of the system review is to certify the type of equipment, system operation, appropriate channel loading and spectrum availability. The Office of Management and Budget (OMB) Circular A-11 states that funding for the system will not be released until the NTIA issues its system certification. The SPS requires different types of information and varying levels of detail for each trunked LMR system option. For example, if an applicant is proposing to modify an existing trunked LMR system, the SPS requires information only on the details of the proposed modification to ensure that it is compliant with NTIA regulations, rather than extensive information on the entire system, because the system has already been certified. If an applicant is proposing to build a new trunked system, the applicant must determine if the proposed LMR trunking technology has been previously certified. If the technology has been previously certified, the applicant must submit information to the SPS to certify the operation of the technology in the proposed environment. If the technology has not been previously certified, the applicant must submit technical and operational systems data to the SPS for review. [11]

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[9] *The FCC notes that an early recommendation on this matter is appropriate because, in the event trunking will be used, the work on standard setting must commence as soon as possible.*

5.14 Compatibility with Legacy Systems

In the simplest case, new analog conventional systems are compatible with legacy analog configurations (assuming the absence of vendor-to-vendor incompatibilities). However, achieving compatibility between current digital conventional systems and legacy analog system represents a challenge. Of the open standards, TIA/EIA-102 is the only suite of standards that has addressed over-the-air compatibility with legacy analog LMR systems. TIA/EIA-102 Phase I requirements provide over-the-air compatibility of Phase I conventional digital equipment with legacy conventional analog equipment.

Digital trunked systems usually employ a gateway technique for migration from analog systems. The technique consists of installing the new system as an overlay and creating a connection (gateway) between the old and the new network using the baseband (audio) level to make them interoperable. This way, both systems can work simultaneously, allowing a gradual transition to the new system.

Since hybrid systems consist of conventional and trunked overlays, all compatibility considerations that apply to the two systems individually will be correct for the respective overlays of a hybrid system.

5.15 Required User Discipline

As mentioned previously, an essential characteristic of conventional systems is that only one user can communicate over a half-duplex channel at a time. To circumvent call congestion and blocking, users must actively monitor or listen to the channel and wait for it to become free. If a conversation between two users is ongoing, the user must maintain discipline and avoid interrupting the conversation. Consequently, conventional networks require a significant amount of user discipline on the part of each radio user to ensure that all the users on the network are able to share the channel. A conventional network does not make use of a network controller and control channel to identify a free channel within the overall network.

Users on trunked networks do not have to monitor the system for an available channel to make a call. The network does it for them. After the PTT button is pushed, depending on user's access priority level, the trunking controller:

1. Assigns the user a channel, if there is one available
2. If none is available and the user requires a priority access, puts the user in the beginning of a waiting queue. If the user does not require a priority access, puts the user in the end of the queue.
3. When a channel is assigned, the user is usually notified by the radio audibly.

Consequently, trunked networks do not require any user involvement to select an available channel and do not require channel-sharing discipline from their users as in conventional systems. They do require patience during system busy times waiting for a free channel. Nonetheless, other types of network discipline that prevent misuse and possible overloading of a trunked network, such as unauthorized or overly long telephone and two-way calls, are critical to efficient operation of trunked networks. Most trunked systems provide built-in system management capabilities to prevent these violations.

Since hybrid networks consist of conventional and trunked overlays, all network considerations that apply to the two systems individually will be correct for the respective overlays of a hybrid network.

5.16 Network Management

Network management of a conventional network includes maintaining network components, allocating and managing user groups (also known as talk groups) among available channels, upgrading network components when necessary, managing encryption capabilities, managing and operating over-the-air features, optimizing performance, and managing intersystem interoperability. These network management responsibilities are not unique to conventional networks when compared with other types of LMR configurations. Since most conventional networks do not make use of computer logic to handle network operation, they require more manual management and have fewer automated management functions than trunked networks.

Network management of a trunked network also includes maintaining network components, upgrading network components when necessary, managing encryption capabilities, managing and operating over-the-air features, optimizing performance, and managing intersystem interoperability. Compared with conventional network management, trunked network management requires more complex network configuration and planning. Depending on organizational mission and user requirements, a choice of network trunking type (transmission or conversation trunking) must be made with associated hang and time-out times. Allocating and managing talk groups on a trunked network has a greater importance, since, if done improperly, it can degrade network performance and capacity to a great degree, similar to assigning too many users to a conventional channel. To control misuse that may lead to network overloading, such as unauthorized or overly long telephone and person-to-person calls, network management has to establish a conversation time-out feature, or use network accounting.

Since hybrid networks consist of conventional and trunked overlays, all network management considerations that apply to the two systems individually will be correct for the respective overlays of a hybrid network.

5.17 Network Operator Training

Depending on a particular system configuration, training of conventional network operators/dispatchers is not complex and is provided by many agencies in-house. Nonetheless, larger conventional systems may require a greater and more detailed knowledge of system configuration than in trunked systems. Many public safety professional associations have mini courses that provide operator training. Network maintenance personnel must understand basic radio communications principles and are trained either in-house or by a manufacturer.

Training of trunked network operators/dispatchers is not much more complex and sometimes it is even easier than conventional networks training

Although sometimes provided by many agencies in-house, due to the large size, complexity, and degree of automation of some trunked networks, network maintenance personnel must undergo extensive training and frequent updates. Usually, such training is available from radio system manufacturers and is a often part of the original contract. The training typically includes fundamentals of radio communications, trunked network configuration and maintenance, base station and console equipment maintenance and testing, and maintenance and troubleshooting of the wired-to-wireless link. The duration of the training can be from two to four weeks depending on the complexity of the system, technical background of the individuals, and the degree of familiarity with the particular technology.

Since hybrid networks consist of conventional and trunked overlays, dispatch and maintenance personnel should be trained to operate and maintain both types of systems.

5.18 Network Cost Effectiveness

The cost effectiveness of a particular architecture can be determined only on a case-by-case basis, since it depends on many case-specific considerations and conditions. Among the considerations that need to be taken into account when building and costing a system are the following:

- Mission
- Number of users
- Number of user groups
- User group sizes
- Available spectrum
- Coverage requirements
- Type of terrain
- Acceptable call setup delay
- Data transmission requirements
- Security and encryption requirements
- Interoperability requirements
- Available interconnect options.

Some very general comparisons of estimated costs associated with network capacity versus cost performance are given in Exhibit 13. The assumptions and mathematical capacity considerations are attached in Appendix C.

The results of this comparison show that although conventional architecture cost is generally lower than that of trunked, cost efficiency is determined most by technology used, specific configuration, and user options selected, not by type of architecture.

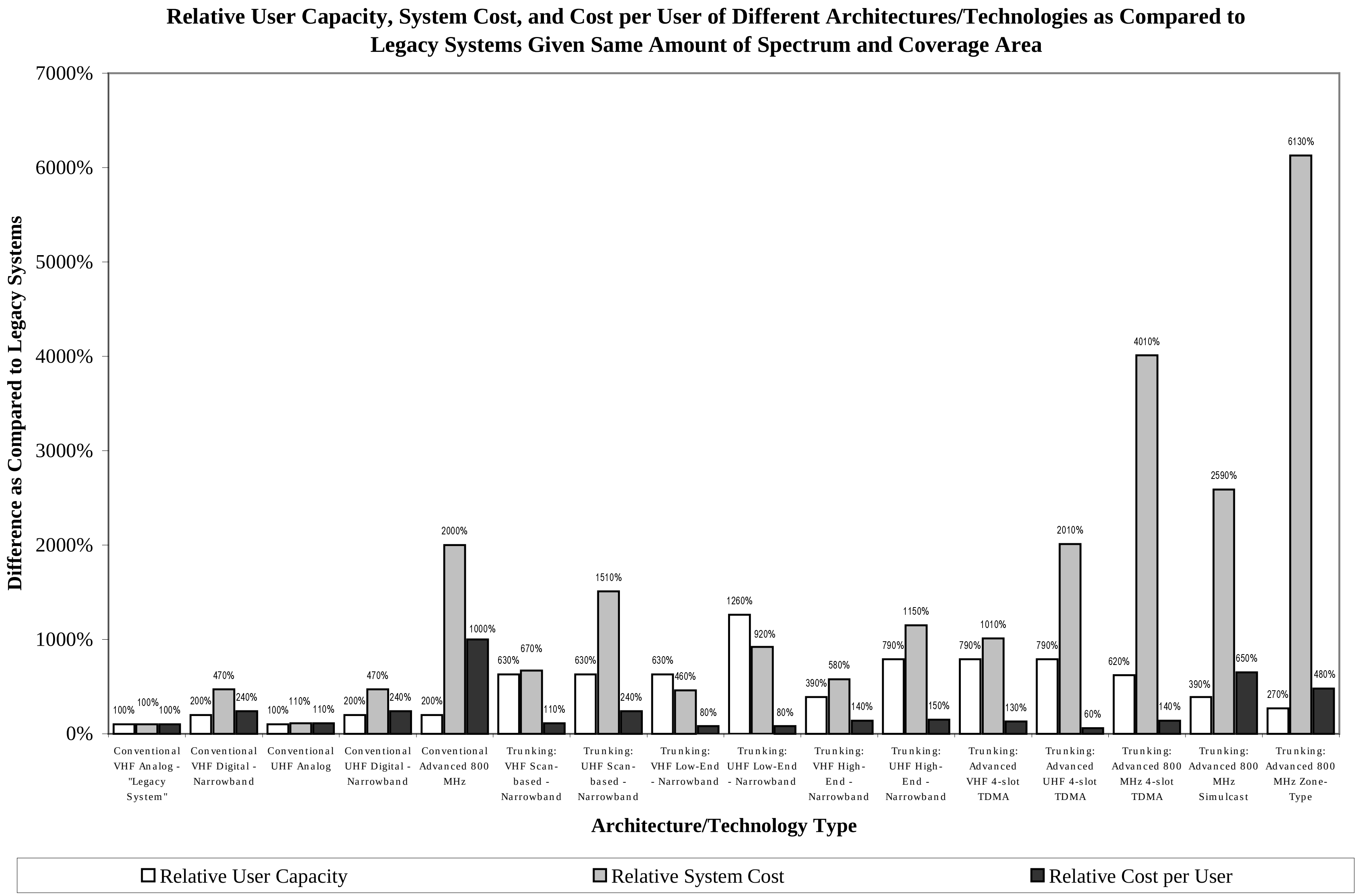

Exhibit 13 Estimated Network Architecture/Technology Capacity and Cost Comparison in Relation to Legacy Systems

5.19 Considerations for Migration to Trunking

One of the most important considerations when migrating to a trunked system is usually cost. As was concluded in the previous section, the type of architecture does not greatly affect the cost of a system. Cost is largely a function of a technology choice (analog versus digital, lower bands versus 800 MHz, FDMA versus TDMA), specific configuration (simulcast, multicast, zone-type), and selected user options (roaming, encryption, over-the-air rekeying, etc.). As shown in Exhibit 13, the estimated difference in the upfront costs of legacy and state-of-the art networks is so significant (between 400 and 2400 percent) that many organizations often have difficulty finding necessary funds[10]. Nonetheless, with some advanced technologies, when network cost is calculated on a per-user basis, it can be lower than that in legacy systems by up to 40 percent, even though the advanced network provides all the benefits of new technology, including data transmission, encryption, and security. Per-user savings are achieved because the advanced networks have the capacity to handle a much greater number of users than the legacy systems.

Beside the financial hurdles, there are legislative and technical considerations concerning available spectrum that make migration to trunking on frequencies below 800 MHz difficult. Decentralized trunked networks, in which radios scan the available channels and find one that is clear, have been used on the lower LMR bands since the 1970s. Now, centralized trunked networks are also permitted on frequencies between 150 and 512 MHz (except 220-222 MHz), if the following requirements are met (per FCC Second Report and Order FCC 97-61 [PR Docket No. 92-235 adopted on February 20, 1997 and released on March 12, 1997]; see 90.187 of 47 CFR):

1 The licensee has an exclusive service area (470-512 MHz band only); or
2 The licensee does not have an exclusive service area, but obtains consent from all licensees who have co-channel and/or adjacent channel stations as follows:
    2.1 Trunking will be permitted by the FCC on frequencies where applicant or licensee does not have an exclusive service area, provided that all frequency coordination requirements are complied with and consent is obtained from all of the affected licensees (Exhibit 14).

Proposed Station Bandwidth	Consent Has To Be Obtained from Licensees with Operating Frequencies Removed from Proposed Station by:
25 kHz	15 kHz
12.5 kHz	7.5 kHz
6.25 kHz	3.75 kHz

Exhibit 14 Table of Co-Channel and Adjacent Channel Frequency Coordination Requirements

10 *These calculations are based on the calculated maximum theoretical user capacity provided by a specific technology and architecture.*

2.2 Consent also has to be obtained from licensees with service areas (Exhibit 15) that overlap a circle with radius 113 km (70 mi.) from the proposed base station. (For more information see 90.205 of 47 CFR). Or, alternatively, applicants may submit an engineering analysis based upon generally accepted engineering practices and standards, which demonstrates that the service area of the trunked network does not overlap any existing stations whose service areas overlap a circle with radius 113 km (70 mi.) from the proposed base station.

Proposed Station Band	Service Area Calculated as a Contour at:
150-174 MHz	37 dBu
421-512 MHz	39 dBu

Exhibit 15 Table of Service Area Calculation Requirements

3 The consensual agreements among licensees must specifically state the terms agreed upon and a statement must be submitted to the FCC indicating that all licensees have consented to the use of trunking.

4 Trunking of networks licensed on paging-only channels or licensed in the Radiolocation Service is not permitted by the FCC.

Currently, no provisions allow LMR licensees in the bands below 470 MHz to obtain an exclusive service area. The FCC proposed that some form of exclusivity be allowed in the shared LMR bands below 470 MHz, but has not yet ruled on this issue. Licensees operating in the 470-512 MHz band may obtain an exclusive service area if they meet requirements in the Exhibit 16.

Type of Organization	Loading Requirement
Public Safety Pool	50 user units per channel
Industrial/Business Pool	90 user units per channel

Exhibit 16 Table of Service Area Calculation Requirements

Meeting all these licensing requirements in order to migrate to a trunked network in the bands below 800 MHz could be a difficult and time-consuming process unless a decentralized trunked network is proposed.

Another hurdle to migration to trunked is the allocation of legacy channels. The channels that were assigned for simplex operation are sometimes not suitable for half and full duplex operation which is necessary for trunking. To suppress unwanted harmonics, intermodulation, and general interference between forward and reverse frequencies, transmit and receive (T-R) frequencies should have a minimum specified separation, usually greater than 1 MHz (potentially much greater and increasing with frequency). In the VHF band, where a significant percentage of frequencies was licensed for simplex communications, T-R separations are inconsistent, with some as small as 120 kHz. These spacings require customized installations with separate antennas and costly notch-and-pass filters targeted at specific frequencies. In these cases, off-the-shelf equipment with broad pass bands can rarely be used with satisfactory results, causing increased cost. This problem also exists in the UHF band. In the UHF band, where T-R separation of a given channel is typically 5 MHz, T-R splits can still be as little as 500 kHz as multiple channels may be in operation at a single site. While co-channel and adjacent channel interference concerns are not as great as in the VHF band, due to smaller propagation range on these frequencies, network designers must still provide customized installations in the UHF band to account for site-specific requirements. Again, these installations usually include separate antennas and costly filtering equipment. The comparison of installation costs of filtering equipment in these bands done by the PSWN program [6] shows that cost would likely double due to insufficient T-R separation.

Another spectrum issue arises when migrating to a trunked network. The number of frequencies is, in many cases, insufficient for optimizing load capacity of a trunked network. As shown in Appendix B, the capacity improvement from trunking increases as the number of channels increases. If a system has only two or three channels, the improvement is insignificant. As discussed in earlier chapter, if multiple sites are needed for coverage and a zone-type trunked architecture is used for a network, the total number of channels required by the network will be calculated as N*R, where N is number of channels per site and R is a frequency reuse ratio (typically 4 or 7). A 5-channel network with a frequency reuse ratio of four, for example, needs 20 channels. If it is a centralized trunked network, one of the channels at each site is used for control and the traffic is handled by the remaining four channels. In many cases agencies do not have access to additional channels in the lower LMR frequency bands and they employ simulcast-type of trunked system design. Simulcast networks have significantly lower user capacity than zone-type networks and are significantly more expensive, since the transmitters at each site need to be phase-locked to minimize interference in overlapping coverage areas, requiring additional equipment.

Agencies sometimes resolve many of the migration issues by teaming up with neighboring jurisdictions and agencies and pooling their spectrum and financial resources. A multi-agency/multi-jurisdiction approach for building trunked LMR networks offers significant benefits:

- Combined channel resources provide a better trunking capacity improvement
- Economies of scale allow a lower per user investment
- Often the organizations work on adjacent or shared channels, making it easier to gain exclusivity for these channels
- A multi-jurisdictional network provides a wider coverage area for each of the jurisdictions
- Better communications interoperability results among agencies on one network.

6.0 SUMMARY

The most significant difference between conventional, trunked, and hybrid architectures is network load capacity for systems with greater than 60 users (mission specific). The analysis conducted for this report determined that other considerations were not affected by the choice of network architecture type to the same degree. Typically, trunking allows a system to serve more users with the same amount of spectrum or less. Since spectrum has become a scarce resource, this property of trunking will drive its use in the future.

APPENDIX A. LIST OF ACRONYMS

APCO	Association of Public-Safety Communications Officials International, Inc.
AMPS	Advanced Mobile Phone System
bps	Bits per second
CDMA	Code-Division Multiple Access
CDPD	Cellular Digital Packet Data
CFR	Code of Federal Regulations
CSMA	Carrier Sense Multiple Access
EIA	Electronics Industry Association
ID	Identification number
FAS	Frequency Assignment Subcommittee
FCC	Federal Communications Commission
FDMA	Frequency-Division Multiple Access
GOS	Grade of Service
GSM	Global System for Mobile communications
IRAC	Interdepartment Radio Advisory Committee
kbps	Kilobits per second
kHz	Kilohertz
LMR	Land Mobile Radio
MHz	Megahertz
ms	Millisecond
NTIA	National Telecommunications & Information Administration
PC	Personal Computer
PSWN	Public Safety Wireless Network
PTT	Push-to-talk
RF	Radio frequency
SCADA	Supervisory Control and Data Acquisition
SPS	Spectrum Planning Subcommittee
TDMA	Time-Division Multiple Access
TIA	Telecommunications Industry Association
UHF	Ultra High Frequency band
UHF-T	Ultra High Frequency band for Television
VHF	Very High Frequency band

APPENDIX B. IMPACT OF ARCHITECTURE ON NETWORK CAPACITY AND CALL DELAY

This appendix illustrates the impact of using conventional and trunked systems on network capacity and call delay. Traffic modeling shows that the computer-controlled access capability of trunked systems provides less call delay and thus greater throughput as traffic load in a typical system increases.

Exhibit 17 compares transmit delays for conventional and trunked channels as a function of loading.

Two types of traffic models were used to perform an estimate of trunking load capacity, one for each of the trunked system designs. The Engset Model, which presumes that blocked calls are lost with finite sources, was used for calculating theoretical load capacity of a trunked system with decentralized control. The Delay Model, a finite source model, which presumes that blocked calls are delayed, was used for calculating theoretical load capacity of a trunked system with centralized control. Note that these are just theoretical models that do not take into account many capacity-limiting factors of real system implementations, such as specific system configuration, signal strength, etc.

Exhibit 18 compares conventional and trunked capacity[11] for up to 20 channels using each model, where P is probability of a successful call by an average user. Because the scale of this exhibit makes it difficult to see differences when only a few channels are involved, Exhibit 19 offers a comparison of capacity estimates for systems with up to five channels.

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11 *Unfortunately, Delay Model calculations for number of channels higher than ten could not be performed due to software limitations*

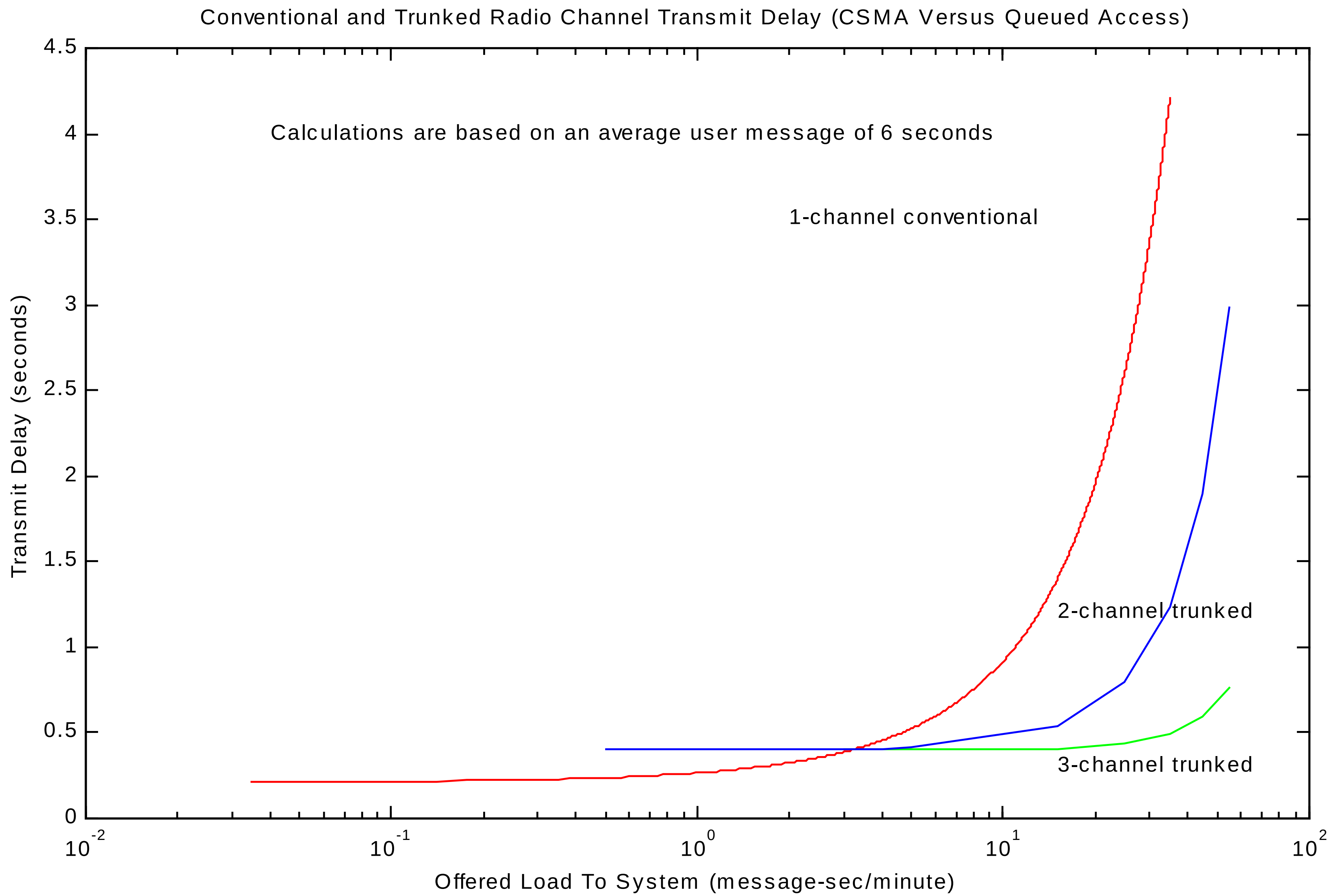

Exhibit 17 Conventional and Trunked Radio Channel Transmit Delay Comparison (CSMA Versus Queued Access)

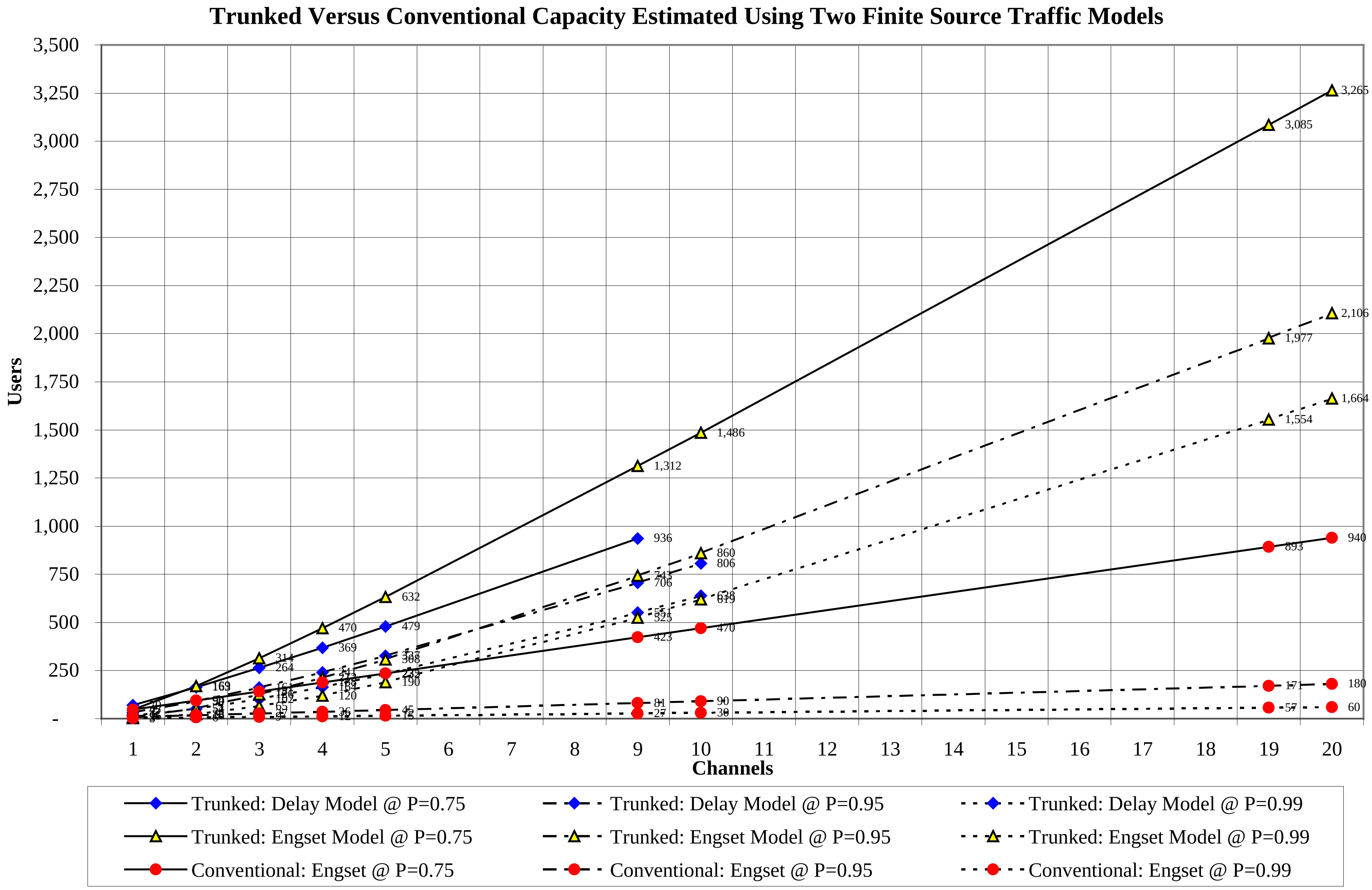

Exhibit 18 Trunked versus Conventional Capacity Estimated Using Two Finite Source Traffic Models

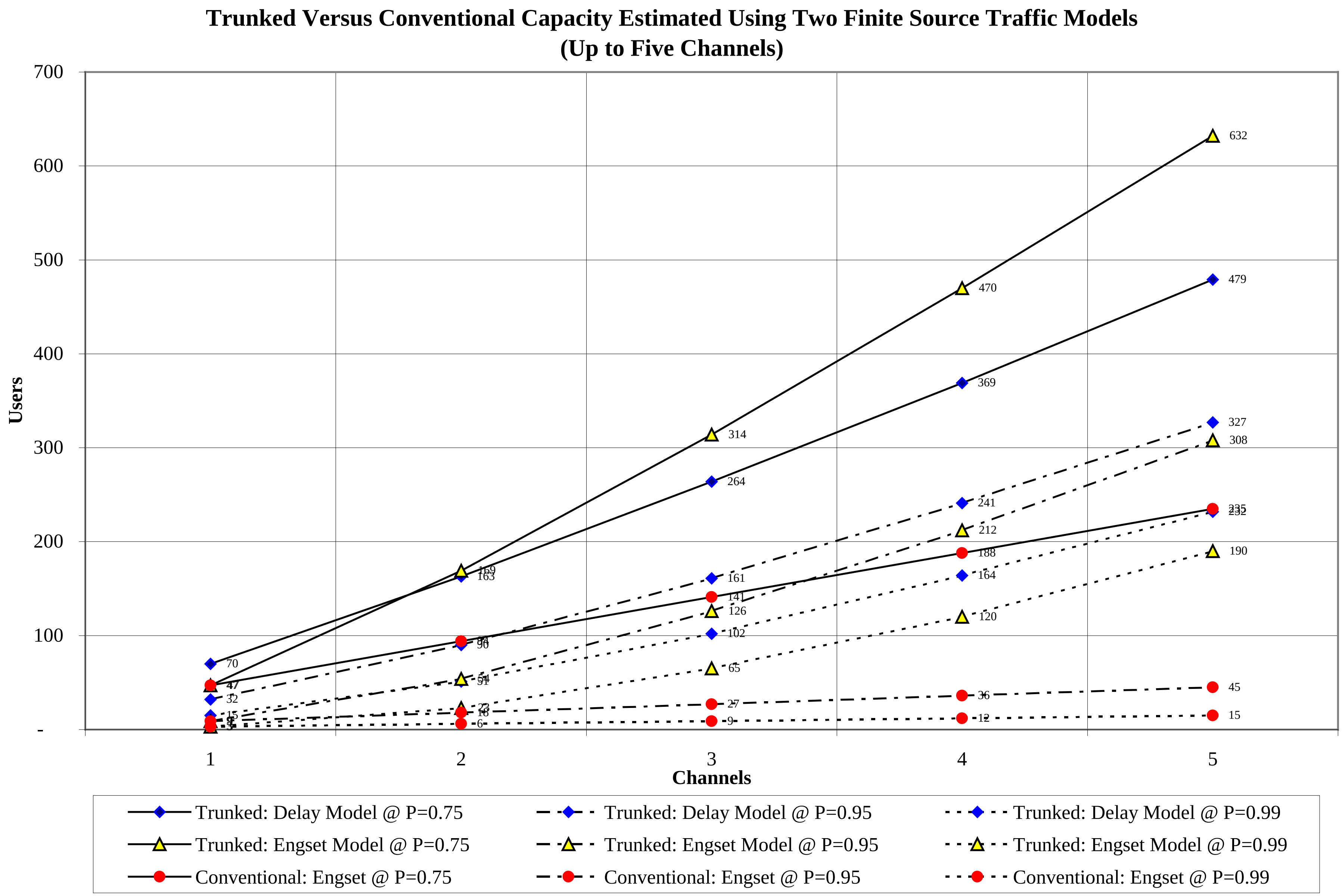

Exhibit 19 Trunked versus Conventional Capacity Estimated Using Two Finite Source Traffic Models (Up to Five Channels)

APPENDIX C. COSTING ASSUMPTIONS AND MATHEMATICAL CAPACITY CONSIDERATIONS FOR TRUNKED SYSTEMS

C.1 Assumptions

1. All systems have coverage over same geographic area
2. Coverage of VHF, UHF and 800 MHz systems is assumed to be provided by a respective number-of-sites ratio of 1:2:4.
3. All systems use the same amount of spectrum. Consequently, if the legacy conventional analog FM broadband system with a number of channels N has a total spectrum at N*25 kHz, a newer system with a channel bandwidth X has a number of channels calculated as N_1=N*25 kHz/X
4. Average per user load on the system is 0.0073 Erlangs as was estimated in [1].
5. The additional cost of phase-locking equipment for simulcast systems was not considered
6. New facilities (site facilities, dispatch centers, etc.) are not taken into account

C.2 Traffic Models Used

1. For conventional capacity – Engset Model results for one channel are multiplied by the number of channels.
2. For decentralized trunked with no queueing – Engset Model is used for finite sources.
3. For centralized trunked systems (with queueing) – Delay Model is used for channels (N_1-1), allowing for one control channel.
4. Results of the calculations by these models are below:

Model	Capacity, Number of Users Supported								
Channels	**1**	**2**	**3**	**4**	**5**	**9**	**10**	**19**	**20**
Delay Model (N_1-1)	-	70	163	264	369	479	936	N/A	N/A
Engset Model	47	169	314	470	632	1,312	1,486	3,085	3,265
Conventional	47	94	141	188	235	423	470	893	940

APPENDIX D. REFERENCE LIST

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APPENDIX E. GLOSSARY

A

access method	The ability and means necessary to store data, retrieve data, or communicate with a system. FDMA, TDMA and CDMA are examples. [8]
analog modulation technique	Process whereby message signal, which is the analog of some physical quantity, is impressed on a carrier signal for transmission through a channel (e.g. FM). [10]
analog signal	**1**. A signal that has a continuous nature rather than a pulsed or discrete nature. *Note:* Electrical or physical analogies, such as continuously varying voltages, frequencies, or phases, may be used as analog signals. **2**. A nominally continuous electrical signal that varies in some direct correlation with another signal impressed on a transducer. *Note:* For example, an analog signal may vary in frequency, phase, or amplitude in response to changes in physical phenomena, such as sound, light, heat, position, or pressure. [7]
antenna	Any structure or device used to collect or radiate electromagnetic waves. [7]
audio throughput delay	Waiting time delay from audio input at sending unit until audio output at receiving unit. [8]

B

backward compatibility	Ability of new units to operate within an "old" system infrastructure or to directly intercommunicate with an "old" unit. [8]
bandwidth	The difference between the limiting frequencies of a continuous frequency band. Typically measured in kilohertz. May be considered the amount in kilohertz required for a single communications channel. [8]
base station	**1**. A land station in the land mobile service. **2**. In personal communication service, the common name for all the radio equipment located at one fixed location, and that is used for serving one or several calls. [7]
baseband	The original band of frequencies produced by a transducer, such as a microphone, telegraph key, or other signal-initiating device, prior to initial modulation. *Note 1:* In transmission systems, the baseband signal is usually used to modulate a carrier. *Note 2:* Demodulation recreates the baseband signal. *Note 3:* Baseband describes the signal state prior to modulation, prior to multiplexing, following demultiplexing, and following demodulation. *Note 4:* Baseband frequencies are usually characterized by being much lower in frequency than the frequencies that result when the baseband signal is used to modulate a carrier or subcarrier. [7]

C

call congestion	The ratio of calls lost due to a lack of system resources to the total number of calls over a long interval of time. [8]
call delay	The delay experienced when a call arriving at an automatic switching device finds no idle channel or facility available to process the call immediately. [8]
call setup time	The overall length of time required to establish a circuit-switched call between users or terminals. [8]
carrier	**1**. A wave suitable for modulation by an information-bearing signal. **2**. An unmodulated emission. *Note:* The carrier is usually a sinusoidal wave or a uniform or predictable series of pulses. *Synonym:* **carrier wave**.
carrier frequency	**1.** The nominal frequency of a carrier wave. **2**. In frequency modulation, *synonym* **center frequency**. [7]
carrier sense multiple access (CSMA)	A network control scheme in which a node verifies the absence of other traffic before transmitting. [7]
catastrophic degradation	The rapid reduction of the ability of a system, subsystem, component, equipment, or software to perform its intended function. *Note:* Catastrophic degradation usually results in total failure to perform any function. [7]

channel A single unidirectional or bidirectional path for transmitting or receiving, or both, of electrical or electromagnetic signals. [8]

channel capacity The maximum possible information transfer rate through a channel, subject to specified constraints. [7]

channel rate The data rate at which information is transmitted through the channel, typically stated in bits per second (bps). [8]

channel spacing Typically measured in kilohertz from the center of one channel to the center of the next-adjacent-channel. May, or may not, be identical to bandwidth. [8]

channelization The use of a single wideband, *i.e.*, high-capacity, facility to create many relatively narrowband, *i.e.*, lower capacity channels by subdividing the wideband facility. [7]

code-division multiple access (CDMA) A coding scheme, used as a modulation technique, in which multiple channels are independently coded for transmission over a single wideband channel. *Note 1:* In some communication systems, CDMA is used as an access method that permits carriers from different stations to use the same transmission equipment by using a wider bandwidth than the individual carriers. On reception, each carrier can be distinguished from the others by means of a specific modulation code, thereby allowing for the reception of signals that were originally overlapping in frequency and time. Thus, several transmissions can occur simultaneously within the same bandwidth, with the mutual interference reduced by the degree of orthogonality of the unique codes used in each transmission. *Note 2:* CDMA permits a more uniform distribution of energy in the emitted bandwidth. [7]

collision In a transmission system, the situation that occurs when two or more demands are made simultaneously on equipment that can handle only one at any given instant. [7]

communications system A collection of individual communications networks, transmission systems, relay stations, tributary stations, and data terminal equipment usually capable of interconnection and interoperation to form an integrated whole. Note: The components of a communications system serve a common purpose, are technically compatible, use common procedures, respond to controls, and operate in unison. [7]

comparator In land mobile service, a functional unit that compares strengths of a signal received by different receiving stations and selects the strongest for further processing.

conventional radio system Non-trunked, similar to telephone party-line in that the user determines availability by listening for an open channel. [10]

coverage **1**. In radiocommunications, the geographical area within which service from a radiocommunications facility can be received. [7] **2**. The geographic area included within the range of, or covered by, a wireless radio system. Two systems cannot be made compatible through patching unless the coverage areas overlap. [10]

D

data Representation of facts, concepts, or instructions in a formalized manner suitable for communication, interpretation, or processing by humans or by automatic means. Any representations such as characters or analog quantities to which meaning is or might be assigned. [7]

data communication The transfer of information between functional units by means of data transmission according to a protocol. *Note:* Data are transferred from one or more sources to one or more sinks over one or more data links. [7]

de-key Turn the transmitter off (release the Push-to-Talk switch). [8]

delay time The sum of waiting time and service time in a queue. [8]

demodulation The recovery, from a modulated carrier, of a signal having substantially the same characteristics as the original modulating signal. [7]

demultiplexing The separation of two or more channels previously multiplexed; *i.e.,* the reverse of multiplexing. [7]

desensitization The reduction of desired signal gain as a result of receiver reaction to an undesired signal. *Note:* The gain reduction is generally due to overload of some portion of the receiver resulting in desired signal suppression because the receiver will no longer respond linearly to incremental changes in input voltage. [7]

digital Characterized by discrete states. [7]

digital modulation technique Technique for placing a digital data sequence on a carrier signal for subsequent transmission through a channel. [10]

digital signal A signal in which discrete steps are used to represent information. *Note 1:* In a digital signal, the discrete steps may be further characterized by signal elements, such as significant conditions, significant instants, and transitions. *Note 2:* Digital signals contain m-ary significant conditions. [7]

digital speech interpolation In digital speech transmission, the use of periods of inactivity or constant signal level to increase the transmission efficiency by insertion of additional signals. [7]

digitalization The migration from analog to digital communications technologies.

duplexer A device that isolates the receiver from the transmitter while permitting them to share a common antenna. *Note 1:* A duplexer must be designed for operation in the frequency band used by the receiver and transmitter, and must be capable of handling the output power of the transmitter. *Note 2:* A duplexer must provide adequate rejection of transmitter noise occurring at the receive frequency, and must be designed to operate at, or less than, the frequency separation between the transmitter and receiver. *Note 3:* A duplexer must provide sufficient isolation to prevent receiver desensitization. [7]

E

encipher [To] Convert plain text into an unintelligible form by means of a cipher. [7]

encode **1.** To convert data by the use of a code, frequently one consisting of binary numbers, in such a manner that reconversion to the original form is possible. 2. [To] convert plain text to equivalent cipher text by means of a code. 3. To append redundant check symbols to a message for the purpose of generating an error detection and correction code. [7]

encrypt **1**. [A] generic term encompassing encipher and encode. **2**. To convert plain text into unintelligible forms by means of a cryptosystem. Note: The term *"encrypt"* covers the meanings of *"encipher"* and *"encode."* [7]

end-to-end encryption The encryption of information at its origin and decryption at its intended destination without any intermediate decryption. [7]

erlang A dimensionless unit of the average traffic intensity (occupancy) of a facility during a period of time, usually a busy hour. *Note 1:* Erlangs, a number between 0 and 1, inclusive, is expressed as the ratio of *(a)* the time during which a facility is continuously or cumulatively occupied to *(b)* the time that the facility is available for occupancy. *Note 2:* Communications traffic, measured in erlangs for a period of time, and offered to a group of shared facilities, such as a trunk group is equal to the average of the traffic intensity, in erlangs for the same period of time, of all individual sources, such as telephones, that share and are served exclusively by this group of facilities. *Synonym* **traffic unit**. [7]

erlang-B distribution Erlang distribution of the first kind, or erlang loss formula. [8]

erlang-C distribution Erlang distribution of the second kind, or erlang delay formula. [8]

F

fail-safe operation **1**. Operation that ensures that failure of equipment, process, or system does not propagate beyond the immediate environs of the failing entity. **2**. A control operation or function that prevents improper system functioning or catastrophic degradation in the event of circuit malfunction or operator error. [7]

failure The temporary or permanent termination of the ability of an entity to perform its required function. [7]

fault **1**. An accidental condition that causes a functional unit to fail to perform its required function. **2**. A defect that causes a reproducible or catastrophic malfunction. *Note:* A malfunction is considered reproducible if it occurs consistently under the same circumstances. **3**. In power systems, an unintentional short-circuit, or partial short-circuit, between energized conductors or between an energized conductor and ground. [7]

Federal Communications Commission An independent regulatory commission which includes a board of Commissioners, nominated by the President and confirmed by the Senate, having the power to regulate non-Federal wire and radio telecommunications in the United States. [10]

format In data transmission, the arrangement of contiguous bits or frame sequences which make a group, word, message or language. [8]

frequency For a periodic function, the number of cycles or events per unit time. [7]

frequency assignment **1**. Authorization, given by an Administration, for a radio station to use a radio frequency or radio frequency channel to use a radio frequency or radio frequency channel under specified conditions. **2**. The process of authorizing a specific frequency, group of frequencies, or frequency band to be used at a certain location under specified conditions, such as bandwidth, power, azimuth, duty cycle, or modulation. *Synonym* **radio frequency channel assignment**. [7]

Frequency Assignment Subcommittee (FAS) An NTIA Interdepartment Radio Advisory Committee subcommittee responsible for reviewing individual agency requests for frequency assignment. It analyzes individual frequency applications for electromagnetic compatibility with existing frequency authorizations. [11]

frequency assignment authority The power granted an Administration, or its designated or delegated leader or agency via treaty or law, to specify frequencies, or frequency bands, in the electromagnetic spectrum for use in systems or equipment. Note: Primary frequency assignment authority for the United States is exercised by the National Telecommunications and Information Administration (NTIA) for the Federal Government and by the Federal Communications Commission (FCC) for non-Federal Government organizations. International frequency assignment authority is vested in the Radiocommunication Board of the International Telecommunication Union.

frequency bands Frequency bands where land mobile radio systems operate in the United States including the following:

High HF	25-29.99 MHz
Low VHF	30-50 MHz
High VHF	150-174 MHz
Low UHF	450-470 MHz
UHF TV Sharing	470-512 MHz
700 MHz	764-776/794-806 MHz
800 MHz	806-869 MHz.

frequency hopping [The] repeated switching of frequencies during radio transmission according to a specified algorithm, to minimize unauthorized interception or jamming of telecommunications. Note: The overall bandwidth required for frequency hopping is much wider than that required to transmit the same information using only one carrier frequency. [7]

frequency modulation Modulation in which the instantaneous frequency of a sine wave carrier is caused to depart from the center frequency by an amount proportional to the instantaneous value of the modulating signal. *Note 1:* In FM, the carrier frequency is called the center frequency. *Note 2:* FM is a form of angle modulation. [7]

frequency sharing The assignment to or use of the same radio frequency by two or more stations that are separated geographically or that use the frequency at different times. *Note 1:* Frequency sharing reduces the potential for mutual interference where the assignment of different frequencies to each user is not practical or possible. *Note 2:* In a communications net, frequency sharing does not pertain to stations that use the same frequency. [7]

frequency-division multiple access (FDMA) **1**. The use of frequency division to provide multiple and simultaneous transmissions to a single transponder. [7] **2**. A channel access method in which different conversations are separated onto different frequencies. FDMA is employed in narrowest bandwidth, multiple-licensed channel operation. [10]

full-duplex operation An operating method in which transmission is permitted, simultaneously, in both directions of a telecommunications channel. [8]

G

gateway **1**. An interface that provides the necessary protocol translation between disparate networks. [8] **2**. A type of network relay that attaches two networks to build a larger network. A translator of message formats and addresses, gateways typically make connections through a modem to other mail systems or services. [10]

graceful degradation Degradation of a system in such a manner that it continues to operate, but provides a reduced level of service rather than failing completely. [7]

grade of service (GOS) **1**. The probability of a call's being blocked or delayed more than a specified interval, expressed as a decimal fraction. *Note:* Grade of service may be applied to the busy hour or to some other specified period or set of traffic conditions. Grade of service may be viewed independently from the perspective of incoming versus outgoing calls, and is not necessarily equal in each direction. **2**. In telephony, the quality of service for which a circuit is designed or conditioned to provide, e.g., voice grade or program grade. *Note:* Criteria for different grades of service may include equalization for amplitude over a specified band of frequencies, or in the case of digital data transported via analog circuits, equalization for phase also. [7]

H

half-duplex operation Operation in which communication between two terminals occurs in either direction, but only one direction at a time. *Note:* Half-duplex operation may occur on a half-duplex circuit or on a duplex circuit, but it may not occur on a simplex circuit. *Synonyms* **one-way reversible operation, two-way alternate operation**. [7]

handoff In mobile systems, the process of transferring a call in progress from one site transmitter and receiver and frequency pair to another site transmitter and receiver using a different frequency pair without interruption of the call.

heterodyne **1**. To generate new frequencies by mixing two or more signals in a nonlinear device such as a vacuum tube, transistor, or diode mixer. *Note:* A superheterodyne receiver converts any selected incoming frequency by heterodyne action to a common intermediate frequency where amplification and selectivity (filtering) are provided. **2**. A frequency produced by mixing two or more signals in a nonlinear device. [7]

hybrid A functional unit in which two or more different technologies are combined to satisfy a given requirement. *Note:* Examples of hybrids include *(a)* an electric circuit having both vacuum tubes and transistors, *(b)* a mixture of thin-film and discrete integrated circuits, and *(c)* a computer that has both analog and digital capability.

I	
Interdepartment Radio Advisory Committee (IRAC)	A committee of appointed Federal agency representatives that serve in an advisory capacity to the Assistant Secretary of Commerce for Communications and Information, and Administrator, NTIA, in carrying out its spectrum management activities. The IRAC comprises a main committee, four subcommittees, and an international group. [11]
interference	The effect of unwanted energy due to one or a combination of emissions, radiation, or inductions upon reception in a radiocommunication system, manifested by any performance degradation, misinterpretation, or loss of information which could be extracted in the absence of such unwanted energy. [7]
intermodulation	The production, in a nonlinear element of a system, of frequencies corresponding to the sum and difference frequencies of the fundamentals and harmonics thereof that are transmitted through the element. [7]
interoperability	**1**. The ability of systems, units, or forces to provide services to and accept services from other systems, units, or forces and to use the services so exchanged to enable them to operate effectively together. **2**. The condition achieved among communications-electronics systems or items of communications-electronics equipment when information or services can be exchanged directly and satisfactorily between them and/or their users. The degree of interoperability should be defined when referring to specific cases. [7]
interoperability standard	**1**. A document that establishes engineering and technical requirements that are necessary to be employed in the design of systems, units, or forces and to use the services so exchanged to enable them to operate effectively together. [7] **2**. Established protocol that provide common interface. [10]
interoperation	The use of interoperable systems, units, or forces. [7]
intersymbol interference	**1**. In a digital transmission system, distortion of the received signal, which distortion is manifested in the temporal spreading and consequent overlap of individual pulses to the degree that the receiver cannot reliably distinguish between changes of state, *i.e.,* between individual signal elements. *Note 1:* At a certain threshold, intersymbol interference will compromise the integrity of the received data. *Note 2:* Intersymbol interference attributable to the statistical nature of quantum mechanisms sets the fundamental limit to receiver sensitivity. [7]

K	
key	The parameter defining an encryption code or method. [8]
kilohertz (kHz)	A unit of frequency denoting one thousand (10^3) Hz. [7]

L	
lost call	A call that has not been completed for any reason other than cases where the call receiver (termination) is busy. [7]

M	
megahertz (MHz)	A unit of frequency denoting one million (10^6) Hz. [7]
modulation	The process, or result of the process, of varying a characteristic of a carrier, in accordance with an information-bearing signal. [7]
modulation scheme	The technical process used for transmitting messages through a wireless radio channel. [10]
multicast	To transmit identical data simultaneously to a selected set of destinations in a network.

multipath The propagation phenomenon that results in radio signal's reaching the receiving antenna by two or more paths. *Note 1:* Causes of multipath include atmospheric ducting, ionospheric reflection and refraction, and reflection from terrestrial objects, such as mountains and buildings. *Note 2:* The effects of multipath include constructive and destructive interference, and phase shifting of the signal. *Note 3:* In facsimile and television transmission, multipath causes jitter and ghosting. [7]

multiplexing The combining of two or more information channels onto a common transmission medium. *Note:* In electrical communications, the two basic forms of multiplexing are time-devision multiplexing (TDM) and frequency-division multiplexing (FDM). [7]

mutual aid channel A national or regional channel that has been set aside for use only in mutual aid interoperability situations, usually with restrictions and guidelines governing usage. [10]

N

narrowbanding The migration to systems operating using narrower bandwidths.

National Telecommunications and Information Administration The Executive Branch agency that serves as the President's principal advisor on telecommunications and information policies and is responsible for managing the Federal Government's use of the radio spectrum.

network An interconnection of three of more communicating entities. [7]

O

operation The method, act, process, or effect of using a device or system. [7]

P

packet A sequence of binary digits, including data and control signals, that is transmitted and switched as a composite whole. The data, control signals and possibly error control information, are arranged in a specific format. [8]

packet switching The process of routing and transferring data by means of addressed packets so that a channel is occupied during the transmission of the packet only, and upon completion of the transmission the channel is made available for the transfer of other traffic. [8]

patch A control center subsystem that permits a mobile or portable radio on one channel to communicate with one or more radios on a different channel through the control center console. [10]

priority **1**. Priority, unless specifically qualified, is the right to occupy a specific frequency for authorized uses, free of harmful interference from stations or other agencies. [7] **2**. In voice communications systems, one of the levels of precedence assigned to a user unit for the purpose of preemption of communication services.

propagation The motion of waves through or along a medium. *Note:* For electromagnetic waves, propagation may occur in a vacuum as well as in material media. [7]

protocol A set of unique rules specifying a sequence of actions necessary to perform a communications function. [8]

PTT Abbreviation for "Push-to-Talk," the switch on a subscriber unit which, when pressed, causes the subscriber unit to transmit. [8]

push-to-talk (PTT) operation In telephone or two-way radio systems, that method of communication over a speech circuit in which the talker is required to keep a switch operated while talking. *Note:* In two-way radio, push-to-talk operation must be used when the same frequency is employed by both transmitters. For use in noisy environments, or for privacy, some telephone handsets have push-to-talk switches that allow the speaker to be heard only when the switch is activated. *Synonym* **press-to-talk operation**. [7]

Q

quantization A process in which the continuous range of values of an analog signal is sampled and divided into non-overlapping (but not necessarily equal) subranges, and a discrete, unique value is assigned to each subrange. *Note:* An application of quantization is its use in pulse-code modulation. If the sampled signal value falls within a given subrange, the sample is assigned the corresponding discrete value for purposes of modulation and transmission. [7]

quantization noise Noise caused by the error of approximation in quantization. *Note:* Quantization noise is dependent on the particular quantization process used and the statistical characteristics of the quantized signal. *Synonym* **quantizing noise**. [7]

queue A set of items, such as telephone calls or packets, arranged in sequence. *Note:* Queues are used to store events occurring at random times and to service them according to a prescribed discipline that may be fixed or adaptive. [7]

queueing The process of entering elements into or removing elements from a queue. [7]

queueing delay In a radiocommunication system, the time between the completion of signaling by the call originator and the arrival of a permission to transmit to the call originator.

R

radio channel An assigned band of frequencies sufficient for radio communication. *Note 1:* The bandwidth of a radio channel depends upon the type of transmission and the frequency tolerance. *Note 2:* A channel is usually assigned for a specified radio service to be provided by a specified transmitter. [7]

radio equipment As defined in *Federal Information Management Regulations*, any equipment or interconnected system or subsystem of equipment (both transmission and reception) that is used to communicate over a distance by modulating and radiating electromagnetic waves in space without artificial guide. This does not include such items as microwave, satellite, or cellular telephone equipment. [7]

radio frequency (RF) Any frequency within the electromagnetic spectrum normally associated with radio wave propagation. [7]

radiocommunication Telecommunication by means of radio waves. [7]

refarming An FCC effort to develop a strategy for using private land mobile radio (PLMR) spectrum allocations more effectively so as to meet future communications requirements. This is to be accomplished primarily by dividing channel bandwidths (*i.e.* narrowbanding). [10]

relay Base station that typically receives signals on one frequency, processes and retransmits out on another frequency in order to extend talkout range. [10]

RF repeater **1**. An analog device that amplifies an input signal regardless of its nature, *i.e.*, analog or digital. **2**. A digital device that amplifies, reshapes, retimes, or performs a combination of any of these functions on a digital input signal for retransmission. *Note:* The term *"repeater"* originated with telegraphy and referred to an electromechanical device used to regenerate telegraph signals. Use of the term has continued in telephony and data communications. [7]

S

signal The detectable transmitted energy which carries information from a transmitter to a receiver. [8]

simplex operation Operating method in which transmission is made possible alternately in each direction of a telecommunication channel, for example by means of manual control. *Note:* In general, duplex operation and half-duplex operation require two frequencies in radiocommunication; simplex operation may use either one or two. [7]

spectrum The usable radio frequencies in the electromagnetic distribution. Specific frequencies have been allocated to the public safety community. They include:

High HF	25-29.99 MHz
Low VHF	30-50 MHz
High VHF	150-174 MHz
Low UHF	450-470 MHz
UHF TV Sharing	470-512 MHz
700 MHz	764-776/794-806 MHz
800 MHz	806-869 MHz.

Spectrum Planning Subcommittee (SPS) A subcommittee of the Interdepartment Radio Advisory Committee that reviews agency requests for new, or major modifications to, communications or space systems for electromagnetic compatibility and regulatory compliance. [11]

spread spectrum **1**. Telecommunications techniques in which a signal is transmitted in a bandwidth considerably greater than the frequency content of the original information. *Note:* Frequency hopping, direct sequence spreading, time scrambling, and combinations of these techniques are forms of spread spectrum. **2**. A signal structuring technique that employs direct sequence, frequency hopping or a hybrid of these, which can be used for multiple access and/or multiple functions. This technique decreases the potential interference to other receivers while achieving privacy and increasing the immunity of spread spectrum receivers to noise and interference. Spread spectrum generally makes use of a sequential noise-like signal structure to spread the normally narrowband information signal over a relatively wide band of frequencies. The receiver correlates the signals to retrieve the original information signal. [7]

squelch A radio circuit that eliminates noise from the speaker when no transmitted signal is present. [8]

subcarrier A carrier used to modulate another carrier, and so on, so that there can be several levels of subcarriers, *i.e.*, several intermediate carriers. [7]

subscriber unit A mobile or portable radio unit used in a radio system. [8] *Synonym* **user unit, user radio**.

system Any organized assembly of resources and procedures united and regulated by interaction of interdependence to accomplish a set of specific functions. [8]

system robustness The measure or extent of the ability of a system, such as a computer, communications, data processing, or weapons system, to continue to function despite the existence of faults in its component subsystems or parts. *Note:* System performance may be diminished or otherwise altered until the faults are corrected.

T

talk group A subgroup of radio users who share a common functional responsibility and, under normal circumstances, only coordinate actions among themselves and do not require radio interface with other subgroups. [10]

telemetry The use of telecommunication for automatically indicating or recording measurements at a distance from the measuring equipment. [7]

terminal A device capable of sending, receiving, or sending and receiving information over a communications channel. [7]

throughput The number of bits, characters, or blocks passing through a data communication system, or portion of that system. *Note 1:* Throughput may vary greatly from its theoretical maximum. *Note 2:* Throughput is expressed in data units per period of time. [7]

throughput delay The total time in ms between the initiation of a voice or data signal, *i.e.*, push-to-talk, until the reception and identification of the identical signal at the received output speaker or other device. [8]

TIA/EIA-102 Standards A joint government/industry standards-setting effort to develop technical standards for the next generation of public safety radios, both voice and data. [10]

time division multiple access (TDMA) **1**. A communications technique that uses a common channel (multipoint or broadcast) for communications among multiple users by allocating unique time slots to different users. *Note:* TDMA is used extensively in satellite systems, local area networks, physical security systems, and combat-net radio systems. [7] **2**. A channel access method in which different conversations are separated into different time slots. [10]

transceiver A device that performs, within one chassis, both transmitting and receiving functions. [7]

transducer A device for converting energy from one form to another for the purpose of measurement of a physical quantity or for information transfer. [7]

transmission delay The time in ms required for transmission of a voice frame or data packet through a communication channel. [8]

transponder An automatic device that receives, amplifies, and retransmits a signal on a different frequency. [7] *Synonym* **RF repeater**.

trunk A single transmission channel between two points that are switching centers or nodes, or both. [8]

trunked (system) Systems with full feature sets in which all aspects of radio operation, including RF channel selection and access, are centrally managed. [8]

trunking An infrastructure dependent technique where communications resources, comprised of more than one logical channel (trunk) are shared amongst system users by means of an automatic resource allocation management technique based upon statistical queueing theory and resident in the system's fixed infrastructure. Typically usage requests follow a Poisson arrival process and the resource allocator assigns communications resources in response to requests form system users. As demand for service exceeds system capability at that time, service must be increasingly denied immediate access. This action is termed "blocking," with the blocked service request being queued for a later service response. The offered grade of service of the system is inversely proportional to the probability of blocking (e.g. lower probability of blocking offers a higher grade of service potential). The dynamic resource allocation methodology of trunking results in the establishment of functional channels defining resource availability by means of dynamically allocating logical channels both to particular subscribers and for specific functions. These functional channels can be used for the conveyance of payload information, system control or a combination thereof. [8]

trunked radio system A system that integrates multiple channel pairs into a single system. When a user wants to transmit a message, the trunked system automatically selects a currently unused channel pair and assigns it to the user, decreasing the probability of having to wait for a free channel for a given channel loading. [10]

type 1 product [A] classified or controlled cryptographic item endorsed by the National Security Agency for securing classified and sensitive U.S. Government information, when appropriately keyed. *Note:* The term refers only to products, and not to information, key, services, or controls. Type 1 products contain classified National Security Agency algorithms. They are available to U.S. Government users, their contractors, and federally sponsored non-U.S. Government activities subject to export restrictions in accordance with International Traffic in Arms Regulation. [7]

type 2 product Unclassified cryptographic equipment, assembly, or component, endorsed by the National Security Agency, for use in telecommunications and automated information systems for the protection of national security information. *Note:* The term refers only to products, and no to information, key, services, or controls. Type 2 products may not be used for classified information, but contain classified National Security Agency algorithms that distinguish them from products containing the unclassified data algorithm. Type 2 products are subject to export restrictions in accordance with the International Traffic in Arms Regulation. [7]

type 3 algorithm [A] cryptographic algorithm that has been registered by the National Institute of Standards and Technology and has been published as a Federal Information Processing Standard for use in protecting unclassified sensitive information or commercial information. [7]

type 4 algorithm [An] unclassified cryptographic algorithm that has been registered by the National Institute of Standards and Technology, but is not a Federal Information Processing Standard. [7]

U

user A person, organization, or other entity (including a computer of computer system), that employs the services provided by a telecommunication system, or by an information processing system, for transfer of information. *Note:* A user functions as a source of final destination of user information, or both. *Synonym* **subscriber**. [7]

V

vocoder *Abbreviation for* **voice-coder**. A device that usually consists of a speech analyzer, which converts analog speech waveforms into narrowband digital signals, and a speech synthesizer, which converts the digital signals into artificial speech sounds. *Note 1:* For communications security purposes, a vocoder may be used in conjunction with a key generator and a modulator-demodulator to transmit digitally encrypted speech signals over narrowband voice communications channels. These devices are used to reduce the bandwidth requirements for transmitting digitized speech signals. *Note 2:* Some analog vocoders move incoming signals from one portion of the spectrum to another portion. [7]

W

waveform The representation of a signal as a plot of amplitude versus time. [7]

wireless terminal Any mobile terminal, mobile station, personal station, or personal terminal using non-fixed access to the network.