Design Considerations in a Modern Land Mobile Radio System

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Abstract

Modern Land Mobile Radio has the potential for large growth in the near future. Current regulations have set the stage for a required transition to more spectrally efficient technologies. While several organizations are working to ease this transition, there still remain many details and feature sets which the end user must decide amongst and often there is no clear dividing line between these choices.

This thesis provides a high-level view of the distinguishing components in modern LMR systems. Discussions related to trunked channel allocation, coverage, costs, security, and other capabilities are given. The application to and effect on everyday users is also considered. Several quantitative examples are provided to assist the end-user in determining when a solution is viable. The discussion and analysis included reaffirm that LMR design is complex and wide-ranging. Ultimately, the designer must evaluate needs and technologies to provide a course of action which is optimum and justifiable.

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Chapter 1

Introduction

1.1 Overview

The prevalence of Land Mobile Radio (LMR) systems can be seen throughout the world, in both the public and private sectors. Consumers heavily utilize wireless radio technology such as Citizen Band radio and the Family Radio Service. However, the main use of LMR spectrum is by business and government entities wishing to maintain efficient, reliable communication among their employees. From small companies dispatching technicians on service calls to large emergency agencies coordinating volunteers and relief efforts in a disaster, both businesses and the public at large have benefited from wireless radio in the form of Land Mobile Radio.

One significant user of LMR spectrum is the law enforcement community. Officers and agents find the coordination and instantaneous communication capabilities of a LMR radio invaluable. From routine status checks to situational awareness and covert lifelines, law enforcement entities rely on their radios to get or send information right when it is needed. It is not surprising then that the usefulness of LMR has brought about an abundance of system deployments. Each new deployment brings additional spectrum requirements. These new systems are typically placed in the VHF and UHF bands. However, ever increasing demands for spectrum from many types of wireless service have prompted several changes to frequency allocations to relieve the congestion. Examples of these changes include the addition of available spectrum in the 900 MHz band [APC77] and the reallocation of UHF television channels for LMR use [Ors95].

More recently, the National Telecommunications and Information Administration issued a mandate that all federal LMR users should begin operating within 12.5 kHz channels [NTI00]. With current analog technology using 25 kHz of spectrum [Ors95], the narrower channels will essentially provide twice as many channels in the same bandwidth. However, a majority of the mobile and portable units, along with their base stations, used in older LMR systems are not compatible with the newer standard and cannot be upgraded. As a result, completely new standard-compliant systems are being developed and deployed.

An environment where new innovations and features can be integrated as part of the new systems has been created by the mandated change out of existing equipment. The new features of most interest include digital signaling, channel trunking, and data communication. These features promise to increase system capacity, provide clearer communication, and increase user effectiveness. Other capabilities extend from the previous three technologies. However, they also create some new logistical challenges. In considering the deployment of a new LMR network, the entire available feature set needs to be understood and evaluated. Some features may increase the usefulness of the system while others only complicate its operation and reduce the overall benefit to the user.

Throughout this thesis, notations are made regarding relevant Project 25 (P25) specifications. P25 is a standard developed by the Association of Public-Safety Communications Officials International (APCO) and is intended to provide a smooth transition from the current analog LMR technologies to narrowband compliance. P25 also aims to provide interoperable radio solutions from different manufacturers.

1.2 Outline of Contents

The thesis is organized in the following manner. Chapter 2 offers a brief overview of how LMR has developed. Included is a discussion of the technology and techniques used to provide service. The societal repercussions of LMR use are also reviewed. The chapter ends by presenting the present state of currently deployed LMR systems.

Chapter 3 provides a wide-ranging discussion of the services and features of modern LMR systems. Issues including transmission techniques, channel allocation methods, security concerns, and intangible properties are reviewed. Where general concepts are mentioned, specific applications to LMR are made. Several focused examples are provided to illustrate potential tradeoff evaluations that will inevitably need to be made in structuring a to-be-deployed radio system. Finally, a small comparison is provided between LMR and a related wireless technology, cellular telephony.

Chapter 4 discusses possible improvements to modern LMR and alternate means of providing LMR capabilities. Alternate use of existing system structures are examined to determine if reallocation of resources can provide improved performance. Near-future technologies are also examined to determine their usability as a platform for LMR service offerings. These include the use of Push-to-talk (PTT) functionality in 3^{rd} Generation (3G) cellular networks and software-defined LMR radios.

Chapter 5 provides a brief summary of results. It also gives a brief overview of potential continued research topics.

1.3 Contributions

The contributions of this thesis are:

- A compact discussion of radio system concerns that impact a majority of present-day LMR users is presented. Sources that are guiding modern LMR deployments and have extensive LMR experience are referenced to present a consensus view of relevant issues.

- The application of Erlang traffic models to typical LMR scenarios leads to average performance statistics. These statistics and scenarios are usable in the planning phases of future LMR deployments. Several interpretation approaches are provided to facilitate contrasting vantage points in the evaluators' minds and assist in the decision making process.

- Discussion of intangible factors applicable to modern LMR design is presented. Information is presented such that an evaluator should be able to determine the relative value of the various intangible components or, at the least, be aware of their existence.

Chapter 2

Traditional Design of Land Mobile Radio

The development of LMR has occurred over many years. Multiple companies have designed and constructed many different systems. Once these systems were deployed, they remained relatively fixed in structure and feature sets. This results from the fact that basic user needs were met. Justifying the expense of newer, more advanced systems could not be done with functional older systems in place [NTI00]. Also, due to the proprietary nature of newer systems, older hardware would need to be totally replaced. Instead of investing in newer technologies, users implemented workaround upgrades for older systems. Ultimately, old systems tended to serve long beyond their intended lifespan. It is with this understanding that we examine the average deployed LMR system.

The following chapter discusses the following topics. Section 1 reviews the physical system structure of traditional LMR. This includes a discussion of the various transmit/receive configurations and the overall communication approach used in LMR. Section 2 looks at the capabilities and limitations of traditional systems. Section 3 examines the effects that occurred with the advent of LMR. Finally, Section 4 discusses the technological advances which facilitate the structure of modern LMR.

2.1 Traditional System Structure

Many older communication systems, including LMR, used analog means to transmit information. Original LMR systems used amplitude modulation (AM) to carry voice traffic. However, broadcast AM was highly susceptible to noise and thus, voice clarity was degraded, sometimes significantly. Eventually, reception quality improved with the advent of frequency modulation (FM) [Bow78]. As such, currently deployed analog LMR systems use FM.

Along with the progression of transmission techniques was the development of various handset styles. Originally, wireless communication components were bulky and consumed large amounts of power. This was of little concern at base sites. However, this created a significant problem for mobile units. Size and power restrictions initially limited radios to an in-car form factor, a mobile implementation. However, as circuit technology improved, both size and power requirements reduced [Hol85] to the point that radios could be carried by an individual and operated for a suitable amount of time, a portable implementation. Current systems consist of both mobile and portable units. The key difference between mobile and portable radios is that while mobile units lack the ability to go with the user when they leave their vehicle they have a high transmit power. Portable units transmit significantly less power and thus, have a reduced talk-in range [Bou00]. Talk-in and talk-out ranges are the maximum distances at which a radio can transmit to and receive from a base station, respectively. These ranges may be similar or different for a given handset depending on its antenna type and transmit power.

Traditional systems are organized using several linked site configurations. Each configuration allows the user to operate over a much greater distance than their handset alone allows. This is because the base site receives the user's transmission and rebroadcasts it at a higher power and usually from a location with better coverage characteristics. The most basic system is known as a single site system [Bou00]. One base tower is provided to rebroadcast communications from handsets within the tower's coverage area (see Figure 2.1.1). Typically, single site systems are implemented for smaller entities wishing to cover a limited operating area.

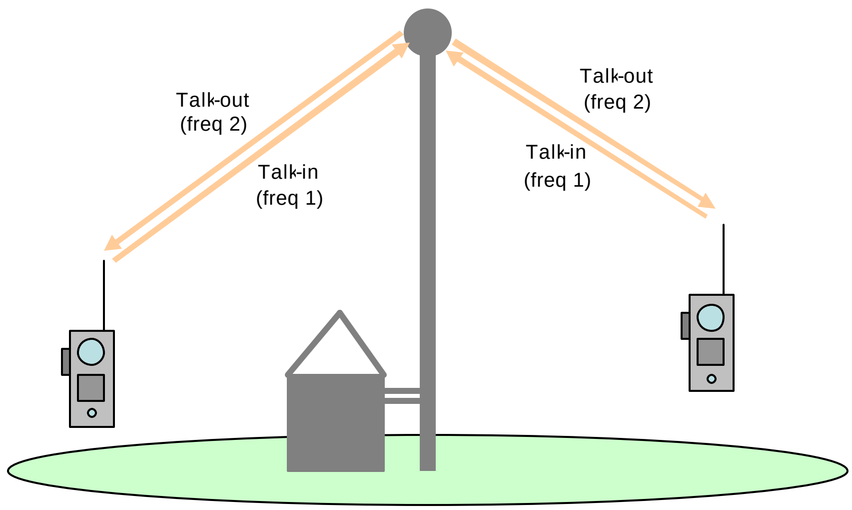

Figure 2.1.1: Single Site LMR System

If wider area coverage is needed, several other layouts, known as multisite systems, are available. One configuration, called a voting system, has multiple towers distributed throughout an area to receive handset transmissions (see Figure 2.1.2). The incoming transmissions are routed to a central controller which selects the strongest signal. The strongest signal is then rebroadcast from a single tower [Mot03a]. This configuration provides better talk-in coverage without the complication of having multiple transmitting towers in the system. More complex multisite implementations allow all sites to receive and transmit (see Figure 2.1.3). Simulcasting utilizes multiple sites transmitting in parallel on the same channel [Bou00]. The requirement of just one channel for wide-area coverage is a significant benefit of simulcasting. Multicasting is the other multisite implementation in which information is simultaneously transmitted from multiple sites. However, for multicasting each tower uses a different channel to transmit the same information [Mot03a]. The frequencies used by each tower are selected such that two towers do not interfere considerably with each other. As more base sites are added to a multicasting system, more spectrum is required. Therefore, frequency reuse by insufficiently separated towers is required to keep the system's overall spectrum utilization reasonable.

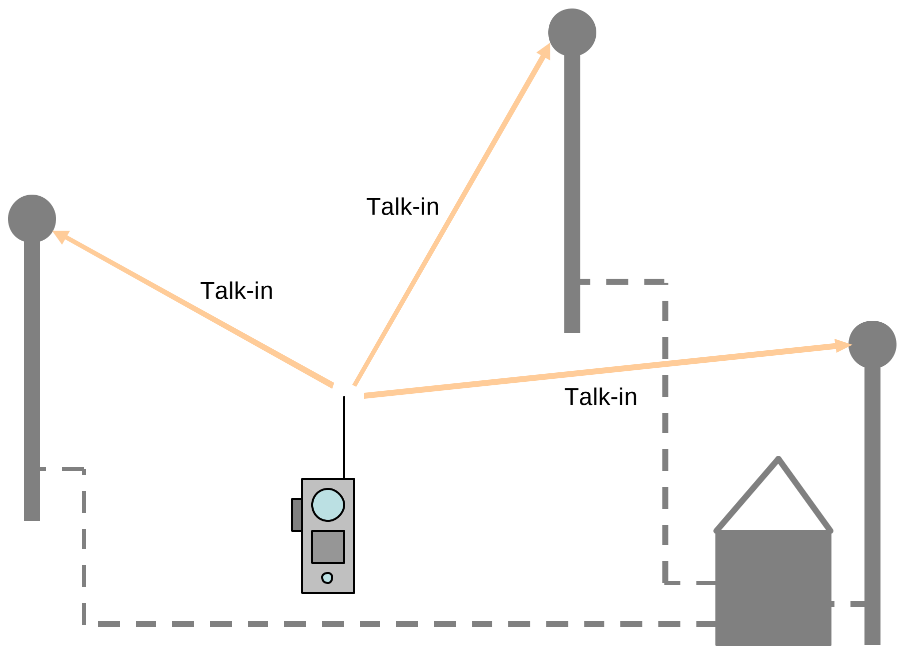

Figure 2.1.2: Multisite Voting System

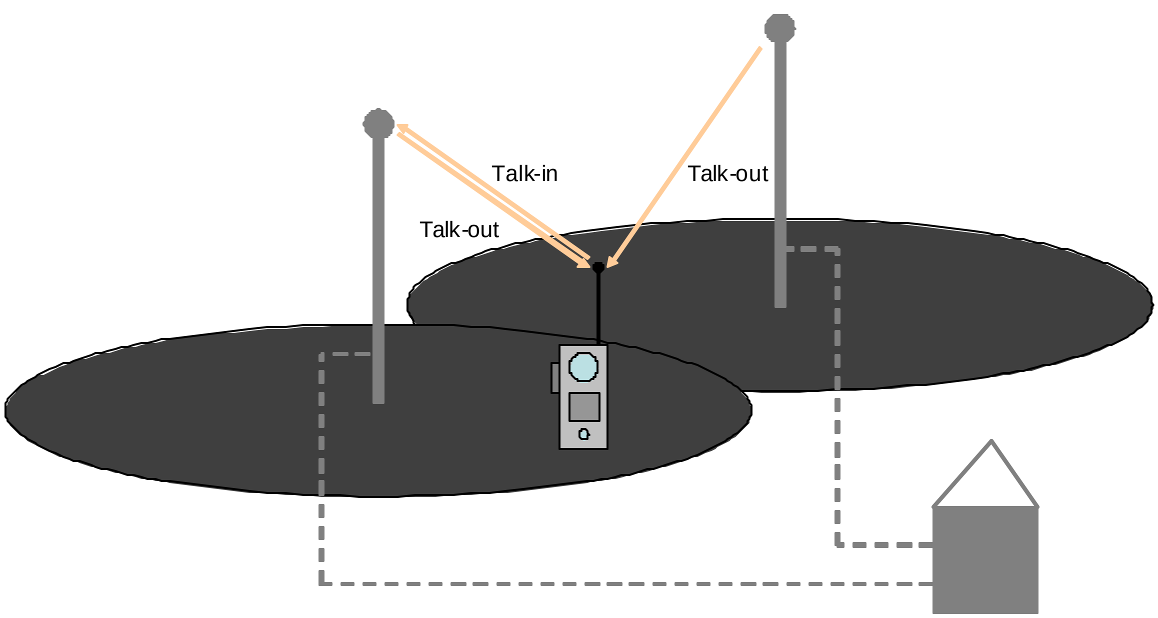

Figure 2.1.3: Multisite Simulcast or Multicast System

User grouping is also a common component in traditional systems. Grouping is achieved through various means such as channel selection or sub-audible tones. In basic multi-channel systems, the channel a user selects limits the calls that are received by the user. Therefore, the user is essentially part of a group that contains all the other users on the selected channel. [Lav00] discusses a real-world implementation of this technique. In more complex systems, multiple groups can be created on a single channel through the use of sub-audible tones. Handsets in these systems are equipped with an automatic squelch which activates when all but the tone of the desired group is transmitted [Bou00]. In this way, all calls from outside the user's group are never heard.

2.2 Design Concerns Using the Traditional System Structure

As current LMR systems were deployed in the field, several general design concerns appeared. First, the use of analog transmission was prone to gradual quality degradation as the user moved away from the signal source, be it a base station or another handset. This performance falloff led to less than optimal performance throughout a majority of the system's coverage. Transmissions were often intelligible but not noise free.

With the advent of portable radio use in LMR systems, concerns over equal talk-out and talk-in capabilities appeared. Portables, with their reduced transmit power, suffer from an inability to return transmissions to base stations a significant distance away. Solutions to this problem included the use of high gain base station antennas or the installation of additional receiving towers to increase coverage. However, the tradeoff for a higher gain antenna is antenna directionality [APC77] and, ultimately, a more complex base radio configuration. Further, the deployment of additional towers is not an ideal solution because new deployments are costly and time consuming.

Simulcasting also created several concerns for those deploying early LMR systems. Specifically, it was found that signal interference occurred whenever the signal strength of two towers was approximately equal in an area. This created areas where reception should be possible but was poor or non-existent [Bou00]. As such, careful initial engineering is required to ensure that in areas of signal overlap either the interfering carrier phases are very closely matched or the signal strength of one interferer is significantly less than the other. If equal carrier strengths are desired, synchronization can be achieved through the addition of timing circuits at each simulcasting site [Hol85].

Another concern in early systems was the minimal security of privacy features in analog systems. When some level of privacy was desired, frequency inversion and variants of the concept were available. However, these security measures could be reversed. Of more concern was the fact that this type of security reduced the effective range of units using it [Bou00]. Difficulties with older security measures sometimes led users to operate in the clear, unencrypted mode for convenience [PSW02c].

2.3 Societal Effects of LMR Use

The coming of wireless technology and, more specifically, land mobile radio lead to several changes in public and private circles. First, as more employees began to have wireless two-way communications capabilities with their main offices, less time was spent out of contact. Also, though early telephone services afforded police officers the ability to respond quickly to local emergencies, they were required to wait by a telephone. LMR changed this by allowing the officers to quickly respond even while on patrol [Bow78].

Once users were able to freely move about their operating areas, several changes occurred. First, the service areas where companies worked increased in size. Now that workers could be remotely directed to their next appointment, they no longer needed to spend time checking-in at the main office. Almost instant communications could be established whenever and wherever needed. The home office could also add, delete, or reprioritize assignments throughout the day and redirect their workers accordingly [Bow78]. Second, wasted time in transit was significantly reduced. Repeated trips to obtain needed items or to consult others for advice were now handled by a radio request for a delivery or with a question asked over the airwaves [Bow78].

LMR systems also empowered their users. This concept was embodied in the phrase: you cannot outrun Motorola. Essentially, once a user is able to interact with others without being in physical proximity to them, they are able to coordinate efforts and gather more diverse information. This information leads to a much wider situational awareness. For law enforcement activities, officers could now gain an overall view of a situation and plan ahead as they dealt with emerging problems. Also, should an individual become hurt or need other assistance, help can be summoned from a great distance.

Concerns over radiated energy also appeared. The effects of radiated energy on the body were not fully understood. As such, having portable transmitters near the head led to public concern over LMR use [APC77]. This concern also extended to other wireless technologies. No definitive conclusions as to the overall safety of RF energy have been made at present and studies on the issue continue.

2.4 Developments Leading to Modern LMR

In the coming of the modern LMR, several technological and structural changes occurred to traditional LMR. Once the initial technical challenges of LMR were overcome, system designers began to look at improving spectral performance. Advances in microelectronics also allowed for more compact implementations [Bow78]. Computer-controlled systems enabled advanced capabilities such as wide-area trunking, digital signaling, and data services. Along with these new features, a desire for interoperability among different public safety entities developed [APC78]. Users not only wished to communicate with their own immediate coworkers and teams, but also with other LMR users they might work with occasionally. P25 is one modern initiative designed to establish interoperability within the LMR user community.

One significant difference between existing LMR systems and modern LMR is the potential to utilize trunking. The FCC first encouraged the use of trunking by mandating that systems requiring 5 or more channels in the 900 MHz band use this technique [APC77]. Trunking offers more efficient spectrum use by occupying all of the available channels during peak periods of demand [Bou00]. A trunked system also allows multiple agencies to share their spectrum. Pooled spectrum results in considerably more system capacity and the ability to easily facilitate interoperability. However, this system structure also requires a considerably more complex control subsystem [Bow78] and the addition of a control channel to signal commands to users' radios. Further discussion of trunking is provided in Chapter 3.

Another improvement to traditional LMR came with the introduction of digital signaling. Digital signaling allowed for greater control over user handsets. One example of this is the ability to disable a P25 radio or listen to ambient noise received by a handset [Mot03b]. Digital signaling also enabled the use of digital voice transmission. In comparison to analog, digital voice quality is more consistent throughout a system's service area [Arc98]. However, due to the use of error correction coding, performance degrades rather quickly at the coverage fringe. Also, the addition of complex encryption to digital information is considerably easier than applying security features to analog signals.

The addition of higher speed data services also marks a leap forward in LMR technology. Though voice information remains the primary use of LMR systems, data capabilities in the field greatly assist many users. Many deployed systems currently provide low rate data which is used to search databases and file reports remotely [Mot94]. With the promise of higher data rates comes the potential for sending images such as fingerprints, criminal photographs, or building blueprints [Ors95].

Chapter 3

Concerns in Implementing Modern LMR Systems

To indicate that a modern LMR system is complex is to understate the functionality provided by that system. The extensive use of LMR has provided much experience and understanding regarding the potential problems with and the desired features of modern LMR systems. In considering the deployment of new systems, practical experience with LMR plays an important role in intuitively knowing how to evaluate design tradeoffs. Choices must be made such that system performance, availability, and capacity are adequate during both emergency situations and routine operational periods [APC77].

The following chapter discusses the various features and properties of a modern LMR. Section 1 discusses the performance and feature differences between analog and digital systems. Spectral efficiency is evaluated in section 2. Section 3 considers implementing a trunked or conventional network structure. Special attention is given to the transition point between conventional and trunking use. Section 4 looks at coverage issues and roaming throughout the system. Security throughout an LMR system is discussed in section 5. Section 6 is concerned with system ease of use. The level of interoperability that a modern LMR exhibits is evaluated in section 7. Section 8 discusses several LMR cost points and how they should be evaluated. The degree of control over infrastructure is considered in Section 9. And finally, Section 10 provides a brief comparison of LMR versus cellular technologies.

3.1 Analog versus Digital Information Transmission

One of the aspects that distinguish modern LMR from older systems is the use of digital signaling. The denotation of digital, as opposed to analog, is in reference to the format of voice transmissions through a system. This does not exclude the fact that other components within an LMR may function digitally. All LMRs which use trunking have digital control systems [Mac96], but older trunked systems are still considered to be analog due to analog voice signals. This section endeavors to discuss various system components and their performance as they relate to either digital or analog hardware. It is noted that digital information transmission is assumed throughout this thesis unless otherwise stated.

Use of digitally encoded voice provides the most user-noticeable gain from modern LMRs. As such, P25 standards dictate that voice quality must be equal to or exceed analog performance [APC99]. Voice quality is paramount in order to allow reliable, efficient conveyance of information. Poor quality leads to repetition of information. Thus, communication channels are occupied longer than is truly necessary, reducing system capacity and the overall effectiveness of those communicating.

Another benefit of digital voice systems is the exact reproduction of the digital information transmitted. For this to be true, it is assumed that all system components are digital between both users. Both digital and analog systems use components that add thermal noise along the entire communication path. However, digital systems may include regenerative signal processing which allows for an exact estimation of the original digital information to be recovered.

At present, digitized voice also provides a level of privacy from monitoring. A majority of the current scanners in use can only interpret analog transmissions [PSW02c]. As such, most users cannot listen to digital transmissions. However, new scanners that can decode digital voice information are available. Therefore, digitization itself is not considered a security feature, and the current privacy benefit will decrease with time.

With the advent of digital transmission, both modulation schemes and reception characteristics have changed. In the case of P25, the Phase I modulation is a modified form of FSK known as Compatible Four-level Frequency Modulation (C4FM). The combination of digital signaling and a new modulation type produces different signal reception characteristics. One such characteristic, as previously mentioned, is the fact that performance is relatively stable until the coverage fringe where performance rapidly declines. For users familiar with analog LMR, this property may lead to some concern. As they travel to the edge of their coverage area, their radio may abruptly stop functioning instead of offering analog's gradual service dropoff.

The use of digital signaling on the control channel also provides significant benefit. Specifically, support for individual handset IDs is created, and from this, many system features are derived. Directly, the ID of a unit currently communicating can be determined and displayed. If the ID is associated with a specific person or vehicle, monitoring IDs may give some idea of the people involved in a situation. Individual IDs implemented on a trunked system create the potential for additional call types. For instance, one-to-one calling is now possible along with multigroup calling [APC78]. In the first type of call, users can communicate directly and privately without the entire group hearing the call. However, this does not exclude monitoring by system operators and other authorized persons. In the second call type, while conventional systems allow calling from one user to a group of users, more advanced systems allow multiple groups to temporarily combine and receive the same calls. The end result is users and system operators having more flexibility to meet their communications needs at the moment [APC78]. Also, should the present situation change, the groupings and capabilities can be reconfigured quickly.

The computing capabilities included in digital handsets enable increased performance. Since all internal components are assumed to be digital, digitized voice information is presented to the unit in its native format. Audio processing such as feedback cancellation or noise reduction can be easily imposed through the use of digital signal processor (DSP) operations. Signal processing such as error correction and signal interpolation can be applied to correct and compensate for transmission errors. Secure communications is available by encrypting voice and data using mathematical routines [Bou00]. Though it is simple to execute a math operation, logistical simplicity in maintaining an encrypted system is not implied. Use of encryption will be further discussed in Section 5.

Another complement to the computing capabilities of digital handsets is the ability to pass data from the radio link to an external device such as a mobile computer terminal. While this is not a feature unique to modern LMR, the speed increase marks a jump in performance as seen over LMR networks. P25 systems require a 9600 bps data rate and standards-based network connection characteristics [APC99]. This provides system operators the flexibility to deploy a wide variety of data handling resources in the field and the assurance that a reliable connection is available to networked resources.

Digital controllers offer the prospect of greater safety and higher capacity. The processing power inherent in modern digital controllers allows for priority access [APC78]. Priority access allows traffic to be ranked as it enters the network. When all channels become occupied, higher priority traffic is given first access to the next available channel while lower priority traffic is further delayed. Though unit priorities are usually fixed, it is possible for these priorities to change. P25 allows traffic to be designated as emergency-type traffic [APC00], thus facilitating its timely delivery. Priority access, in general, improves safety and perceived performance of the service by ensuring that high-priority users are given preference and faster network access times. Digital controllers also provide a platform on which to implement multiple access schemes which promise greater system capacity. Current multiple access schemes include time-division (TDMA), frequency-division (FDMA) and code-division (CDMA). Modern systems such as TETRA and iDEN employ TDMA, while a majority of P25 systems employ FDMA. No current implementations of CDMA LMR are known.

In comparison, analog systems provide several benefits and challenges. User familiarity with voice clarity and reception rolloff is one motivation to employ analog voice in a modern LMR system. Another motivation relates to scanner monitoring. Should agencies desire that the public be able to easily listen to some or all communications, non-trunked, analog transmission provides the simplest means. This results in openness towards, public accountability to, and the situational awareness of the community [PSW02c]. However, the use of analog transmission does create some challenges. While extensive experience is available with analog systems, implementing signal modification and effective privacy methods is complicated. For example, encryption is available for analog systems, but it involves converting the voice information into digital form before transmission [Bou00]. This is similar to the digitization and encryption process done in a digital system though without the regenerative signal handling.

3.2 Spectral Efficiency

While increased capacity is a prime motivator for the development of modern LMR, increased spectral efficiency is one means to that end. Increased spectral efficiency is defined as the ability to serve additional users within a given amount of spectrum [APC77]. Greater spectral efficiency is now required because the amount of spectrum allocated to LMR is scarce and generally fixed. Juxtaposed to this is the fact that the number of users is ever increasing. Frequency congestion studies show that several LMR frequency bands are reaching the saturation point. For example, high-band VHF is designated as highly congested throughout most of the United States in [Ors95].

Spectral efficiency can be achieved through several means. First, the bandwidth designated for one channel determines the number of channels available in a spectrum allotment. Smaller channels facilitate more users and thus increase spectral efficiency. As a side note, channel size also affects the modulation type and ultimately the complexity of the radio equipment required. Second, use of advanced multiple access schemes, such as time-division multiple access (TDMA), can increase spectral efficiency [Ors95] by a factor of two or more. Finally, allocating one segment of spectrum for use by multiple services can yield higher spectrum occupancy rates [Ors95]. Assuming collision avoidance methodologies are used, spectrum can be shared effectively in this manner.

P25 provides increased spectral efficiency in the following ways. Assuming an original channel size of 25 kHz, P25 specifications aim to double or quadruple effective spectrum utilization [APC99]. This is achieved using either frequency-division multiple access (FDMA) or TDMA. FDMA operation increases spectrum efficiency by occupying a 12.5

or 6.25 kHz channel space and using modulation types of C4FM and Compatible Quadrature Phase Shift Keying (CQPSK), respectively [APC00]. TDMA does not alter the channel size but rather, creates 2 or 4 timeslots where information can be exchanged [APC99]. For TDMA, the traffic carrying capacity must be equal to or greater than the comparable FDMA technique. It should be noted that while users should not see a marked difference in performance between FDMA and TDMA systems, TDMA requires considerably more complex radio equipment.

3.3 Trunked versus Conventional Channel Allocation

In considering a modern LMR deployment, the selection of trunking or conventional channel allocation should be evaluated. Trunking provides higher system capacity at the expense of requiring a sophisticated control system. Conventional systems are far less complex but do not offer as much configurability. This section presents the various advantages and disadvantages of implementing a trunked and/or conventional system. Also, an evaluation of which technique should be used under various circumstances is explored.

First, definitions of channel allocation schemes are needed. A conventional system operates in such a way that the handset selects which channel it transmits on and monitors. Should the handset be transmitting through a repeater, the channel selection refers to a channel pair, one for inbound traffic and the other for outbound traffic. In contrast, trunking systems have controllers that designate which channel a handset uses. Trunking requires the use of a control channel where all handsets request service and receive channel switching commands. If a handset is about to receive a call, a message is sent across the control channel telling the handset to switch to the appropriate channel and begin receiving information. When a handset desires to transmit, it requests radio resources over the control channel. If the controller has an available channel, the handset is instructed to switch to that channel and begin transmitting. If no channel is free, the call is queued or blocked.

Both the selection of an allocation scheme and whether calls are queued or blocked affects the overall capacity of the system. In a conventional system, a user is unable to communicate if his channel is currently in use. The failed call is considered dropped. A user must wait for their selected channel to become free before communicating, even if other channels in the system are free. However, in a trunked system, extra traffic is carried by moving users around to unused channels. No call is queued or blocked until all channels are in use.

The use of trunking has been considered for a significant period of time. The FCC first mandated the use of trunking in LMR when it allocated additional LMR spectrum in 1974 [APC77]. Though more spectrum was allocated, regulators knew that the available spectrum would not be sufficient if not utilized efficiently. As such, continued encouragement of trunking has persisted even though current usage patterns indicate that the average LMR system uses only one channel or channel-pair [Ors95].

While trunked systems provide many benefits, the conventional mode of operation is still prevalent. Conventional single-site implementations are considered to be the simplest LMR structure. Knowing this, the APCO 16 standard, a predecessor to P25, stated that if the trunking capabilities within a system fail, a conventional mode of operation should be available [APC78]. As such, conventional capabilities are assumed to be part of any trunked system, if only in the form of simplex communication.

A trunking system structure also provides the opportunity for multiple agencies to combine resources. By each agency sharing their radio spectrum, the resulting system can handle more traffic than the respective separate systems. Also, if the agencies experience different high traffic periods, each receives a higher overall system performance [Ors95]. Lastly, by using the same underlying system, joint communications and coordination can also be established quickly through simple user regrouping.

Since both conventional and trunked operations are available in modern LMRs, a determination of which should be used is needed. It has been mentioned that trunking provides a more efficient use of radio spectrum while conventional techniques offer system simplicity. There exists a crossover point where the conventional simplicity benefit gives way to trunking efficiency. The following is a discussion of where that point exists in regards to average LMR usage.

The performance of a LMR is measured by the grade of service (GOS) provided. GOS is mathematically determined using the work of A. K. Erlang [Bea88]. In a blocking system, GOS is the probability that a user requesting service will have their call blocked. Erlang establishes that the probability of blocking for a blocking system is

$$E_{1,N}(A) = \frac{\frac{A^N}{N!}}{1 + \frac{A^1}{1!} + \frac{A^2}{2!} + \ldots + \frac{A^N}{N!}} \tag{3.1}$$

where A is the traffic offered and N is the number of jointly trunked channels. GOS for a queuing system is the probability that a user requesting service will have to wait for access to a channel. Erlang established that the probability of delay for a queuing system is

$$E_{2,N}(A) = \frac{\frac{A^N}{N!}\left(\frac{N}{N-A}\right)}{\sum_{r=0}^{N-1}\left(\frac{A^r}{r!}\right) + \frac{A^N}{N!}\left(\frac{N}{N-A}\right)} \tag{3.2}$$

Erlang's equations, though originally used for telecommunications capacity estimations, can also be applied to LMR. Erlang assumed the following conditions for his capacity modeling: call initiations occur randomly and are modeled by the Poisson distribution, the system exhibits statistical equilibrium, and any distribution can be used to model the length of calls. Erlang also assumed that calls were either dropped or queued relative to the scenario being investigated. Given these assumptions, one concern is noted. Dispatch systems will not necessarily conform to these models. In dispatch systems with a limited number of dispatchers, users are more likely to be waiting for dispatch assistance rather than radio system resources [Hoa91].

The following items are assumed in the crossover analysis. First, the average traffic offered by a single LMR user is 18 seconds per hour or .005 Erlangs (E) [Chr91]. Second, three types of systems are considered. The first is a standard trunked system utilizing multiple channels and queuing calls received after all channels are full. The second is a typical conventional system that drops calls attempted when all channels are occupied. Dropped calls are not retried. The third system is a hybrid with conventional channel allocation, but it is assumed that blocked users will retry their call until it is completed. This is a form of manual queuing where the user is responsible for acquiring a channel. The hybrid system uses a single-channel trunked model for simulation purposes. For the conventional and hybrid scenarios, the traffic load applied to the collective trunked system channels is evenly split over the individual conventional channels.

In the first scenario considered, a constant traffic is offered to the three test systems. The number of channels in each system is varied and the resulting blocking/delay probability is calculated. Figure 3.3.1 assumes 100 users are in each system presenting a total of .5 E of traffic. For the one channel case, the conventional scheme provides a lower blocking probability because entering traffic that is blocked is never transmitted. In comparison, since the trunked and hybrid systems queue calls, all traffic presented must be transmitted. Therefore, the channel is occupied more frequently and incoming traffic experiences more delay. Once two or more channels are utilized, the trunked system shows its traffic handling efficiency by sending traffic over any channel as they become available. The conventional and hybrid systems show higher blocking/delay probabilities because presented traffic can only be sent on the originating channel. Again, the hybrid system shows a higher delay probability than the conventional system because the hybrid system must transmit all traffic presented. Two observations should be noted. First, an acceptable blocking probability for LMR is 2% [Web99]. Second, the crossover point shifts to the right as offered traffic increases.

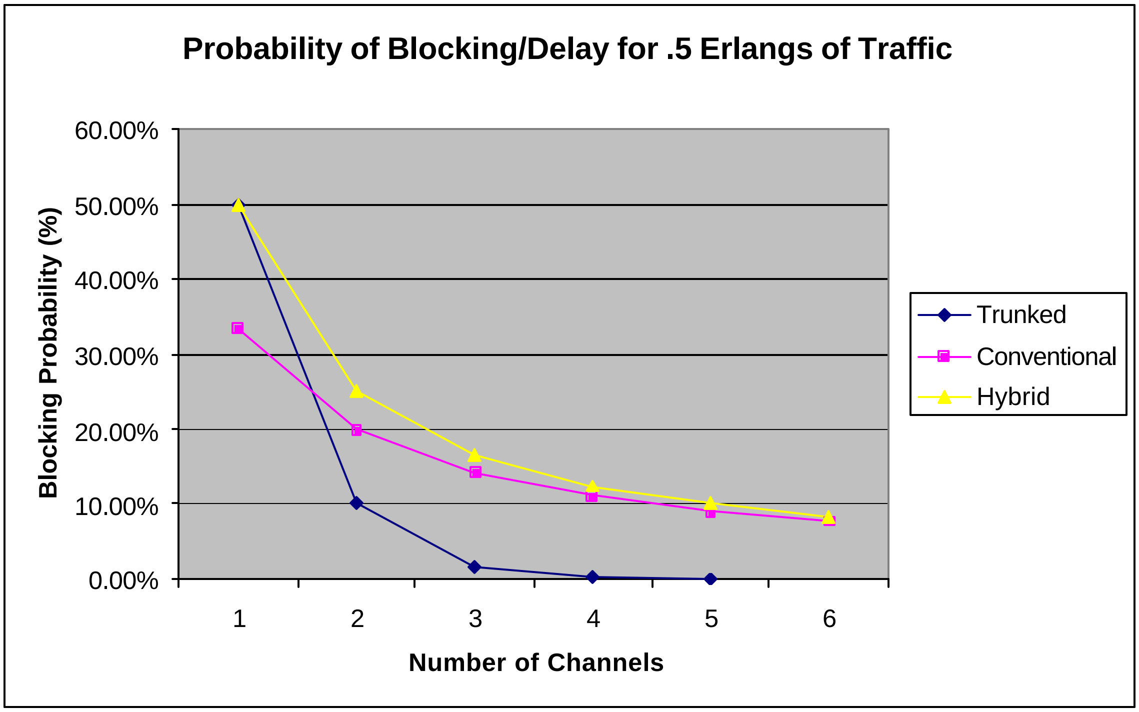

Figure 3.3.1: Probability of Blocking/Delay Given Constant Traffic

Consideration was also given to the degree in which trunking provides an advantage over conventional systems. As shown in Figure 3.3.2, trunking provides similar capacity performance to the other systems when only one traffic channel is available. However, trunking shows significantly increased capacity once several channels are combined. It is noteworthy that the conventional and hybrid systems offer only linear capacity gains as more channels are used.

An alternate scenario is also considered where offered traffic varies and the number of channels required to accommodate the traffic is determined. Figure 3.3.3 shows that, while the conventional and hybrid systems' channel requirements increase exponentially, trunked channel requirements increase more gradually. This indicates that as system loading increases, the trunked system handles the traffic more gracefully. Also, as loading grows, the trunked system will provide the desired service with a minimum of additional channels.

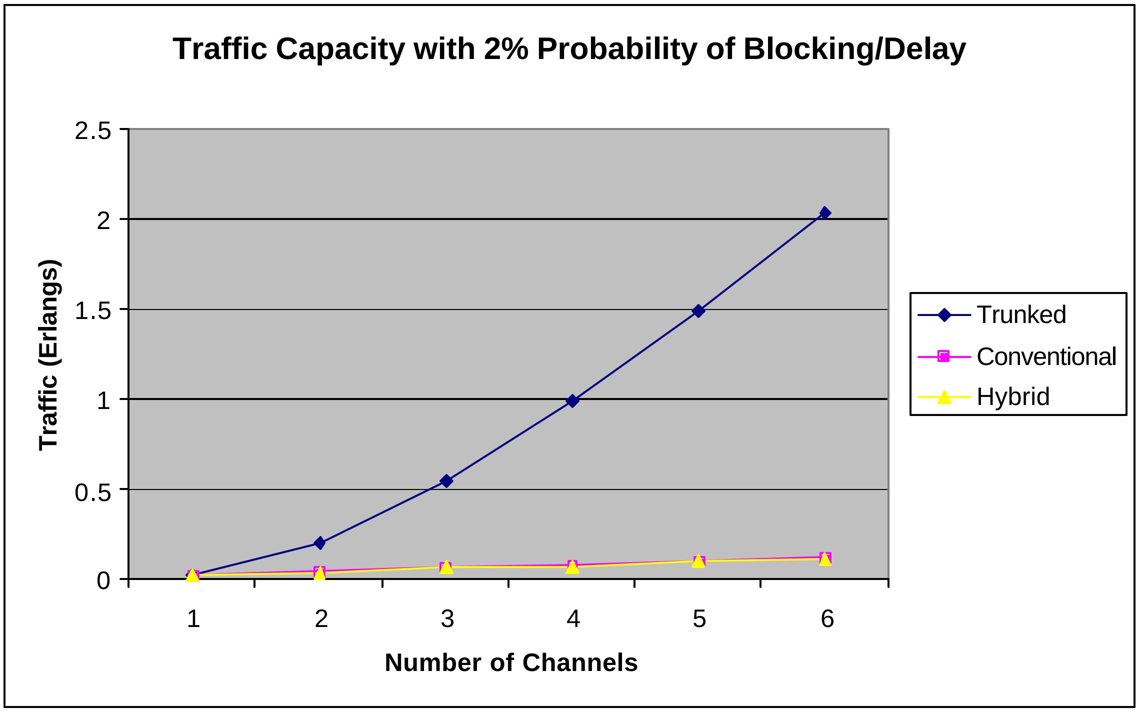

Figure 3.3.2: System Capacity for Given Probability of Blocking/Delay

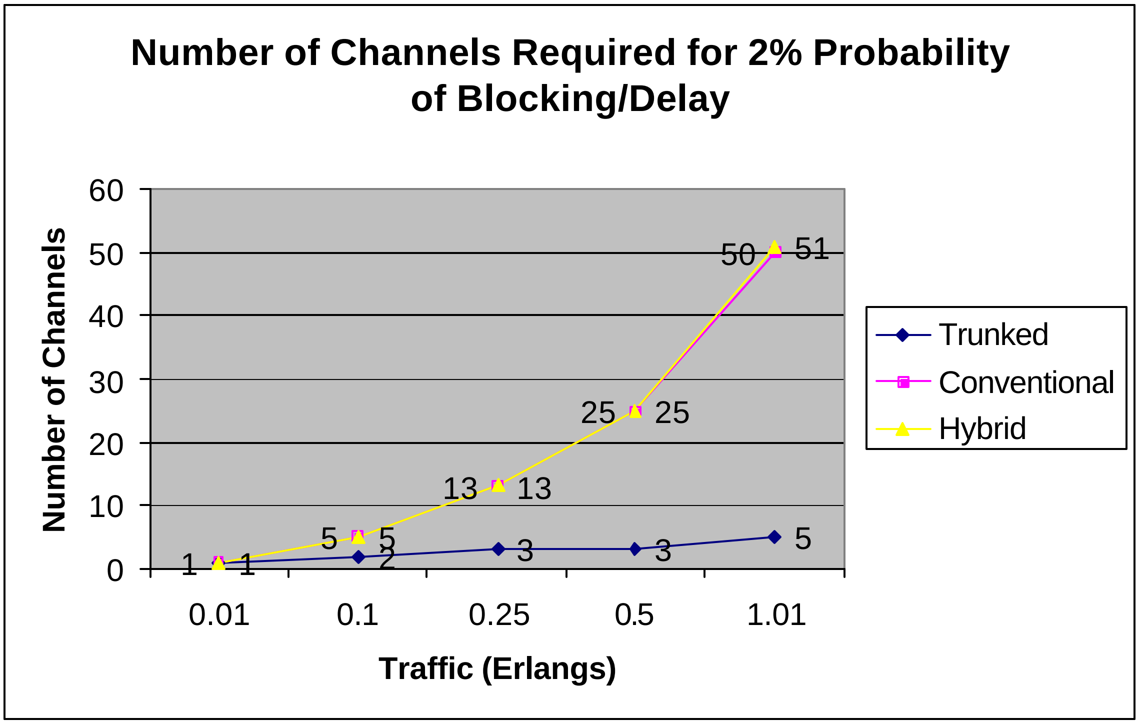

Figure 3.3.3: Number of Channels for Given Probability of Blocking/Delay

A practical comparison is now presented for consideration. Generally, conventional systems are considered well-suited for low user-density areas while high-density areas require trunked configurations. A relationship exists such that as user-density increases, the number of calls made in a given area increases. In order to sustain a desired level of blocking/delay, such as 2%, the tower coverage must be altered. This comparison is offered to show the relative limits on tower coverage given a specific system type. Calculations are done purely on a user-density basis and no considerations are made for propagation effects. The previous Erlang models are used to simulate trunked and conventional 1, 2, and 4 channel systems. Low and high-density areas of 1 user per 50 km^2 and 1 user per 1 km^2, respectively, are assumed.

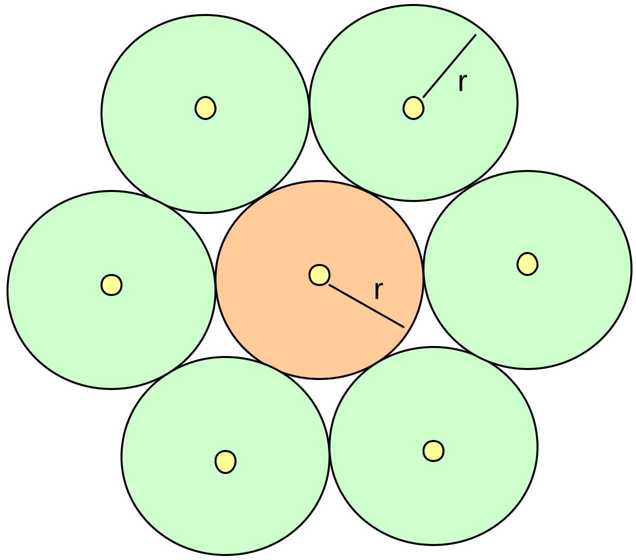

Figure 3.3.4: Multi-Tower System with Individual Coverage Radii of r km

Several interesting results were observed. First, independently of user density, both conventional and trunked systems show similar performance if only one channel is available. Once 2 or more channels are available, the trunked systems offer greater coverage while maintaining consistent performance. For the low-density cases with 2 or more channels, the trunked systems show significantly greater coverage capabilities. And the high-density cases show an excess of double the range when trunking is used. The previous outcomes are displayed in Figure 3.3.5.

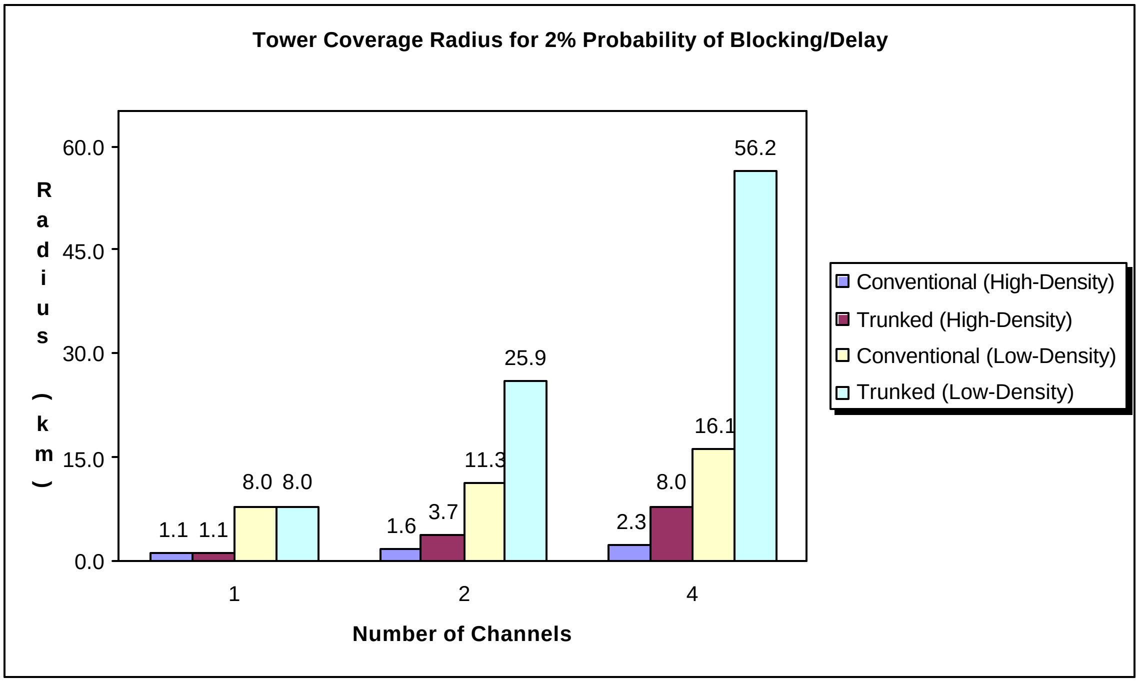

Figure 3.3.5: Coverage Radius in Various Systems and User Densities for Given Probability of Blocking/Delay

The previous example is now extended to find a crossover point related to user density. For this determination, it is assumed that the tower provides a 15 km coverage radius. The outcomes for 1, 2, and 4 channel systems can be seen in Figure 3.3.6. A blocking/delay probability of 2% or less is considered acceptable. Results indicated that for low-density areas of less than .05 users per km^2 or 35 users per tower, a 4-channel conventional system can provide sufficient performance. Should higher densities be required, trunking techniques should be applied. In the case of a 4-channel trunked system, approximately .6 users per km^2 or 424 users per tower can be supported.

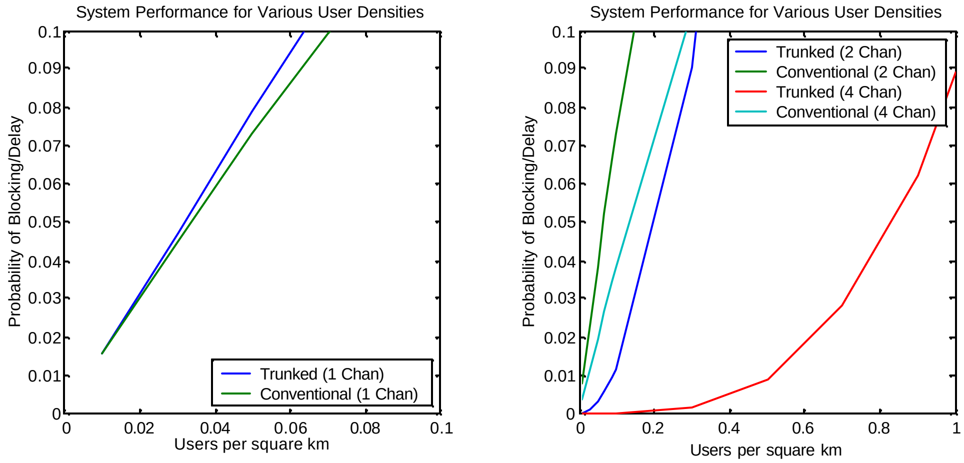

Figure 3.3.6: Probability of Blocking/Delay for Various User Densities

Several different ways to evaluate trunked performance were also examined. While probability of delay has been previously defined, [Bea88] extends the formula to produce the average delay experienced by any call in a system. It is in the form

$$\bar{w} = \frac{E_{2,N}(A)}{N - A} \tag{3.3}$$

Figure 3.3.7 plots the performance of trunked systems given a constant delay probability and an average call delay. While the probability of delay metric fixes the number of calls that can be delayed, the average delay metric relaxes that requirement. The system is then evaluated on an acceptable delay basis. As a result, an increase in capacity is perceived. Both metrics are useful in determining system performance, though each approaches capacity from a different direction.

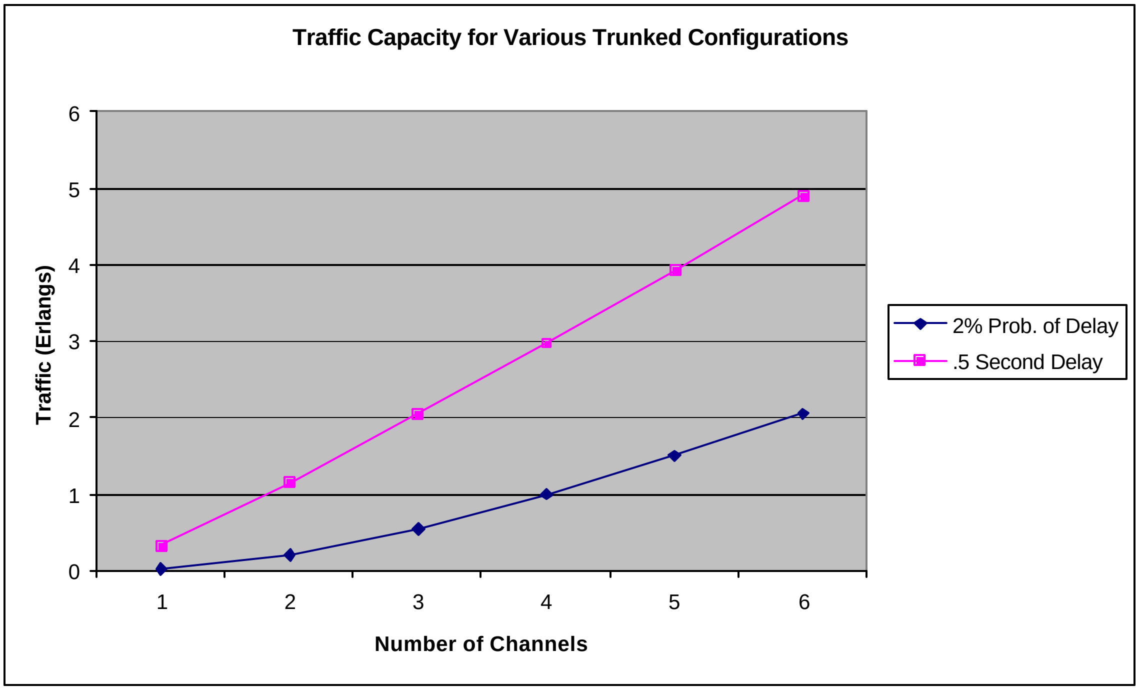

Figure 3.3.7: Comparison of Trunked Probability of Delay and Average Call Delay

A final consideration applies mainly to wide-area systems. Modern LMR systems offer the option of mixed-mode operation with both conventional and trunked areas. This allows design freedom in customizing areas to meet capacity or feature-related user needs. With some standards such as P25 requiring compatibility between trunked and conventional operating modes, it is possible that a specific manufacturer's implementation will use the same components in either configuration. This would make future mode changes easy to employ. However, if mixed operation is used, users will be required to know where and which type of system they are using in the current area. This results in increased training for personnel who roam throughout the system.

3.4 Coverage and Roaming

Once a system structure has been chosen, the desired service area where the LMR will function must to be determined. Previously deployed LMR systems can serve as a guide indicating where coverage is currently and needs to be added. If no current deployments are available, use of propagation model simulations can provide approximate coverage statistics. However, simulation results are not accurate enough to be used as the sole determiner of tower placement, and propagation surveys should be conducted to ensure acceptable coverage [Bou00].

In general, some LMR users require coverage over large geographic regions. The goal is maximum coverage with a minimum of resources, and thus the use of a strategically sited, wide-area system with mobile coverage most easily accommodates these needs. Coverage is only required where a majority of operations occur. Simplex, or radio-to-radio, communication can be used when users are beyond coverage boundaries. It should be noted that coverage may be limited if spectrum is unavailable in an area. However, national spectrum allocations exist [Ors95] and use of such can ease planning concerns.

The frequency band selected for a LMR system can also affect the coverage and structure of the system. Current public safety frequency allocations are indicated in [PSW99b] and span 9 different bands. Currently deployed systems are predominantly found in the VHF, UHF, and 800 MHz bands. Each band exhibits different propagation characteristics. However, the 800 MHz band has properties which may make it less suitable for LMR use [PSW99b]. Also, low-band VHF exhibits erratic propagation behavior as transmissions may sometimes go considerably further than expected [Ors95]. Band selection also affects the handsets purchased. Though the same handset may be available for multiple bands, manufacturers tailor the radio hardware, such as the antenna, to operate in the band specified. Thus, a VHF radio will not necessarily be able to communicate with UHF handset, even if they appear to be the same radio. Finally, deployable coverage is also dictated by the amount of radio congestion in a given area. In comparing VHF and UHF systems, UHF shows less congestion throughout a majority of the United States, and the 800 MHz band is less congested still [Ors95].

For scenarios where additional temporary coverage is needed, a mobile repeater with associated handsets can be used [PSW02a]. However, this configuration does not guarantee connectivity to the wider, permanent system. Also, further discussion of in-building or underground coverage is available in [PSW02a].

In observing various standards, several capabilities and requirements have been established to assist with coverage problems. First, for those using an APCO16-compliant handset, standards dictate that the user must be notified when the handset is beyond system coverage [APC78]. This allows the user to field diagnose low performance as a reception issue or a handset problem and take appropriate action to re-establish communication. Secondly, P25 states that conforming systems will provide coverage comparable to older analog systems without the need for additional tower sites [APC99]. The fact that old sites can be upgraded or reused greatly reduces system conversion complexity from a design and deployment standpoint.

Once a wide-area system is deployed, the modern LMR offers the ability to roam between the various areas in the system. With P25's unique identification number in each handset, any manufacturer's product can be used in any area. Further, as the handset roams, its identity is authenticated in each area it enters [APC99]. This ensures that only authorized units can operate on the system wherever used.

3.5 Security Methods

Secure communications are of great concern to LMR users. Modern LMR offers several options to secure transmissions. Perceived security by the user, along with physical system security, plays an important role in accomplishing the task of security.

Often, when users think of providing security for their transmissions, encryption is what is first considered. Modern LMR includes the capability to transmit information with or without encryption. P25 currently offers various types of encryption including the widely used Digital Encryption Standard (DES) and the capability to handle proprietary solutions [Sto95]. However, many users have shown interest in the newer Advanced Encryption Standard (AES) and its implementation in LMR is foreseeable. This is a result of advancements in encryption and decryption techniques. While DES offered sufficient security at its introduction, the increased computational abilities of modern computers have made determining the key in use considerably easier. As such, only legacy use of single DES is allowed in government systems [FIP99]. The AES effort was begun to create a new cipher that was much more secure. The AES algorithm was selected and became effective on May 26, 2002 [NIS02].

The use of encryption adds complexity to the system on several levels. On the signaling level, much more processing is required to ensure that the required decipherment information is received. Unlike unencrypted transmissions where a call is received and simply demodulated, encrypted transmissions must be received, demodulated, decipherment information must be extracted, then the message must be decrypted, all before the message can be emitted to the user. In P25 systems, should initial key information be missing, the handset must wait 360 ms for this information to be retransmitted [APC00]. This process serves to increase system complexity but should not complicate daily user operation. Also, since an allotment for encipherment information is automatically made as part of each voice transmission in P25 systems, no performance decrease is seen by activating the encryption feature.

The complexity seen by the user involving encryption relates to secure practices. [PSW01] indicates several areas where the security of encryption can be compromised. These include revealing the identity of the current encryption key or keys in use. If the key is known, decrypting the signals is elementary. However, the possibility exists to determine a key by observing transmitted signals over time. To circumvent this, the keys in use must be changed frequently. The agency employing encryption must either have designated personnel to ensure timely key rotation or have protocols in place to ensure that individual users perform this function successfully. Key rotation must occur simultaneously to ensure that all handsets can communicate. [PSW01] also indicates that additional training is required to successfully implement this procedure. As with the nonuse of analog security techniques due to high maintenance requirements [PSW02c], effective planning regarding routine key changes is needed to ensure that encryption use is not neglected.

Security can also be provided through non-encryption means. Operational protocols should dictate what is not be discussed over the radio, indicate code phrases to use when discussing sensitive issues, and stress that even encrypted conversations should not be considered private [PSW01]. Users should also be informed of other available means of communicating when restricted topics are to be discussed. While digital signaling and trunking provide some benefit in making user conversations difficult to decode and follow, ultimately, the security of any operation depends on the user exercising good judgment in conveying appropriate information via the appropriate means.

Timely conveyance of information can also affect the security of an operation. Features such as priority calling and call preemption [APC78] provide the user with means to pass information as quickly as possible to those that need it. In emergency situations, this can vastly affect the outcome of a rapidly developing set of circumstances. It should be noted that both priority access and call preemption only have an effect when all channels are occupied. Under non-peak loads, all users are typically granted immediate access to an available channel.

Security of the system itself is also a concern. P25 systems offer a unit disable feature where a handset can be forced to cease operation. Such a unit, if not disabled, could be used to monitor or block system resources [Lav00]. This feature minimizes the duration of a security compromise and once activated, restores full confidence in the system's security.

Finally, the efficient use of a LMR system is dependent on infrastructure remaining in place and operational. Physical security and the prevention of damage to infrastructure are paramount in guaranteeing system operation. Damage by vandals and tampering with or theft of hardware can render part or all of a system unavailable [PSW01]. While redundant capabilities would deal with this possible scenario, this is cost prohibitive for most organizations.

3.6 Ease of Use

While not a technically evaluated component of system design, ease of use is a concern in modern LMR development. System operation modes, perceived characteristics, and system complexity all affect the ease with which users interact and system operators maintain the system. This section attempts to expound on some ease of use issues and their effect on system operation.

As mentioned before, trunked systems provide automatic channel selection dictated by a central controller. By removing the user from the channel selection process, trunking removes the need for locational awareness. In a conventional system, if simulcasting is not used, the user must know which channel in the current area reaches the local repeater. As the user moves to different areas, he must change to the appropriate frequencies. In a trunked system, the system tracks the handset and issues instructions on which channel to use in the current area [APC78]. Users are freed to use the radio rather than be concerned with how to use the radio.

The user's comfort level with various system functionality translates into more effective feature use. Just as hospital workers are unable to successfully use equipment they are not trained on [Fou96], untrained radio users will fail to successfully operate their equipment. Training and good feature layout are needed to overcome a reluctance to utilize a given feature. Non-use of a feature leads to less effective communication, reduced system performance, and/or security problems. However, if a feature is designed to appear more efficient to the user, he is more inclined to use it. Fewer button presses to acquire a feature or custom-configured buttons provide convenience when repetitively setting radio controls. Ease of feature use also extends to emergency situations where the user is under stress. In this case, feature activation should require minimal thinking. Ultimately, the most needed operations should be the most easily accessible on the handset. Finally, user comfort comes from the physical design of the user equipment. An ergonomically optimized layout, while not a critical component, affords ease over extended use.

Ease of use also extends to the system operators who control and configure the system. P25 addresses these concerns by offering over-the-air programming for system radios [APC99]. Use of such a feature allows modifications remotely and without any physical contact. Operators are then able to remain centrally located and address more concerns quickly.

Overall, ease of use is an integral part of implementing a modern LMR. P25 has ease of use as a stated goal [APC99]. While reaping intangible benefits such as user satisfaction, its inclusion in design considerations is beneficial.

3.7 Legacy and Manufacturer Interoperability

Interoperability is another defining component of modern LMR. The need exists for multiple groups to combine expertise and radio resources on a project. The long lead times required to interconnect radio systems are inconvenient. Further, emergencies require coordinated communication as quickly as possible. Many legacy LMR systems have been deployed, many of which are proprietary solutions. While the user perceives each handset to be similar, the underlying systems do not necessarily work together. Interoperable solutions are needed to provide adequate connectedness and response time.

Federal agencies have recognized the benefits of interoperable solutions especially during events where agencies were unable to communicate. Waco, TX and the Oklahoma City bombing are events where the failure to interoperate was documented [Ors95]. Various initiatives have been created, such as the Integrated Treasury Network (ITN) and the Public Safety Wireless Network program (PSWN), to establish guidelines and coordinate efforts in deploying interoperable modern LMR systems. P25 states interoperability between multiple organizations' systems and legacy equipment as a goal [APC99].

As part of planning and deploying future interoperable solutions, consideration of near-term solutions is also needed. Direct connections between different organizations' dispatch consoles provide an efficient means to create interoperability [PSW02b]. This solution serves as a semi-permanent to permanent option. A more mobile approach is to interconnect multiple systems through their respective handsets [PSW02b]. This serves as a temporary solution for circumstances such as an emergency and only connects LMRs that are directly involved in the operation. Finally, use of mutual aid channels create interoperability when needed. For these channels, all involved users switch to the appropriate channel to coordinate efforts on a particular project. It should be noted that mutual aid channels require users' radios to operate in the same frequency band and to use the same transmission technique.

Some modern LMR systems provide backwards compatibility as a form of interoperable communication. The primary motivation for this is facilitating a gradual migration from a traditional to modern LMR system [Lav00]. As newer system hardware is deployed, it is able to carry traditional signals until enough or all of the system is upgraded. Then operations can be switched into a modern mode. In an alternate scenario, backwards compatibility also opens the possibility of operating a newer radio on a widely deployed traditional system. Assuming that new coverage areas are created and legacy coverage is retained, the newer handsets would have the capability to operate in modern areas and travel to legacy areas. In this scenario, the handset is operating similarly to the way a digital cellphone roams in analog mode when outside its digital coverage. P25 facilitates these scenarios by requiring equipment be backward compatible with a manufacturer's analog technology [APC00].

In considering modern LMR design, the use of non-proprietary designs at common points such as the Common Air Interface in P25 creates the potential for multiple manufacturers to develop interoperable components [APC00]. Having multiple manufacturers provide compatible products creates a competitive environment. Competition is a stated goal of P25 [APC99]. Also, when purchasers are able to buy gradually from multiple manufacturers, they are able to receive the best-priced technology and configure their systems with the greatest flexibility.

3.8 Costs

Costs are an ever present concern in deploying new technology. This section discusses costs related to LMR systems and offers a cost-benefit analysis. Definite costs are not provided as these vary by vendor bid, quantity, and time of deployment. Rather, relative comparisons points are given and possible cost reductions are indicated.

As an entity endeavors to determine the cost of deploying a new LMR, several areas need to be considered. First, hardware within the system is the most easily quantified expense. Once a selection of various features and the quantity of user equipment required is complete, a vendor can provide a bid that states expected system cost. Second, the cost of physical infrastructure such as towers, equipment buildings, associated utilities, and access roads needs to be gathered. Remote installations may not be easily accessed or serviced by utilities. Therefore, infrastructure costs can far outpace equipment costs. Finally, recurring costs such as maintenance, operation, training, continued upgrades, and utilities should be figured for the long-term. Depending on the system chosen, these expenses may or may not be large over the lifetime of the system. Also, costs approximations for similar systems previously deployed may be available from vendors, manufacturers, or other entities using modern LMR systems.

The cost areas just mentioned can be construed from several perspectives. First, new system costs can be evaluated in regards to the startup expenses of a previous system. Once evaluated, the system upgrade may be less expensive than an older system in inflation adjusted cost. Since upgrades are needed periodically, this may serve as justification for a high perceived initial investment in the new system. Second, justification for increased expenses can also be made on the basis of the new feature sets which require significantly more complex hardware. When the added features decrease user workload or increase worker efficiency, the additional costs are offset by the benefit realized. Third, [PSW99a] suggests evaluating the upgrade gains on a per user benefit scale. For this measure, as the number of users serviced increases given a fixed system cost, the benefit per user increases.

The addition of encryption to a modern LMR can considerably increase the cost of the system. This feature is often charged on a per handset basis. [PSW02c] discusses the cost-benefit and indicates that it may not justify the use of encryption. In addition, modern LMRs like P25 offer Over-the-Air Rekeying (OTAR). OTAR requires additional hardware, extra spectrum in conventional systems, additional user training, and recurring user action.

Several cost reduction mechanisms exist to reduce the overall cost of a new/upgraded LMR. First, since all types of standards-based systems may have similar components, the cost of different feature sets may be similar and more a matter of whether the feature is active or not. Co-siting hardware with previously deployed equipment or leasing space in already constructed facilities can greatly reduce initial investment but will still involve recurring fees. Finally, designing for mobile rather than portable coverage will greatly reduce the number of base stations required. While a portable has an effective range of about 5 km, mobiles can operate from 10-60 km away [Bou00].

The transition to a modern LMR system involves considerable expense. In order to help determine whether a new deployment should be undertaken, a cost-benefit analysis can be performed. The following is a cost-benefit analysis intended to be applicable to a wide array of potential LMR users. The model used is very general and is customizable to specific user requirements.

The cost-benefit components involved in the model fall into several categories. First, certain costs are considered quantifiable expenses, such as the number of additional personnel, and have definite values and quantities. These are easiest to incorporate into cost-benefit analyses and can be most accurately estimated. Subjective components involve items which often do not have a physical presence but affect perceived system value. Items such as increased security or the ability to interoperate are subjective and relative in value for different user groups. This creates great difficulty in determining an equitable price for such items. Some costs, such as infrastructure investments, are upfront expenses and occur only once. Other costs and benefits are recurring and may vary by year. Examples of these are training or cost sharing savings. Finally, the FCC narrowband compliance benefit is considered to be a future benefit as the mandate takes affect in year 2005. The complete cost-benefit analysis is shown in Table 3.8.1.

Costs	Unit Cost	2003	2004	2005	2006	2007	2008	2009
System Planning (per hour)	$50	$160,000	$0	$0	$0	$0	$0	$0
Infrastructure								
Radios (200 users)	$4,000	$800,000	$0	$0	$0	$0	$0	$0
Basestations (5)	$400,000	$2,000,000	$0	$0	$0	$0	$0	$0
Training	$50	$30,000	$0	$10,000	$0	$10,000	$0	$10,000
Maintenance (per month)	$5,000	$60,000	$60,000	$60,000	$60,000	$60,000	$60,000	$60,000
Additional Staff (1)	$20	$41,600	$41,600	$41,600	$41,600	$41,600	$41,600	$41,600
Yearly Cost		**$3,091,600**	**$101,600**	**$111,600**	**$101,600**	**$111,600**	**$101,600**	**$111,600**
Cumulative Cost		**$3,091,600**	**$3,193,200**	**$3,304,800**	**$3,406,400**	**$3,518,000**	**$3,619,600**	**$3,731,200**
Benefits	**Unit Benef**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
Shared System Cost Savings		$753,867	$33,867	$33,867	$33,867	$33,867	$33,867	$33,867
Improved Voice Quality (per month)	$30	$72,000	$72,000	$72,000	$72,000	$72,000	$72,000	$72,000
Secure Communications (per month)	$30	$72,000	$72,000	$72,000	$72,000	$72,000	$72,000	$72,000
Interoperability (per month)	$90	$216,000	$216,000	$216,000	$216,000	$216,000	$216,000	$216,000
FCC Narrowband Compliance (per month)	$150	$0	$0	$360,000	$360,000	$360,000	$360,000	$360,000
Yearly Benefit		**$1,113,867**	**$393,867**	**$753,867**	**$753,867**	**$753,867**	**$753,867**	**$753,867**
Cumulative Benefit		**$1,113,867**	**$1,507,733**	**$2,261,600**	**$3,015,467**	**$3,769,333**	**$4,523,200**	**$5,277,067**
Yearly Cost/Benefit (Negative = Excess Cost)		**-$1,977,733**	**$292,267**	**$642,267**	**$652,267**	**$642,267**	**$652,267**	**$642,267**
Cumulative Cost/Benefit		**-$1,977,733**	**-$1,685,467**	**-$1,043,200**	**-$390,933**	**$251,333**	**$903,600**	**$1,545,867**

Table 3.8.1: General Cost-Benefit Analysis for 7-Year Modern LMR Deployment

General trends within the analysis are as follows. The initial investments involved in deploying the system create a considerable first-year expense. Investments in system planning, new radios, base station equipment, and necessary training combine to provide a one-time charge of $2,990,000. As such, the first year's cumulative cost-benefit is negative. However, once the initial investment is made, yearly costs decrease significantly. This results in following yearly cost-benefits being positive. These combine to create a positive cumulative cost-benefit by year 2007 and an overall benefit from the system. It will be noted that the cumulative cost-benefit is not an actual positive cash flow. This is because many of the benefit components are conceptual in nature. Rather, the plan to deploy the system is considered viable because a net benefit is realized.

The previous analysis is now extended to consider when a system upgrade should take place. Several rational can be used to determine when a new deployment is useful. First, and most elementary, is upgrading when any benefit is perceived. In this scenario, a new system provides some utility, but ultimately, the overall expense may not be justified. An example of this would be fielding a system with increased data rates when current data services are sufficient. Users would experience increased performance. However, the general question must be asked if faster data rates or clearer transmissions or additional capacity are reason enough to invest.

A second reasoning as to upgrade timing focuses on handling needs only when they arise. Under this thinking, the current system is used until its capabilities cannot directly meet a developing need. Users are then forced to invent creative solutions or else purchase new equipment. This rational is reactionary and often leaves users waiting for needed upgrades to occur. In the meantime, the quick solution planning cycle can be become quite costly as rushed planning may require changes during the deployment phase. These changes may also cause further delay. An example of need-only driven implementation is if additional jurisdiction is given to an agency and prior coverage planning has not taken place. During the time between new responsibilities and new system deployments, alternate communication means must be utilized. Alternate communication means such as cellular phones or pagers may not provide all the needed functionality and are not easily integrated into the existing radio system.

Rational that focuses on future planning offers the best strategy for timely deployment and maximum benefit versus system investment. As with the previous cost-benefit analysis, when the cost-benefit of a system is positive, the system is a good candidate for implementation. Cost-benefit analyses allow system planners to anticipate future needs, theoretically supply for them, and determine if the examined solutions are worthwhile. If several scenarios are compared in this manner, an optimum solution can be determined. However, practical concerns may dictate that the optimum choice not be used. In this case, the remaining cost-benefit analyses allow another suitable selection to be made.

Once a future solution has been chosen, implementation timing still needs to be determined. Timely implementation dictates that a system is deployed before the benefits lost by waiting exceed the future benefits realized and before the cumulative cost-benefit becomes negative. Ideally, a solution is implemented immediately in order to reap the maximum benefits. This timing strategy assumes that a product has a fixed functional period. At the end of that period, a new product provides a superior solution or integrates the previous product's capabilities into its own. Table 3.8.2 shows this strategy applied to the previous cost-benefit scenario.

Year Implementation Begins	2003	2004	2005	2006	2007	2008	2009
Cumulative Cost	$3,731,200	$3,619,600	$3,518,000	$3,406,400	$3,304,800	$3,193,200	$3,091,600
Cumulative Benefit	$5,277,067	$4,883,200	$4,489,333	$3,735,467	$2,981,600	$2,227,733	$1,473,867
Benefit Lost due to Delay	$0	$393,867	$787,733	$1,541,600	$2,295,467	$3,049,333	$3,803,200
Cumulative Cost/Benefit	$1,545,867	$1,263,600	$971,333	$329,067	-$323,200	-$965,467	-$1,617,733

Table 3.8.2: Delayed Implementation Cost-Benefit Analysis

Several items from the delayed implementation analysis should be mentioned. Due to the 2009 ending date, it is inferred that a product introduced at the beginning of year 2010 renders the current system under consideration obsolete. Also, while the benefits lost due to delay do not exceed the cumulative benefits until year 2008, the cumulative cost-benefits become negative after year 2006. Therefore, year 2006 is the last year in which deployment of the system should be considered.

3.9 Control Over Infrastructure

With financial concerns heavily affecting the operational capabilities and future planning of modern LMR systems, the purchase and deployment of such systems are being scrutinized to ensure optimum benefit for the cost. New philosophies have developed related to how a LMR might be reorganized to provide comparable service at a reduced expense. One such concept is sharing infrastructure and associated costs. This section focuses on issues that agencies planning to share their LMR resources may encounter.

Trunking provides a sharing opportunity like no other. Trunking enables users to pool resources such as radio spectrum and infrastructure while still maintaining the appearance of autonomous systems. This scenario requires cooperation among the agencies that are sharing resources to ensure that the system operates efficiently and that maintenance is timely [APC77]. If system problems arise, the agencies must collectively plan corrections and complete the task to all parties' satisfaction. Also, bad operational practices in one organization can occupy resources needed by another group, thus reducing the overall system performance.

Another alternative to operating an in-house LMR system is outsourcing the LMR network itself. If a LMR provider can be found in the service area required, use of their service does not require a large investment in infrastructure or hardware. Should no suitable provider be found, deploying the required hardware and infrastructure and then outsourcing maintenance and upgrades may lead to a beneficial outcome. For any of these outsourced scenarios, quality-of-service (QOS) agreements are required to guarantee the desired level of system performance, the response time to, and priority of system problems which may arise. It is noted that if outsourcing is in the form of purchased service, there exists the possibility of private and commercial traffic also sharing the system.

Finally, when system resources are shared or outsourced, future changes and upgrades to the system are of great concern. These changes affect all users through the added costs and downtime required to implement them. Problems during an upgrade can affect users systemwide. Further, in a shared system, adding coverage or other features may only benefit portions of the user population, thus not justifying the cost sharing principle.

Overall, sharing resources can provide benefits to all involved. However, organizations must be flexible in accommodating the needs of all groups involved. Clearly defined responsibilities and open discussion are required to ensure that all users are and remain satisfied.

3.10 LMR versus Cellular Technology Comparison

In evaluating a communication tool such as LMR, it is beneficial to establish a frame of reference by making comparisons with similar technologies. One popular communication tool is the cellular phone. The consumer market for cellular service has seen large increases in recent years. Cell phones provide connectivity wherever the user is, and service can be found in many locations throughout the world. The following comparisons evaluate the typical case deployments of the respective technologies.

LMR and cellular telephony share several significant features. First, both have their primary goal as a convenient, efficient communication medium. The wireless nature of both systems allows users to interact without being restricted to specific locations. Second, both are used primarily for voice communication. The original architectures for both technologies were designed to handle voice traffic while data capabilities were added later. Next, the coverage of each system is constrained by the transmission capabilities of users' handsets. Finally, early implementations of each system used similar channel bandwidths. These LMR and cellular systems utilized 25 and 30 kHz channels, respectively [Rap02].

Though there are several commonalities between the technologies, significant differences also exist. Several differences appear in regards to internal system architecture. Most significantly, while LMR provides communication in a one-to-many fashion, cellular systems connect users in a one-to-one manner. Also, while call handoff is provided in cellular systems, none is available for LMR users. Finally, cell phones are infrastructure dependent, relying on base stations and mobile switching centers to provide critical call functions. LMR handsets can use simplex mode to communicate with other users in the immediate area independent of fixed infrastructure.

Several other contrasts exist between LMR and cellular phones. Typically, a LMR system is owned by one entity and is intended for use by personnel in that organization. Cellular systems operate in a service fashion where the owner sells system access to many different users. Coverage strategies also vary between cellular and LMR systems. LMR systems are arranged to provide maximum coverage with the possibility of poor coverage in some areas. Exact coverage is often not known. For cellular systems, towers are arranged to provide the best coverage possible. In such systems, continual effort is made through activities such as drive testing to identify coverage weaknesses and achieve optimum performance.

The handset form factors used in LMR and cellular systems also vary. LMR systems are known to utilize both mobile and portable handsets. Cellular systems predominantly use portable handsets though they are commonly referred to as mobile phones. The handsets also are different in regards to transmission power. P25 portable and mobile radios operate at a maximum output of 5 and 110 W respectively [Mot01]. Compare this to cellular handsets, which may operate at up to several watts but typically transmit under 1 W.

Finally, several items in regards to the channels utilized are different. Channel allocation is typically handled by the LMR handset. This occurs when the user presses the talk button and the radio immediately begins transmitting on the selected channel. In a cellular system, the phone requests resources from the system controller. Once resources are granted, the user may begin communicating. Another difference is that LMR handsets only occupy the selected channel when the talk button is depressed. Otherwise, other users may utilize the channel. In cellular systems, the handset is granted sole access to resources until the call is ended. Lastly, while original LMR and cellular systems used similarly-sized channels, newer systems show great disparities in channel bandwidths. Modern LMR systems can utilize 12.5 and 6.25 kHz channels while various 2G and 3G cellular systems require 200 kHz, 1.25, 3.75, or 5 MHz of bandwidth to operate [Rap01].

Chapter 4

Future Technologies and Techniques

While modern LMR promises to provide for current user needs, several technologies and techniques have potential application to LMR services. Reallocating unused data bits in the voice packets of P25 systems may lead to better services or improved performance. Cellular telephone systems based around 3G standards contain operating modes that could potentially carry LMR traffic. Also, the advent of software-defined radio architectures create the potential for the development of multi-mode handsets. These near-future technologies may ultimately enhance, complement, or replace current LMR systems.

4.1 Alternate Resource Allocation

Current implementations of modern LMR such as P25 include native support for voice encryption. While this service adds value and security for many users, those who do not utilize this feature still transmit pad bits to conform to the standard. This extra data capacity could be applied to increase system performance or carry additional information. This section looks at the current P25 encryption structure. Alternate options are considered relative to the available radio resources and existing computational capabilities.

In order to establish a baseline for new services, the use of DES encryption for P25 systems is examined. The DES algorithm has been widely used throughout the world and is known for its computational simplicity. The algorithm computes a result by repeating 16 rounds of the following calculations [FIP99]. Each round requires operations on the encryption key and on the input data. One round of processing on the key involves 1 or 2 circular shifts on 2 28-bit registers. This result is selectively combined into a 48-bit value used for that round's encipherment. The encipherment calculation involves the expansion of a 32-bit word into 48 bits, a 48-bit XOR operation, processing through 8 4x16 lookup tables, and the selective reduction of the result from 48 to 32 bits. Since each voice super frame in a P25 system contains 18 voice packets of 144 bits each and the DES algorithm processes 64 bits at a time, 41 rounds are required to process an entire super frame of voice data. This translates into approximately 1968 circular shifts, 1750 AND operations, 1750 compare operations, and 875 ADD operations, 656 XOR operations, and 5248 table lookup operations per super frame. In total, the DES algorithm requires approximately 6999 operations and 5248 table lookups per super frame. This all occurs in 360 ms or less. It is noted that in order to decrypt the message, only the operations affecting the key must be modified, but the basic round structure is reused.

Several important parameters in P25 also need to be mentioned. P25 systems provide 96 bits of information and 144 bits of error correction related to encryption per super frame. Combining these categories yields 240 extra bits per 2592 bits of existing voice/error correction data. In regards to P25, the vocoder generates 4400 bits-per-sec (bps) or 88 bits per voice packet. An (18,11) effective-rate error correction code is then applied. However, the actual channel coding is a mixture of (23,12) Golay and (15,11) Hamming codes. This results in 7200 bps of voice data/error correction being generated in 144-bit packets [For00].

By reallocating the bits and processing timing not used for encryption, performance improvements may be possible. The simplest change would involve adding an extra layer of coding on top of existing error correction. For this case, no modification to the standardized encode structure would be required. An extra final coder stage would be added before transmission and the presence of the additional coding process would be indicated in the link control bits reserved for future use. When considering the implementation of this change, an average of 13 bits per voice packet is provided. Over a 144-bit packet, 13 bits is not sufficient to support block coding. As such, coding over top of the standardized, coded voice packet structure is not feasible.

Another possible coding alteration would be to fundamentally modify the standardized coding structure for P25 voice packets. Currently, 48 and 33 bits of uncoded voice information are coded with Golay and Hamming codes, respectively. The remaining 7 bits are left uncoded [For00]. Due to the limited number of additional bits available per packet, coding can only be extended in a limited way. This would involve Golay coding 60 bits and Hamming coding the remaining 28 bits for a net error correction bit count of 11 bits. Using this technique, all voice packet information would now have coding protection. The performance gain realized using this method would be perceived in the form of additional voice clarity at the receiver though not increased operating range. This is due to the fact that the additional coding does not affect the most important portions of vocoder information. It should be noted that a voice packet coded in the previous manner could be transmitted over a P25 network but could not be decoded by a handset lacking the knowledge of this coding structure.

The use of convolutional coding was also considered. It was found that decoding complexity is the key component in evaluating the use of a coding scheme. For convolutional coding, the Viterbi algorithm is the most efficient decoding method [Pro01]. As such, the Viterbi algorithm requires 2^k metric calculations per code word for a given (n,k) code. For example, in (23,12) Golay coding, decoding of one code word requires 4096 metric calculations. This requirement far exceeds the DES algorithm's complexity over the length of a super frame. Unless Viterbi decoding is inherently provided in the intended receiver, convolutional coding is not an option.

A final option for use of the available bits is increasing the slow-rate data included with each voice transmission. Currently, 32 bits of data with 32 bits of error correction are included in each super frame. An additional 120 bits of data with same-rate error correction could be added for an increase in the data rate from approximately 89 bps to 422 bps.

4.2 LMR-like Services over 3G Cellular Networks

While the advent of 3G cellular systems is purported to usher in a new era for wireless phone users, it may also fulfill LMR user needs. Packet data services have been integrated into 3G networks. When voice-over-IP techniques are applied, voice information can be transported over the data network [New03]. With short setup times and QOS guarantees [3GP03], packet data facilitates PTT between single users. Packet handling techniques similar to computer network multicasting provide one-to-many packet transmissions and enable group calls. One such example of PTT in 3G systems is QChat [PSW02d].

The main motivation for the development of 3G systems was to provide higher rate data [PSW02e]. While LMR user voice needs are largely meet by previous systems, utilizing high-bandwidth data applications remains a tempting future capability. Fully 3G systems promise data rates in excess of 2 Mbps and the ability to handle high-quality video or document display. Early 3G components such as cellular phones, PC cards, and modems are available and offer sub-2 Mbps data rates. These early systems will be upgraded to full 3G capability in the future.

Another advantage of 3G cellular systems is the large coverage area available to the user. Since 3G capabilities are sold as a service to the customer, the system owner is motivated to extend coverage to the widest area possible. If current 2G coverage is used as a guide, 3G coverage will far exceed the coverage seen in any current LMR system. Also, since new technologies such as smart antennas are likely to be integrated into 2.5 and/or 3G cellular networks, greater range will be achievable by a user's handset when compared to previous cellular networks.

Several features of 3G systems offer convenience, added security, and the potential for rapid deployment of new features. First, GPS location capabilities are a part of new 3G handsets made for the American market. This offers the average consumer the benefit of automatic location capabilities in an emergency. For LMR use, dispatchers would have location data available as part of routine transmissions. Central or field managers can gain greater situational awareness if GPS information is fed to a mapping system. It is noted that GPS satellite transmissions can only be received outdoors, excluding location capabilities within buildings and underground. Another feature that adds usefulness is the inclusion of processing functionality and software languages such as Java in user handsets. As needs develop for new capabilities, providers are able to load new software directly into the handset. New features can be added to multiple handsets almost simultaneously and over-the-air. This gives flexibility to meet future challenges and keeps user equipment from becoming ineffective as a communication platform.

4.3 LMR Applications of Software-Defined Radios

The software-defined radio concept has served to revolutionize thinking regarding radio structure and functionality. With an ever increasing number of radio standards and services, hardware developers creating multi-mode radios in the traditional fashion are required to integrate more and more discrete systems into one package. This creates both size and power concerns [Ree02]. A Software-defined radio (SR) takes the bulk of the hardware functionality in a traditional radio and handles it centrally through software processing. The following is high-level examination of SR. The general SR concepts discussed are adapted from [Ree02] and are augmented with specific LMR applications.

The key benefit to SR is its reconfigurability. LMR users desiring to interoperate find multiple widely-deployed proprietary solutions spread over several disparate bands. SR provides a platform that can efficiently service these different systems. The need to quickly interoperate in temporary scenarios, such as special task forces, reflects the utility of reconfigurable radios. As LMR standards are refined or deployed systems are optimized, system operators have more room to customize their radio's performance. Should new modulation techniques and communication standards emerge, there is also the potential to upgrade existing components. Similarly, as new systems are deployed, SR handsets can utilize both old and new systems. Older systems would then be able to serve as a backup or as additional coverage.

The increased processing capabilities inherent in SRs offer the potential to improve the performance of LMR handsets. The inclusion of more robust and computationally complex decision algorithms allow for increased transmission robustness and extended operating range. Both of these are much desired attributes of LMR systems. Also, the cross-channel connection properties of SR lend themselves well to providing increased data speeds. By utilizing multiple channels simultaneously, users would be able to retrieve information more quickly in the field.

However, there are complicating factors in using SR in LMR. The disparate bands previously mentioned present a challenge to the RF hardware incorporated in the SR handset. In servicing all the bands with one unit, size will be a great concern, especially for portable implementations. Also, it has been noted that mode switching times can be excessive in SRs. Depending on the capabilities of a specific SR, this may create a performance problem as the radio communicates between multiple networks. In a minimal implementation, a handset may be receiving in one or more modes and then need to reconfigure to transmit in another. The potential for a more than normal delay in call setup exists.

SRs may also serve as bridging systems for incompatible LMR systems. In this scenario, the SR receives native-type data from multiple radio systems. The information is reformatted by the SR into the native formats of the other associated LMR systems and is then retransmitted.

Finally, a SR in its ideal form is infrastructure-type independent. It is capable of configuring in the manner currently needed and reconfiguring in the next moment for the next system encountered. Ultimately, the user is able to communicate anywhere there is any sort of communication infrastructure available. While the Software Defined Radio Forum is currently working to establish requirements for such a radio, [Ree02] notes that no ideal SR is currently realized. As such, SR remains a technology with applications today and offers a glimpse of a future where LMR systems interoperate seamlessly and effortlessly.

Chapter 5

Conclusion

The following chapter provides an overview of the results in this thesis. Also, potential future evaluations are given.

5.1 Summary of Results

The main goal of this thesis was to provide a usable overview of LMR design concerns and associated analytic evaluations. Coverage of many topics was provided and only key components in each topic as related to LMR systems were discussed.

Beginning with Chapter 2, a foundational view of LMR development was provided. The changes resulting from the deployment of LMR were indicated as far reaching and mostly beneficial. Overall, LMR was considered effective in encouraging efficient work practices and useful in improving service, security, and situational awareness.

Chapter 3 took a wide-ranging view of modern LMR systems. The essential components of a modern LMR were discussed and tradeoffs in evaluating features were presented. Topics such as digital voice transmission, coverage determinations, and usability were discussed. A crossover analysis was conducted related to trunking versus conventional channel allocation, and both were found to be applicable in different scenarios. Finally, a cost-benefit analysis revealed that a limited timeframe exists for LMR systems to be deployed before the current technology is no longer viable. This analysis, like other analyses, is customizable to fit other scenarios.

Chapter 4 presented near-future technologies which may be able to provide or improve LMR service. Reallocation of encipherment information in P25 systems was found to be applicable only in a constrained set of circumstances. Also, 3G cellular systems and SR technologies were found to have the potential to augment LMR in the future. However, it is unclear whether either will be exploited to their full potential.

5.2 Future Work

Future work related to this thesis may include the following.

- Evaluating other error correction techniques available without regard to complexity may allow for significant performance improvements. Current coding techniques rely on basic block codes and may benefit from more complex convolutional coding.

- Further study regarding the interest in and use of 3G PTT services and their effectiveness in providing comparable service may be beneficial. This, combined with a greater understanding of the risks involved in outsourcing essential communications capabilities, would benefit the LMR user community greatly.

- Further determination as to whether the concept of manual queuing is used in practice may be beneficial. Whether blocked users find other means to convey the information or decide to forego using radio communication should be explored.

- Evaluate SR bridging technology in regards to providing LMR interoperability. Consider the applicability of SR as a temporary interconnect option and as a permanent bridging solution.

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Vita

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