NTIA Report 08-451

ASSESSMENT OF ALTERNATIVE FUTURE FEDERAL LAND MOBILE RADIO SYSTEMS

technical report

U.S. DEPARTMENT OF COMMERCE National Telecommunications and Information Administration

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EXECUTIVE SUMMARY

In May 2003, President Bush established the Spectrum Policy Initiative to promote the development and implementation of a United States spectrum policy for the 21st century. In response to the Spectrum Policy Initiative, the Secretary of Commerce established a Federal Government Spectrum Task Force and initiated a series of public meetings to address policies affecting spectrum use by the federal government, state, and local governments, and the private sector. In June 2004, the Secretary of Commerce released two reports that included the recommendations resulting from these activities. In November 2004, the President directed the federal agencies to develop a plan to implement the recommendations contained in the reports. One of the recommendations called for the National Telecommunications and Information Administration (NTIA) to develop analytic approaches, software tools, and engineering techniques for evaluating and improving the efficiency and effectiveness of federal spectrum use.

To evaluate the efficiency of federal spectrum use, NTIA performed a study that compares the spectrum resources used by several alternative land mobile radio (LMR) system architectures employing trunked radio technology to the spectrum resources used by the current conventional LMR systems. This study considered the 162-174 MHz federal LMR band in the Washington, D.C. area. NTIA selected the Washington, D.C. area because it represents a spectrally congested environment and the 162-174 MHz band because it represents the most heavily used federal land mobile frequency band.

LMR systems operate using conventional and/or trunking methods. Conventional LMR systems dedicate a single channel (radio frequency channel) to a specific group of users who share it. Since radios on conventional LMR systems transmit and receive on a single channel, the user must wait if the channel is occupied by another user. Trunking is a proven technology that permits a large number of users to share a relatively small number of channels. Unlike conventional LMR technology, trunking allows for the automatic sharing of multiple channels. The trunked system dynamically allocates the mobile user's access to the available channels. Currently, most of the federal agencies are using conventional LMR systems in the 162-174 MHz band. However, several agencies are deploying trunked LMR systems.

The NTIA study presents three alternative trunked LMR system architectures. The distinguishing characteristic of these three system architectures is the size of the service area associated with the trunked system base stations. The service area represents the area over which the base station supports radio communications with mobile users. NTIA considered three system architectures. The first system architecture uses large service areas for the entire coverage area (Large-Service-Area-Only). The second system architecture uses a combination of medium service areas where there is a high concentration of users and large service areas where there are a medium or low concentration of users (Large-Medium-Service-Area-Mixed). The third system architecture is a combination of overlapping large and small service areas with the small service areas used for high concentrations of users (Large-Small-Service-Area-Overlapping). NTIA also considered three potential levels of federal agency participation: 30 percent agency participation representing partial participation by the current federal users of the conventional LMR systems; 100 percent agency participation representing full participation by the current federal users of the conventional LMR systems; and 300 percent agency participation representing future expanded use by the federal users. The three system architectures combined with the three levels of agency participation provides nine unique trunking scenarios. NTIA studied each trunking scenario within a 100-mile radius coverage area centered in Washington, D.C. The frequency assignment data from the GMF and channel occupancy measurements performed by the NTIA Institute for Telecommunication Sciences (ITS) enabled NTIA to derive traffic levels expressed in Erlangs for the service area of each base station. The traffic levels provided a basis to determine the number of channels required (spectrum requirements) for the different trunking scenarios. NTIA developed spectrum requirements for each trunking scenario based on 12.5 kHz channel spacing in the 162-174 MHz band, and a 70-mile (113 kilometer) frequency reuse distance criterion used by the Federal Communications Commission (FCC) for LMR systems. The table below summarizes the number of frequency assignments required for each of the nine trunking scenarios considered in this study.

Number of Required Frequency Assignments in the 162-174 MHz Band for Different Trunking Scenarios

Trunked LMR System Architecture	**Number of Required Frequency Assignments in the 162 – 174 MHz Band**[a] **(100 Mile Radius Coverage Centered in Washington D.C.)**		
	30% Agency Participation[b] (partial participation, the remaining 70% continue with conventional systems)	**100% Agency Participation** (current level – total participation, all conventional system users participate in the trunking system)	**300% Agency Participation** (trunking system supporting three times the current number of users)
Large-Service-Area-Only System[c]	124[d]	166	264
Large-Medium-Service-Area-Mixed System	146	194	296
Large-Small-Service-Area-Overlapping System	158	200	302

a. Based on 12.5 kHz channel spacing, the 162-174 MHz band consists of 960 channels.
b. The required number of frequencies shown for 30% level of agency participation represents only the frequencies required for the trunked system. In addition, the 70% of users that remain employing conventional LMR systems would require approximately 367 frequency assignments.
c. Service area is the area over which the base station supports radio communications with mobile users.
d. This report assumes access to the entire 162-174MHz band. However, a single agency does not have access to the entire band, but is limited to a subset of frequencies (e.g., allotments). In many instances, it may not be possible to select enough interference free frequencies (inter-modulation and adjacent channel interference) to satisfy the requirements for a large number of channels at a single base station.

As of November 2002, the GMF had 524 frequency assignments associated with base stations at specific locations in the 162-174 MHz band within a 100-mile radius of Washington D.C. The 524 frequency assignments do not include area frequency assignments (e.g., base stations are not constrained to a specific location) or other non-LMR frequency assignments (e.g., weather channels). As shown in the table above, frequency requirements for the nine trunking scenarios fall far below the 524 frequency assignments currently used by conventional LMR systems with base stations at specific locations. The frequency requirements for the trunking scenarios contained in this study also considered additional channel usage to support emergencies and future growth as shown for the 300 percent level of agency participation.

For the 100 percent level of agency participation, approximately 32 percent or 166 of the 524 frequencies in the GMF are needed for the Large-Service-Area-Only System, approximately 37 percent or 194 are needed for the Large-Medium-Service-Area-Mixed System, and approximately 38 percent or 200 are needed for the Large-Small-Service-Area-Overlapping System. Since the 30 percent and 300 percent levels of agency participation do not directly correspond to the existing users, NTIA could not determine the actual number of frequencies required for conventional LMR systems from the GMF, and could not perform a direct comparison of the frequency requirements for the trunked LMR system at these two levels. However, fewer frequencies are required for all three trunked system architectures for the 30 percent and 300 percent levels of agency participation as compared to the number of frequencies required for the existing conventional LMR systems.

The report concludes that the trunked LMR systems use less spectrum resources than conventional LMR systems. In addition, trunked LMR systems servicing a large number of users are more spectrum efficient than trunked LMR systems servicing a small number of users due to more efficient sharing of the available channels. In this study, the number of users per frequency increased by a factor of 2.5 for the 100 percent level of agency participation and by a factor of 4.7 for the 300 percent level of agency participation as compared to the number of frequencies used for the 30 percent level of agency participation.

The report also concludes that a proper design of base station frequency use in the areas where there is a high concentration of users is a key consideration in obtaining a high frequency reuse. Such reuse reduces the necessary spectrum resources. If a shared trunked LMR system is implemented in the Washington D.C. area, NTIA believes there will be sufficient frequencies in the 162-174 MHz band to support more users with the appropriate frequency reuse scheme. For example, the 300 percent level of agency participation (3 times the current number of users) requires approximately 30 percent of the 960 assignable 12.5 kHz channels in the band. Trunked LMR systems shared by federal agencies would be an effective approach to more efficient use of the 162-174 MHz band.

As shown in the report, shared trunked LMR systems can be designed to use less spectrum resources as compared to individual conventional LMR systems, while still achieving the same grade of service requirements (probability of a call being blocked and call waiting time). Therefore, spectrum efficiency can be improved while maintaining the same level of operational effectiveness.

This report presents a study of hypothetical LMR system designs, and does not provide detailed design specifications. Instead, it provides a comparison of spectrum resources used by the alternative trunked LMR system designs and conventional LMR systems. Although this study addressed only the 162-174 MHz LMR band in the Washington D.C. area, NTIA believes the methodology presented in this report could be applied to other LMR bands in spectrally congested areas.

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GLOSSARY AND TERMS

ASC	Average Signal Capacity
BS	Base Station
CCH	Control Channel
C/I	Carrier-to-Interference Ratio
DCO	Design Channel Occupancy
dB	Decibels
dBi	Decibels of gain of an antenna referenced to the zero dB gain of a free-space isotropic radiator
dBm	Decibels above one milliwatt
dBμV/m	Electric field strength in decibels referenced to 1 μV/m
FCC	Federal Communications Commission
GMF	Government Master File
Gn	Network Grade of Service
GoS	Grade of Service
ITS	Institute for Telecommunication Sciences
kHz	Kilohertz
km	Kilometer
LMR	Land Mobile Radio
MHz	Megahertz
NMS	Network Management System
NOC	Network Operation Center
NOAA	National Oceanic and Atmospheric Administration
NTIA	National Telecommunications and Information Administration
P25	Association of Public Safety Communications Officials International Project 25
PCS	Personal Communications Service
PSTN	Public Switched Telephone Network
PSWAC	Public Safety Wireless Advisory Committee
PSWN	Public Safety Wireless Network
PTT	Push to Talk
RCPC	Reverse Channel Power Control
RSMS	Radio Spectrum Measurement System
RX	Receive
SC	Signal Capacity
SCAP	Signal Capacity Analysis Program
TCH	Traffic Channel
TX	Transmit
VHF	Very High Frequency (30 to 300 MHz)
μV/m	Microvolt per meter

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SECTION 1
INTRODUCTION

1.1 Background

The National Telecommunications and Information Administration (NTIA) is the Executive Branch agency principally responsible for developing and articulating domestic and international telecommunications policy. NTIA acts as the principal advisor to the President on telecommunications policies pertaining to the Nation's economic and technological advancement and to the regulation of the telecommunications industry. Accordingly, NTIA conducts studies, makes recommendations regarding telecommunications policies and presents executive branch views on telecommunications matters to the Congress, the Federal Communications Commission (FCC), and the public. Furthermore, NTIA manages federal use of the radio frequency spectrum.

In May 2003, President Bush established the Spectrum Policy Initiative to promote the development and implementation of a United States spectrum policy for the 21st Century. In response to the Spectrum Policy Initiative, the Secretary of Commerce established a Federal Government Spectrum Task Force and initiated a series of public meetings to address policies affecting spectrum use by the federal government, state, and local governments, and the private sector. The recommendations resulting from these activities were included in two reports released by the Secretary of Commerce in June 2004.[1] In November 2004, the President directed the federal agencies to develop a plan to, implement the recommendations contained in the reports.[2] One of the recommendations called for the NTIA to develop analytic approaches, software tools, and engineering techniques for evaluating and improving the efficiency and effectiveness of federal spectrum use.

As discussed in the Spectrum Policy Initiative reports, the radio frequency spectrum is a critical resource used by the federal government to perform congressionally mandated missions. Efficient use of the spectrum is one of the cornerstones for obtaining maximum usage of the available spectrum. NTIA and the federal agencies realize that the primary way to satisfy the growing demands for spectrum in the land mobile radio (LMR) frequency bands is to employ more spectrum efficient technologies. For example, in response to Congressional legislation, NTIA developed a plan that selected a 12.5 kHz channel width for re-channeling the 162-174 MHz and 406.1-420 MHz federal LMR frequency bands, effectively doubling the number of available channels.[3] In addition to transmitter performance standards, NTIA has adopted receiver performance standards for LMR

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1. National Telecommunications and Information Administration, U.S. Department of Commerce, *Spectrum Policy for the 21st Century – The President's Spectrum Policy Initiative: Report 1* (June 2004), available at http://www.ntia.doc.gov/reports/specpolini/presspecpolini_report1_06242004.htm;
Spectrum Policy for the 21st Century – The President's Spectrum Policy Initiative: Report 2 (June 2004), available at http://www.ntia.doc.gov/reports/specpolini/presspecpolini_report2_06242004.htm.

2. White House Executive Memorandum, Subject: *Improving Spectrum Management for the 21st Century* (November 23, 2004). The latest released document for this subject is: National Telecommunications and Information Administration, U.S. Department of Commerce, *Spectrum Management for the 21st Century – Plan to Implement Recommendations of the President's Spectrum Policy Initiative* (March 2006), available at http://www.ntia.doc.gov/osmhome/reports/ImplementationPlan2006.htm.

3. Telecommunications Authorization Act of 1992, Pub. L. 102-538, 106 Stat. 3533 (1992).

systems in an effort to increase spectrum efficiency.[4] This report assesses the use of trunked radio technology to increase spectrum efficiency in the federal LMR bands.

1.2 Objective

The objective of this report is to compare the spectrum resources used by several alternative LMR system designs employing trunked radio technology to the spectrum resources currently used by conventional LMR systems to determine methods of improving spectrum efficiency for federal government operations.

1.3 Approach

The study presented in this report uses the results of two previous NTIA studies. The first study created a database of frequency assignments from the Government Master File (GMF) in the 162-174 MHz band, within a 100-mile radius of Washington D.C.[5] NTIA selected the Washington D.C. metropolitan area because it represents a spectrally congested environment and the 162-174 MHz band because it represents the most heavily used federal land mobile frequency band. As part of the first study, NTIA developed a metric referred to as average signal capacity (ASC) to assess the geographical coverage capabilities of base stations operating in the 162-174 MHz band. A second study used field measurements to characterize the federal LMR channel usage in the 162-174 MHz band.[6] The study in this report uses the results of the two previous studies to derive the geographical coverage and traffic level specifications in terms of Erlangs needed to design alternative shared trunked LMR systems that would provide the same level of performance and coverage as the current conventional LMR systems but in a more spectrally efficient manner.[7]

To evaluate and improve the efficiency of federal spectrum use, the study in this report assesses several alternative LMR system designs in 162-174 MHz band employing trunked radio technology. It examines, based on frequency assignment data contained in the GMF and channel occupancy measurements, top-level LMR system designs that will accommodate the same amount of traffic that is being carried today. The study does not provide detailed design specifications or a complete set of specific frequencies for the alternative trunked systems. Instead, the study provides a comparison of

4. Both transmitter and receiver performance characteristics must be considered for maximum spectrum efficiency. *See* National Telecommunications and Information Administration, U.S. Department of Commerce, *Receiver Spectrum Standards, Phase 1 – Summary of Research into Existing Standards*, NTIA Report 03-404 (November 2003).

5. National Telecommunications and Information Administration, U.S. Department of Commerce, *Federal Land Mobile Operations in the 162-174 MHz Band in the Washington D.C. Area, Phase 1: Study of Agency Operations*, NTIA Report 06-440 (August 2006) (Federal Land Mobile Operations Report). English units were used to define the study area (100-mile radius) for the calculations in the Phase 1 report. For consistency, the study in this report will continue to use English units.

6. National Telecommunications and Information Administration, U.S. Department of Commerce, Institute for Telecommunication Sciences, *Measurements to Characterize Land Mobile Channel Occupancy for Federal Bands 162-174 MHz and 406-420 MHz in the Washington, D.C. Area,* NTIA Report TR-07-448 (July 2007) (Channel Occupancy Measurement Report).

7. An Erlang is a traffic equivalent to full time occupancy of a channel for an hour. For example, one channel used continuously for 60 minutes, or two channels with a combined usage of 60 minutes.

spectrum resources used by the alternative trunked LMR system designs and conventional LMR systems. The alternative LMR system designs are used to determine whether a more efficient use of the LMR spectrum can be accomplished with a trunked LMR system. The methodology developed in this report is general in nature, and thus can be applied to other LMR bands in other geographic areas.

This report presents three alternative trunked LMR system architectures for the 162-174 MHz band. The distinguishing characteristic of these three system architectures is the size of the service area associated with the trunked system base stations. The service area is the area over which the base station supports radio communications with mobile users. Three potential levels of federal agency participation were also considered in the alternative trunked LMR systems: 30 percent agency participation representing partial participation by the current federal users of the conventional LMR systems; 100 percent agency participation representing full participation by the current federal users of the conventional LMR systems; and 300 percent agency participation representing future expanded use by the federal users. The three system architectures combined with the three levels of agency participation resulted in nine unique trunking scenarios.

The alternative LMR system designs studied all employ proven trunked radio technologies widely in use today. The trunked radio network size (channel requirements) were calculated using the Erlang-C model for various traffic levels along with the grade of service specification for each architecture in order to address the sharing of spectrum resources.[8] The system spectrum requirements for each trunking scenario were computed based on frequency plans developed using the 70-mile (113 kilometer) frequency reuse distance criteria specified by the FCC for LMR systems.[9]

8. The Erlang model is a widely adopted network traffic analysis model that can be used to determine the channel requirements of a trunked radio system.

9. 47 C.F.R. § 90.187.

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SECTION 2
DESIGN APPROACH FOR ALTERNATIVE FUTURE LMR SYSTEMS

The design approach for the alternative future LMR systems uses existing trunking technology. Trunking permits a large number of users to share a relatively small number of channels. The user's access to the base station is dynamically allocated to the available channels. A brief description of trunking technology is provided in this section along with the design approach for the alternative LMR systems. Appendix A provides a more detailed description of trunked radio technology.

2.1 Fundamentals of Trunking Technology

"Trunking" gets its name from the telephone industry. A trunk is simply a telephone line between two central office locations that multiple users share. Often, there are many trunks between the same two locations. When a user wants to make a telephone call, that user receives one of these trunked lines to use for the duration of their call. When the call is over, that user gives up the telephone line and someone else can use it.

For a trunked radio system, there is not a fixed assignment of channels to users but the assignment is dynamic. A radio sends a transmission to the control channel of a base station to request communication with a specific talk-group. An unused channel will be assigned automatically to that radio, while the trunking central controller (computerized switch) will alert the other radios in the same talkgroup what channel to use to receive the message. At the completion of the call, all radios return to monitor the control channel for additional transmissions, and the channel is released and is available for other users. In a trunked system, a radio channel is assigned to a user only when the user is ready to communicate. This scheme minimizes the idle time of the available radio channels since users only access the channels when needed. When the channel is not used, the channel is released and returned to a common pool so it can be assigned to other users. Trunked radio technology takes advantage of the probability that in any number of users, not everyone will need to access a channel at the same time. Therefore, with a given number of users, fewer discrete channels are required.

2.2 Rationale for Using Trunked Radio Systems

Trunked radio systems provide the ability to send and receive voice and low data rate information in a highly efficient and cost effective manner. Trunked radio systems utilize technologies similar to the computer-controlled telephone networks to logically organize a large number of users into an orderly communications network. A computerized central switch, referred to as a central controller, makes channel selections and other decisions previously made by the user. Channel assignment is automatic and completely transparent to the individual users. Figure 2-1 illustrates a typical trunked radio system configuration.

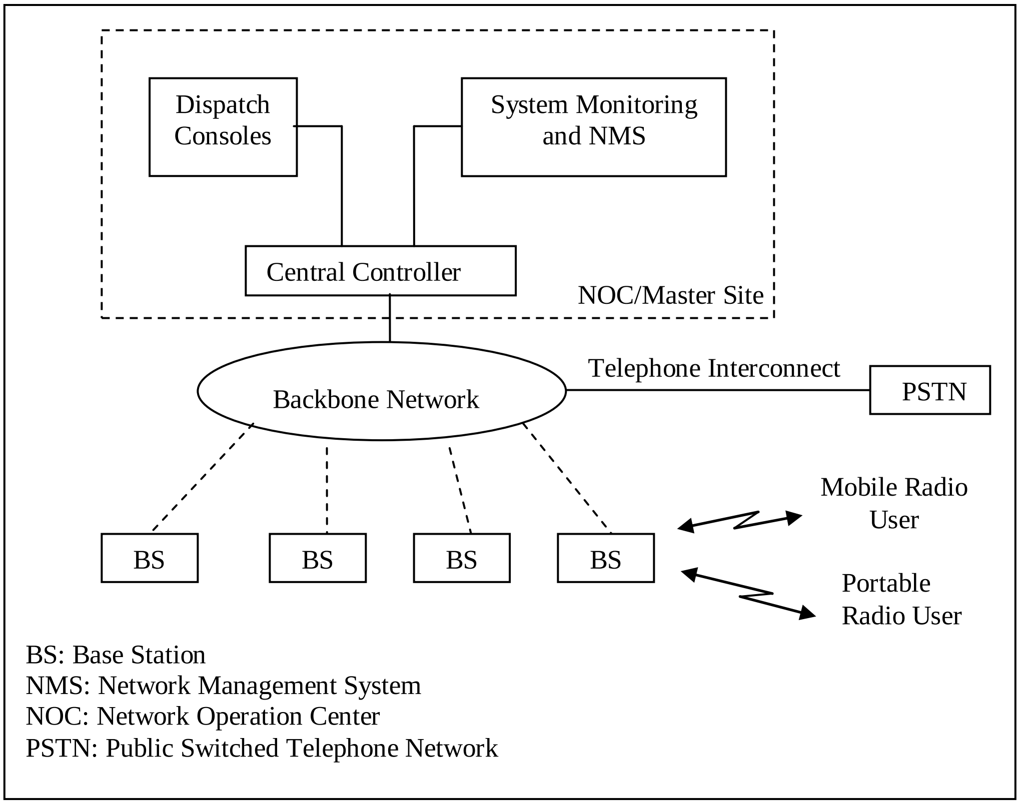

Figure 2-1. Typical Configuration of a Trunked Radio System

2.2.1 Spectrum Efficiency in Trunked Radio Systems

Trunking provides great improvements in spectrum efficiency by allowing all channels to be shared by all users, thus reducing congestion and requiring fewer channels and radio frequencies. By dynamically assigning channels between users on an "as required" basis, considerably fewer channels are required to satisfy the same number of users as compared to a conventional system using dedicated channels that are reserved even while carrying no traffic. Instead of requiring that traffic on a channel be kept very low in order to be immediately available to others, the trunked radio system ensures high channel availability by switching the new user to any channel that is not currently being used. This technique simultaneously permits high average traffic on channels and high availability whenever a channel is needed. This technique is especially effective in increasing the amount of traffic that can be carried when users require very high channel availability.

The improvement in spectrum efficiency will occur even if a trunked system is used by one agency or multiple agencies with common and/or same mission requirements, where all users have the same busy hour. When systems are shared by different agencies with different duties and missions, and the busy hours are different, the improvement from sharing is even greater (e.g., the low usage period for one agency could be a busy time for another agency). This allows one agency to accommodate its busiest-hour requirements using channels that are not needed by other agencies experiencing low usage at that time. In the extreme case of a major emergency for one or more agencies, priorities could be enabled that would shift channel availability from lower-priority missions to the highest-priority missions, having the effect of shifting more channels to the high-priority mission than would ever have been available on a non-shared, single-agency conventional LMR system.

The peak channel activity measured in the Washington D.C. area during an eight-day measurement period is shown in Figure 2-2.[10] The figure shows the busiest hour of the entire week for each measured frequency in the 162-174 MHz band. The figure shows that the channel activity for each frequency is different throughout the week and occurs on a fairly random basis. Figure 2-2 also shows that there are general patterns of being more busy during the weekdays and less busy on weekends. The measurements indicate that the peak usage is not occurring within one specific period and can occur during different days of the week. The channel usage measurements indicate that sharing a common trunked radio system would be especially effective since the channel activity for the different agencies is dispersed.

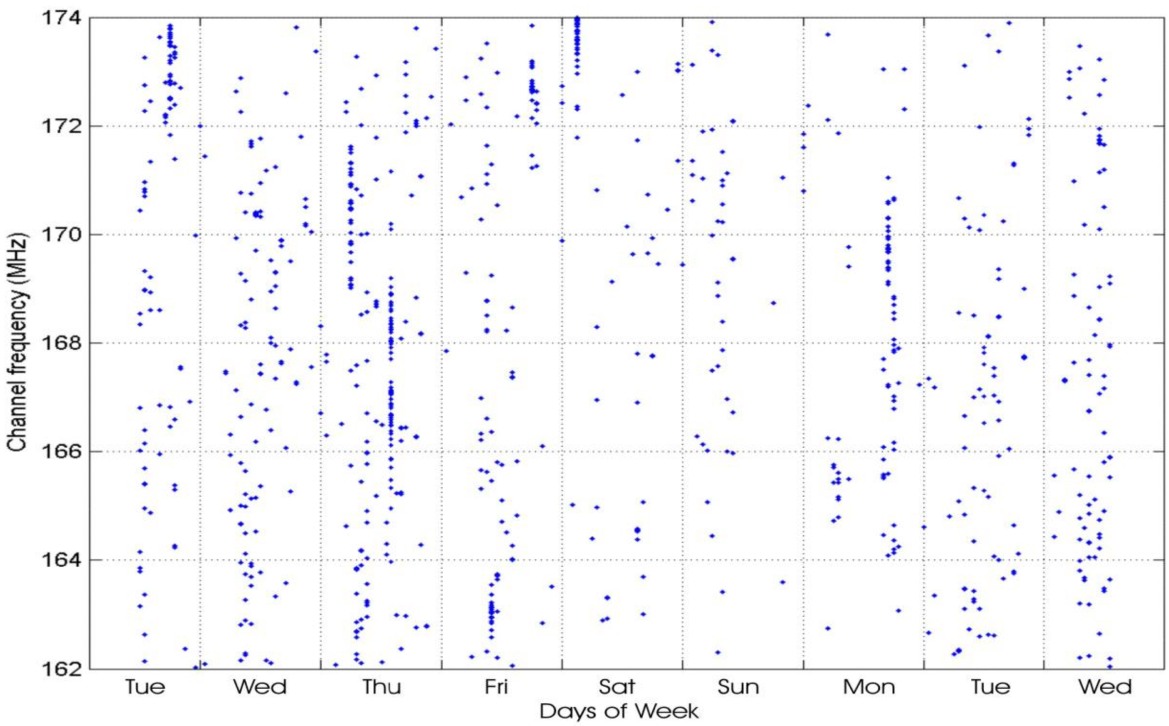

Figure 2-2. Busiest Hour of the Week for Each Channel in the 162-174 MHz Band

2.2.2 Features of Trunked Radio Systems

Systems employing trunked radio technology offer many benefits besides spectrum efficiency, which include:

- Larger coverage areas where all users on the system have coverage over the entire area, not just in the relatively small areas around each base station that agencies deem crucial for communications, which is a typical coverage area for single-agency systems;
- Interoperability with other agencies and users on the system completely defined by talk-group management, as needed to handle special events or emergencies;

10. *See supra* note 6, the Channel Occupancy Measurements Report, NTIA Report TR-07-448, Figure 27.

- Faster system access since there is no need to monitor the channels prior to use;
- More user privacy because users in the same talk-groups are given exclusive access to a voice channel for the duration of a conversation;
- Flexible expansion because talk-groups can be added or modified without necessarily requiring additional channels or modifying existing radios;
- Dynamic regrouping which allows the system to reassign units so users can talk between departments for special events; and
- Protection of lost or stolen radios since any radio can be disabled remotely by the central controller.

These benefits allow federal users to create their own functional talkgroups for each department and operation group within departments, and to include specific agency requirements (e.g., multi-level priority, dynamic regrouping, inter-agency or multi-agency interoperability) so there should be no decrease in the effectiveness of an agency performing its missions.

The ability to combine multiple departments or agencies under one system while maintaining independent operations is the cornerstone of the trunking advantage. The advanced features listed above will also help ensure that each user has reliable, quick access to a channel during emergencies.

2.3 Erlang Formulas and System Design Assumptions

Erlang is a basic unit of telecommunications traffic intensity. One Erlang is equivalent to the amount of traffic carried in a continuously occupied channel in one hour, or 3600 seconds. The Erlang model is a widely adopted network traffic analysis model that is used to determine the channel requirements for wireline and trunked LMR systems. The Erlang-C formula is designed around the queuing or waiting type theory that a random call request arrives and is held in a queue for a specified period until the call request is satisfied.

Trunked radio systems are queuing or waiting type radio systems. Therefore, the Erlang-C model can be used in the network dimension computations in the study. Dimensioning or sizing a trunked radio system is the process of calculating the number of traffic channels required to provide an adequate GoS with an acceptable waiting time for the mobile users in the system. In addition to the number of traffic channels calculated, a control channel must be added to each base station. Each channel requires two frequencies for a paired transmitter and receiver (TX/RX) allowing for full-duplex operation.

GoS is defined as the probability that a call will be blocked or delayed. For a trunked radio system, the GoS is a function of the probability that a call request has to wait to be served (delayed) and the probability that the waiting time (in the queue) exceeds the reference waiting time W_0 in seconds:[11]

The probability that a call waiting or delay exceeds the waiting time, W_0, is computed using Equation 2-1:

$$\text{GoS} = P(W > W_0) = P_D e^{[-(N-A)W_0/H]} \qquad (2\text{-}1)$$

11. Jose M Hernando and F. Perez-Fontan, *Introduction to Mobile Communications Engineering*, Artech House (1999); Roger L. Freeman, *Reference Manual For Telecommunications Engineering, Volume 1, Third Edition*, *Chapter 1-5*, A Wiley-Interscience Publication, John Wiley & Sons, Inc. (2002).

Where the probability that a call has to wait (P_D) is given by the Erlang-C formula in Equation 2-2:

$$P_D(A,N) = \frac{\frac{A^N}{N!} \times \frac{N}{N-A}}{\sum_{K=0}^{N-1} \frac{A^K}{K!} + \frac{A^N}{N!} \times \frac{N}{N-A}} \qquad (2\text{-}2)$$

Where

- P_D: Probability that a call has to wait;
- A: Call traffic in Erlangs;
- N: Number of traffic channels;
- W_0: Reference waiting time in queue in seconds; and
- H: Average busy hour holding time in seconds.

The average busy hour holding time H is defined as the average call duration in a busy hour that includes radio push-to-talk (PTT) switch time, message length and channel hang time.[12]

When A is known, an iterative process can be performed to compute the network size in terms of the number of traffic channels required (N). The iterative process then increases N until the resulting GoS requirement is satisfied.

Typical federal public safety systems use the following parameters in the Erlang-C statistical model design:[13]

- GoS: 1 percent probability of a call having to wait longer than the allowable waiting time;
- W_0: 1 second allowable waiting time; and
- H: 4 second average busy hour holding time.

The above parameters mean that a user requesting service will obtain a channel within 1 second for 99 percent of all requests, and calls occupy the channel 4 seconds on average. This means that if a channel is not immediately available (e.g. because all of the channels are in use), the request will be placed in a queue with other requests, and the waiting time for a channel will exceed 1 second in only 1 percent of the cases.

2.4 Design Methodology for the Alternative Trunked LMR Systems

The alternative trunked LMR system designs considered in this report are based on the analysis of GMF frequency assignments and channel occupancy measurements in the 162-174 MHz band within

12. When the PTT is released, the assigned channel remains on until the pre-programmed delay is expired. During the delay period, the users can return to the same channel, which refers to message trunking. If an assigned channel becomes available immediately upon PTT release, this is referred to as transmission trunking.

13. The design parameters used in this study were recommended by the public safety industry and radio manufacturers. The GoS of 1 percent is also recommended in the Public Safety Wireless Advisory Committee (PSWAC) Report, *Spectrum Requirements Subcommittee (SRSC) Final Report, Appendix D, Public Safety Wireless Communications User Traffic Profiles and Grade-Of-Service Recommendations* (September 1996) at 76 (676).

the Washington D.C. metropolitan area. A brief description of the GMF analysis and channel occupancy measurements is given below.[14]

2.4.1 Average Signal Capacity Maps

In the Federal Land Mobile Operations Report, NTIA Report 06-440, NTIA derived the ASC maps by processing the frequency assignment data contained in the GMF for all federal radio users. The ASC is a metric developed by NTIA to assess the geographic coverage of existing conventional radio systems and therefore provides the coverage requirements for each service area of alternative trunked LMR systems operating in the 162-174 MHz band. The ASC maps show the number of independent receivable radio signals per square mile from each base station in the GMF.

To develop the ASC map, a 100-mile radius area centered on Washington, D.C. was divided into one square mile subsections. The coverage areas for each base station associated with a specific location were determined by the Signal Capacity Analysis Program (SCAP) using a terrain dependent propagation model.[15] The SCAP assigned each square mile subsection with a received signal level of at least 100 µV/m (-80 dBm) as being in the base station coverage area.[16] The following paragraphs provide an overview of the ASC calculations.

For each base station (one frequency assignment in the GMF), the coverage area (all subsections with received signal strength of at least 100 µV/m or -80 dBm) was calculated by the SCAP. The total coverage area K in square miles was divided into one, $1/K$, to determine a density function for that base station. If, for example, the coverage area is 200 square miles, the density function will be 0.005/square mile. This value was then assigned to each one square mile subsection within the base station coverage area. Then the next base station and assigned frequency were selected and this procedure was repeated until all the base stations within the 100-mile study radius were taken into account. The ACS calculations only considered base stations with fixed locations in the GMF. There are also frequency assignments in the GMF that are not constrained to a specific location referred to as area assignments.[17] Since area frequency assignments would not be used to support any local radio infrastructure they were not considered in the ASC calculations.

For each one square mile subsection, the density function entries for each base station were combined to yield the ASC for that subsection. If the summation for each one square mile

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14. A detailed discussion of the GMF analysis is provided in the Federal Land Mobile Operations Report, NTIA Report 06-440, and a detailed description of the channel occupancy measurements is provided in the Channel Occupancy Measurement Report, NTIA Report TR-07-448.

15. The terrain dependent propagation loss values in the SCAP were computed using the Irregular Terrain Model (ITM) in the point-to-point mode. The software model is available on the website: http://flattop.its.bldrdoc.gov/itm.html.

16. The ASC maps produced in the Federal Land Mobile Operations Report, NTIA Report 06-440 assumed that the base station coverage areas were defined by all areas where the transmitter provided a received signal strength of at least 10 µV/m (-100 dBm). However, it was determined that the 10 µV/m receive signal strength was too low because the 10 µV/m resulting coverage areas were too spread out to be realistic, while the 100 µV/m resulted in more realistic coverage areas with greater concentration where actual users were expected to be, e.g., downtown urban areas and highway rather than mountain and rural areas.

17. Examples of area assignments include: US&P (United States and Possessions), US (the 50 states and the District of Columbia), and USA (the 48 contiguous states and the District of Columbia).

subsection is 0.25, this means that an average of 25 percent of one channel (one independent signal) is available to a randomly deployed user in that subsection. The ASC maps can then be used to determine the number of independent receivable radio signals per square mile. In this study, the ASC maps are used to provide an assessment of the geographic coverage capabilities of each base station for the existing conventional LMR systems.

2.4.2 Design Channel Occupancy

The trunked LMR system design must provide adequate service at peak traffic hours as well as handle emergency incidents. Thus, another important factor used in the analysis to determine the number of channels needed for the different trunked LMR system architectures is the busy hour channel occupancy or usage for each channel.

The ITS Radio Spectrum Measurement System (RSMS) channel occupancy measurement effort provided data to compute Hourly Channel Percent Occupancy for the current LMR systems. The data was measured for all LMR channels, for each hour and for each day of the measurement period. This Hourly Channel Percent Occupancy data was then averaged across all the channels in the band for each hour of the day. These average values for each hour of the day were then averaged with the corresponding hours of the day across all days of the measurement period to compute the Band Occupancy by Time-of-Day. As discussed earlier, the ASC calculations did not consider area frequency assignments. The channel occupancy measurements on the other hand will include both frequency assignments with fixed base station locations and area frequency assignments. As shown in the measurement report, if area assignments are not considered, the Band Occupancy by Time-of-Day for the LMR frequency assignments for base stations at specific locations was 2.1 percent which is higher than the 1.6 percent overall maximum value of Band Occupancy by Time-of-Day.[18] In addition to accommodating routine channel usage, a future trunked LMR system should be designed to handle increased channel usage associated with disasters or emergencies. There should also be provisions for channel usage to support future growth. Therefore, for this study, NTIA decided to design the alternative future trunked LMR system to handle 5 percent channel occupancy across the band. In this study, the 5 percent is referred to as the Design Channel Occupancy (DCO).

2.4.3 Service Area Definitions

The ASC values within the coverage area of a given base station thus were summed to determine the traffic level for this given base station that would need to be provided by the trunked system to replicate the number of users served by the existing conventional LMR systems. The coverage area of this given base station was defined conceptually by a hexagon service area in the study.[19] Each service area was assumed to be associated with one base station. As discussed in the Section 3, several cases required more than one base station for a service area. The summation of the ASC values within the boundaries of each service area are referred to as $\sum$ASC.

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18. Figure 30 in the Channel Occupancy Measurement Report, NTIA Report TR-07-448. The details of the RSMS measurements and the channel usage calculations are provided in the report as well.

19. In this study, base stations are shown at the center of each service area, whereas in the real system, they would be located to take advantage of terrain and existing facilities.

To perform the alternative LMR trunked system design, the size of the service areas and traffic levels were defined. The size of the hexagon service areas were categorized as follows:

- The large service areas provide an approximate 20-mile-radius geographic coverage, and represent the most common base station coverage and are used commonly in large geographic areas with a low-concentration of users.
- The medium service areas provide an approximate 12-mile-radius geographic coverage, and are used in the areas with a high- and medium- concentration of users.
- The small service areas provide an approximate 7-mile-radius geographic coverage, and are typically used in the areas with a very high-concentration of users.

An example of an ASC map with hexagon service areas overlaid is shown in Figure 2-3. The service areas for the base stations were not selected in accordance with the traffic volume or geographic features, but were superimposed on a map to cover the entire 100-mile radius geographic area considered in this study. Therefore, the service areas with a low-concentration of users can have a small number of users (e.g., light color areas shown in Figure 2-3) while the service areas with a high-concentration of users can have many users (e.g., dark green areas shown in Figure 2-3). Each hexagon on the map is assigned an identification (ID) number, which is used to identify the service area in the study.

2.4.4 Channel Requirement Methodology

The design methodology used in this study contains several approximations and assumptions. If such a trunked radio system were actually built in the future, a more detailed analysis would be necessary to provide more accurate traffic levels for each base station. Nevertheless, the methodology used in this study provides a rational starting point for evaluating and comparing future LMR system designs.

The type of information used in designing a LMR system is usually expressed in terms of the number of users that could be served by a radio system. The ASC calculation determines the number of independent users that would need to be accommodated in a specific service area. The independent user refers to the independent receivable radio signals (a voice channel). The independent user could be a talk-group or talk-groups with multiple users, or could actually be a single user since many users could be simultaneously listening to a common signal (communicate over one channel with each other). The details of ASC calculations are described in Appendix A of the Federal Land Mobile Operations Report, NTIA Report 06-440.

The major steps in determining the channel requirements for the alternative trunked radio systems are summarized below and discussed in more detail in the preceding paragraphs.

1. The ASC calculations were performed based on 100 µV/m received signal threshold level and displayed on a map, which provides the number of independent users per square mile.
2. The map defining service areas for the base stations of the trunked LMR systems (represented by hexagons) was overlaid on the ASC map.
3. The ASC values in each square mile were summed within each hexagon service area to give total number of independent users to be accommodated by this service area ($\sum$ASC).

4. The calculated ∑ASC values for each service area were multiplied by the DCO (5%) to give the traffic level in Erlangs required for each service area.
5. Using the Erlangs of each service area (A) and other defined parameters (GoS, H, W_0), the number of channels required (N) for each base station was calculated using Equations 2-1 and 2-2.

An example of such an ASC map is shown in Figure 2-3. The map legend, which appears in the lower right corner of Figure 2-3 shows the ASC value range and its corresponding color - the number in the parenthesis on the right side of the range is the count of the number of one square mile subsections with the ASC value in this particular range.

The resulting ∑ASC values represent the total number of independent users that are to be serviced by each service area. A channel that is used 5 percent of the time, represented by the DCO in this study, is equivalent to saying that 0.05 Erlangs of traffic is generated by each channel. Using Equation 2-3, the ∑ASC value for each service area is multiplied by the DCO of 0.05 Erlangs to compute the amount of traffic in Erlangs that the service areas in various alternative trunked LMR systems should be designed to carry:

$$\text{Erlangs per Service Area} = \sum \text{ASC} \times \text{DCO} \qquad (2\text{-}3)$$

The base station is assumed to be located at the center of each hexagon service area in performing the LMR system design analysis. Such regular hexagons approximate a realistic coverage model for base stations. Table 2-1 provides a sample calculation showing how the number of channels for the alternative trunked LMR systems is computed.

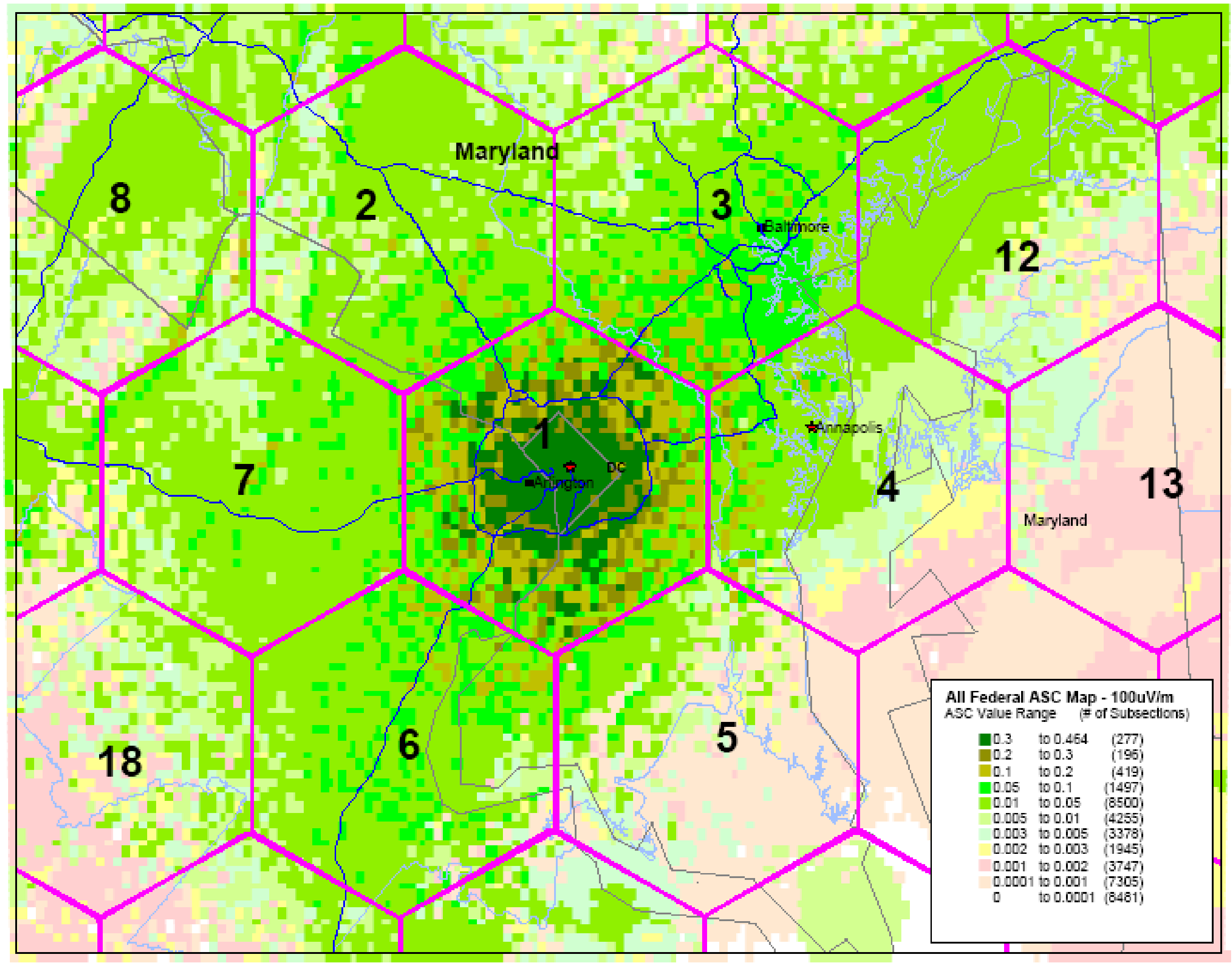

Figure 2-3. Example of ASC Map with Hexagon Service Areas Overlaid

Table 2-1. Sample Trunked LMR System Dimensioning Calculation

Service Area ID	∑ASC per Service Area	Design Channel Occupancy (DCO)	Grade of Service (GoS)	100% Agency Participation	
				Erlangs per Service Area = ∑ASC x DCO	Number of Channels Required
1	202.53	5%	1%	10.13	17
2	26.79	5%	1%	1.34	5
3	46.21	5%	1%	2.31	7
4	20.29	5%	1%	1.01	5
5	8.62	5%	1%	0.43	3

SECTION 3
ALTERNATIVE FUTURE LMR SYSTEM DESIGNS

3.1 System Architecture Selection

This section presents different designs used to determine the spectrum requirements for three trunked LMR system architectures. The methods used to perform the design and analysis for each of the trunked system architectures are described. The channel and frequency requirements for each trunking scenario are determined and compared to those of the existing conventional LMR systems to develop a measure of relative spectrum efficiency. The trunked system architectures designs considered combinations of the following features:

- Larger service areas to provide coverage for large geographic areas;
- Smaller service areas to provide improved coverage in areas with a high-concentration of users, while using larger service areas to provide coverage in areas with a medium- or low-concentration of users; and
- Overlapping architecture, with large and small service areas overlapped in areas with a high-concentration of users, which combines the above two features while taking advantage of redundant service (over the large service area and the small service area) and creating higher channel availability during localized emergencies.

Three different trunked radio system architectures were analyzed: Large-Service-Area-Only, Large-Medium-Service-Area-Mixed, and Large-Small-Service-Area-Overlapping. The first two system architectures represent common characteristics and techniques employed in public safety system designs. The third system architecture is a design approach employing some new features for trunked LMR systems.[20]

3.1.1 Large-Service-Area-Only System Architecture

This system architecture uses all large hexagon service areas for the entire coverage area (100-mile radius). Using a large service area to provide coverage over a large geographical area is a common design practice for public safety LMR systems. Figure 3-1 shows the service areas overlaid on the ASC map. The calculations used to determine the channel requirements for this system architecture are shown in Table 3-1.

The first column in Table 3-1 contains the service area ID shown in the middle of each hexagonal service area on the map. The second column contains ∑ASC within that hexagonal service area derived from the 100 µV/m ASC map. The DCO in the third column indicates each independent user was assumed to use a channel 5 percent of the time. The fourth column provides the required GoS level (1%) for each service area. The number of Erlangs required for each service area to support the 100 percent level of agency participation (e.g., total participation in the trunked LMR system by federal users) was computed using Equation (2-3). The number of Erlangs for each service area at the 30 percent and 300 percent levels of agency participation were then computed by

20. The overlapping design is a new concept where some technical requirements may not be supported by current trunked radio equipment such as overlapping service.

multiplying the number of Erlangs for the 100 percent level by factors of 0.3 and 3 respectively. The actual number of Erlangs required for each service area are shown in the first column under each agency participation level heading and are used to determine the number of trunking channels required for each service area.

The results in Table 3-1 show that for the 30, 100 and 300 percent levels of agency participation, the increase of the total number of channels required for each service area is not equal to the agency participation level multiplier of 0.3 and 3, but is actually much less. The number of channels required in the service areas with a high-concentration of users (e.g., Service Area #1, #2, #3,etc.) is increased by a larger percentage than the number of channels in the service areas with a low-concentration of users (e.g., Service Area #13, #14, #15, etc.). This is because the channels in the areas with a high-concentration of users were already carrying traffic close to the maximum number of Erlangs for that number of channels, and the increased traffic could be accommodated only by adding more channels. However, in the areas with a low-concentration of users, less traffic is carried on each channel, and the increased traffic could be accommodated by increasing the number of Erlangs on each channel.[21]

While interpreting the results, it should be noted that the ASC calculations were based on the analysis of the GMF database. The GMF does not contain data describing detailed user geographic locations or their true operational range. Therefore, several assumptions were made during different stages of the analysis. The area showing a large quantity of receivable signals on the ASC map may have only few users in reality. For example, Service Areas #8 and #19, west of the Washington D.C. area, include a tall mountain ridge. Due to this geographic feature, the SCAP model predicted that those areas received many signals. Since it was assumed that a user can be uniformly located over the area where a signal can be received, a large number of users (e.g., high ASC values) are shown on the ASC map in these areas. However, in reality, the mountain area may have only a few users, and could be served by a single base station on the ridge with an antenna high enough to provide coverage beyond the 20-mile hexagon radius.

Due to hardware limitations such as site inter-modulation, maximum total transmit power, noise, and receiver filtering, there is typically a maximum limit of 32 channels including the traffic channels and control channels at each base station.[22] A large service area can be served by more than one base station. Based on the Erlang calculation, 40 channels are required for the 300 percent level of agency participation for Service Area #1 which is located in an area of heavy usage. The required number of channels is greater than can be accommodated by one base station for a practical engineering design. One solution for this problem is discussed in the next subsection.

As shown in Table 3-1, the Large-Service-Area-Only System architecture requires 35 service areas to provide coverage to the Washington D.C. area. The total number of Erlangs (from ASC map) for

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21. Referring to Table A-2 in Appendix A, for example, 0.5386 Erlangs is the maximum capacity for three channels while 1.0103 Erlangs is the maximum capacity for 4 channels. Any increase of number of Erlangs within the range of 0.5386 to 1.0103 can be accommodated by four channels. When the number of Erlangs exceeds the 1.0103, an extra channel must be added to the service area to accommodate the new users.

22. The study in this report was based on access to the entire 162-174 MHz band. However, a single agency does not have access to the entire band, but instead is limited to a subset of frequencies (e.g., allotments). In many instances, it may not be possible to select enough interference free frequencies (inter-modulation and adjacent channel interference) to satisfy the requirement for a large number of channels at single base station. Therefore, the number of channels for a base station is restricted and much fewer than the 32 maximum channels.

the 35 service areas is 8.33 Erlangs for 30 percent agency participation, 27.7 Erlangs for 100 percent agency participation, and 83.3 Erlangs for 300 percent agency participation while the number of trunking channels required for each level of agency participation is 85, 125 and 213 respectively. The required channel calculations include only the traffic channels (TCH), and do no include control channels (CCH) that are required for a trunked LMR system. The total number of channels (TCHs + CCHs) required for each trunked system architecture is determined in Subsection 3.3.

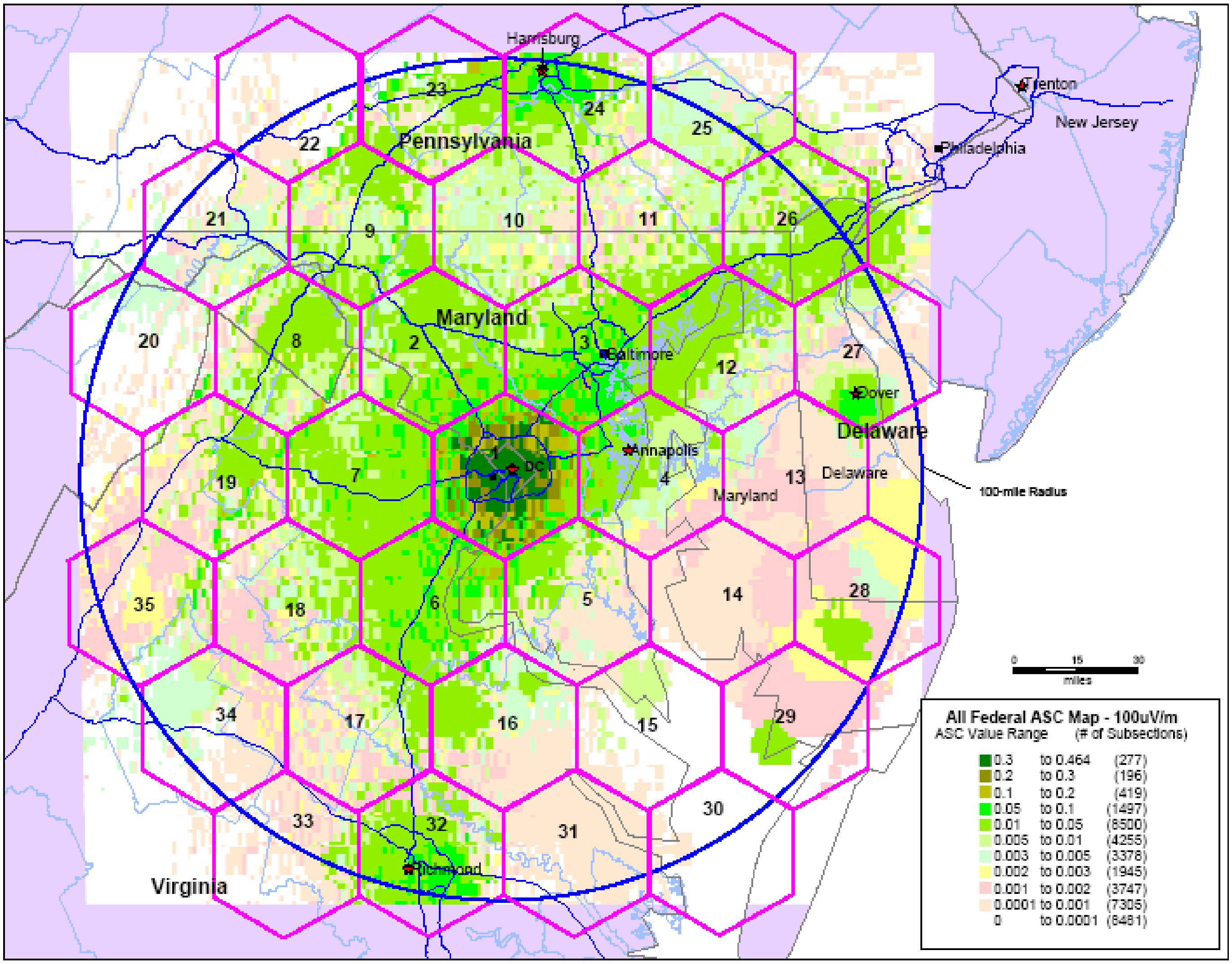

Figure 3-1. Large-Service-Area-Only System Architecture Map

Table 3-1. Network Dimensioning for the Alternative Trunked LMR System with a Large-Service-Area-Only System Architecture

Service Area ID	∑ASC per Service Area	Design Channel Occupancy (DCO)	Grade of Service (GOS)	30% Agency Participation		100% Agency Participation		300% Agency Participation	
				Erlangs per Service Area = 0.3 x ∑ASC x DCO	Number of Channels Required	Erlangs per Service Area = ∑ASC x DCO	Number of Channels Required	Erlangs per Service Area = 3 x ∑ASC x DCO	Number of Channels Required
1	202.53	5%	1%	3.04	8	10.13	17	30.38	40
2	26.79	5%	1%	0.40	3	1.34	5	4.02	9
3	46.21	5%	1%	0.69	4	2.31	7	6.93	13
4	20.29	5%	1%	0.30	3	1.01	5	3.04	8
5	8.62	5%	1%	0.13	2	0.43	3	1.29	5
6	39.66	5%	1%	0.59	4	1.98	6	5.95	12
7	25.81	5%	1%	0.39	3	1.29	5	3.87	9
8	16.73	5%	1%	0.25	3	0.84	4	2.51	7
9	14.84	5%	1%	0.22	3	0.74	4	2.23	7
10	6.32	5%	1%	0.09	2	0.32	3	0.95	4
11	7.73	5%	1%	0.12	2	0.39	3	1.16	5
12	17.44	5%	1%	0.26	3	0.87	4	2.62	7
13	1.96	5%	1%	0.03	2	0.10	2	0.29	3
14	0.80	5%	1%	0.01	1	0.04	2	0.12	2
15	1.02	5%	1%	0.02	2	0.05	2	0.15	2
16	6.13	5%	1%	0.09	2	0.31	3	0.92	4
17	5.07	5%	1%	0.08	2	0.25	3	0.76	4
18	5.81	5%	1%	0.09	2	0.29	3	0.87	4
19	9.20	5%	1%	0.14	2	0.46	3	1.38	5
20	1.46	5%	1%	0.02	2	0.07	2	0.22	3
21	2.19	5%	1%	0.03	2	0.11	2	0.33	3
22	1.39	5%	1%	0.02	2	0.07	2	0.21	3
23	11.73	5%	1%	0.18	2	0.59	4	1.76	6
24	19.20	5%	1%	0.29	3	0.96	4	2.88	8
25	3.32	5%	1%	0.05	2	0.17	2	0.50	3
26	11.54	5%	1%	0.17	2	0.58	4	1.73	6

Continued from Table 3-1 above:

Service Area ID	∑ASC per Service Area	Design Channel Occupancy (DCO)	Grade of Service (GoS)	30% Agency Participation		100% Agency Participation		300% Agency Participation	
				Erlangs per Service Area = 0.3 x ∑ASC x DCO	Number of Channels Required	Erlangs per Service Area = ∑ASC x DCO	Number of Channels Required	Erlangs per Service Area = 3 x ∑ASC x DCO	Number of Channels Required
27	8.57	5%	1%	0.13	2	0.43	3	1.29	5
28	4.03	5%	1%	0.06	2	0.20	3	0.60	4
29	1.81	5%	1%	0.03	2	0.09	2	0.27	3
30	0.03	5%	1%	0.0004	1	0.0013	1	0.0039	1
31	0.36	5%	1%	0.01	1	0.02	2	0.05	2
32	19.94	5%	1%	0.30	3	1.00	4	2.99	8
33	1.23	5%	1%	0.02	2	0.06	2	0.19	2
34	2.05	5%	1%	0.03	2	0.10	2	0.31	3
35	3.59	5%	1%	0.05	2	0.18	2	0.54	3
Total Number of Traffic Channels					**85**		**125**		**213**
Total Number of Erlangs				**8.33**		**27.7**		**83.3**	
Note 1: The total number of channels above does not include the control channels.									
Note 2: The total number of service areas for this system architecture is 35.									

3.1.2 Large-Medium-Service-Area-Mixed System Architecture

The Large-Service-Area-Only System architecture works well for the 30 percent and 100 percent levels of agency participation. However, as shown in Table 3-1, Service Area #1 for the 300 percent level of agency participation requires 40 channels. This is greater than the maximum number of channels that the hardware for a single base station can support. For a base station supporting higher traffic levels, one solution is to split the traffic of one service area between several base stations, each with fewer channels.

It is a typical design technique to use different coverage sizes for the base stations in the same network. In fact, it is often advantageous to use several base stations each with a smaller coverage area to provide better service in areas with a high-concentration of users and base stations with larger coverage areas in areas with a medium- and low-concentration of users. Using this concept, the Large-Medium-Service-Area-Mixed System architecture is examined where four base stations each with a medium service area are used to cover the Service Area #1 instead of a single base station with a large service area.

To simplify the design and calculation of the required number of channels, the four medium service area hexagons were superimposed on the Service Area #1 of the Large-Service-Area-Only System architecture without changing the hexagon layout. The medium service area has a radius of 12 miles. The new Service Area IDs are #1M, #36M, #37M and #38M. The new hexagon layout is shown in Figure 3-2.

There were some overlapping coverage areas created by the four medium service areas and the surrounding large service areas as shown in Figure 3-2. For example, Service Area #1M has some overlapping service areas with Service Area #7 and Service Area #36M has some overlapping service areas with Service Area #2 and #3. The ASC values for overlapping service areas were not included in determining the medium service area channel requirements. This means that the overlapping areas were only counted once. In practice, service areas should be defined more precisely in the actual system design to eliminate large coverage overlaps, although it is an acceptable design practice to have some coverage overlap at the border of two base stations in order to facilitate un-interruptible communications. The overlapping service area design will be discussed in more detail in the next subsection.

The results of the analysis are shown in Table 3-2. Since the required number of channels for Service Area #2 to #35 remained unchanged, Table 3-2 only provides the number of required channels for the four new medium service areas as well as the number of required channels for the entire system architecture.

As shown in Table 3-2, splitting a large service area and assigning a portion of the traffic (Erlangs) to several smaller service areas will decrease the channel requirements for the base stations of each service area. However, distributing the traffic equally or unequally from one service area to several service areas increases the total number of channels required for the same level of service (GoS, reference waiting time, and average hold time). For example, the four medium service areas require 17, 9, 18 and 10 channels respectively for a 300 percent level of agency participation. This results in a total of 54 channels compared to the original 40 channels required for Service Area #1.

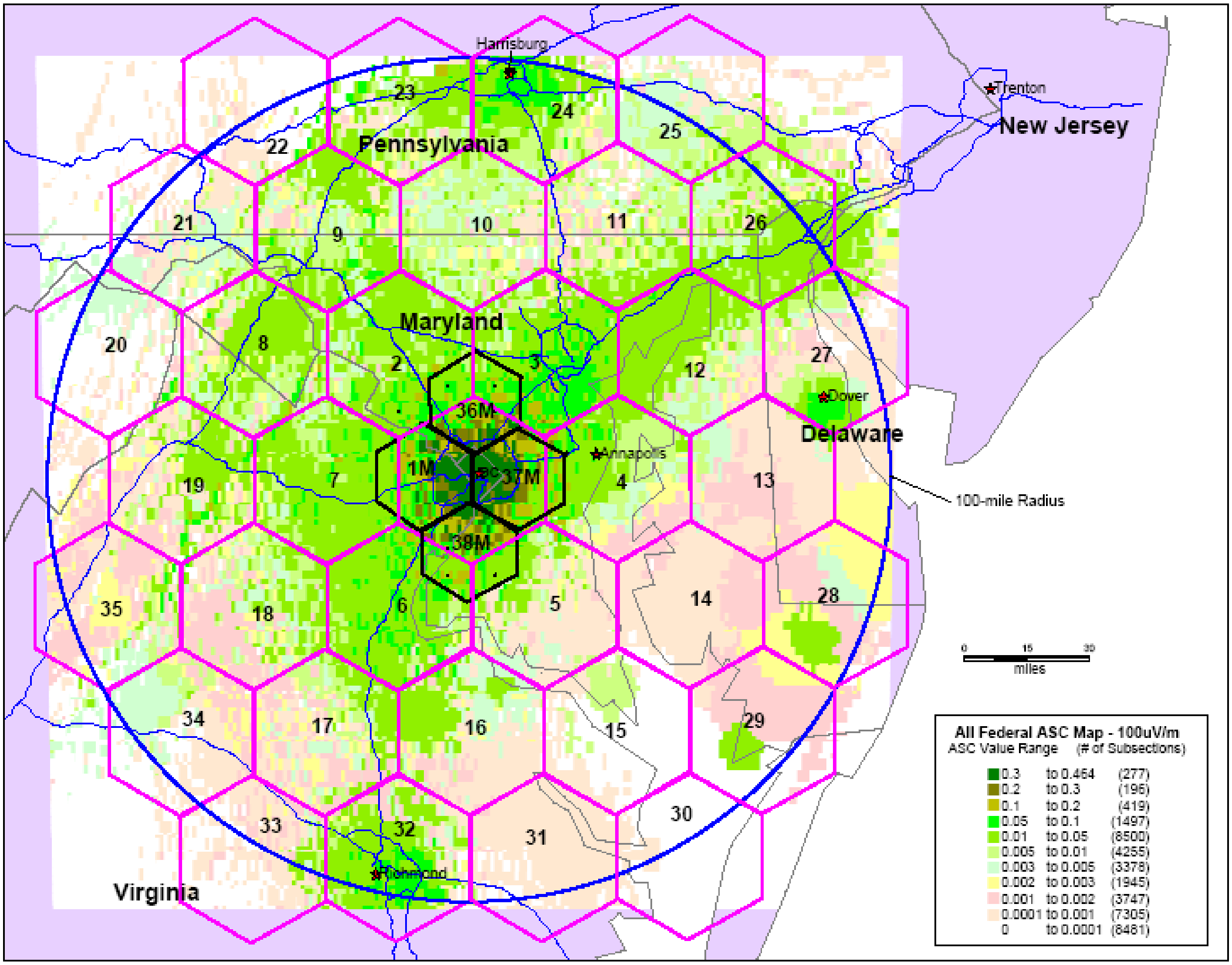

Figure 3-2. Large-Medium-Service-Area-Mixed System Architecture Map

Table 3-2. Network Dimensioning for the Alternative Trunked LMR System with a Large-Medium-Service-Area-Mixed System Architecture

Service Area ID	∑ASC per Service Area	Design Channel Occupancy (DCO)	Grade of Service (GoS)	30% Agency Participation		100% Agency Participation		300% Agency Participation	
				Erlangs per Service Area = 0.3 x ∑ASC x DCO	Number of Channels Required	Erlangs per Service Area = ∑ASC x DCO	Number of Channels Required	Erlangs per Service Area = 3 x ∑ASC x DCO	Number of Channels Required
1M	68.13	5%	1%	1.02	5	3.41	8	10.22	17
36M	27.83	5%	1%	0.42	3	1.39	5	4.17	9
37M	74.77	5%	1%	1.12	5	3.74	9	11.22	18
38M	31.80	5%	1%	0.48	3	1.59	6	4.77	10
Sub-Total Number of Traffic Channels					**16**		**28**		**54**
Including Service Area #2 to #35									
Total Number of Traffic Channels					**93**		**136**		**227**
Note 1: The total number of channels above does not include the control channels.									
Note 2: The results are for medium service areas only. The results for Service Area #2 to #35 are shown in Table 3-1.									
Note 3: The total number of service areas for this system architecture is 38.									

3.1.3 Large-Small-Service-Area-Overlapping System Architectures

The first two system architectures, Large-Service-Area-Only System and Large-Medium-Service-Area-Mixed System, were analyzed as possible future shared trunked LMR systems. A third system architecture, which is a combination of overlapping large and small service areas is analyzed with the smaller service areas placed in the locations where there is a high-concentration of users.

Large service areas are used to provide coverage to users that are distributed over a large geographic area, while smaller service areas are used to provide coverage for users that are concentrated in smaller areas. Using small service areas, especially in locations where there is a high-concentration of users (e.g., downtown Washington D.C.), is a well-known technique in the cellular communications industry to provide better coverage to users as well as coverage inside buildings, basement parking lots, inside tunnels, etc. The base stations of the small service areas are also closer to the users of mobile and portable radios with low transmitter power. This facilitates the transmission of higher data rates over shorter distances without increasing transmitter power. Furthermore, using the design of a large service area overlapping several smaller service areas, the large service area can supplement its channels to the small service area channels. This will create a total communications capability that is well beyond the capabilities of the small service areas alone, that could be used to handle localized emergencies. In addition, base stations with smaller service areas employing lower transmit power will reduce the interference areas and increase frequency reuse.

The architecture analyzed for Large-Small-Service-Area-Overlapping uses large hexagonal service areas identical to the Large-Service-Area-Only System, in conjunction with a group of seven small hexagonal service areas superimposed in the Washington, D.C. urban area. The small service areas have a 7-mile radius as shown in Figure 3-3, with a service area approximately 1/9 as large as the large service area. Since federal user location data is not available in the GMF, the traffic within the overlapping areas has been divided equally in the Erlang calculation between the large service area and each of the small service areas. The small service areas were overlaid on the ASC map and a ∑ASC value was determined for each individual small service area (#36-#42). The ∑ASC value for each small service area was divided in half with half of the corresponding ∑ASC allocated to the small service area. The ∑ASC value for large service area #1 for this system architecture was determined by subtracting the ∑ASC values associated with the seven small service areas from the ∑ASC value for the service area #1 determined for the Large-Service-Area-Only System architecture (Table 3-1). The resulting seven ∑ASC values, listed in Table 3-3, were used to develop the channel requirements for the trunked system employing the seven overlapping service areas. The results of the channel requirements analysis are shown in the Table 3-3.

A user in overlapping service areas can receive service from either the base station associated with the large service area or one of the base stations associated with the small service areas since they provide service to the same geographical areas. Those base stations share the traffic with an overall GoS level of 1 percent and a 1-second call waiting time. Thus, the GoS level in the overlapping large and small service areas must be adjusted. In this analysis, the term Gn is defined as the network GoS considering the overlap of the large and small service areas. The term G is the designed individual base station GoS. A user that has access to two base stations has an equal probability (G) of not being served by either base station. Therefore, the probability of not being served by both base stations is determined by $Gn = G \times G$, or $G = (Gn)^{1/2}$. It should be noted that many other base station GoS combinations could be chosen to satisfy the desired network GoS (Gn) depending on the actual system requirements. The calculation for overlapping designed GoS could become very complicated when overlapping coverage is created by more than one base station. To simplify the study, the overlap of the large service area and each of the small service areas is considered as 100 percent. Since the Gn is 1 percent, the GoS for large service area (Service Area #1) and small service areas (Service Area #36 to Service Area #42) is adjusted to 10 percent as shown in Table 3-3. The GoS of 1 percent for Service Area #2 to Service Area #35 remains unchanged.

Table 3-3 shows the results of channel requirement calculations for the large service area and the seven small service areas. The results of Service Area #2 to Service Area #35 are identical to those shown in Table 3-1, where large service areas provide coverage in areas with a medium- or low-concentration of users. The total number of service areas for this system architecture is 42. The number of traffic channels required is 95 (30% agency participation), 135 (100% agency participation), and 226 (300% agency participation).

Although the use of small service areas could have some considerable advantages as discussed above, there are also some problems. The first problem is that many federal LMR users (as well as many non-federal public safety users) are organized as large, geographically dispersed talkgroups. This means that as service areas are reduced in size, the talkgroups may be spread across multiple service areas. Since the entire talkgroup must be able to hear all of the talkgroup communications, channels will need to be used in all of the service areas containing talkgroup members. In the worst case, one could imagine talkgroup members spread across all of the service areas, resulting in no net gain of communications capacity. The geographic location of talkgroup members is therefore an important (but currently unknown) factor in determining whether small service areas will actually result in improving spectrum efficiency.

The relative advantages of the small service areas in allowing higher frequency reuse as well as permitting the use of lower power transmitters needs to be balanced against the requirements where large service areas are necessary to serve users operating over a large geographic area and small service areas are needed to serve large concentrations of users.

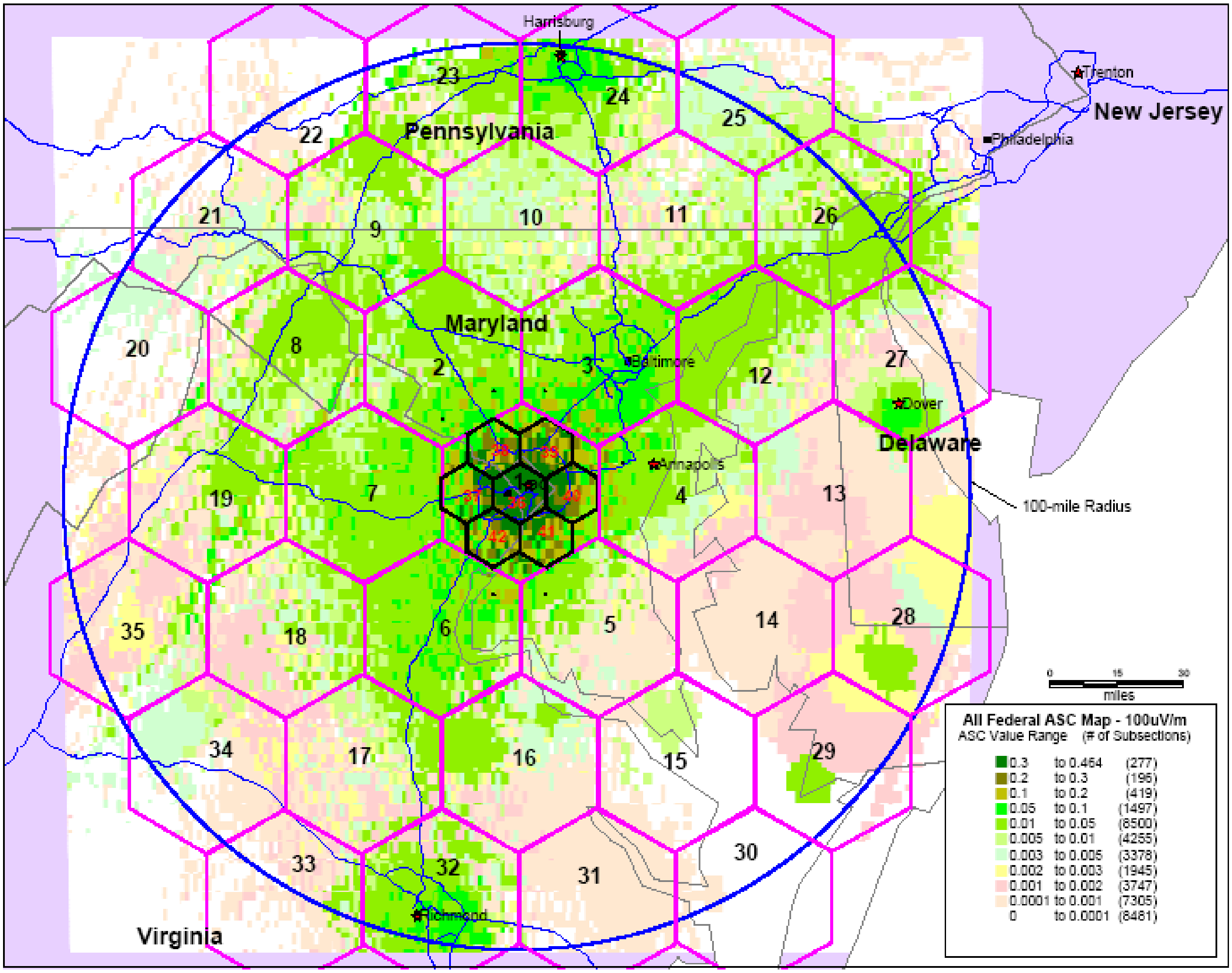

Figure 3-3. Large-Small-Service-Area-Overlapping System Architecture Map

Table 3-3. Network Dimensioning for the Alternative Trunked LMR System with a Large-Small-Service-Area-Overlapping System Architecture

Service Area ID	∑ASC per Service Area	Design Channel Occupancy (DCO)	Grade of Service (GoS)	30% Agency Participation		100% Agency Participation		300% Agency Participation	
				Erlangs per Service Area = 0.3 x ∑ASC x DCO	Number of Channels Required	Erlangs per Service Area = ∑ASC x DCO	Number of Channels Required	Erlangs per Service Area = 3 x ∑ASC x DCO	Number of Channels Required
1	112.90	5%	10%	1.69	4	5.65	9	16.94	21
36	19.72	5%	10%	0.30	2	0.99	3	2.96	6
37	9.00	5%	10%	0.14	2	0.45	2	1.35	4
38	11.33	5%	10%	0.17	2	0.57	2	1.70	4
39	13.26	5%	10%	0.20	2	0.66	3	1.99	5
40	13.22	5%	10%	0.20	2	0.66	3	1.98	5
41	12.50	5%	10%	0.19	2	0.62	3	1.87	4
42	10.60	5%	10%	0.16	2	0.53	2	1.59	4
Sub-Total Number of Traffic Channels					**18**		**27**		**53**
Including Service Area #2 to #35									
Total Number of Traffic Channels					**95**		**135**		**226**
Note 1: The total number of channels above does not include the control channels.									
Note 2: The results for Service Area #2 to #35 are shown in Table 3-1.									
Note 3: The total number of service areas for this system architecture is 42.									

3.2 Initial Frequency Requirements

In order to determine if the alternative trunked LMR systems can satisfy the design goals and use less spectrum than conventional LMR systems, the frequency requirements for each of the trunking scenarios must be determined.

Based on the hexagon service area layout maps (Figure 3-1, Figure 3-2 and Figure 3-3), the frequencies were assigned starting from the central downtown area, Service Area #1, and proceeding to outlying areas on a service area-by-service area basis. As in any large network design, a frequency reuse scheme was used. The assumptions and guidelines that were used to develop the frequency plan for each of the trunking scenarios are described in the following paragraphs.

Many factors affect the frequency assignment process such as terrain shielding, building blockage, adjacent site distance, antenna height, transmit power, receive signal level, and carrier-to-interference ratio (C/I) requirement. Since many of these factors were unknown, a simplified approach based on a minimum frequency reuse distance was used to develop the frequency plan for the different LMR trunking scenarios. In this study, a distance separation criterion of 70 miles between co-channel base stations (center to center) was used as the frequency reuse distance. A frequency reuse distance of 70 miles will provide a minimum C/I ratio of approximately 18 dB for co-channel base stations with the same size service areas, i.e. 20-mile radius.

The frequency reuse determination will be described using the Large-Service-Area-Only System architecture (see Figure 3-1). Because of the 70-mile reuse distance criterion, the separation distance between service areas such as Service Area #1 and #13 or Service Area #1 and #14 is not sufficient. To satisfy the reuse distance criterion there must be at least two service areas between service areas that reuse the same frequency. For example, frequency reuse is possible between Service Area #1 and Service Areas #20 through #35. Frequency reuse is also possible between Service Area #2 and Service Areas #13 through #17 or Service Areas #25 through #35. Furthermore, a subset of the frequencies from Service Area #2 can be reused in Service Area #13 and then again in Service Area #16 or #17. However, none of the frequencies associated with Service Area #2 can be reused in each of the Service Areas #18 through #12 (clockwise) because of the reuse distance criterion.

The 70-mile reuse distance criterion dictated that Service Areas #1 through #7 (designated as the primary service areas in this analysis) must each have a unique set of frequencies. Because of the traffic requirements of Service Areas #1 through #7, they will generally require more frequencies than the other service areas. Taking the factors discussed above into consideration, the frequency reuse scheme summarized in Table 3-4 was developed.

Table 3-4 shows which service areas were considered for reuse of the frequencies associated with each primary service area. This frequency reuse scheme is not unique. Other arrangements for Service Areas #8 through #35 are possible. However, Table 3-4 was used in this analysis to guide the frequency reuse evaluation. The frequency reuse evaluation for the trunking scenario of Large-Service-Area-Only System architecture with 30 percent agency participation is used to further describe the procedures used in this analysis. The reuse evaluation was carried out using channels instead of frequency assignments (e.g., there are two frequencies for each channel). Since full duplex operation is necessary, each channel requires two unique frequencies.

Table 3-4. Example of Frequency Reuse Scheme

Primary Service Areas	Reuse Service Areas
#1	#20 through #35[a]
#2	#13 through #17[a] and #25
#3	#15 through #19[a] and #22
#4	#17 through #9[a] and #30
#5	#19 through #11[a] and #33
#6	#9 through #13[a]
#7	#11 through #15[a]
a: The subset of frequencies from the primary service area and reused in these service areas are also constrained by the 70-mile reuse distance criterion within the reuse service area grouping.	

The channel requirements for the Large-Service-Area-Only System architecture were summarized in Table 3-1 under the column heading for 30 percent agency participation. The process first requires that Service Areas #1 through #7 be assigned a total of 27 unique channels (which is 54 frequency assignments). These channels will be referred to in terms of a numeric (1 through 7) denoting the service area and a letter designating each channel associated with the service area. For example, channels 1-A through 1-H are the eight channels associated with Service Area #1. Similarly, channels 2-A through 2-C are the three channels associated with Service Area #2.

The process began with the reuse of channels in Service Areas #2 through #7. Service Area #1 channels are used in the outer ring of the service areas and were considered last. Service Area #8 requires three channels and channels from Service Areas #4 and #5 (see Table 3-4) can be used. Service Area #8 was assigned channels 4-A through 4-C. Service Area #9 requires three channels and was assigned channels 6-A through 6-C. This process was continued through all of the service areas resulting in the channel assignments shown in Table 3-5.

As shown in Table 3-5, the channel requirements for Service Areas #8 through #35 can be accommodated by the reuse of channels assigned to Service Areas #1 through #7. Therefore, only the original 27 unique channels are required for this trunking scenario. This procedure was carried out for the other Large-Service-Area-Only trunking scenarios with similar results. The channel assignments for Service Areas #1 through #7 could be reused in the other service areas.

For the trunking scenarios of Large-Medium-Service-Area-Mixed System architecture, the Service Areas #1M, #36M, #37M, and #38M along with Service Areas #2 through #7 each required a unique set of channel assignments. The reuse analysis, as previously explained, was then followed. The result was the unique channel assignments were adequate for the trunking scenarios.

The trunking scenarios of Large-Small-Service-Area-Overlapping System architecture were evaluated using the same procedure and the initial unique channel assignments were adequate.

Table 3-5. Example of Channel Assignments
(Large-Service-Area-Only System Architecture with 30% Agency Participation)

Service Area	Assigned Channels
#8	4-A through C
#9	6-A through C
#10	5-A and B
#11	7-A and B
#12	6-A through C
#13	2-A and B
#14	2-C
#15	3-A and B
#16	3-C and D
#17	2-A and B
#18	3-A and B
#19	3-C and D
#20	1-C and D
#21	1-A and B
#22	3-A and B
#23	1-F and G
#24	1-C through E
#25	2-A and B
#26	1-A and B
#27	1-F and G
#28	1-D and E
#29	1-B and C
#30	4-A
#31	1-A
#32	1-E through G
#33	5-A and B
#34	1-C and D
#35	1-A and B

Using the procedure described in the preceding paragraphs, the frequency requirements for traffic channels (TCHs) were developed for each of the trunking scenarios and the results are summarized in Table 3-6.

To determine the frequency requirements for each trunking scenario, the frequency plan must include frequency assignments for control channels (CCHs).[23] Each base station for a centralized trunked system has one dedicated CCH. Sometimes, there is a redundant CCH, which carries traffic during normal operation. Since the CCH transmits continuously and serves the entire base station all the time, the CCH frequency planning for the entire network is very conservative and more complicated in actual design to eliminate any type of interference. For the purpose of this

23. The alternative approach used on decentralized trunked systems is to have no dedicated CCHs but to send control information over idle voice channels. This requires the mobiles to scan free voice channels carrying control information. For very small systems, this has the advantage of making all channels available for voice calls, and is more spectrally efficient than a trunked system with dedicated CCHs since no additional frequencies are required for CCHs. However, because any voice channel can potentially become the control channel at any time, calls can be missed during the relatively long scanning time.

study, unique frequencies were assigned to all CCHs although the frequency reuse criterion used for determining the TCHs can also be used for the CCHs. Since one base station can handle the traffic for most service areas, the number of CCHs required for most trunking scenarios in this study was equal to the total number of service areas. The only exception was in a few cases when the service area had a large number of channels to accommodate a higher number of users (e.g., 40 channels at 300 percent agency participation in the Large-Service-Area-Only System). In this case, the service areas were broken down to multiple base stations each with a smaller number of channels to meet the limitations on the maximum number of channels for a base station (32 channels). To address this case, a few extra CCHs were added to the total number of channels to determine the frequency requirements for those trunking scenarios.

3.3 Design Summary and Analysis

3.3.1 Summary Table

The total number of channels required and associated number of frequencies for each of the three system architectures for each of the trunking scenarios are summarized in Table 3-6.[24] These results are based on the hypothetical design and the assumptions made during different stages of the analysis and calculations.

The Large-Service-Area-Only system architecture with 100 percent agency participation is used to explain how the frequency requirements are determined using the TCH and CCH requirements. The Large-Service-Area-Only system architecture for 100 percent agency participation, the total number of frequencies required is 166. This number was first calculated by adding the number of channels required for areas with a high-concentration of users (17) to the number of channels required for areas with a medium- and low-concentration of users (108) for a total number of 125 TCHs (Table 3-1). The number of control channels required was equal to the number of service areas (35) in this case. Therefore, the total number of channels required for the system was the number of channels required for the traffic and control channels added together, or 160 (125 + 35). However, by using the frequency reuse scheme, the actual frequency requirement derived from the frequency plan for the traffic channels was 48 unique frequency pairs to support full duplex operation, which is much less than 125 channels. Unique frequencies were assigned to all control channels, which is 35 pairs. Therefore, with two frequency assignments required for each channel, the 166 total number of frequency assignments was calculated by adding 48 and 35 together, or 83, and then multiplying the summation by a factor of 2. The values of the total number of frequency assignments for other trunking scenarios were calculated in the same manner.

The frequency requirements shown in the Table 3-6 indicates that although the majority of the frequencies are used in the areas with a high-concentration of users, many of these frequencies can be reused in any areas with a medium- and low-concentration of users as long as 70-mile reuse distance criterion is satisfied. For example, 17 frequency pairs or 34 frequency assignments are required for Service Area #1 at 100 percent agency participation for the Large-Service-Area-Only System architecture, which is approximately 35 percent of 48 frequency pairs for TCHs in this scenario. The total number of frequencies required was determined by the frequency use in the areas with a high and concentration of users (e.g., Service Area #1 to Service Area #7).[25] Therefore, the proper design of channel requirements in areas where there is expected to be a high concentration of users is a key to obtain greater frequency reuse, thus reducing the necessary frequency resources.

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24. More base stations with fewer traffic channels may be required to provide the same level of service in the service areas as described in the study, especially in the areas of high concentration of users. Therefore, the total number of channels and the total number of frequencies required could be higher than the results presented in this report.

25. Within the areas with a high and medium concentration of users, frequency reuse was not possible because of the 70-mile reuse distance established for this study.

Table 3-6. Summary of Frequency Requirements for Different Trunking Scenarios

Trunked LMR System Architecture	Parameters	Frequency Requirements		
		30% Agency Participation	**100% Agency Participation**	**300% Agency Participation**
Large-Service-Area-Only (Coverage Radius: Large = 20 miles) (Total 35 Service Areas)	Number of Channels Required for Service Area #1(Areas of High-Concentration of Users)	8	17	40
	Number of Channels Required for Service Areas #2-#35 (Areas of Medium- and Low-Concentration of Users)	77	108	173
	Total Number of Traffic Channels (TCHs)	85	125	213
	Total Number of Control Channels (CCHs)	35	35	36
	Total Number of Channels Required for the System (TCHs + CCHs)	**120**	**160**	**249**
	Total Number of Frequency Pairs Required for TCHs (TX/RX pair)	27	48	96
	Total Number of Frequency Pairs Required for CCHs (TX/RX pair)	35	35	36
	Total Number of Frequency Assignments Required for the System (TX+RX)	**124**	**166**	**264**
Large-Medium-Service-Area-Mixed (Coverage Radius: Large = 20 miles, Medium = 12 miles) (Total 38 Service Areas)	Number of Channels Required for Four (4) Medium Service Areas (Areas of High-Concentration of Users)	16	28	54
	Number of Channels Required for Service Areas #2-#35 (Areas of Medium- and Low-Concentration of Users)	77	108	173
	Total Number of Traffic Channels (TCHs)	93	136	227
	Total Number of Control Channels (CCHs)	38	38	38
	Total Number of Channels Required for the System (TCHs + CCHs)	**131**	**174**	**265**
	Total Number of Frequency Pairs Required for TCHs (TX/RX pair)	35	59	110
	Total Number of Frequency Pairs Required for CCHs (TX/RX pair)	38	38	38
	Total Number of Frequency Assignments Required for the System (TX+RX)	**146**	**194**	**296**
Large-Small-Service-Area-Overlapping (Coverage Radius: Large = 20 miles, Small = 7 miles) (Total 42 Service Areas)	Number of Channels Required for Service Areas #1 and #36-#42 (Areas of High-Concentration of Users)	18	27	53
	Number of Channels Required for Service Areas #2-#35 (Areas of Medium- and Low-Concentration of Users)	77	108	173
	Total Number of Traffic Channels (TCHs)	95	135	226
	Total Number of Control Channels (CCHs)	42	42	42
	Total Number of Channels Required for the System (TCHs + CCHs)	**137**	**177**	**268**
	Total Number of Frequency Pairs Required for TCHs (TX/RX pair)	37	58	109
	Total Number of Frequency Pairs Required for CCHs (TX/RX pair)	42	42	42
	Total Number of Frequency Assignments Required for the System (TX+RX)	**158**	**200**	**302**

3.3.2 Comparison of Frequency Requirement

Comparison of the total number of frequencies required for the alternative trunked LMR systems with current frequency usage in the GMF for conventional LMR systems provides a measure of relative spectrum efficiency. The level of federal users obtained from the GMF represents the 100 percent agency participation considered in this analysis. There were 524 frequency assignments associated with base stations at specific locations in the GMF for the 162-174 MHz band within 100-mile radius of Washington D.C.[26] Table 3-7 shows the frequency usage comparison between the 524 frequency assignments used in the GMF and the three alternative trunked LMR system architectures at the 100 percent level of agency participation.

Table 3-7. Frequency Usage Comparison for LMR Systems

LMR System	Total Number of Frequencies Used at 100% Level of Agency Participation	Percent Frequency Usage of Trunked System Relative to Conventional System
Conventional	524	----
Large-Service-Area-Only Trunked	166	32%
Large-Medium-Service-Area-Mix Trunked	194	37%
Large-Small-Area-Overlapping Trunked	200	38%

As shown in Table 3-7, only 166 frequencies are required for the Large-Service-Area-Only System, which is approximately 32 percent of the frequencies used for conventional LMR systems. For the Large-Medium-Service-Area-Mixed System only 194 frequencies are required, which is approximately 37 percent of the frequencies used for conventional LMR systems. For the Large-Small-Service-Area-Overlapping System, only 200 frequencies are required, which is approximate 38 percent of frequencies used for conventional LMR systems. The number of frequencies that would be required for conventional LMR systems at the 30 percent level of agency participation and the 300 percent level of agency participation cannot be determined from GMF, thus, a direct comparison of the frequency usage cannot be made. The comparison of frequency usage in Table 3-7 clearly shows that the trunking system architectures use frequencies more efficiently than individual conventional LMR systems.

An example of the frequency requirements as a function of the level of agency participation for the Large-Service-Area-Only trunked LMR system architecture is provided in Table 3-8. Comparing the 30 percent and 100 percent levels of agency participation, only 42 additional frequencies are required to support three times the number of users. Similarly, comparing the 30 percent and 300 percent levels of agency participation, only 140 more frequencies are required to support ten times the number of users. As shown in Table 3-8, frequency requirements do not increase at the same rate as the level of agency participation.

26. The 524 frequencies were derived from GMF in the 162-174 MHz band. The frequency assignment records considered are within a 100-mile radius of Washington D.C. for LMR systems with specific locations, excluding all area assignments. The frequencies used by National Oceanic and Atmospheric Administration (NOAA) for weather broadcasts, wildlife tracking and other non-LMR systems in the band were also excluded from consideration. The frequency assignment results from the GMF were compared to the channel occupancy measurement data to obtain the channel usage for each frequency.

Table 3-8. Example of Frequency Requirements Versus Level of Agency Participation (Large Service-Area-Only System Architecture)

Trunked LMR System Architecture	Parameters	30% Agency Participation	100% Agency Participation	300% Agency Participation
Large-Service-Area-Only	Total Number of Erlangs Carried by System from Table 3-1	8.3	27.7	83.3
	Total Number of Frequencies Required (Traffic and Control Channels) from Table 3-6	124	166	264

An example of the relative frequency efficiency versus level of agency participation for the Large-Service-Area-Only trunked LMR system architecture is shown in Table 3-9.

Table 3-9. Example of Relative Frequency Efficiency Versus Level of Agency Participation (Large Service-Area-Only System Architecture)

Trunked LMR System Architecture	Comparisons	30% Agency Participation	100% Agency Participation	300% Agency Participation
Large-Service-Area-Only	Number of Erlangs per Frequency	(8.3/124) 0.067	(27.2/166) 0.167	(83.3/264) 0.316
	Ratio of Required Frequencies Relative to 30% Level of Agency Participation	(124/124) 1.0	(166/124) 1.3	(264/124) 2.1
	Ratio of Number of Erlangs per Frequency Relative to 30% Level of Agency Participation	(0.067/0.067) 1.0	(0.167/0.067) 2.5	(0.316/0.067) 4.7

As shown in Table 3-9, the larger the system in terms of Erlangs carried, the more efficient it becomes in terms of the amount of traffic that can be carried per amount of spectrum (number of frequencies used). Table 3-8 and Table 3-9 show that for the 30 percent level of agency participation, 124 frequencies are required and the system was designed to carry a total of 8.3 Erlangs of traffic, 0.067 Erlangs per frequency. For the 100 percent level of agency participation, the system was designed to carry 27.7 Erlangs of traffic and requires 166 frequencies, 0.167 Erlangs per frequency. For the level of 300 percent agency participation, the system was designed to carry 83.3 Erlangs of traffic and requires 264 frequencies, 0.316 Erlangs per frequency. Therefore, the system designed for 100 percent level of agency participation is 2.5 times as efficient compared to the system designed for 30 percent agency participation. The system designed for an agency participation of 300 percent is 4.7 times as efficient as the system designed for a 30 percent level of agency participation. The number of users per frequency is a more common parameter to use than the number of Erlangs per frequency where the relative comparison ratios based on either one of them are the same (see Erlang formulas in Appendix A). Furthermore, as shown in Table 3-9, the number of users per frequency increased by a factor of 2.5 for the 100 percent level of agency participation and by a factor of 4.7 for the 300 percent level of agency participation as compared to the frequency usage at an agency participation level of 30 percent.

The results for the Large-Medium-Service-Area-Mixed and Large-Small-Service-Area-Overlapping system architectures will be similar to those shown in Table 3-8 and Table 3-9.

The frequency usage comparison with current GMF data shows that the trunking system architectures use frequencies more efficiently than conventional LMR systems. Moreover, the analysis based on the level of agency participation shows that larger capacity trunked systems offer much higher frequency efficiency than the smaller capacity systems.

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SECTION 4
CONCLUSION

Trunking is a proven technology that permits a large number of users to share a relatively small number of channels. Unlike conventional LMR systems, where the user must wait if the channel is occupied by another user, trunking allows for the automatic sharing of multiple channels. Access to the trunked system is dynamically allocated to the available channels. Because trunked LMR systems shared channels, they can offer more efficient use of the radio spectrum than conventional LMR systems.

This study presented three different alternative trunked LMR system architectures in the 162-174 MHz band: a Large-Service-Area-Only System, a Large-Medium-Service-Area-Mixed System, and a Large-Small-Service-Area-Overlapping System. Three potential levels of federal agency participation were considered: 30 percent agency participation representing partial participation by the current federal users of conventional LMR systems; 100 percent agency participation representing full participation by the current federal users of conventional LMR systems; and 300 percent agency participation representing future expanded use by the federal users. The three system architectures combined with the three levels of agency participation resulted in nine unique trunking scenarios. Each trunking scenario was studied within a 100-mile radius coverage area centered in Washington, D.C. The frequency assignment data from the GMF and channel occupancy measurements were utilized to derive traffic levels expressed in Erlangs for the service area of each base station. The traffic levels were used to determine the number of channels required for the different trunking scenarios. The spectrum requirements for each trunking scenario were developed based on 12.5 kHz channel spacing in the 162-174 MHz band, and the 70-mile frequency reuse distance criterion.

For the 100 percent level of agency participation, approximately 32 percent or 166 of the 524 frequencies in the GMF are needed for the Large-Service-Area-Only System. For the Large-Medium-Service-Area-Mixed System, approximately 37 percent or 194 of the 524 frequencies in the GMF are needed. The Large-Small-Service-Area-Overlapping System requires approximately 38 percent or 200 of the 524 frequencies in the GMF. The study in this report clearly shows that fewer frequencies are required for the trunked system architectures as compared to the total number of frequencies required for the existing conventional LMR systems.

This study quantifies how the number of users per frequency increases for trunked LMR systems servicing a large number of users as compared to trunked LMR systems servicing a small number of users. The number of users per frequency increased by a factor of 2.5 for the 100 percent level of agency participation and by a factor of 4.7 for the 300 percent level of agency participation as compared to the frequency usage for the 30 percent level of agency participation. By combining spectrum resources in a shared system, agencies can implement trunking systems with improved trunking capacity, total coverage area, multi-agency interoperability and advanced control, monitoring and system management capabilities.

The results of frequency planning for each of the trunking scenarios show that, although the majority of the frequencies are used by service areas where there is a high-concentration of users, many of these frequencies can be reused in service areas where there are medium- and low-concentration of users for assignments that satisfy the 70-mile frequency reuse criterion. For a trunked LMR system in a metropolitan area, the total number of frequencies required is primarily dominated by frequency usage of service areas where there is a high concentration of users. The proper design of the base station capacity in the high usage areas is a key to obtain high frequency reuse, reducing the necessary spectrum resources for better spectrum management.

This study shows that if a shared trunked LMR system is implemented in the Washington D.C. area, there will be sufficient frequencies in the 162-174 MHz band to support future federal LMR spectrum requirements. For example, the 300 percent level of agency participation (3 times the current number of users) requires approximately 30 percent of the 960 assignable 12.5 kHz channels in the 162-174 MHz band. Thus, trunked LMR systems that are shared by federal agencies are an effective approach to more efficient use of the federal LMR frequency bands.

This study also shows that the use of overlapping small cells does not save frequencies, compared to the use of Large-Service-Area-Only though all of the analyzed architectures use frequencies more efficiently than the present case of independent conventional systems. The apparent lack of frequency savings with the small cells is probably due to the use of the 70-mile frequency reuse criteria. More detailed frequency reuse models based on appropriate C/I criteria should show a frequency reuse improvement for the overlapped cells.

This study is based on hypothetical LMR system designs, and does not provide detailed design specifications. Instead, this study provides a comparison of spectrum resources used by the alternative trunked LMR system designs and conventional LMR systems. Although this study only addressed the 162-174 MHz LMR band in the Washington D.C. area, application of the method presented in this report to other LMR bands in spectrally congested areas, should produce similar results.

APPENDIX A

TRUNKING EFFICIENCY AND HYBRID SYSTEMS

A.1 Trunking Efficiency

Trunking allows a large number of users to share a relatively small number of channels for a base station. Trunking efficiency is a measure of the number of users (radio terminals) that can be served at particular grade of service (GoS) with a particular configuration. Equation A-1 below is used to calculate the traffic level in Erlangs for a base station:[1]

$$A = (M \times L \times H) / 3600 \qquad \text{(A-1)}$$

Where

- A: Call traffic level in Erlangs
- M: Total number of users per base station
- L: Average busy hour call attempts per user
- H: Average busy hour holding time in seconds

The number of users (M) for a base station can be calculated using Equation A-2:

$$M = A \times 3600 / (L \times H) \qquad \text{(A-2)}$$

Table A-1 provides some statistical numbers for average call attempts and average holding time for the busy hour.[2]

Table A-1. Statistical Numbers for Average Call Attempts and Average Holding Time for the Busy Hour

Call Type	Busy Hour Call Attempts per User	Average Busy Hour Holding Time
Group Call	6.5	4 seconds
Individual Call	0.2	4.2 seconds
Telephone Interconnect	0.01	60 seconds

Using values in Table A-1, a typical public safety traffic level per user per call in Erlangs in a busy hour is:

$$(6.5 \times 4+0.2 \times 4.2+0.01 \times 60) / 3600 = 0.0076 \text{ Erlangs/user}$$

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1. Jose M Hernando and F. Perez-Fontan, *Introduction to Mobile Communications Engineering,* 1999 Artech House.

2. Data referenced to tutorial paper *Traffic Analysis* from radio manufacturer M/A-Com presented in 2004. Four seconds holding time for a group call is used in this analysis.

Since one Erlang is 3600 seconds of calls, the 0.0076 Erlangs is equivalent to 27.36 seconds per call per user. Therefore, the total number of users for a base station in Equation A-2 can also be calculated using Equation A-3:

M = (Total Erlangs per Base Station) / (Traffic Load per user per call in Erlangs) (A-3)

The total average holding time (H) is calculated as:

(6.5 x 4 + 0.2 x 4.2 + 0.01 x 60) / (4 + 4.2 + 60) = 4 seconds

Trunked radio systems are queuing or waiting type radio systems. The Erlang-C model is used in the network dimension or size computations. Dimensioning or sizing a trunked radio system means calculating the number of traffic channels required to provide an adequate GoS with an acceptable queuing time or waiting time for the mobile users in the system. In addition to the number of traffic channels calculated, a control channel must be added to each base station. Each channel requires two frequencies for a paired transmitter and receiver (TX/RX) allowing for full-duplex operation.

GoS is defined as the probability that a call will be blocked or delayed. For a trunked radio system, the GoS is a function of the probability that a call request has to wait to be served (delayed) and the probability that the waiting time (in the queue) exceeds the reference waiting time W_0 in seconds.[3]

The probability that a call waiting or delay exceeds the waiting time W_0 is computed using Equation A-4:

$$\text{GoS} = P(W > W_0) = P_D e^{[-(N-A)W_0/H]} \qquad \text{(A-4)}$$

Where the probability that a call has to wait (P_D) is given by the Erlang-C formula in Equation A-5.

$$P_D(A,N) = \frac{\frac{A^N}{N!} \times \frac{N}{N-A}}{\sum_{K=0}^{N-1} \frac{A^K}{K!} + \frac{A^N}{N!} \times \frac{N}{N-A}} \qquad \text{(A-5)}$$

Where:

P_D: Probability that a call has to wait;
A: Call traffic level in Erlangs;
N: Number of traffic channels;
W_0: Reference waiting time in queue in seconds; and
H: Average busy hour holding time in seconds

3. Jose M Hernando and F. Perez-Fontan, *Introduction to Mobile Communications Engineering*, Artech House (1999); Roger L. Freeman, *Reference Manual For Telecommunications Engineering, Volume 1, Third Edition, Chapter 1-5*, A Wiley-Inter-science Publication, John Wiley & Sons, Inc. (2002).

For a GoS = 1%, H = 4 seconds, W_0 = 1 second and traffic load 0.0076 Erlangs per user, the number of channels per base station (N) vs. Erlang values (A), the number of users per base station (M) and the number of users per channel (M/N) at the busy hour were calculated using Equations A-3, A-4 and A-5 and are shown in Table A-2. Figure A-1 shows the number of channels as a function of the number of users. The Erlang values shown in Table A-2 are for the maximum number of users associated with that number of channels per base station, thus the number of users is the maximum that this number of channels can handle at the busy hour. This only represents the busy hour. Therefore, the system should be able to serve many more users during other times because the traffic load beyond the busy hour will be less (e.g., half or third of the busy hour load). The total number of channels shown in Table A-2 does not include control channels.

As shown in Table A-2, a base station with one channel handles only two users when the traffic load is 0.0076 Erlangs/user. However, the number of users that the base station can serve increases much faster than the number of channels. This demonstrates that a trunking system can increase spectrum efficiency tremendously. However, the spectrum efficiency of a trunking system may not be fully realized when the traffic level is very small. For example, when there is partial agency participation in the trunked system most of base stations have very low traffic levels (small Erlang values). However, the same number of channels required for partial agency participation in the trunked system can accommodate many more users when there is greater agency participation in the trunked system. Trunking technology is very efficient for land mobile radio systems because a larger number of users can be served much more efficiently with a smaller number of channels as compared to conventional land mobile radio systems. Moreover, trunked systems with a large number of users offer much higher frequency efficiency than trunked systems servicing a small number of users.

The rate of increase for trunking efficiency decreases when the number of channels gets too high. This is demonstrated by the fact that the number of users does not increase linearly with the number of channels (for a low number of channels) as shown in Figure A-1. As the number of channels increases beyond a point, the change in users approaches a fixed increment with the change in the number of channels. The trend of the number of users to increase will continue to be a constant number beyond 20 channels.

Table A-2. Trunked Radio Network Dimensioning (Busy Hour)

Number of Channels / Base Station (N)	Traffic in Erlangs (A)	Number of Users / Base Station (M)	Number of Users / Channel (M/N)
1	0.0127	2	2
2	0.1854	24	12
3	0.5386	71	24
4	1.0103	133	33
5	1.5625	206	41
6	2.1729	286	48
7	2.8276	372	53
8	3.5172	463	58
9	4.2352	557	62
10	4.9766	655	65
11	5.7378	755	69
12	6.516	857	71
13	7.3089	962	74
14	8.1147	1068	76
15	8.932	1175	78
16	9.7594	1284	80
17	10.596	1394	82
18	11.4407	1505	84
19	12.293	1618	85
20	13.1521	1731	87
21	14.0173	1844	88
22	14.8883	1959	89
23	15.7643	2074	90
24	16.6453	2190	91
25	17.5313	2307	92
26	18.4213	2424	93
27	19.3153	2541	94
28	20.2123	2660	95
29	21.1143	2778	96
30	22.0183	2897	97
31	22.9253	3016	97
32	23.8363	3136	98
33	24.7483	3256	99
34	25.6643	3377	99
35	26.5823	3498	100
36	27.5023	3619	101
37	28.4253	3740	101
38	29.3493	3862	102
39	30.2763	3984	102
40	31.2043	4106	103

Note: All calculations above were based on the following parameters: GoS = 1%, H = 4 seconds, W_0 = 1 second and traffic load 0.0076 Erlangs/user (or 27.36 seconds per call per user).

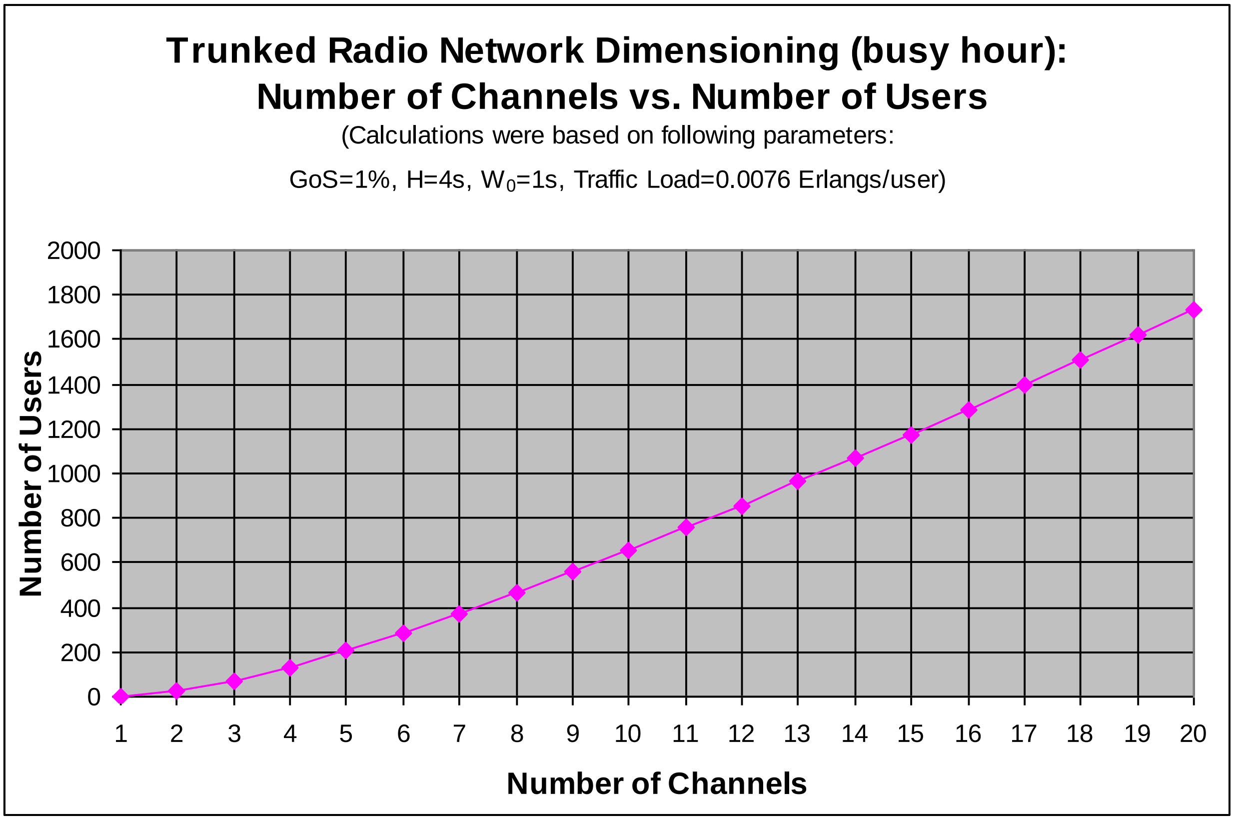

Figure A-1. Trunked Radio Network Dimensioning

A.2 Hybrid LMR Systems

Trunking technology provides major advancements for two-way radio communications. Since its development, public safety agencies at all levels of government as well as critical infrastructure entities and enterprise corporations are increasingly implementing trunked LMR systems to meet their advanced communications requirements. However, a trunked site in very low-traffic areas may not be the most efficient system because of low channel usage when the talk-group is geographically spread over different base stations. It is possible to combine different technologies in one system to take advantage of all of them.

A.2.1 Combining Conventional and Trunked LMR Systems

The trunked radio systems are designed to best meet the communications needs of having high communications traffic volume, requiring multiple channel communications and inter-agency or multi-agency interoperability. In contrast, conventional systems are typically used for wide-area coverage with small number of radio users and low communications traffic volume. These are usually the requirements of public safety agencies in large rural areas. Therefore, there are trade-offs to be considered in the decision between a trunking and conventional system.

Implementing a hybrid system, combining conventional and trunked systems within a single system, may be an effective way for agencies to obtain the benefits of trunking where they need it most such as in large metropolitan areas, having high user density and interoperability requirements. Radios designated to operate in both the conventional mode and the trunked mode can be programmed to operate in either mode. Users are required to select either the conventional mode or trunked mode on their radio prior to making a call. When operating in a conventional site area, users would then monitor the conventional channel and wait until it is available, similar to a conventional system. When operating in a trunked site area, they just press the Push-to-Talk (PTT) button to make a call, similar to trunked operation.

A.2.2 Using Simulcast Technology

For talk-groups that are widely dispersed, channels may have to be provided at several sites to provide the required coverage. The transmission of the same information on different channels is not the optimum way to use spectrum. For example, if a particular multi-site system uses a 12:1 frequency reuse pattern, a given frequency might be usable only every twelfth site. Full coverage across all sits could require as many as 12 different frequencies. For an occasional requirement, the use of multiple separate channels at different sites may not cause a significant waste of spectrum; but for heavy use of widely dispersed talk-group requirements, the use of simulcasting on a few channels maybe a better way. Simulcast technology uses the same frequency on each site, allowing coverage across many sites with only a single frequency.

Simulcast systems use several geographically separated base stations/repeaters that transmit on exactly the same frequencies simultaneously. These networks require a timing system to synchronize each transmitter on the network to assure that transmissions on the same frequency are in phase to reduce the heterodyne interference. Should a traffic analysis show that there are geographically dispersed talk-groups that would regularly require channels across multiple sites, it may be advantageous to provide trunking systems that simulcast on one or more channels at some or all sites. In another words, simulcast technology can be used on a few channels as required as part of the overall trunking system. Whenever a large geographically dispersed talk-group required service, this service would be provided through the use of a simulcast channel. If all simulcast channels were already in use, the service could be provided with multiple trunked channels.

For a large, wide-coverage, and multi-agency trunking system the total simulcast trunking system (all channels in the system are simulcast channels) is not recommended, pending a more thorough understanding of the proportion of such geographically dispersed talk-groups. Unless there are a very large number of widely dispersed talk-groups, it is likely that the disadvantages of total simulcast architecture would outweigh the advantages. It prevents the frequency reuse in the entire network because the same frequencies are required at low-traffic area sites with fewer users as are required at high-traffic volume sites.

Only with a detailed traffic analysis can the advantages of simulcast for a particular system be determined. A major unknown in such analysis is the location of users belonging to talk-groups that would be serviced by such a system.