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Quantifying the Costs of a Nationwide Broadband Public Safety Wireless Network[†]

Ryan Hallahan[‡] and Jon M. Peha[§]
Carnegie Mellon University

Abstract

The problems facing the public safety wireless communication systems in the US could be significantly reduced or eliminated through the deployment of a single nationwide network that serves all public safety personnel. Two major efforts towards such a nationwide network are the Integrated Wireless Network (IWN), a program only for federal emergency responders, and an effort by the FCC to create a public-private partnership in the 700MHz band that serves state and local emergency responders; the future of both projects is uncertain due in part to concerns surrounding cost. To inform these concerns, this paper presents the first version of a fully transparent model to estimate cost for two fundamental approaches: a *public-safety-only network* and a *public-private partnership* which serves both public safety and commercial subscribers. We apply this general model to four scenarios: 1. a public-safety-only network that only serves all public safety personnel (i.e. local, state, and federal) on 10MHz of spectrum in the 700MHz band, 2. a public-private partnership that serves all public safety personnel and commercial subscribers on 20MHz of spectrum in the 700MHz band, and 3&4. a network that only serves all public safety personnel in either of the two bands that may be used for the federal-only IWN project (168MHz & 414MHz). In each of these scenarios, we consider networks that carry voice only, data only, and both voice and data. We demonstrate the inefficiencies of the existing public safety infrastructure by showing that a single nationwide network could be built in its place with a small fraction of the tower sites and spectrum. In fact, the cost of building an entire nationwide system is comparable to what is likely to be spent in just a few years on the existing infrastructure. More specifically, for the public-private partnership carrying voice and data, we found deployment costs on the order of $10 billion which is less than the $15 – 20 billion previously estimated. For the public-safety-only network carrying voice and data at 168MHz, we found deployment costs on the order of $6 billion. Thus, if sufficient spectrum can be identified, the current IWN system could be extended to include state and local responders and provide broadband data without a significant increase in cost. In addition, these cost estimates are highly dependent on some key parameters, such as those related to capacity and coverage reliability, over which there has been little serious debate. If a public-private partnership is to be successful, values must be established for such parameters before bids are sought. Otherwise, potential bidders cannot even roughly estimate their costs. Additionally, we find that 83% of US area is currently covered by existing public safety wireless systems, whereas some claim the population build-out requirement established by the FCC would cover just 63% of the US, and the actual coverage is more likely to be roughly 50%. We also show that the estimated cost savings from relaxing the existing build-out requirements are overstated.

[†] The authors gratefully acknowledge the financial support of the MacArthur Foundation.
[‡] Ryan Hallahan, Ph.D. Student in the Department of Engineering and Public Policy, Carnegie Mellon University, hallahan@cmu.edu
[§] Jon M. Peha, Professor of Electrical Engineering and Public Policy, Carnegie Mellon University, peha@cmu.edu, www.ece.cmu.edu/~peha

1 Introduction

Considering the important role that they play in ensuring the safety of the public, the existing public safety wireless communication systems in the United States are far from adequate. This can be attributed to several factors, but chief among them is that the many public safety agencies across the country deploy networks independently with limited coordination or standardization with neighboring agencies [1]. The potential deployment of a nationwide public safety wireless system presents an opportunity to solve some of these current problems [2].

A major impediment to the deployment of a nationwide public safety wireless network is the substantial estimated cost of such a project as well as the uncertainty surrounding this cost. By understanding these costs better and understanding what factors impact them, policymakers may be better able to determine if any of the proposals currently being considered are even feasible and if so whether or not they present a cost savings when compared to supporting the existing infrastructure. In addition to cost, there are some fundamental differences between the current proposals for deploying a nationwide public safety network and policymakers must understand and be able to weigh the tradeoffs between these proposals. In this paper, we provide a first-cut analysis of the costs of various network proposals including a nationwide public-private partnership and a nationwide network that serves only public safety while investigating the tradeoffs between each of them, with more detail coming in future work.

In section 1.1, we provide some background on the existing public safety wireless communications infrastructure in the US, identify the factors which have contributed to its unfortunate state, and discuss why a nationwide network is a possible solution. In section 1.2, we present and compare the recent proposals for a nationwide public safety network in the US, and present some alternatives that have not received wide attention. In section 1.3, we discuss the research questions this work hopes to address and highlight the important concepts at the root of these questions. Section 1.4 discusses the outline of this paper.

1.1 Background

Instead of a nationwide network, in the past, state and local public safety agencies have deployed their own wireless communications systems. There are currently more than 50,000 state and local public safety agencies using mobile radio systems for wireless communication in the United States [3]. These agencies employ approximately 1.1 million first responders [4]. However, the majority of these agencies are relatively small, having fewer than 50 users [3]. A US spectrum policy of allocating spectrum individually to these agencies has led to that spectrum being substantially fragmented and allocated across 10 bands[1] ranging from 20MHz to 4900MHz [5] [6] [7] [8]. Having many small agencies deploy their own systems has substantially increased the cost of the existing infrastructure while simultaneously making inefficient use of the spectrum [1].

In addition, the limited coordination between agencies when deploying communication systems and the lack of a widely adopted technical standard [9] [10] has led to existing systems that are prone to failure when needed most [1]. Unfortunately, several recent tragedies[2] have been

[1] Appendix A summarizes the federal and non-federal public safety spectrum allocations.
[2] Perhaps the most tragic example is the loss of life during the rescue efforts in the aftermath of the World Trade Center attacks on 9/11. The lives of 121 firefighters were lost because they were unable to receive an evacuation

directly attributed to failures in the existing public safety communications infrastructure [11] [12]. Interoperability is the term given to the ability to communicate across agencies, and a lack of which is a commonality shared by those recent tragedies. However, in addition to the large-scale disasters, a lack of interoperability is an issue that public safety agencies must deal with on a routine basis [13]. While interoperability problems have received considerable study [14] [15] [16] [17] and recent efforts have been focused on reducing these interoperability issues [18] [19] [20], even if these issues were solved entirely, the majority of existing public safety communication systems would still be limited in functionality to narrowband voice, use more spectrum and cost more to maintain than a single network shared by all public safety agencies [1].

A nationwide public safety wireless network avoids many of the shortcomings of the previous policy [2]. Instead of planning thousands of systems independently, there is a single network to be designed and deployed. By combining these users into a single pool, spectrum can be allocated and used much more efficiently and technical interoperability issues are inherently solved by the use of a single technology on the network. Additionally, building a new nationwide network presents an opportunity to deploy a broadband system which can introduce data capabilities such as streaming video and internet access to users who previously had to rely on voice-only systems.

1.2 Proposals

There a two fundamentally different proposals for the creation of a nationwide public safety wireless network, a proposal for a system that would serve only public safety users and a public-private partnership that would serve both commercial and public safety users on the same network [2].

An example of a proposal for a public-safety-only network is the Integrated Wireless Network (IWN). This is a proposal by the US Departments of Justice, Treasury, and Homeland Security for a nationwide wireless system that would serve up to 80,000 federal public safety users [21]. As it currently stands, this network will provide mission critical voice service across the nation [22] but the technology[3] used will not support broadband data applications [23] [24]. It is expected that the network will use spectrum from the federal allocations at 160MHz and/or 400MHz as most of the agencies that will use this network have their existing land mobile radio (LMR) operations concentrated in these two bands [25]. It is possible that by expanding this system to support broadband data applications as well as serve local and state public safety users there are potential cost savings and spectral efficiency gains as compared to independently building two nationwide networks to support these user groups separately, as discussed in [26]. Currently, extending IWN does not appear to be a proposal that policymakers are seriously considering and this paper studies whether or not it deserves increased consideration.

In addition to proposals for a public-safety-only network like IWN, there have been proposals for a public-private partnership network that would serve both public safety and commercial users

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call issued over police radio [11]. However, this is not an isolated problem: Hurricane Katrina in 2005 [12], the Oklahoma City bombing in 1995 and the first attack on the World Trade Center in 1993 [6] all demonstrate the shortcomings of the existing public safety wireless communication systems.

[3] It is planned that IWN will be based on the Project 25 (P25) technology standard. Phase I of this standard operates on 12.5 kHz channels enabling voice or 9.6kbps data service [23] [24].

[27]. A key motivation for a public-private partnership is the observation that a majority of the time, public safety users do not use all of the available capacity on their wireless systems [28] [29] [2]. This reality is due to the fact that public safety communication systems are designed for worst-case capacity demand scenarios but, thankfully, most of the time these large-scale emergencies are not taking place. This implies that if a commercial and public safety entity were to share spectrum, a majority of the time the commercial partner could use some of the public safety spectrum to serve commercial subscribers while allowing the public safety partner access to both the public safety and commercial spectrum in the rare emergencies when it is needed.

In August 2007, in response to an innovative proposal [30] in the US for a public-private partnership between a commercial wireless carrier and state and local public safety agencies, the FCC designated a 10MHz portion of the 700MHz spectrum band specifically for public safety broadband use. Most notably, this spectrum was licensed nationwide to a single representative of public safety [27] as opposed to individually to each state and local agency. Additionally, the FCC created a 10MHz commercial license for the spectrum adjacent to the public safety allocation, which was auctioned in February 2008 [31]. The winner of that auction would have been obligated to build a nationwide public-safety-grade network on the 20MHz of combined spectrum to be shared by public safety and commercial users [27]. This was done in an attempt to have a commercial entity fund and build out a public-safety-grade network in exchange for discounted access to spectrum. This auction concluded without a winning bidder emerging, a fact that has been widely attributed to the considerable uncertainty about the requirements that would be placed on the network[4] [32] [33]. With no winning bidder emerging from the auction, the FCC is reexamining the rules that were attached to the commercial block of spectrum and is considering changes before it is reauctioned. In this paper we consider both a potential public-private partnership on 20MHz of spectrum in the 700MHz band and a public-safety-only network on 10MHz of spectrum in the same band.

1.3 Research Questions

While these new proposals represent large steps in a new direction for public safety communications, many questions remain unanswered. This work hopes to inform the current debate by addressing the following fundamental questions about the cost of a nationwide network.

First, what will a nationwide wireless communication system for public safety cost? Previous cost estimates vary considerably, and their results are hard to assess because they tend to be unclear about the methods used and assumptions made [34] [35] [36] [37]. This paper presents an extensible model that is used to compare the number of cells required by current proposals for a nationwide network. Although the model is not static in that further refinements are expected over time, the fact that all assumptions are transparent makes this a valuable tool for policy assessment. This paper focuses on the number of cell sites required because the deployment and operating costs of a network are roughly proportional to the number of cell sites required.

[4] The FCC left many of these requirements to negotiations between the commercial partner and public safety licensee. Prior to the auction, the public safety licensee did release a document of desired system design requirements [33] however these requirements were still negotiable.

When considering a public-safety-only scenario, we compare the cost of each proposal to the cost savings associated with maintaining and upgrading existing public safety infrastructure. When considering a public-private partnership scenario, we compare the cost predicted by our model to industry estimates of the cost of a public-private partnership. We also compare the predicted number of cell sites required for a public-private partnership to the number of cell sites required for a public-safety-only network and estimates of the number of cell sites deployed in existing commercial systems. The findings in this paper represent the initial results of our model and future work will examine additional proposals and network design requirements.

Second, what system characteristics have the largest impact on the number of cell sites required for each of the current proposals for a nationwide network? Many factors impact the required number of cells for a network and these factors often differ between typical public safety and commercial wireless systems. In particular, the following system factors are studied in this paper: the amount of area covered, the frequency and bandwidth of the spectrum allocation, the amount of communications capacity required on the network, and the technical requirements of a public-safety-grade network.

When considering the coverage area of a network, commercial cellular systems are built so that most areas where paying customers reside and travel are served while public safety users need coverage wherever emergencies can occur. This is important because in a wireless system, the number of cells required is highly dependent on the total area covered by the system. For this reason, we determine the area currently covered by existing public safety systems and investigate the impact on the number of cell sites required as the fraction of US population and land area covered by a new nationwide system is varied.

We also examine how costs change and how the relative merits of a public-safety-only network and a public-private partnership may differ depending on which and how much spectrum the FCC and/or NTIA make available. The number of cells required in a wireless network is dependent on the size of the cells in the network and the size of a cell is dependent on the frequency and bandwidth of the spectrum used. As the frequency increases, the size of a cell tends to decrease. Meanwhile, as the bandwidth is increased, the capacity that a cell can support increases. For the proposals studied in this paper, we will be concerned with frequencies between 160MHz and 700MHz with bandwidth allocations between 7.5MHz and 20MHz.

The capacity required in a cell by commercial cellular users and first responders is different. These capacity differences can be seen at the individual user level where first responders may require higher data rate applications like video, and in the aggregate, when many first responders must respond to the same emergency where they are concentrated within a single cell. Therefore, the number of cell sites required for each proposal is studied for a variety of capacity requirement scenarios.

When designing a wireless network, commercial cellular users and first responders typically have different requirements (e.g. the availability of a wireless signal within buildings or the reliability of a signal in the coverage area), so in a shared public-private network it may be necessary to determine where on that continuum a network planner should design. However, it is important that the design is not a compromise that is unnecessarily expensive for commercial users and inadequate for public safety. Thus, a public-private partnership is a tradeoff (i.e. with the advantage of sharing capacity and the disadvantage of dissimilar requirements) and we examine the impact of these dissimilar requirements.

1.4 Paper Layout

In section 2 of this paper, we introduce the framework of the model we developed to calculate the number of cell sites required by each proposal considered. This model takes several variables as inputs and section 3 discusses the appropriate numerical values to use for the inputs when designing for public-safety-only and public-private partnership network. In Section 4, a Geographic Information System (GIS) model is introduced and then used to calculate the area currently covered by the existing public safety wireless infrastructure. This result is then used as an estimate of the area a nationwide, broadband, public safety wireless network should serve. Section 5 provides a review of the proposals studied, the numerical value chosen for the inputs that are specific to each proposal, and a summary of all the numeric values used as inputs to the model. Section 6 provides the results of the model with an estimate of the cost for each proposal studied and investigates how results change as the input values are varied. Finally, section 7 provides a discussion of our conclusions.

2 Model Development

In this section, we introduce the framework of the extensible model we developed to calculate the number of cell sites required by a public-safety-grade network under a variety of conditions. This section begins with an overview of the model layout in section 2.1, which introduces the important concepts used and discusses the major assumptions made. Sections 2.2 – 2.5 describe the major components of the model in detail: estimating capacity required in a cell, estimating the minimum signal power required at a receiver, estimating factors which affect the received signal power between transmitter and receiver, and estimating the size of a cell based on signal power lost between transmitter and receiver. Section 2.6 summarizes how all four components relate to form a system of equations that are solved for the input values discussed in section 3.

2.1 Overview

The most cost-effective design for the proposals we study of a nationwide public-safety-grade broadband wireless system is based on a cellular architecture. Costs in a cellular architecture are highly dependent on the number of cells. Therefore, to estimate the cost of a network, we first develop a model to predict the required number of cells for that network.

We calculate the expected number of cell sites per region (i.e. zip code) as follows. Let C_i be the expected area per cell if population density were uniform, and equal to the population density in region i. Let A_i be the area of region i. We assume that the expected number of cell sites in region $i = A_i / C_i$. The population density in region i is determined using nationwide zip code level[5] population statistics [38]. Expected cell size depends on population density for several reasons including the fact that the capacity required in a cell and the appropriate propagation model for a cell are dependent on population density. The model calculates the expected area per cell in each region in 4 steps: by calculating the capacity required in a cell, then by

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[5] The U.S. Census Bureau records the population, population density, and geographic area data at several levels of granularity including Census Blocks (8+ million cover the U.S.), Zip Code Tabulation Areas (30+ thousand cover the U.S.) and Counties (3+ thousand cover the U.S.).

calculating the minimum received signal power required for the capacity required, then by calculating the maximum amount of signal power that can be lost in the path between transmitter and receiver, and finally by calculating the radius of a cell based on the maximum amount of power that can be lost in the path.

At a high level, these calculations require that we first define the capacity required in a cell as a function of first responder density. We show in section 3 that first responder density is a linear function of population density. Next, we show that the minimum power received from each mobile device at the base station in each cell (i.e. the receiver sensitivity) is a function of the capacity required in that cell. Then, we use a link budget to determine the maximum amount of strength that the signal is allowed to lose as it travels from the handset to the basestation (i.e. the maximum allowable path loss or *PL*). A link budget takes into account the power of the transmitted signal, the minimum signal power required at the basestation, increases in signal power due to antennas, and decreases in signal power due to factors such as outdoor obstacles in the signal path and the signal having to penetrate walls. Finally, we use a propagation model that differentiates urban, suburban, and rural regions to calculate the radius of a cell. This model accounts for the maximum allowable path loss, frequency of operation, and height of the basestation antenna.

In practice, every single cell will have a unique coverage area determined by a number of localized factors; however, we avoid laying out exactly where every cell tower in the country must sit by assuming that the distribution of population densities of cells is the same as the distribution of population density within occupied zip codes. Zip code level granularity appears to be reasonable given that, as we will see in Section 6, the number of cells nationwide is comparable to the number zip codes.

In this work, when technology dependent numerical values are required for analysis, we use numbers that are consistent with the CDMA2000 evolution broadband wireless standard. CDMA2000 is a well developed and widely deployed 3G standard, which would be one potential candidate technology for a nationwide broadband wireless system. Although the technology actually used in a next-generation system may or may not be CDMA2000, it is a reasonable basis for cost estimates as it has been considered in other analysis of a broadband public safety system [37] [39] [40] and has recently been chosen as the technology standard for a city-wide public safety broadband deployment [41].

Consistent with a CDMA2000 network, we have assumed that the bandwidth allocated under each proposal is divided into 1.25MHz channels with traffic distributed equally across the channels [42]. As is typically done for CDMA systems, our model considers a network with a universal frequency reuse or a frequency reuse factor of 1, meaning that every cell can operate on each channel. This paper focuses on the uplink as it is assumed to be the limiting link in determining the size of a cell as is usually the case in a CDMA system where the mobile devices have lower transmit power limits than basestations and cochannel interference from other mobiles operating on the same channel is present at the basestation [42]. To limit cochannel interference, among other reasons, cells are typically sectorized in a CDMA system. We have assumed that all cells in our network have 3 sectors per cell. We further assume that the uplink is perfectly power controlled as is typically assumed when analyzing CDMA systems [42] [43].

Perfect power control means that the power a mobile device transmits at is controlled so that the power received at the basestation from mobiles communicating with that basestation is no greater than that necessary for adequate communications. Some of these parameters will be varied in future work.

When calculating cell area as a function of radius, one must account for the fact that cells overlap, typically by 10 – 30% [42] [44]. We have assumed an overlap of 17%, which would be consistent with cells that are hexagonal as opposed to circular. Further, we assume no fault tolerance in the design of this public safety network. This means the network is designed knowing that the loss of any cell site means a loss of service in some area. This design is no worse than what public safety has today, but the creation of a nationwide public safety network presents an opportunity to add fault tolerance [2]. Fault tolerance could make a big difference in the response efforts for disasters similar to Hurricane Katrina where the communications infrastructure is partially destroyed during the disaster. Future work may consider the tradeoff between the cost of a network and the addition of fault tolerance.

2.2 Capacity Model

For each cell, it is necessary to calculate the capacity required as this capacity can have a significant impact on the cell's size. In commercial networks the capacity required in a cell is well understood and network planners often have historical usage data to consider when designing a network. Unfortunately, with the limited deployment of broadband data networks for public safety use in the US, there is a lack of empirical evidence for capacity required in a public-safety-only or public-private partnership cell. There is no widely accepted model of capacity requirements for public safety, which is a serious problem for cost estimates, and more generally for policy formulation. Further work is needed in this area. So, in the absence of an established model, we will suggest one viable possibility and use it as the basis for analysis. This section develops a general model for the capacity required in a cell by public safety users on a broadband wireless network while the actual numerical values used in our simulations are discussed in section 3.

We design the system to accommodate two sources of public safety traffic present during a large-scale emergency. One source of traffic will come from public safety personnel who are responding to the large-scale emergency. The second source is routine traffic which is due to routine communications activity and is not part of the emergency response. Because the large-scale emergency may occur when routine traffic is at its peak, the total public safety capacity required in a cell is the sum of the peak capacity required by each of these two traffic sources.

Considering first the emergency traffic, we design the system such that capacity will be sufficient for a large-scale emergency that is localized, even in the worst-case for a localized emergency, which would occur if the emergency response takes place entirely within a single cell and in the worst part of that cell (i.e. the edge). We are designing for a large-scale emergency that is relatively localized in nature (e.g. a plane crash, a large building fire, a terrorist bombing, etc.). By designing the system such that every cell can accommodate this kind of localized disaster, it seems likely that a disaster such as an earthquake or hurricane that is spread across many cells will also have sufficient capacity, but this is beyond the scope of our model.

This approach is similar to the existing work on capacity requirements for emergency response which also focuses on localized events [45] [46].

The magnitude and nature of a large-scale emergency as well as the response to that emergency may vary depending upon where in the US the event occurs. More specifically, the capacity required in a cell due to an emergency response may be dependent on the number of first responders in the vicinity of that cell who are available to respond. Similarly, the nature of the emergency may be such that areas with higher population density may need even more first responders to protect the affected population. As will be discussed in greater detail in section 3, we have observed a linear relationship between population density and the density of first responders in the US. The following figure provides a graphical representation of the model developed of the capacity required in a cell as a function of the population density in that cell.

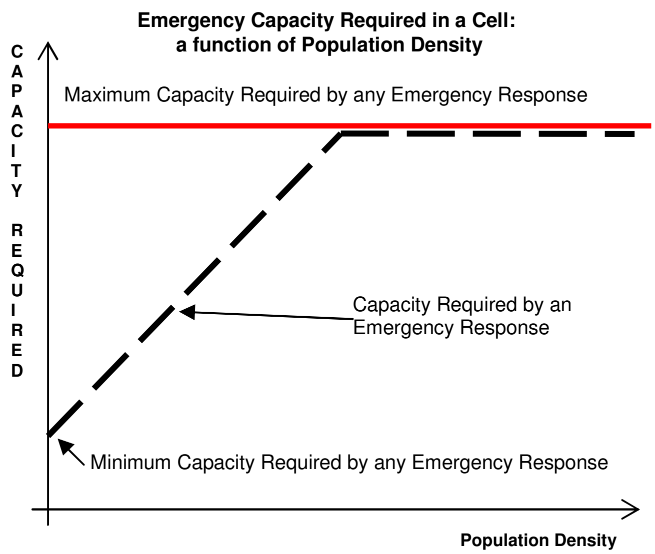

Figure 2.1a: A plot of the capacity required in a cell as a function of the population density in that cell.

In the figure above, we have designed the system such that even the most rural cells (i.e. cells with a population density of zero) require a non-zero capacity. This appears reasonable considering the fact that large-scale emergencies can occur anywhere (e.g. a plane crash). In this case, the response is composed of public safety personnel based outside of the cell, responding to the emergency. Therefore, we establish a baseline value which represents a minimum amount of emergency response capacity required in every cell and we assume it is equal to 10% of the capacity required in the most urban cell. This appears reasonable given that the response to large-scale emergencies that occur in extremely rural areas, such as the response to the crash of Flight 93 on 9/11, have an initial response approximately 10 – 20% the size of the initial response to large-scale emergencies in urban areas, such as the 9/11 terrorist attack on the Pentagon [47] [48] [49]. As the population density of a cell increases from zero, there will be a nonzero number of first responders predicted in that cell. These first responders will respond to the emergency in addition to the responders that will come from outside of the cell. In this portion of our model, the capacity required in a cell increases linearly with population density from the baseline minimum value up to a threshold maximum value. The threshold value is the upper bound on the amount of capacity required in any cell. This bound is due to an expected limit on the number of first responders who could effectively participate in an emergency response effort that is localized within a cell. The value of this threshold capacity is discussed in section 3.

The second source of public safety traffic is routine traffic. We assume that routine traffic is the same whether or not a large-scale emergency is occurring. We propose that the routine capacity required in a cell varies linearly with population covered by the cell (which we calculate as the product of the population density in the cell and the size of the cell).

In addition to public safety traffic, any public-private partnership will need to accommodate traffic from commercial users. We assume that the system will be designed so that there is sufficient capacity to meet the expected needs of commercial users and routine public safety traffic when there is no large-scale emergency going on, and capacity is sufficient to meet the needs of public safety during large-scale emergencies. During a large-scale emergency, any capacity not needed by public safety will be available to commercial users, but there is no guarantee that there will be sufficient capacity to carry all their traffic. We assume that the commercial capacity required in a cell varies linearly with the population covered by the cell. We assume that the market penetration (i.e. the fraction of the population covered by a cell that subscribes to the service) is constant across the nation.

The figure below shows the relationship between the capacity required in a cell by commercial subscribers and routine traffic and the population covered by the cell.

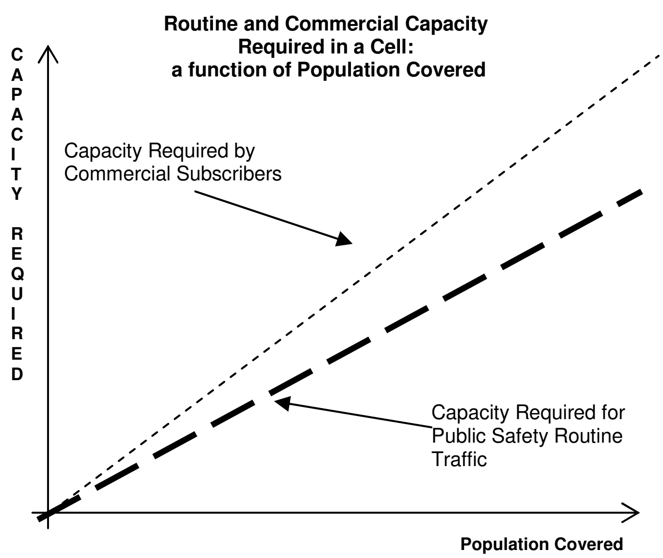

Figure 2.1b: A plot of the capacity required in a cell as a function of the population covered in that cell.

2.3 Receiver Sensitivity

In a wireless system, the strength of a signal decreases as it travels. If the signal is too weak when it reaches the receiver, the transmitter and receiver cannot sustain communications. This threshold is often called the receiver sensitivity, the exact value of which has a large impact on the size of the cell. More specifically, the receiver sensitivity in a wireless system is defined as the minimum acceptable signal level at the receiver which will support suitable operation at a given datarate.

In a CDMA system, the receiver sensitivity is dependent upon the instantaneous noise and interference environment (which is related to the capacity required) and the ratio of bit energy to noise that is required to achieve the transmit datarate desired by the user.

In link budget analysis, receiver sensitivity is often stated as a constant value independent of desired user datarate and the interference environment. This may be reasonable in some systems where capacity required is constant across cells and desired user datarate is constant. But this is not true in our model, so we derive the following equations for receiver sensitivity in a CDMA environment based on previous work by [42] [43].

Section 2.3.1 defines the minimum acceptable received signal power as a function of interference. Section 2.3.2 then determines the receiver sensitivity the system must be designed for and expresses the receiver sensitivity as a function of capacity required. Section 2.3.3 identifies how this receiver sensitivity relates to first responder density and population density.

2.3.1 Received Signal Power and Interference

The ability of the ith user to operate at a desired datarate is dependent on the strength of the transmitted signal when it is received at the basestation, the bit energy to noise ratio required for adequate operation at that datarate, and the noise and interference environment at the basestation. In a CDMA system, we can express the minimum acceptable received signal power, s_i, for the ith user to support the desired datarate, R_i, in the following form [42]:

$$s_i \equiv \left(\frac{E_b}{N_o}\right)_i \bullet \frac{R_i}{W} \bullet (\eta + I_{SC,i} + I_{OC,i}) \qquad (2.3\text{-}1)$$

Where:

s_i	= minimum acceptable received signal power of the ith user in the sector	(W)
W	= channel bandwidth	(Hz)
R_i	= datarate or information bit rate desired by the ith user in the sector[6]	(bps)
$(E_b/N_o)_i$	= bit energy to noise ratio required for operation at datarate R_i	
η	= environmental noise (predominantly thermal noise) power at the receiver	(W)
$I_{SC,i}$	= cochannel interference power to the ith user due to users from the same sector	(W)
$I_{OC,i}$	= cochannel interference power to the ith user due to users from other sectors	(W)

As discussed in section 2.1, the equation above assumes that the spectrum allocated is divided into channels of bandwidth W, with traffic distributed equally across these channels, and each cell divided up into equal sized sectors.

2.3.2 Receiver Sensitivity and Capacity

For network planning purposes, the receiver sensitivity of interest is that of the most demanding user in the sector. Since equation (2.3-1) gives the minimum acceptable received signal power,

[6] The ratio of W/R is often referred to as the processing gain.

s_i, in the sector for the ith user, we define the receiver sensitivity of a sector as the largest value of s_i in the sector.

Since we know the datarate desired by the most demanding user in the sector, the only unknowns in the receiver sensitivity equation are the interference terms, $I_{SC,i}$ and $I_{OC,i}$. In a CDMA system, there is a relationship between the total capacity required on the channel and the interference on the channel. An increase in capacity is due to either the number of users that operate on the channel increasing or the datarate of users on the channel increasing. In either case, the power transmitted on the channel and received at the basestation increases. Since it is a shared channel, a user considers all of the power received at the basestation due to other users as interference. Thus, the measure of capacity required also serves as a measure of interference.

In a public-safety-only system, we express same-sector interference, $I_{SC,i}$, as the sum of all the signals received per channel at the base station due to the two sources of public safety traffic[7]. Additionally, it is typical in a CDMA system to state the interference due to other sectors, $I_{OC,i}$, as a fraction of same sector interference, $I_{SC,i}$ [42]. However, we have designed for an emergency response that is localized within a cell, and we assume that all other cells are only carrying routine public safety traffic. Thus, $I_{OC,i}$, is assumed to be a fraction of interference due to routine traffic and we calculate the receiver sensitivity, s, as follows:

$$s \equiv \frac{\beta_{MAX} \bullet \eta}{1 - \left(\sum_{k=1}^{n} \beta_k + (1 + fract) \sum_{l=1}^{m} \beta_l \right)} \qquad (2.3\text{-}2)$$

Where:

$\beta_i \equiv \left(\left(\frac{E_b}{N_o} \right)_i \bullet \frac{R_i}{W} \right) \Big/ \left(1 + \left(\frac{E_b}{N_o} \right)_i \bullet \frac{R_i}{W} \right)$ and is a measure of the capacity that user i requires.

β_i increases with user i's need for greater data rates, and with the energy to noise ratio required to sustain any given data rate.

$\sum_{k=1}^{n} \beta_k$ Is the sum of the β_i terms for all n users that are responding to a localized emergency within a sector per channel. This term is a measure of the capacity required by the emergency response per channel in a sector.

$\sum_{l=1}^{m} \beta_l$ Is a measure of the capacity required by routine traffic per channel in a sector.

fract Is a fraction of interference due to routine traffic which represents the other sector interference.

β_{MAX} Is the largest β_i value of any active user.

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[7] A more detailed derivation is provided in Appendix B

In a similar manner as above, we derive the following equation for the receiver sensitivity of a user in a public-private partnership network:

$$s \equiv \frac{\beta_{MAX} \bullet \eta}{1-(1+fract)\left(\sum_{q=1}^{p}\beta_q + \sum_{l=1}^{m}\beta_l\right)} \qquad (2.3\text{-}3)$$

Where:

$\sum_{q=1}^{p}\beta_q$ Is a measure of the capacity required by commercial subscribers per channel in a sector.

As discussed in section 2.2, the capacity required by routine traffic is a function of first responders served and the capacity required by commercial subscribers is a function of population served; both of which vary by cell . Considering that the capacity required is distributed across the available channels in a sector, we define the following equations for the jth cell:

$$\sum_{k=1}^{n}\beta_k \equiv \beta_{SUM} / Num \qquad (2.3\text{-}4)$$

$$\sum_{l=1}^{m}\beta_l \equiv \left(A_{hexagon,j} / Sect\right) \bullet \rho_{FR,j} \bullet \rho_{\beta RT} / Num \qquad (2.3\text{-}5)$$

$$\sum_{q=1}^{p}\beta_q \equiv \left(A_{hexagon,j} / Sect\right) \bullet Pen \bullet \rho_{POP,j} \bullet \rho_{\beta SUB} / Num \qquad (2.3\text{-}6)$$

Where:

Num = the number of uplink channels available in the sector

β_{SUM} = the capacity required for the response to a localized emergency per sector

$A_{hexagon,j}$ = the area of the jth cell

$Sect$ = the number of sectors in the jth cell

$\rho_{FR,j}$ = the first responder density in the jth cell

$\rho_{\beta RT}$ = a measure of the capacity required per first responder due to routine traffic.

$\rho_{POP,j}$ = the population density in the jth cell

Pen = the market penetration of the provider as a fraction of population covered

$\rho_{\beta SUB}$ = a measure of the capacity required per commercial subscriber on the network.

As discussed in section 2.2, a public-private network will be designed such that the capacity is sufficient to meet expected needs of commercial users when there is no large-scale emergency, and such that the capacity is sufficient to meet the needs of public safety during large-scale emergencies. Thus, the receiver sensitivity in the jth cell becomes the larger of the following:

$$s_{PUBLIC\_SAFETY,j} \equiv \frac{\beta_{MAX} \bullet \eta}{1-\left(\beta_{SUM} / Num + (1+fract)\left(A_{hexagon,j} / Sect \bullet \rho_{FR,j} \bullet \rho_{\beta RT}\right) / Num\right)} \qquad (2.3\text{-}7)$$

$$s_{COMM,j} \equiv \frac{\beta_{MAX} \bullet \eta}{1-\left[\left(A_{hexagon,j} / Sect \bullet (1+fract)\right)\left(\left(Pen \bullet \rho_{\beta SUB} \bullet \rho_{Pop,j}\right)+\left(\rho_{FR,j} \bullet \rho_{\beta RT}\right)\right) / Num\right]} \quad (2.3\text{-}8)$$

2.4 Link Budget

In a wireless channel, a link budget can be used to account for all of the factors that increase or decrease the strength of a transmitted signal at the receiver. These increases are typically referred to as gains while the decreases are referred to as losses. These gains and losses can greatly impact the size of a cell. This section will identify and briefly discuss the gains and losses which should appear in a link budget appropriate for a wireless network while the actual numerical values of these terms appropriate for a public-safety-grade network are discussed in section 3.

For a public-safety-grade cellular system, the power received at a receiver, *S*, is equal to the initial transmit power of the signal, *EIRP*, plus the gain of the receiving antenna, G_{RX}, minus the summation of any losses, $\sum L$ in the channel (with all terms expressed in decibels or dB[8]).

$$S = EIRP + G_{RX} - \sum L \qquad \{\text{in dB}\} \qquad (2.4\text{-}1)$$

We can decompose the summation of losses into two main components *PL* and *LM*. *PL* represents the path loss, which is the distance (between transmitter and receiver) dependent component of loss due to the signal being attenuated as it propagates through space. Path loss is typically the largest loss in the link budget and will be studied in more detail in section 2.5 where an appropriate propagation model is discussed. *LM* represents all of the loss margins to account for distance-independent components of loss including the margins to ensure reliable coverage indoors and outdoors and miscellaneous margins to account for losses due to implementation issues like cabling and connector losses and scenario losses due to receiver orientation. The link budget used for this model is based on the related work in [5] [42] [50] [51] [52] and given by the following equation which has been solved for path loss, *PL*:

$$PL = EIRP + G_{RX} - L_{IMPLEMENT} - L_{SCENARIO} - L_{RELIABLE} - L_{BUILD} - S \qquad \{\text{in dB}\} \qquad (2.4\text{-}2)$$

Where:

EIRP	Effective Isotropic Radiated Power	(dBm)
S	Receiver Sensitivity	(dBm)
G_{RX}	Receiver Antenna Gain	(dBi)
$L_{IMPLEMENT}$	Receiver Implementation Losses	(dB)
$L_{RELIABLE}$	Shadowing + Fast Fading Margin	(dB)
L_{BUILD}	Building Penetration Margin	(dB)
$L_{SCENARIO}$	Scenario Loss Margin	(dB)

Expressing transmit power as EIRP in the link budget above is a common way of combining any gains or losses internal to the transmitter, such as transmitter antenna gain, with the power with which signals are transmitted. Since the transmitting antenna gain is included in this term, the

[8] X in dB = $10*\log_{10}(X)$ in absolute units

only gain above is that of the receiving antenna. The receiving antenna gain is a measure of how effectively the antenna captures more power in certain directions than in others.

The reliability margin determines how reliable communications are within the outdoor coverage area of the cell. This margin is necessary to account for a signal being shadowed by an obstruction in the path from transmitter to receiver. Additionally, this margin accounts for the possible fast fading of a signal due to multipath effects wherein a signal interferes destructively with itself as it takes multiple paths to the receiver. Similarly, the building margin determines how reliable communications are within indoor environments. This margin is necessary to account for a signal being attenuated as it penetrates building walls.

The implementation margin includes any losses due to the signal being attenuated as it travels through cabling between the receiving antenna and basestation. This margin also includes any losses due to mismatches and connectors at the basestation. The scenario margin estimates losses due to receiver orientation and polarization mismatches as well as signal obstruction due to the body of the user.

2.5 Propagation Model

Path loss is the reduction in strength of a wireless signal as it travels through space. Path loss depends on many factors including frequency, antenna height, terminal location relative to obstacles and reflectors, and link distance, among other factors. Most importantly, it is this dependence on link distance that has a considerable effect on the size of a cell. This section presents the propagation model that will be used to relate path loss to cell radius while the actual numerical values used in the model are discussed in section 3.

A propagation model is typically used when estimating the median path loss in a wireless network. For this paper, the Hata propagation model [53], a model based on Okumura's empirical measurements of path loss [54], was chosen as it is arguably the most commonly used model in the wireless industry for large-scale network planning. This model makes relatively accurate predictions while requiring only minimal environment specific information [5] [43]. While propagation models exist [55] [56] that are more precise at predicting the path loss between a specific transmitter-receiver pair by taking into account location-specific factors which affect a radio signal our goal is not to determine the cell size for a specific location. Rather, our work is interested in the size of a cell averaged over many similar locations and the Hata model is sufficient since it is assumed that the location-specific deviations will tend to average out.

The equations used in the Hata model are different for urban, suburban, or rural regions. This classification is commonly made based on population density [57]. There is no universally accepted population density threshold which separates these categories. The dividing line between rural and urban varies from fewer than 50 to 400 people per square kilometer and the dividing line between suburban and urban varies from fewer than 1,000 to 10,000 people per square kilometer [37] [33] [57] [58]. We have defined rural as having less than 100 people per square kilometer and urban as having more than 1900 people per square kilometer as these values are inline with the values used in similar analysis [57].

The Hata model, given in the following equation [5], predicts median path loss (PL) based upon the frequency of the wireless signal (f), the height of the base station (h_b), the height of the mobile radio (h_m), and the distance of separation between the transmitter and receiver (r):

$$PL = 69.55 + 26.16 \bullet \log_{10}(f) - 13.82 \bullet \log_{10}(h_b) - a(h_m) + (44.9 - 6.55 \bullet \log_{10}(h_b)) \bullet \log_{10}(r) - K \qquad (2.5\text{-}1)$$

Where:

Mobile Adjustment: $a(h_m) = (1.1 \bullet \log_{10}(f) - 0.7) \bullet h_m - (1.56 \bullet \log_{10}(f) - 0.8)$

Urban Adjustment: $K = \begin{cases} 4.78 \bullet (\log_{10}(f))^2 - 18.33 \bullet \log_{10}(f) + 40.94\,; & \text{Rural} \\ 2 \bullet (\log_{10}(f/28))^2 + 5.4\,; & \text{Suburban} \\ 0; & \text{Urban} \end{cases}$

This model is valid for the following ranges of input values:

Path Loss:	PL	in dB
Frequency:	f	= 150 – 1500 MHz
Radius:	r	= 1 – 20 km
Mobile Height:	h_m	= 1 – 10 m
Base Height:	h_b	= 20 – 200 m

2.6 Solving the System of Equations

From the equations established in the previous three sections, it is possible to predict the average radius of a cell in each region. Plugging the expression for receiver sensitivity, equation (2.3-9), and propagation loss, equation (2.5-1), into the link budget developed in section 2.4 yields:

$$K_5 \bullet \log_{10}(r) + 10 \bullet \log_{10}\left(\frac{K_1}{1-(K_2+K_3)}\right) = K_0 - K_4 + K \qquad \{\text{in dB}\} \qquad (2.6\text{-}1)$$

Where:

$$K_0 = EIRP + G_{RX} - L_{RELIABLE} - L_{BUILD} - L_{IMPLEMENT} - L_{SCENARIO}$$

$$K_1 = \beta_{MAX} \times \eta$$

$$K_2 = \begin{cases} \beta_{SUM} / Num & \text{for Emergency Traffic} \\ \left(A_{hexagon,j} / Sect \bullet (1+fract)\right)\left(Pen \bullet \rho_{\beta SUB} \bullet \rho_{Pop,j}\right) / Num & \text{for Commercial Traffic} \end{cases}$$

$$K_3 = (1+fract)\left(A_{hexagon,j} / Sect \bullet \rho_{FR,j} \bullet \rho_{\beta \mathrm{RT}}\right) / Num$$

$$K_4 = 69.55 + 26.16 \bullet \log_{10}(f) - 13.82 \bullet \log_{10}(h_b) - a(h_m)$$

$$K_5 = (44.9 - 6.55 \bullet \log_{10}(h_b))$$

$$K = \begin{cases} 4.78 \bullet (\log_{10}(f))^2 - 18.33 \bullet \log_{10}(f) + 40.94 & \text{Rural} \\ 2 \bullet (\log_{10}(f/28))^2 + 5.4 & \text{Suburban} \\ 0 & \text{Urban} \end{cases}$$

From equation (2.6-1), it can be observed that the radius of a cell is dependent only on the frequency of operation, height of the base station, effective isotropic transmitted signal power, receiving antenna gain, implementation and scenario losses, shadowing and fading margins, building penetration margins, as well as the datarate and required bit energy to noise ratio for the most demanding user in a cell in addition to the required capacity and bit energy to noise ratio for all active users in a cell. In section 3, the appropriate values for each of these parameters will be determined and discussed in more detail.

3 Model Inputs

In section 2, we presented the equations that our model is based on and each of these equations is dependent on several variables. This section will identify the proper numerical values which should be used when evaluating these equations for a public-safety-grade wireless network. For many of the inputs studied, there is considerable uncertainty in the numerical value they should take. For these uncertain inputs, we present base case estimates which are then varied in section 6. Given the range of values that may be appropriate, the values chosen in the base case and the results they produce are not meant to be the final word on this topic. Instead, we present the base case values to enable exploration of the proposals presented in section 1 but future work will include additional analysis.

Section 3.1 presents the input values for the equation of receiver sensitivity presented in section 2.3. This includes a regression model to relate population density to first responder density, base case values for the various measures of capacity discussed, and estimates of noise in the channel. Section 3.2 discusses the values to be used in the link budget presented in section 2.4 which includes values for transmitter power and receiver antenna gain as well as the several losses present in the channel. Finally, section 3.3 considers the values used in the Hata propagation model which was described in section 2.5 and includes a discussion of mobile height and basestation antenna height.

3.1 Receiver Sensitivity Inputs

In section 2.3, the expressions for receiver sensitivity in both public safety and public-private partnership networks are given as equation (2.3-7) and (2.3-8). These expressions are dependent on the density of users in the cell, the capacity required by users in the cell and the noise environment in the cell. In section 3.1.1, we present a regression model that relates population density to first responder density. In sections 3.1.2 and 3.1.3, we present estimates of the several measures of capacity required to calculate the receiver sensitivity for public safety and commercial users respectively. In section 3.1.4, we present an estimate of other sector interference as a fraction of same sector interference. Finally in section 3.1.5, we present a model of noise power at the receiver.

3.1.1 Regression Model: Population Density vs. Density of First Responders

In section 2.2 we presented a model of capacity demanded in a cell that is a function of the density of first responders in a cell. However, the zip code level dataset used in our analysis only provides population density statistics. This section describes the regression model we developed to relate population density to density of first responders.

Our regression analysis shows that the number of first responders per area is roughly proportional to population density. The following three equations represent the linear equations that best fit a Metropolitan Statistical Area (MSA)'s population density, $\rho_{Population}$, versus that MSA's police density, ρ_{Police}, firefighter density, ρ_{Fire}, and emergency medical personnel (EMS) density, ρ_{EMS}, respectively, based on 2005 employment [59], [60], [61] and census [62] data. Equations (3.1-1), (3.1-2), and (3.1-3) have R^2 values of 0.85, 0.62 and 0.76 respectively, suggesting that they all fit the data reasonably well. Additionally, each of the parameter estimates is statistically significant as summarized in Appendix C.

$$\rho_{Police} = 0.0024\rho_{Population} - 0.032 \quad (3.1\text{-}1)$$

$$\rho_{Fire} = 0.00081\rho_{Population} + 0.022 \quad (3.1\text{-}2)$$

$$\rho_{EMS} = 0.00052\rho_{Population} + 0.019 \quad (3.1\text{-}3)$$

Additionally, we consider federal public safety users on the network by defining the following equation to calculate the total first responder density, ρ_{FR}, in an area:

$$\rho_{FR} = (1 + fed)(\rho_{Police} + \rho_{Fire} + \rho_{EMS}) \quad (3.1\text{-}4)$$

Where:

fed = is the percentage of all public safety users in the response to a large-scale emergency that work for a federal agency

We chose a value of 8% for *fed* which appears reasonable given that there are about 80,000 federal public safety personnel [22] as compared to the 1.1 million first responders in the US [4].

3.1.2 Public Safety Capacity

As discussed in section 2, we have designed the network to accommodate the capacity required by public safety when responding to a large-scale emergency. This public safety traffic determines the value of β_{SUM}, β_{MAX}, and $\rho_{\beta RT}$ used in the calculation of receiver sensitivity in section 2. The value of β_{SUM} is determined by the traffic from public safety personnel who are responding to a large-scale emergency. The capacity required by the user who operates at the highest datarate determines the value of β_{MAX}. The capacity required to support routine traffic determines the value of $\rho_{\beta RT}$.

We consider three traffic scenarios for public safety, wherein the nationwide network carries: 1. (Voice-Only) all public safety voice traffic and nothing else, 2. (Data-Only) all public safety data traffic, and no voice traffic, or 3. (Data and Voice) all public safety traffic including voice and data. The data-only scenario would be appropriate if public safety agencies continue to rely on their existing systems, while the voice and data scenario would (eventually) allow public safety to phase out their existing systems. Numeric values for β_{SUM}, β_{MAX}, and $\rho_{\beta RT}$ must be estimated for each of these three traffic scenarios. None of these values are well known and we therefore consider a wide range of uncertainty in the estimates for each of the capacity parameters in our analysis.

In section 3.1.2.1 we estimate the numeric values for β_{SUM}, β_{MAX}, and $\rho_{\beta RT}$ in the Data-Only traffic scenario. In section 3.1.2.2 we estimate the numeric values for β_{SUM}, β_{MAX}, and $\rho_{\beta RT}$ in the Voice-Only traffic scenario. Section 3.1.2.3 estimates the numeric values for β_{SUM}, β_{MAX}, and $\rho_{\beta RT}$ in the Data and Voice traffic scenario.

3.1.2.1 β_{MAX}, β_{SUM}, and $\rho_{\beta RT}$: Data-Only

First responder usage of broadband systems is not well understood and previous work has focused on estimating the capacity necessary for an emergency response to hypothetical emergency scenarios (i.e. building fires, train accidents, terrorist attacks, etc.) [45] [46] [63] [64] with only limited information available about traffic on existing networks [65].

As a base case estimate, we assume that the worst-case scenario for data traffic is the hypothetical scenario considered by the Spectrum Coalition [45]. They considered a large-scale emergency in Washington D.C. with an emergency response that included federal, state, and local public safety personnel using video and other data applications to monitor and coordinate the response to a biological and chemical terrorist attack.

This work concluded that the following data communications must be supported in the uplink of the busiest sector in the network: two-way video, mapping/location tracking, sensor information, web access, email access. For this scenario, the applications used, estimates for the peak number of active users that use each application, the fraction of these users that are communicating at the same time, and the datarate each of these applications require are summarized in the table below. In this paper, we make no judgment on the accuracy of the numbers presented by the Spectrum Coalition. We chose to use these values because the Spectrum Coalition work is among the most detailed work to date on the data capacity requirements of public safety. Further research and discussion on these numbers is required.

Application	Required Datarate [kbps]	# of Users	Fraction of Users Active	Active Users	Capacity Required [kbps]
Sensors	12	28	0.04	1.1	13
Video	360	240	0.01	2.4	865
Location	6	28	0.05	1.4	8
Web	6	170	0.05	8.5	51
Email	60	170	0.05	8.5	510

Table 3.1: A summary of factors considered by the Spectrum Coalition in their estimate of the capacity required during the response to a large-scale emergency in the busiest sector of the network [45].

Using the capacity values from this table and the corresponding value of required bit energy to noise ratios in a CDMA system [42] [66] we calculate the β_{SUM} and β_{MAX} values as 1.6 and 0.34 respectively based on the equations given in section 2.3.

For routine traffic in the base case, we assume the mean amount of data uploaded per first responder per hour worked $N_{Up\_MB/HourWorked}$ = 2 MB. Because usage varies considerably from one hour to the next, we assume that busy period traffic rate is K times the mean traffic rate. A value of K= 4 would be appropriate if busy periods occurred 20% of the time, and carried 80% of the traffic, and if all of the busy periods were roughly the same. Thus, by the equation below, TP_{DATA_RT} = 4.2 kbps/first responder and $\rho_{\beta RT}$ = 5.2E-3 per first responder.

$$TP_{DATA\_RT} = K \bullet \left(N_{Up\_MB/HourWorked} \bullet 40_{HoursWorked/Week}\right) / \left(168_{Hours/Week} \bullet 3600_{Sec/Hour}\right) \bullet 8_{bits/Byte}$$

3.1.2.2 β_{MAX}, β_{SUM}, and $\rho_{\beta RT}$: Voice-Only

In the base case, we assume that in the worst-case Voice-Only scenario, the same number of responders that were predicted to respond to the emergency in the Data-Only scenario would be present. These responders use only voice communications, and at the busiest time, 5% are active. This means that there 32 voice streams active simultaneously in the worst-case and we calculate the β_{SUM} and β_{MAX} values as 0.94 and 0.03 respectively.

For routine traffic in the base case, we assume the mean percentage of time that a first responder spends talking while on duty $S_{\%Talking}$ = 1%. Because usage varies considerably from one hour to the next, we assume that busy period traffic rate is K times the mean traffic rate, as we assumed with data traffic. A value of K= 4 would be appropriate if busy periods occurred 20% of the time, and carried 80% of the traffic, and if all of the busy periods were roughly the same. Thus, by the equation below, TP_{VOICE_RT} = 0.1 kbps/first responder and $\rho_{\beta RT}$ = 2.8E-4 per first responder.

$$TP_{VOICE\_RT} = K \bullet \left(S_{\%Talking} \bullet 40_{HoursWorked/Week} \bullet 9.6_{kbps}\right) / \left(168_{Hours/Week}\right)$$

3.1.2.3 β_{MAX}, β_{SUM}, and $\rho_{\beta RT}$: Data and Voice

When both data and voice traffic are supported on the network, we have designed for the possibility that peak hour for data coincides with peak hour for voice. Thus the Data and Voice capacity required is equal to the capacity required when only data traffic is carried plus the capacity required when only voice traffic is carried. The value of β_{SUM} for Voice and Data is the sum of its value in the Data-Only and Voice-Only cases which is 2.5 in the base case. Similarly the value of $\rho_{\beta RT}$ in the Voice and Data case is equal to the sum of its value in the Data-Only and Voice-Only cases which is 5.5E-3 in the base case. Meanwhile, the value of β_{MAX} in the Voice and Data case is equal to the larger of the two values for β_{MAX} in the Voice-Only and Data-Only cases which is 0.34 in the base case.

3.1.3 Commercial Capacity

In addition to public safety traffic, a public-private partnership will need to accommodate traffic from commercial users. The system will be designed so that there is sufficient capacity to meet the expected needs of commercial users when there is no large-scale emergency going on, and capacity is sufficient to meet the needs of public safety during large-scale emergencies. The fraction of population covered that subscribes to the commercial service determines the value of Pen. The capacity required to support commercial subscribers on the network determines the value of $\rho_{\beta SUB}$.

For commercial traffic in the base case, we assume the mean amount of data uploaded per commercial subscriber per month $N_{Up\_MB/Month}$ = 200 MB. This value appears reasonable considering the average commercial cellular subscriber talks about 800 minutes each month (which is approximately 50MB) and the usage of wireless data is increasing rapidly [67] [68]. Several major wireless providers have capped usage per subscriber at 5 GB per month [69] [70] [71], so we have assumed mean usage per subscriber is well under these caps. Because usage varies considerably from one hour to the next, we assume that busy period traffic rate is K times the mean traffic rate. A value of K= 4 would be appropriate if busy periods occurred 20% of the time, and carried 80% of the traffic, and if all of the busy periods were roughly the same. Thus, by the equation below, TP_{SUB} = 2.4 kbps/subscriber and $\rho_{\beta SUB}$ = 2.9E-3 per subscriber. There is considerable uncertainty in this value and a large range of values are considered in section 6.

$$TP_{SUB} = K \bullet \left(N_{Up\_MB/Month} \bullet 8_{bits/Byte}\right) / \left(720_{hours/month} \bullet 3600_{\sec/hour}\right)$$

The commercial capacity is a function of the number of subscribers on the network in addition to the capacity required per subscriber. We have defined *Pen* as the market penetration of the commercial provider as a fraction of population covered by the network. Existing nationwide wireless service providers have voice market penetrations of roughly 5% – 25% [67]. In the base case, we design the network so that it can support 10% of the population covered as subscribers (*Pen* = 10%). As with the rest of the capacity inputs, a range of values for *Pen* are studied in section 6.

3.1.4 *fract*: Other Cell Interference as a Fraction of Same Cell Interference

In a CDMA system, the amount of cochannel interference present at a basestation due to other cells in the system is typically treated as a fraction, *fract*, of the cochannel interference due to users in the same cell. The value of *fract* has been studied extensively for commercial systems and values tend to range from 0.5 – 0.7 and we have chosen a value of 0.6 in the base case [42].

3.1.5 Noise

The noise power present at a receiver can have a significant impact on the receiver sensitivity. Since environmental noise power can depend on the frequency of operation, to ensure an extensible model that can be used to study proposals in a variety of frequency bands, we present two equations for noise: one valid at frequencies above 400MHz and one valid at frequencies below 400MHz.

At frequencies above 400MHz, the dominant environmental noise is thermal [72] and we calculate total noise power using the following equation [73]:

$$N_{TOT} = N_P + N_F = 10 \bullet \log_{10}(kTW) + N_F \qquad \{\text{in dB}\}$$

Where:

N_F	= the noise figure of the receiver	(dB)
N_P	= the thermal noise power	(dBm)
k	= Boltzmann's constant	(1.38E-23 J/K)
T	= the temperature at the receiver	(K)
W	= the bandwidth of the received signal	(Hz)

Below 400MHz, the equation for environmental noise power is modified to include an adjustment factor as shown below [72]:

$$N_{TOT} = 10\log_{10}(kTW) + 52 - 29.5 \bullet \log_{10}(f_{MHz}) - K_{adj} + N_F$$

Where:

f_{MHz} = the frequency of the signal (MHz)

K_{adj} = is a constant: 15dB for rural areas, 18 dB for suburban and 25 dB for urban.

It is standard to assume a fixed value equal to room temperature for all receivers (290K) [73]. We use a 1.25MHz channel width which is appropriate for the CDMA system we have considered. Values for noise figures for a base station are typically in the range of 3 – 8 dB and we use a value of 4dB in the base case [42] [50] [74].

3.2 Link Budget Inputs

As defined in section 2.3, a link budget can be used to account for all of the gains and losses present in a wireless channel. Sections 3.2.1 – 3.2.5 will identify numerical values for each of the following gains and losses, respectively: transmit power, antenna gain, loss margins for coverage reliability and in-building coverage, and implementation and scenario losses appropriate for a public-safety-grade system.

3.2.1 Transmit Power

We have chosen to define the transmit power in terms of EIRP. EIRP represents the effective power radiated from the transmitter which means that any losses internal to the transmitter (e.g. due to cabling) and gains from the transmitter antenna are all included in this term.

We have chosen a maximum transmit power equal to the power limit currently imposed on the 700MHz band in the US by the FCC. In the downlink this limit is 1kW ERP (62.15 dBm EIRP) in urban areas and 2kW ERP (65.15 dBm EIRP) in rural areas [75]. In the uplink, the power limit is 30W ERP (46.9 dBm EIRP) for mobile devices and 3W ERP (36.9 dBm EIRP) for portable devices [76]. These power limits are likely comparable to the transmit powers used in systems in the 168MHz and 414MHz federal bands as well.

Since FCC-regulated power limits are stricter in the uplink than in the downlink, cell radius is typically determined based on upstream communications (the downlink has a 30 dB transmit power advantage over portable devices operating on the uplink). While it is possible that users' devices would operate at lower power (e.g. to save battery power), there is no technical reason a new network cannot be designed for devices that operate at the band power limit. We assume in the base case for all proposals that public safety equipment will adopt a value of EIRP equal to the max allowed in the uplink: 37 dBm. By comparison, a typical commercial handset transmits at about 24dBm. In the public-private partnership, commercial handsets may be designed to transmit at a lower power than 37 dBm, thereby choosing to accept a signal reliability that is below what public safety would require, but gaining the advantages of longer battery life and/or smaller and lighter mobile devices. Such a decision would not change the cost of the infrastructure, and therefore falls outside the scope of our model. However, if the devices used by public safety operated at lower power, as some analysts have assumed [57], this would have a significant impact on infrastructure cost. This effect will be examined in section 6.

3.2.2 Antenna Gain

Since we are only considering the uplink, the antenna gain of interest is that of the base station. Antenna gains at the basestation are usually the most significant gains on a radio link and result from capturing more power in certain directions than in others. In our analysis, we assume a standard, 3-sector cell, which typically use panel antennas that range from 9 – 18 dB in gain [42] [44] [50] [51] [52]. In the base case, we chose a value of 18dB for antenna gain. There may be factors such as antenna cost and weight which could lead to an antenna with lower gain being selected; however, these considerations are outside the scope of this paper. Since planning a network with reduced antenna gain can have a significant impact on the number of cell sites required, we examine a range of values in section 6.

3.2.3 Coverage Reliability Margins

The strength of a signal at any location within a cell is uncertain due to shadowing of the signal by obstructions in the path from transmitter to receiver or fast fading of the signal due to multipath effects in the channel. To account for this uncertainty, loss margins are included in the link budget to ensure sufficient signal power is available throughout the coverage area. Increasing this margin increases the reliability of communications within the coverage area of the cell but reduces the cell's size. Therefore, there is a tradeoff between the reliability of communications and the overall cost of the wireless network. Communications reliability in wireless system planning is typically expressed as either a coverage reliability or cell-edge signal reliability. Coverage reliability is defined as the probability that received signal power will be sufficient at any point within the outdoor coverage area of a cell. Cell-edge signal reliability is defined as the probability that received signal power will be sufficient at any point along the outdoor, cell-edge contour.

The FCC left the details of coverage reliability requirements in the public-private partnership to later actions; only giving the guideline that the system be designed consistent with typical public safety communication systems [27] [32]. The public safety licensee, the PSST, has suggested that the system should be designed for 95% coverage reliability [33]. However, best practices in the industry recommend that a public safety system should be built to 97% coverage reliability [72]. We designed the system for 97% coverage reliability in the base case as appropriate for a public-safety-grade system.

Expressing a value of coverage area reliability in a cell as a cell-edge signal reliability makes the calculation of the appropriate margin easier. We have used the method presented in [72] to convert the 97% coverage area reliability value to a value of 89% cell-edge signal reliability. The equation to calculate the reliability margin given a cell-edge signal reliability is provided in [50]. This equation depends on the value chosen for the standard deviation of shadowing, σ_L, which typically ranges from 4 – 8dB [50] [72] [77] [78]. We have used a value of $\sigma_L = 5.6$dB as recommended in [72] which yields a margin for 97% coverage reliability of 12.6 dB. In contrast, 95% coverage reliability requires only 83% cell-edge signal reliability and a margin of 10.3 dB.

3.2.4 In-Building Coverage Margin

The coverage reliability margins included in the link budget will ensure a level of outdoor coverage reliability as discussed in section 3.2.3. However, users who wish to communicate within buildings will experience unreliable service due to the attenuation of signals having to penetrate building walls. While it still may be possible to communicate from within buildings that are near the base station, communications from indoors near the cell edge could be highly unreliable. To account for this, a building penetration margin is included in the link budget. This margin is dependent upon the type of material used to construct the walls of the buildings in which users want to operate. Similar to the coverage reliability margin, there is a tradeoff between the reliability of communications indoors and the overall cost of the wireless network.

The FCC left the determination of in-building margins in the public-private partnership to future actions. However the PSST proposed[9] that the in-building margin be dependent upon the type of environment being served. In the PSST's proposal, the in-building penetration margin is the same for areas classified as rural as it is for open highways: 6 dB [33]. As discussed in a submission to the FCC [32], a 6 dB margin should be sufficient for reliable service in a vehicle, but is likely to be insufficient to penetrate the walls of many buildings. By the PSST's assumptions, 92.3% of the area served is classified as rural and as such, much of the coverage area of the US could have inadequate in-door coverage in many buildings.

We chose a margin of 13 dB for all classifications of area (i.e. rural, suburban, and urban) in the base case. This margin should be sufficient for reliable signal penetration of a single-walled - concrete building[10] [5] [79]. However, this level of margin is still not sufficient for reliable penetration through many types of structures. Since this design choice can significantly impact the number of cell sites required, a range of values is considered in section 6.

3.2.5 Implementation and Scenario Losses

The implementation loss margin includes any losses due to the signal being attenuated as it travels through cabling between the receiving antenna and basestation as well as any losses due to mismatches and connections at the basestation. Typical values for implementation losses at a cellular base station range from 2 – 5 dB and we have chosen a value of 4dB in the base case [42] [44] [50] [51] [52].

The scenario loss margin estimates losses due to receiver orientation and polarization mismatches as well as signal obstruction due to the body of the user. Typical values for scenario losses range from 2 – 5 dB and we have chosen a value of 4dB in the base case [42] [44] [50] [51] [52].

3.3 Propagation Model Inputs

As discussed in section 2.5, the path loss predicted by the Hata model depends on frequency, base station antenna height, mobile device height, and cell radius. Sections 3.3.1 and 3.3.2 present the appropriate values of mobile device and base station antenna height, respectively.

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[9] [33] §2.4.3 (4.) specifies the following building penetration margins depending on the area covered:
Dense Urban = 22 dB; Urban = 19 dB; Suburban = 13 dB; Rural = 6 dB; Highway = 6 dB

[10] Appendix D includes a table which summarizes the empirical results of building penetration loss measurements for a variety of materials.

Section 5 will discuss frequency as it is dependent on the proposal being studied while the model we developed in section 2 solves for the remaining variables: radius and path loss.

3.3.1 Mobile Device Height

The mobile device height is the height at which users hold the handset while operating the device. The value for mobile device height used in analysis of cellular networks typically ranges from 1 – 2 meters and in the base case we chose the most common used value of 1.5m [78].

3.3.2 Base Station Antenna Height

We assumed that tower height in a new system would be comparable to tower heights available today, in part because many antennas are likely to be placed on existing towers. Thus, we analyzed the commercial tower heights for a major US tower company: American Towers. This company operates approximately 23 thousand towers across 49 states in the US. Our analysis of the company's tower portfolio [80] revealed that the mean tower height is approximately 60 meters. We therefore assume a basestation antenna height of 60 meters in the base case.

4 Build-out Requirements for a Nationwide Wireless Network

In section 4.1, we first introduce the concept of a build-out requirement for a nationwide wireless network (i.e. what fraction of the US must be covered by the system) and then present a method of translating between fraction of area covered and fraction of population covered. In section 4.2, we discuss the build-out requirements that were included in the network proposals highlighted in section 1. Section 4.3 concludes with a geographic information system (GIS) model of the area covered by existing public safety wireless systems.

4.1 Fraction of Area vs. Fraction of Population

A build-out requirement can be expressed either as a fraction of the US geographic area that is covered by the system or as a fraction of the US population covered. Requirements expressed as a fraction of population covered will be considered to mean the fraction of population whose homes are covered by the system. (This implicitly imposes no requirements to serve highways, health care facilities, and other places that are not residences.) Our analysis of the number of cell sites required in a network calls for the build-out requirement to be expressed as a fraction of US area covered, where the regions that are not covered are those with the lowest population density. Thus, to support comparisons of results based on build-out requirements expressed in different ways, we must be able to convert a fraction of US population covered to a fraction of US geographic area covered.

If population were uniformly distributed across the US, there would be a straightforward linear relationship between the fraction of area covered and the fraction of population covered; however, that is not the case and it is unclear how to best relate these two fractions. We propose the following method for converting between the two fractions based on analysis of Census Bureau population and area statistics at the zip code and county level. The following table shows the fraction of total population contained in all zip codes/counties for which population density is greater than X and the fraction of total area contained in these zip codes/counties. Inherent in this analysis is the assumption that all zip codes/counties with a population density greater than X will be completely covered and that no area in any zip code/county with population density less than X will be covered. It is possible that in an actual deployment, depending on how the boundaries of zip codes/counties are drawn, that all population in the area could be covered without covering all of the area.

	County Level		ZCTA Level	
%POP	%CONUS AREA	%US AREA	%CONUS AREA	%US AREA
50%	3.5%	3.0%	1.4%	1.2%
75%	13.1%	11.0%	7.1%	5.9%
90%	31.3%	26.5%	21.5%	18.0%
95%	44.3%	37.6%	33.1%	27.8%
96%	48.0%	40.8%	36.6%	30.9%
97%	52.6%	44.7%	41.0%	34.5%
98%	58.7%	50.1%	46.7%	39.4%
99%	68.6%	58.7%	55.3%	46.8%
99.3%	73.0%	62.9%	59.4%	50.3%
99.5%	77.1%	66.8%	63.1%	53.6%
99.9%	90.9%	80.0%	76.6%	65.6%
99.99%	98.0%	91.4%	87.9%	76.3%

Table 4.1: A summary of the conversion from population to area build-out requirements. For various percentages of population coverage, the percentage of area (CONUS and US) that would need to be covered is given.

This table shows that a majority of population is concentrated in a small amount of the area while a large amount of the US contains little population. Considering both zip code and county level results, covering the last 1% of population requires covering an additional 41% to 53% of US area. By comparison, covering the second to last 1% of population (going from 98% to 99%) requires covering an additional 7% to 9% of US area depending on dataset considered.

The granularity of data used (zip code level vs. county level) significantly impacts the conversion from fraction of population covered to fraction of area covered. This illustrates the uncertainty in how much of the area will be covered when build-out requirements are specified as a fraction of population. This uncertainty stems from the fact that the actual area covered depends on the placement and size of the cells used, which policymakers will not know before the network is deployed. Depending on how policymakers estimate the fraction of area that will be covered when a population build-out requirement is established, the wireless provider could meet the population coverage obligation while covering less area than anticipated by policymakers. As will be shown in section 6, the number of cell sites required in a system covering the US is closer to the number of zip codes in the US than to the number of counties so we conjecture that conversions based on zip code level data are likely to be more accurate than based on county level data.

4.2 Build-out Requirements in Existing Proposals

When the FCC established the public-private partnership in the 700MHz band, they specified a similar build-out requirement such that after 10 years 99.3% of the population must be covered [27]. Based on the FCC established build-out requirements, the PSST (i.e. the public safety licensee) generated the following map which estimates the area that would be covered and shows that the commercial partner is not expected to cover a third of the US with the new system [81].

Their analysis predicted that to cover 99.3% of the population it would be necessary to cover 73% percent of the geographic area of CONUS or about 63% of the entire US. Comparing these conversions to the results in section 4.1, it appears the PSST's estimates are consistent with using county level data to predict coverage area from population build-out requirements. As discussed in section 4.1, we believe that performing the conversion in this manner instead of using zip code level data will overestimate the actual area that will be covered by a wireless system. We believe the actual area that will be covered by a wireless system that covers 99.3% of population is closer to 59% of CONUS area (50% of US area).

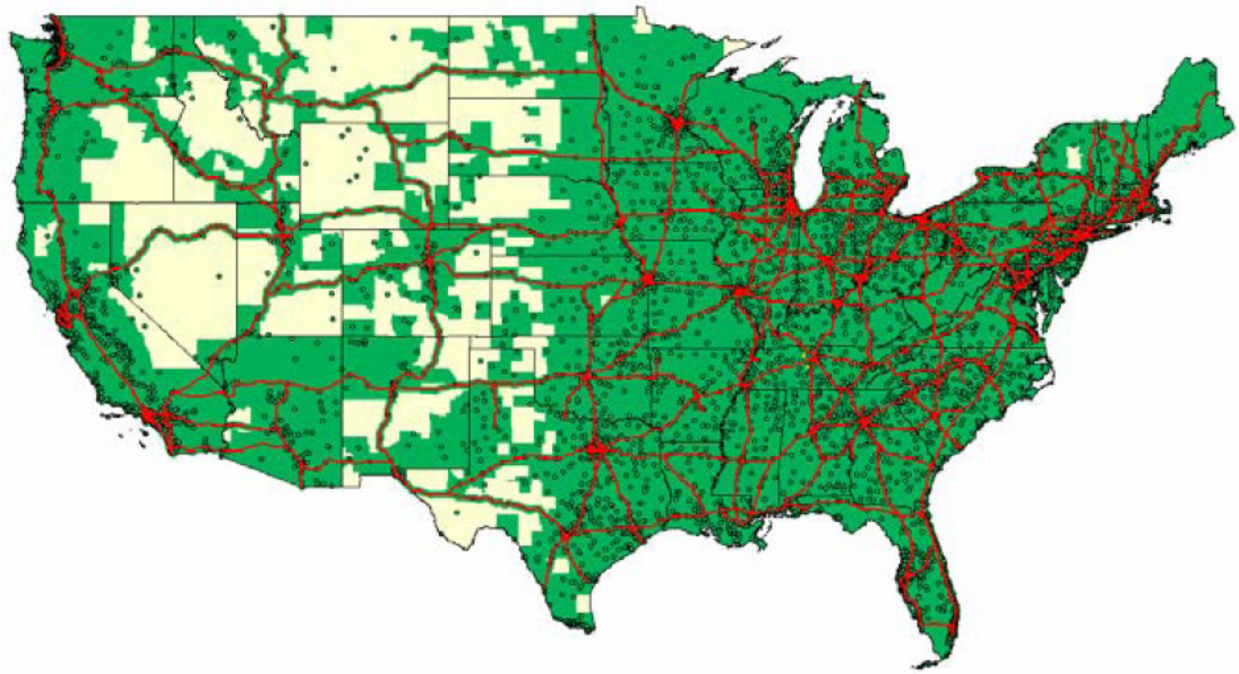

Figure 4.1: A map of CONUS showing the area (in green) that the PSST estimates will have terrestrial coverage from a public-private partnership system that covers 99.3% of population. Source of figure: [81].

4.3 GIS Model of Existing Public Safety Wireless Systems

This section presents an analysis of existing public safety wireless infrastructure which accomplishes two goals: (1) determines how many towers the existing infrastructure requires, enabling comparisons with a new nationwide network to understand potential cost savings, and (2) determines how much of the country is currently covered by the existing infrastructure enabling comparisons of coverage of a new nationwide system with the coverage of today's many systems. Based on previous research [1], we expect to see that a nationwide system would require fewer tower sites than the existing infrastructure deployed by many independent agencies required.

In section 4.3.1, the dataset of transmitter sites used in this analysis is discussed. Section 4.3.2 presents the method used to calculate the coverage area of each transmitter. Section 4.3.3 contains the results of this analysis and a brief discussion.

4.3.1 Dataset of Transmitter Sites

The source dataset for this project was the Private Land Mobile Radio (PLMR) database. This data was obtained February 2008 from the Universal Licensing System (ULS) database maintained by the FCC [82]. The PLMR database contains license details for more than just public safety agencies and therefore we filtered the dataset by Radio Service Code (RSC) to ensure only public safety agencies were included in the analysis[11].

The latitude and longitude coordinates for each transmitter site were extracted along with the frequency of operation, base station antenna height, base station antenna gain, and line losses. For a negligible number of sites, either the latitude/longitude or frequency fields were empty; in this case these records were dropped from the dataset. Similarly, for a small number of records, base station antenna height, base station antenna gain or line losses were incomplete; in this case the field at issue was set to the average value for the dataset.

After filtering, 136,322 records remain as public safety LMR transmitter sites. It is possible that more than one record corresponds to the same tower given that a tower can be shared by several agencies. We calculate the number of unique tower sites by filtering by geographic coordinates and eliminating any duplicate latitude/longitude pairs in the dataset. However, the resolution in the geographic coordinates is such that duplicate coordinates may not necessarily correspond to a single tower but rather two towers sited very near each other. Thus our analysis provides the following bounds on the existing public safety infrastructure:

Upper Bound:	136,322	[Towers]
Lower Bound:	97,660	[Towers]

4.3.2 Link Budget and Propagation Model

Due to the greater power available on the downlink, we have assumed that the uplink will be the limiting case in two-way voice communication for public safety. Thus, similar to the link budget given in section 2, the following is the link budget used for the existing public safety narrowband voice systems:

$$PL = EIRP + G_{RX} - L_{IMPLEMENT} - L_{RELIABLE} - L_{BUILD} - S \qquad \{\text{in dB}\}$$

Where:

$EIRP$	= 37	dBm	(for a typical 5W EIRP portable land mobile radio)
$L_{RELIABLE}$	= 12.6	dB	(for 97% coverage area reliability w/ σ_L = 5.6 dB)
L_{BUILD}	= 13	dB	(for coverage within single-walled concrete buildings)
S	= –119	dBm	(for a typical noise-limited base station w/ N_f=5 dB) [50] [78]

And the values for the following variables are given in the dataset for each transmitter

G_{RX}	Receiving Antenna Gain	(dB)
$L_{IMPLEMENT}$	Implementation Losses at the Receiver	(dB)

The coverage radius for each transmitter was predicted based on the path loss calculated in the link budget and a modified version of the Hata model presented in section 2; the Hata-Davidson

[11] We included records corresponding to the following Public Safety RSCs:
GE, GF, GP, PW, QM, SG, SL, SY, YE, YF, YP, and YW

model. The Hata-Davidson model provides an extension of the basic Hata model up to base station heights of 2500 meters and the full equations are available in [72].

4.3.3 Results: Geographic Area Covered by Existing Infrastructure

Below are the plots of the CONUS and Alaska+Hawaii area covered by **at least one** public safety wireless transmitter site. In the CONUS map, area covered is represented by the green colored portion of the map while in the Alaska+Hawaii map, area covered is represented by the purple colored portion of the map.

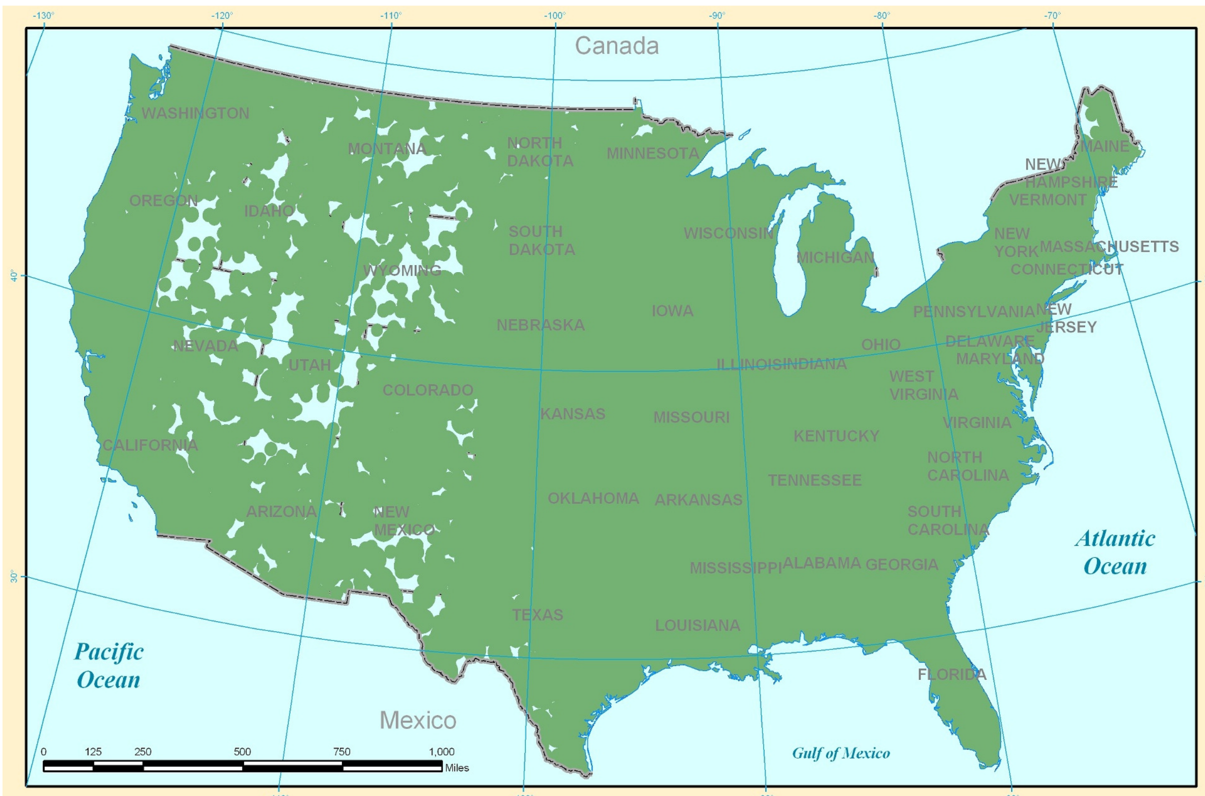

Figure 4.2: A map of CONUS showing the area (in green) that we calculated to have terrestrial coverage in February 2008 from one or more public safety wireless systems.

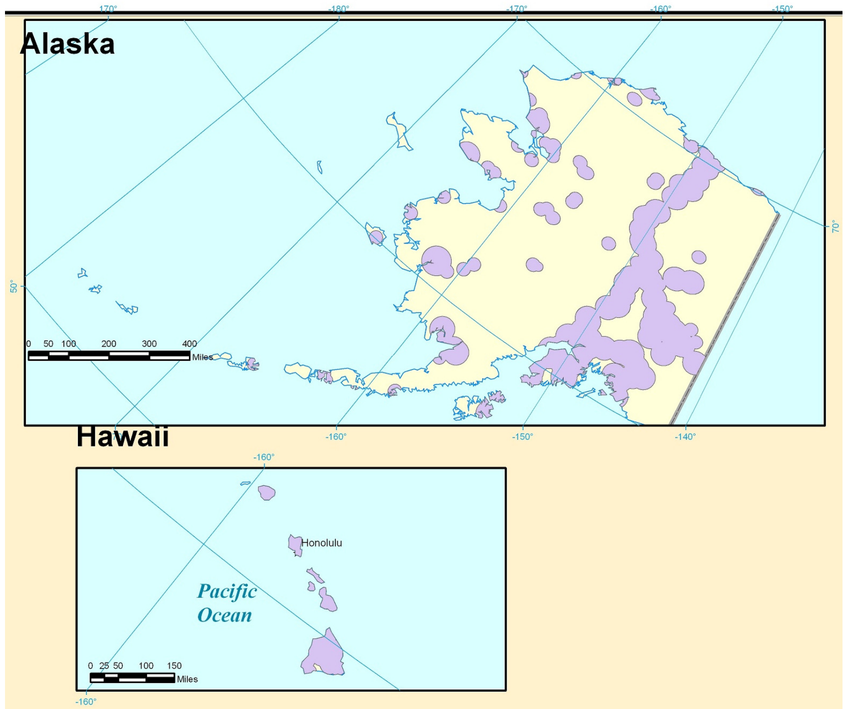

Figure 4.3: A map of Alaska and Hawaii showing the area (in purple) that we calculated to have terrestrial coverage in February 2008 from one or more public safety wireless systems

The following table summarizes the coverage statistics calculated in this analysis:

Region of Interest	Total Area [km²]	Area Covered [km²]	Percent Covered
Alaska	1,717,854	389,460	23.8%
CONUS	8,080,464	7,757,170	95.6%
US	9,826,630	8,175,940	83.2%

Table 4.2: A summary of the total size of Alaska, CONUS and the US [83] as well as the area covered and the fraction of area covered by one or more public safety wireless systems in each region.

As mentioned in section 4.2, the PSST predicted that, under FCC population build-out requirements, 73% percent of CONUS area or about 63% of US area will be covered; although we believe this is an overestimate and the actual coverage would be closer to 59% and 50% of CONUS and US area respectively. Comparing our results in the table above to these area estimates corresponding to the FCC build-out requirements, it appears that considerably more area is currently served by existing public safety communication systems than would be served by the proposed public-private partnership. This means that 20 or 33% of the US area that is currently covered by existing systems would not have access to the new network and would thus have to maintain the existing infrastructure. In the base case, we consider a public-safety-grade network that serves the same fraction of the US currently being served by existing public safety wireless systems (i.e. 83% of US area).

5 Deployment Scenarios

This section provides an overview of the 4 deployment scenarios studied in section 6 which are based on the three proposals for a nationwide public safety network presented in section 1. This section then identifies the numeric values for each input that is specific to the each of the 4 deployment scenarios and concludes with a summary table of all the input values used in the analysis of each deployment scenario.

As discussed in section 1, we are interested in three potential proposals for a nationwide public safety broadband wireless network. From these three proposals, we study 4 deployment scenarios (a deployment scenario is the name given to a distinct set of numerical input values analyzed in section 6): a public-safety-only network operating in the 700MHz band, an extension of the IWN network operating in the 168MHz or 414MHz bands to serve all federal, state, and local public safety users (we treat IWN in each band as a separate scenario), and a public-private partnership that would use public safety and commercial spectrum at 700MHz. For each of the 4 deployment scenarios, we consider the three types of public safety traffic that need to be supported on the network as discussed in section 3: Data-Only, Voice-Only, and Data and Voice. The values of β_{SUM} , β_{MAX} , and $\rho_{\beta RT}$ are different when each of these three traffic types are considered resulting in 12 different combinations of input values studied (3 different traffic types on 4 different deployment scenarios).

The input values that differ between deployment scenarios include frequency, bandwidth, and capacity required are highlighted below. The table below summarizes all of the base case numerical values used for the input parameters in each of the four deployment scenarios and for each of the three traffic types.

Public-Safety-Only Scenario (PS-Only): we consider the public-safety-only scenario on 10MHz of spectrum at 776MHz with all other inputs using the base case estimate values.

Public-Private Partnership Scenario (PubPriv): we consider a potential public-private partnership on 20MHz of spectrum at 776MHz. This is the only proposal we analyze which considers the number of commercial subscribers on the network, *Pen*, and capacity required per commercial subscriber, $\rho_{\beta SUB}$, as given in section 3.

The Extended IWN Scenarios (IWN168 & IWN414): we examine operation in each of the two potential bands (160MHz and 414MHz) as separate deployment scenarios. Considering the 168MHz band is currently divided into at least 240 narrowband channels [25], it is unclear whether or not there is sufficient contiguous spectrum for a broadband deployment. Currently, each of these bands contains 12MHz of federal spectrum however only about 8MHz in each band is used for public safety [5] [25]. This analysis assumes that in each of the bands considered, a 7.5MHz contiguous spectrum allocation can be identified across the nation.

	Input	Deployment Scenario Input Values PS-Only	Pub-Priv	IWN 168	IWN 414	Units	Section	Description
LINK BUDGET	*EIRP*	37	37	37	37	dBm	3.2.1	Transmit Power (3W ERP)
	G_{RX}	18	18	18	18	dBi	3.2.2	Receiver Antenna Gain
	$L_{RELIABLE}$	12.6	12.6	12.6	12.6	dB	3.2.3	97% Coverage Reliability Margin
	L_{BUILD}	13	13	13	13	dB	3.2.4	Building Penetration Margin
	$L_{IMPLEMENT}$	4	4	4	4	dB	3.2.5	Implementation Losses
	$L_{SCENARIO}$	4	4	4	4	dB	3.2.5	Scenario Losses
PROPAGATION	f	776	776	168	414	MHz	5	Transmit Frequency
	h_m	1.5	1.5	1.5	1.5	m	3.3.1	Mobile Height
	h_b	60	60	60	60	m	3.3.2	Base Station Antenna Height
	W	10	20	7.5	7.5	MHz	5	Bandwidth
CAPACITY	$\rho_{\beta SUB}$	--	0.0029	--	--	--	3.1.3	A Measure of Commercial Capacity
	Pen	--	0.1	--	--	--	3.1.3	Commercial Market Penetration
	fract	0.6	0.6	0.6	0.6	--	3.1.4	Other Cell Interference
	N_f	4	4	4	4	dB	3.1.5	Receiver Noise Figure
BUILD OUT	*US_Area*	0.83	0.83	0.83	0.83	--	4.3.3	Fraction of the Land Area Covered
	US_Pop	0.99998	0.99998	0.99998	0.99998	--	4.3.3	Fraction of the Population Covered
TRAFFIC: Data-Only	β_{SUM}	1.6	1.6	1.6	1.6	--	3.1.2.1	A Measure of Total Capacity Required
	β_{MAX}	0.34	0.34	0.34	0.34	--	3.1.2.1	A Measure of Max User Capacity Required
	$\rho_{\beta RT}$	0.00520	0.00520	0.00520	0.00520	--	3.1.2.1	A Measure of Routine Capacity
TRAFFIC: Voice-Only	β_{SUM}	0.94	0.94	0.94	0.94	--	3.1.2.2	A Measure of Total Capacity Required
	β_{MAX}	0.03	0.03	0.03	0.03	--	3.1.2.2	A Measure of Max User Capacity Required
	$\rho_{\beta RT}$	0.00028	0.00028	0.00028	0.00028	--	3.1.2.2	A Measure of Routine Capacity
TRAFFIC: Data&Voice	β_{SUM}	2.5	2.5	2.5	2.5	--	3.1.2.3	A Measure of Total Capacity Required
	β_{MAX}	0.34	0.34	0.34	0.34	--	3.1.2.3	A Measure of Max User Capacity Required
	$\rho_{\beta RT}$	0.00550	0.00550	0.00550	0.00550	--	3.1.2.3	A Measure of Routine Capacity

Table 5.1: A summary of the base case numeric input values for each of the 4 proposals studied.

6 Results

Section 6.1 presents a summary of the required number of cells predicted by our model for each of the 4 base case scenarios and the 3 types of traffic presented in section 5. These results are then used in Section 6.2 to estimate deployment and operating costs for the base cases. Section 6.3 describes how results change when build-out, coverage reliability, and in-building coverage requirements are varied from their base case values. Section 6.4 describes how results change when public safety and commercial capacity requirements a varied from their base case values.

6.1 Summary of Cell Sites Required

The table below summarizes the results of the model simulations for the 4 base case scenarios and the 3 types of public safety traffic presented in section 5. In addition to the cell sites required nationwide, the table shows how the number of cells is distributed across rural, suburban and urban areas.

	Public-safety-only	Extended IWN	Extended IWN	Public-Private
Frequency Band:	**776-MHz**	**168-MHz**	**414-MHz**	**776-MHz**
Bandwidth:	**10-MHz**	**7.5-MHz**	**7.5-MHz**	**20-MHz**
% of US Area Covered:	**83%**	**83%**	**83%**	**83%**
% of US Population Covered:	**99.998%**	**99.998%**	**99.998%**	**99.998%**
VOICE TRAFFIC ONLY				
Rural Cells Required	1,900	400	1,000	4,300
Suburban Cells Required	1,600	500	800	4,700
Urban Cells Required	200	100	100	1,300
Total Number of Cells Required	**3,700**	**1,000**	**1,900**	**10,300**
DATA TRAFFIC ONLY				
Rural Cells Required	8,700	2,100	4,900	9,100
Suburban Cells Required	8,200	3,200	5,000	8,200
Urban Cells Required	1,300	900	800	1,700
Total Number of Cells Required	**18,200**	**6,200**	**10,700**	**19,000**
DATA & VOICE TRAFFIC				
Rural Cells Required	9,400	2,900	6,000	9,200
Suburban Cells Required	11,100	7,200	10,400	8,500
Urban Cells Required	1,700	2,200	2,000	1,700
Total Number of Cells Required	**22,200**	**12,300**	**18,400**	**19,400**

Table 6.1: A summary of the total number of cell sites required in the base case for each of the 4 scenarios studied and the distribution of the required cell sites across rural, suburban and urban regions.

Thus, in the base cases, anywhere from one to 21 thousand cell sites would be required for a nationwide public-safety-grade wireless network, depending on the deployment scenario and traffic carried by the network. Our results are less than other recent estimates by roughly 30 to 50%. To cover 90% of the area of CONUS (which is roughly 80% of the US) using 10MHz of 700MHz spectrum in a public-safety-only system, one analyst estimated that at least 42 thousand cell sites are necessary [37], as compared to 22.2 thousand in our estimate. Their estimate decreases to 27 thousand cell sites for a public-private partnership on 20MHz of 700MHz spectrum, as compared to 19.4 thousand in our estimate. Others have considered a public-private partnership on 20MHz of 700MHz spectrum that covers just 75% of CONUS (i.e. 64% of the US), and produced estimates that 33 thousand [36] to 37 thousand [30] cell sites are required. It is impossible to fully explain differences in these estimates, since previous analysts have not made all their assumptions transparent as we do in this paper. In some cases, they did not do so because the analysts worked for stakeholders who were filing comments with the FCC, and some assumptions were viewed as proprietary.

To put these estimates in perspective, it has been estimated that major wireless operators in the US operate networks of about 25 thousand cell sites each [84], so a nationwide public safety network carrying voice and data traffic would be of comparable scale, and a public safety network carrying voice traffic only would require far less infrastructure.

Additionally, our analysis in section 4 showed that the existing public safety wireless infrastructure consists of 98 – 136 thousand tower sites nationwide. Most of them offer only voice services. Therefore, in the base case, a 700MHz network carrying voice and data could be deployed nationwide with roughly 1/5th the towers that exist today, and a network carrying only voice could be constructed with 1/25th the towers. This demonstrates that today's system is tremendously wasteful and expensive. This huge disparity is partially the result of advances in technology and frequency reuse, but an even more important cause is the fragmented approach to public safety communications wherein many thousands of individual agencies build their own separate systems [1].

Table 6.1 shows that the type of traffic carried on the network can have a significant impact on cell sites required. Going from a system where public safety has only voice to one where public safety has only data dramatically increases the number of cell sites required. In contrast, going from data-only to both data and voice has a much smaller impact on the number of cell sites required. This has implications for those who would argue that a nationwide network should offer data services to public safety, but should forego voice services for public safety as a cost-savings measure. For example, in the public-safety-only network at 776MHz, going from voice-only to data-only requires 6 times as many cells while going from data-only to data and voice requires increasing the number of cell sites by just 20%.

Table 6.1 also shows that frequency can have a significant impact on cell sites required. For example, with all other factors held constant, the extended IWN networks at 168MHz requires about 60% of the number of cells as a comparable network operating at 414MHz. This shows why the low-frequency spectrum used for IWN is so valuable when building a nationwide network; it should be used wisely.

6.2 Cost Comparison

For each cell site in the network, we estimate upfront deployment costs for the infrastructure and recurring annual operating costs. We only consider costs associated with the installation and operation of cell sites, and not the costs of the Mobile Switching Centers (MSCs) and core network, or the costs of network planning and administration. Also, handset costs are not part of the infrastructure, and are therefore not included.

A variety of factors contribute to the upfront and recurring costs of a cell site. The dominant sources of upfront capital costs are the cost of the base station electronics and antennas, the backup power system and the cost to install all of the equipment and mount the antenna. The main recurring costs include the cost to maintain the equipment at the cell site, the utilities and the backhaul costs. Another major cost is the construction or lease of the tower site itself. If the network operator were to build a new tower, this cost should be treated as an upfront one, whereas if space were leased on an existing tower, the cost would be a recurring one. To facilitate comparison with existing analysis, we will consider the cost of towers as an upfront deployment cost.

In existing analysis, the average upfront cost of a cell site ranges from \$200 – \$600 thousand [36] [37] [57] while the average operating cost has been estimated to range from \$50 – \$100 thousand per year [37]. In the table below, we summarize the costs for each of the base case scenarios using an estimate of \$500 thousand per site in upfront deployment cost and \$75 thousand per site in annual operating cost. Future work will study the impact of cell site cost estimates in greater detail.

	Public-safety-only	Extended IWN	Extended IWN	Public-Private
Frequency Band:	**776-MHz**	**168-MHz**	**414-MHz**	**776-MHz**
Bandwidth:	**10-MHz**	**7.5-MHz**	**7.5-MHz**	**20-MHz**
% of US Area Covered:	**83%**	**83%**	**83%**	**83%**
% of US Population Covered:	**99.998%**	**99.998%**	**99.998%**	**99.998%**
VOICE TRAFFIC ONLY				
Upfront Deployment Cost in Millions	$1,850	$500	$950	$5,150
Operating Cost in Millions/Year	$278	$75	$143	$773
DATA TRAFFIC ONLY				
Upfront Deployment Cost in Millions	$9,100	$3,100	$5,350	$9,500
Operating Cost in Millions/Year	$1,365	$465	$803	$1,425
DATA & VOICE TRAFFIC				
Upfront Deployment Cost in Millions	$11,100	$6,150	$9,200	$9,700
Operating Cost in Millions/Year	$1,665	$923	$1,380	$1,455

Table 6.2: A summary of the upfront deployment and recurring annual costs in the base case for each of the 4 scenarios studied.

A base-case public-private partnership network would cost $9.7 billion to deploy and $1.5 billion to operate each year. This is well under the $15 to $20 billion estimates for a public-private partnership covering 75% of CONUS from the PSST [34] and $20 billion estimates from some industry analysts [35] [36]. Our estimate is greater than but more in line with estimates of $5 – $8 billion presented by FCC Chairman Martin in Congressional testimony [85] [86].

We estimate that a base case Extended IWN network at 168MHz that is designed for data and voice traffic will cost $6.2 billion to deploy and $0.9 billion to operate annually. The same network at 414MHz will cost 50% more to deploy and operate annually. By contrast, for the IWN network as it is currently proposed (only serving federal users with voice services and possibly limited data services) estimates of the cost to deploy and operate for 15 years have ranged from $5[12] to $30 billion [22] [87] [88]. If the requisite spectrum blocks are identified, extending IWN to serve all of public safety with interoperable voice and data services would cost about as much as it is expected to cost to serve only federal users on a new primarily-voice system.

Additionally, a nationwide public-safety-only interoperable voice system would cost about $2 billion dollars upfront and about $250 million per year to operate. To put this in perspective, it has been estimated that $100 billion has been spent over the past 20 – 30 years to deploy all of the existing public safety voice systems at the state and local level [89], so a nationwide network would cost considerably less to deploy. Furthermore, the cost of a nationwide network is small even compared to what the US spends to upgrade these existing non-interoperable voice systems.

[12] [22] estimated that IWN will result in $5 billion in life cycle costs through 2021. Life cycle costs are the estimated costs associated with program planning, project implementation, and the operation and maintenance of legacy and IWN communications systems over a 15 year period.

For example, from 2003 through 2005 DHS disbursed $2.1 billion in federal grants to improve interoperability in the existing state and local infrastructure [90]. Moreover, these federal funds represent only a small fraction of what is spent on the existing state and local infrastructure. Even among those localities that received federal grants for communication system upgrades, a survey of mayors indicates that federal grants provide only about 5% of the funding [13]. At the federal level, DOJ estimates that two thirds of their wireless budget goes to maintaining antiquated federal infrastructure and that it would cost the department $900 million just to upgrade their legacy equipment [22]. In fact, it has been estimated that to simply upgrade the entire existing public safety voice infrastructure at the local, state and federal level would cost $15 – $18 billion dollars [3] [91] [92], considerably more than the cost of deploying a single nationwide network.

6.3 The Impact of Build-out, Coverage Reliability, and In-Building Requirements

As discussed in sections 3 and 4, there are several design choices that must be made when planning a nationwide wireless network. These choices have a direct impact on the numeric value chosen for inputs such as fraction of the US area covered or margins for indoor and outdoor coverage reliability, which in turn have a dramatic impact on the number of cell sites required in a network. Sections 6.3.1, 6.3.2, 6.3.3 quantify the impact the build-out, coverage reliability, and in-building coverage requirements, respectively, can have on the number of cell sites required in the 4 base case scenarios with data and voice traffic. Section 6.3.4 quantifies the impact of a range of link budget input values can have on the number of cell sites required.

6.3.1 The Impact of Build-out Requirements

In section 4, we defined the build-out requirement as the fraction of US area or population that must be covered by a proposed nationwide wireless network. Current proposals for a public-private partnership call for 99.3% of US population to be covered by the network [27]. This fraction of population coverage has been estimated to require approximately 75% of CONUS and 64% of US area [33] [81], although we believe the actual percentages would be lower based on our analysis in section 4. Meanwhile, our analysis of the US area covered by existing public safety wireless systems revealed that approximately 83% of US land area is currently served by at least one public safety wireless system. The value chosen for the build-out requirement has a direct impact on the number of cells required for a nationwide network. The following figures show the number of cells required plotted for a range of build-out requirements.

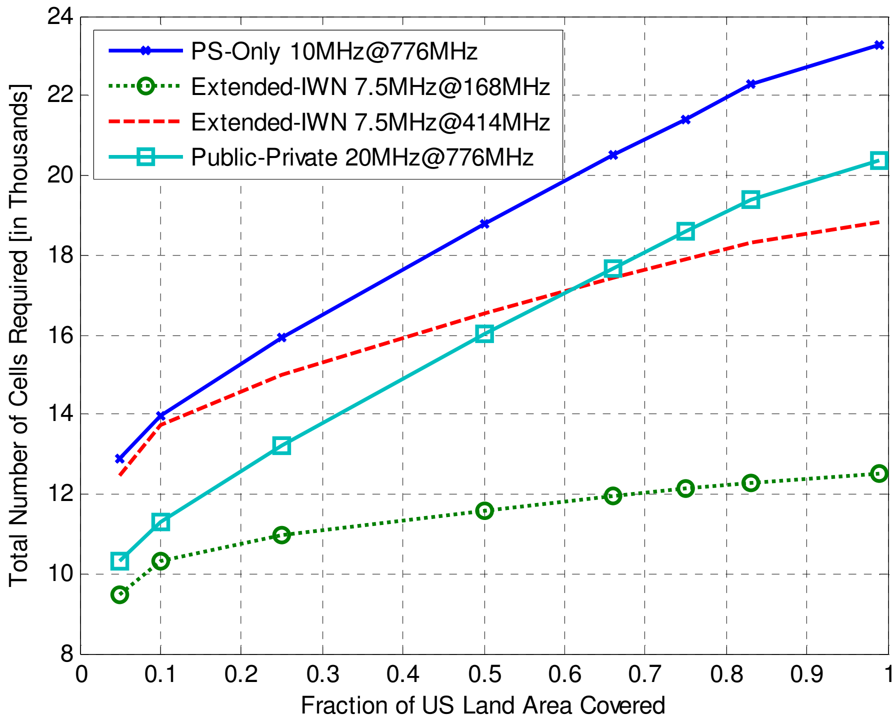

Figure 6.1a: A plot of the number of cell sites required in each of the base-case scenarios for a range of fractions of US land area covered.

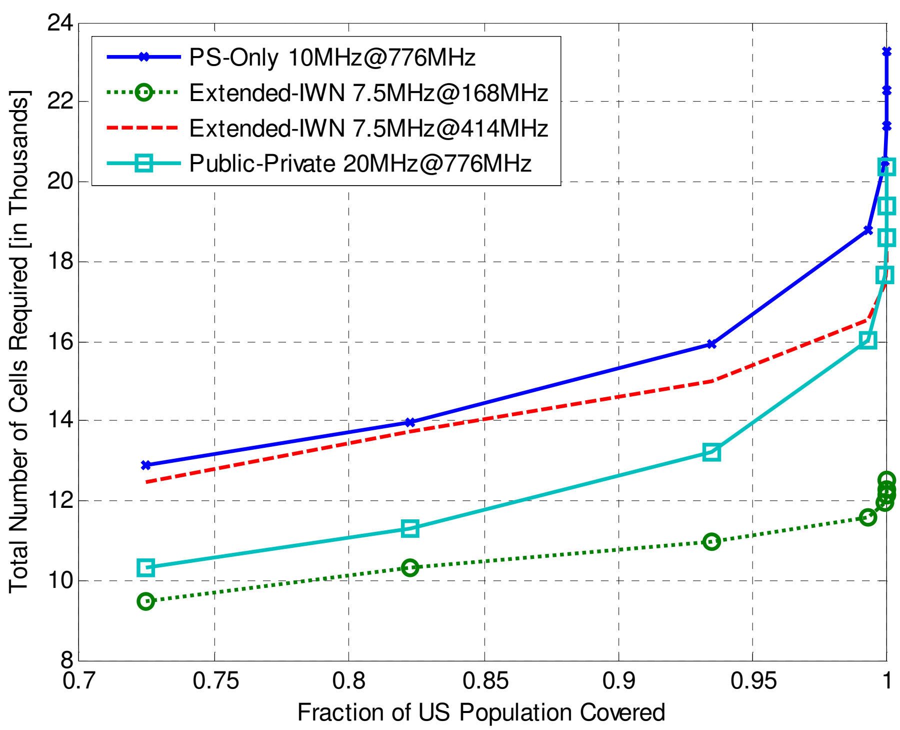

Figure 6.1b: A plot of the number of cell sites required in each of the base-case scenarios for a range of fractions US population covered.

Figure 6.1a shows that the cost of covering another 1% of area actually goes down as you approach 100% of area covered. This effect is greatest for extended IWN, because a lower frequency makes it more cost-effective to cover more area. Thus, IWN frequencies would be best suited for a nationwide network if a block of sufficient bandwidth could be identified. However, in its current form, it does not appear that IWN will cover a majority of the nation despite providing service in all 50 states. Rather, it appears as though IWN will focus on serving cities, borders, and other areas of interest to federal agencies throughout the nation [22].

Covering the last 5% of the US population is more costly because this population is spread over about 70% of the US. However, as shown in Table 6.3, it appears that previous estimates by the FCC [93] may have overestimated this cost.

		Cost Savings from Reducing Population Coverage Requirement		
Source	Reference	From 99.3% to 99%	From 99.3% to 98%	From 99.3% to 95%
Frontline	[93]	$1 Billion	--	--
FCC	[93]	--	$1.6 - $3.1 Billion	$3.1 - $6.1 Billion
Based on Figure 6.1b				
Upfront Savings		$0.11 Billion	$0.35 Billion	$1.1 Billion
Annual Savings		$0.02 Billion	$0.05 Billion	$0.16 Billion

Table 6.3: A summary of the cost savings from reducing the population coverage requirement in a public-private partnership.

6.3.2 The Impact of Coverage Reliability

In section 3, we discussed coverage reliability margins and how they are used to ensure adequate communications reliability for public safety users throughout the cell. The FCC has not established any required level of coverage reliability for a public-private partnership but the guidelines put forth by the public safety licensee calls for margins adequate for 95% coverage reliability within each cell [33]. However, industry recommendations call for 97% coverage reliability in a public-safety-grade system [72]. By contrast, a typical commercial system is designed for only 90% coverage reliability [72]. The following plot shows the increased number of cell sites as the coverage reliability requirements are increased for the 4 base case scenarios with data and voice traffic.

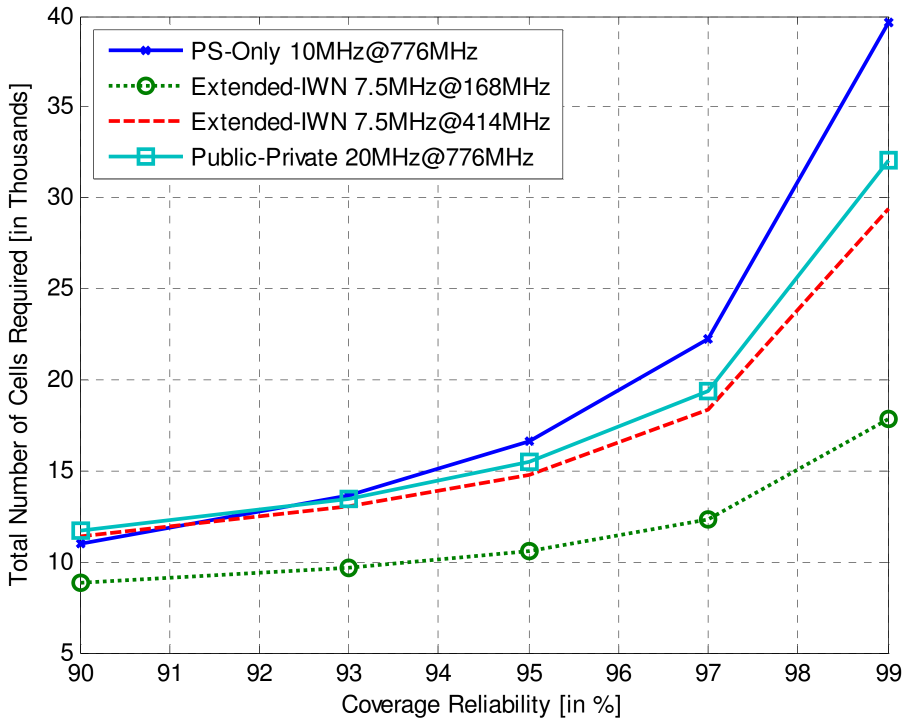

Figure 6.2: A plot of the number of cells required in each of the base-case scenarios for a range of coverage reliability levels.

Figure 6.2 shows the significant impact coverage reliability margins have on the number of cell sites required. A public-private partnership designed to 97% coverage reliability will require approximately 30% more cell sites than the same network designed to 95% coverage reliability. Uncertainty about requirements such as coverage reliability that greatly influence cost contributed to the lack of bidders in the recent 700MHz auction [32]. This important design choice requires additional attention in the public debate.

Figure 6.2 also illustrates a disadvantage of public-private partnerships. While there are great economies from allowing public safety and commercial traffic to share resources, this approach also means that a network for which the majority of users are commercial must be designed to meet more costly public-safety-grade standards. While commercial users may not mind a certain number of dropped calls, public safety users are less tolerant. Serving even one first responder on an otherwise commercial network may mean increasing coverage reliability from 90% to 97%, and according to Figure 6.2, this would roughly double the cost of the network. (Note that we would not see such a dramatic effect if commercial handsets operated at lower power than public safety devices so as to prolong battery life and decrease handset size and weight, as suggested in Section 3.2.1. This is the case because (holding all other requirements constant) a commercial network designed to 90% reliability with lower power devices would require more cell sites than the public-private partnership studied in Figure 6.2 at 90% reliability.)

6.3.3 The Impact of Indoor and Outdoor Coverage Reliability

In addition to the importance of outdoor coverage reliability margins as discussed in section 6.3.2, margins to ensure adequate coverage to public safety users within buildings can have a dramatic impact as well. The FCC has not established any required level of in-building coverage reliability but the current proposal for a public-private partnership calls for margins that vary with the type of area being covered [33]. For about 90% of the US, this proposal calls for a building penetration margin sufficient for coverage within vehicles. However, in our base case, we design the network so that there is adequate coverage in buildings with attenuation characteristics no worse than single-wall concrete for a public-safety-grade system. Figure 6.3 shows that this in-door reliability dramatically increases the number of cell sites needed for a public-private partnership. For example, in a 700MHz public-partnership increasing the requirements from 95% coverage reliability in-car to 95% coverage reliability in-door increases cost by 60% and increasing to 97% reliability and in-door coverage doubles cost. As with coverage reliability, it is essential that more attention be paid to whether or not in-door coverage is included as a public safety requirement, and if so, for what kind of buildings.

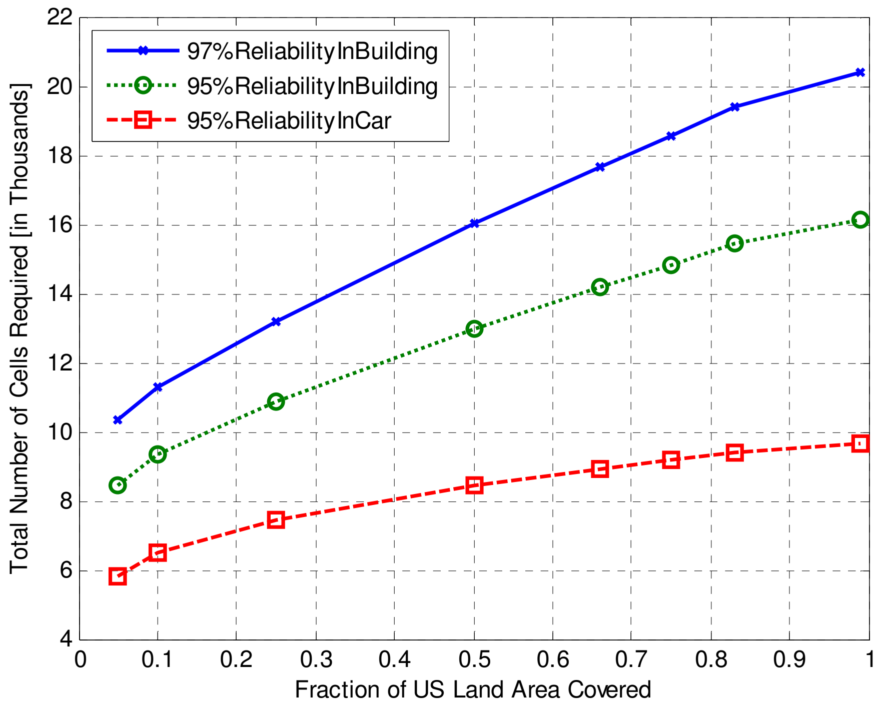

Figure 6.3: A plot of the number of cells required in a public-private partnership at 776MHz for three levels of indoor/outdoor coverage reliability.

6.3.4 The Impact of Link Budget Values

In section 2 we introduced an appropriate link budget for a public-safety-grade system and presented base case input values in section 3. In the link budget, when one of the input values is changed by a fixed amount, the effect on the number of cell sites required is the same no matter in which of the input values the change occurs. For instance the change in number of cell sites required for a 1 dB increase in mobile power, *EIRP*, is equivalent to the change due to a 1dB increase in the base station antenna gain, G_{RX}, which is equivalent to the change due to a decrease in reliability margin by 1dB. We define the link margin as the summation of all the gains and losses in the link budget, except for the path loss and receiver sensitivity which are calculated by the model, as given by the following equation.

$$LINK\_MARGIN = EIRP + G_{RX} - L_{IMPLEMENT} - L_{SCENARIO} - L_{RELIABLE} - L_{BUILD} \qquad \{\text{in dB}\}$$

In the base case, the link margin is about 22dB. By varying the link margin, we are able to study a range of link budget input values without considering each term separately. The following plot shows the number of cells required for a range of link margins values.

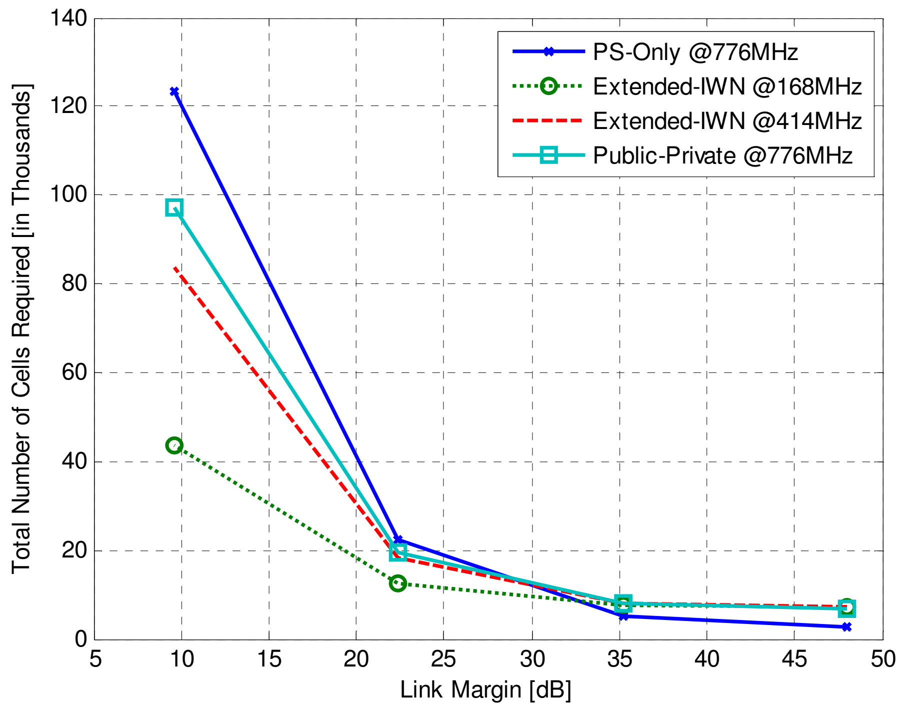

Figure 6.4: A plot of the number of cells required in each of the base case scenarios for a range of link margin values.

The results of this analysis are similar to the trends observed for coverage reliability in section 6.3.2. This is due to the fact that an increase in link margin could potentially be from a decrease in coverage reliability requirements. Just as in section 6.3.2 where a decrease in the coverage reliability requirement results in a decrease in cell sites required for each scenario, an equal increase in link margin results in an equal decrease in the number of cell sites required.

Figure 6.4 shows that changing the link margin by more than a few dB has substantial impact on the number of cell sites required. For example, reduction of link margin from 22dB to 10dB results in a public-safety-only network at 700MHz that requires 120 thousand sites. A 12dB decrease is large, but there are design choices that could lead to such large changes in link budget, such as forcing public safety handsets to transmit at the lower powers that are typical of commercial handsets, deploying inexpensive low-gain antennas, and substantially increasing the margin for in-building penetration.

6.4 The Impact of Capacity Requirements

As discussed in section 3, there is significant uncertainty in the numerical values chosen for the capacity inputs. Modeling the possible range of these uncertain values has a dramatic impact on the number of cell sites required. Section 6.4.1 quantifies the impact the range of public safety capacity requirements can have on the number of cell sites required in the 4 base case scenarios with data and voice traffic. Section 6.4.2 studies the impact of the commercial capacity requirements and market share on the cell sites required in a public-private partnership.

6.4.1 The Impact of Public Safety Capacity Requirements

As discussed in section 2.2, there is considerable uncertainty in the capacity required by public safety on a broadband wireless network. We developed a model of this capacity which is characterized by three input parameters: the capacity required to serve public safety personnel who are responding to a large-scale emergency, β_{SUM} , the capacity required by the user who operates at the highest datarate, β_{MAX} , and the capacity required to support routine traffic, $\rho_{\beta RT}$. We estimated base case values for each of these inputs in section 3.1 and in the following section we consider the impact of varying the numerical value chosen for each of these inputs independently. For each of the plots presented in this section, the 4 base case scenarios are studied for data and voice traffic.

The most uncertain of the three input parameters is the measure of capacity required to support the public safety during a large-scale emergency β_{SUM} . The amount of capacity required is dependent on the scale of the emergency planned for and the type of applications used during the response. The figure below is a plot of the number of cells required for a range of β_{SUM} values.

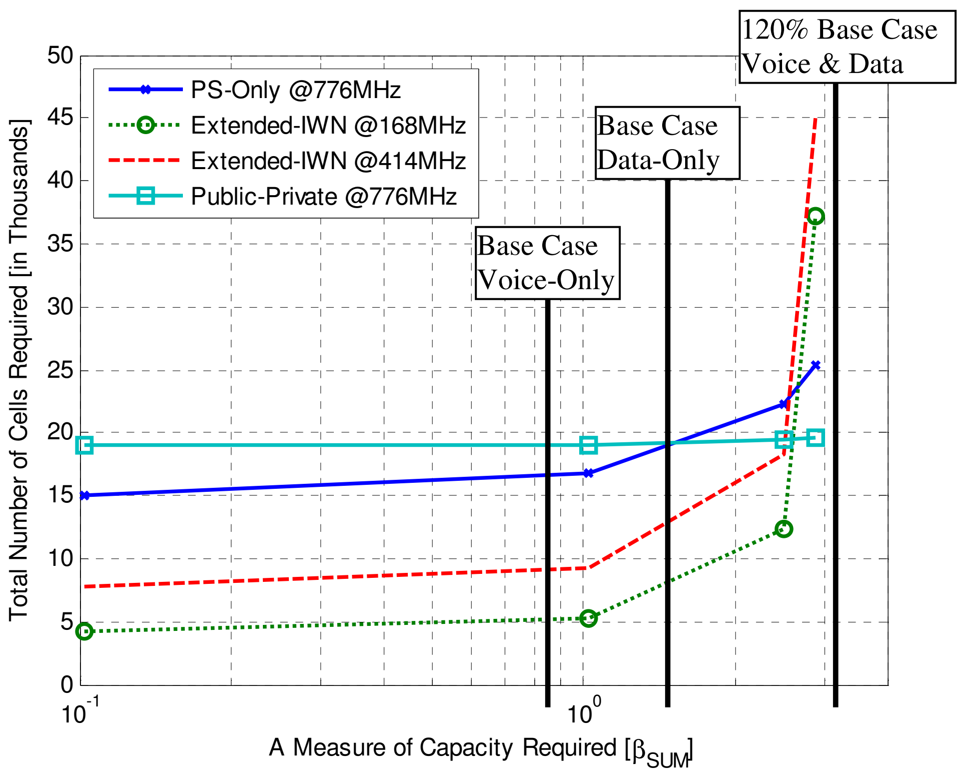

Figure 6.5: A plot of the number of cells required in each scenario for a range of β_{SUM} values.

For the public-private partnership, the capacity required in an emergency has little impact on the number of cells required, because under our base case assumptions, this capacity is needed anyway to serve commercial users. This illustrates a major advantage of sharing public safety and commercial spectrum and infrastructure.

For the public-safety-only scenarios, the magnitude of the emergency does not matter much until it reaches a certain threshold, and then the number sites required increases rapidly. In the plot above, this threshold is at about $\beta_{SUM} = 3$, which is approximately 20% more data and voice capacity[13] than the worst-case scenario hypothesized by the Spectrum Coalition for a large-scale terrorist attack centered on Washington D.C. [45]. The dramatic impact that β_{SUM} values near this threshold can have on the number of cell sites required illustrates why the capacity required by public safety users in an emergency deserves considerable study.

In addition to β_{SUM}, we studied the impact of varying β_{MAX} and $\rho_{\beta RT}$. The following figures show the number of cells required plotted for a range of values for the max capacity required per public safety user β_{MAX} and for a range of values for the capacity required for routine public safety traffic $\rho_{\beta RT}$.

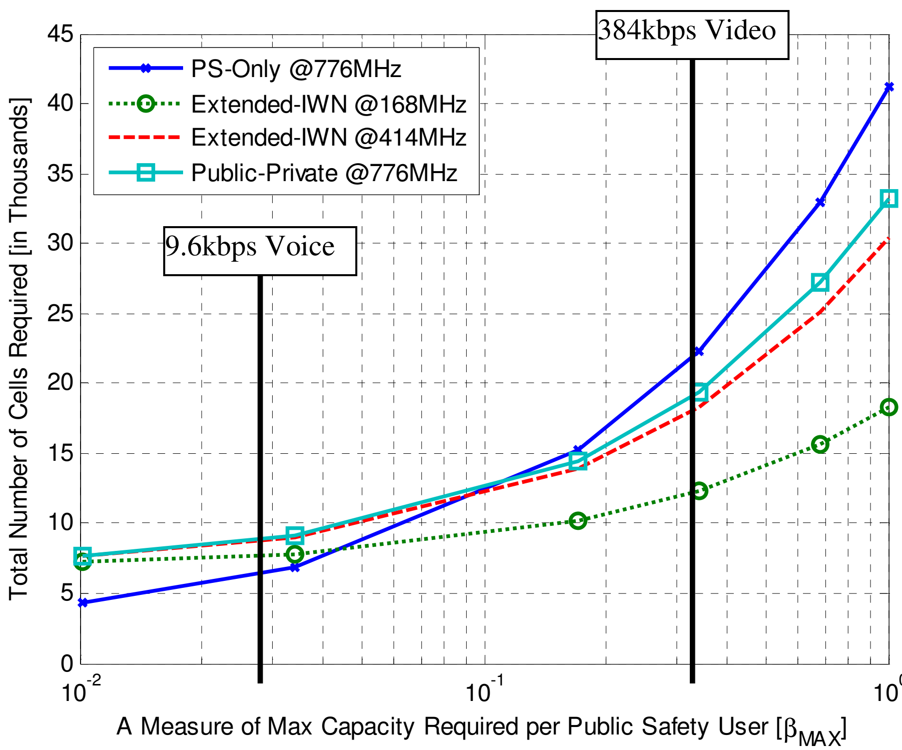

Figure 6.6: A plot of the number of cells required in each of the base case scenarios for a range of β_{MAX} values.

[13] As explained in section 2.3, the value of capacity required is measured in units of β_{SUM} instead of a typical measure of capacity, bps.

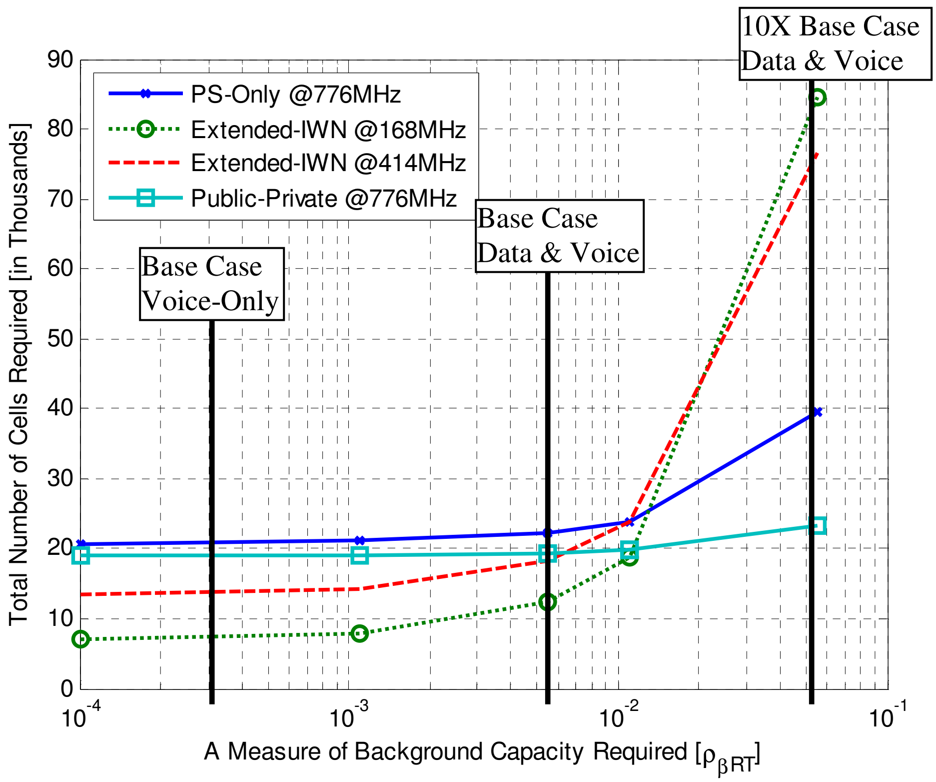

Figure 6.7: A plot of the number of cells required in each of the base case scenarios for a range of $\rho_{\beta RT}$ values.

As the value of β_{MAX} increases, the number of cell sites required in each of the scenarios increases considerably. This means that the highest-datarate application that the system is designed for can greatly impact the cost of the network, even if only one user will require that datarate. For example, designing a system for video applications instead of voice (while keeping all other capacity requirements constant) doubles the number of cell sites required in a public private partnership.

A small amount of routine public safety traffic $\rho_{\beta RT}$ has little impact on the number of cell sites required. However, as $\rho_{\beta RT}$ is increased beyond a threshold, the number of cell sites required for the extended IWN scenarios increases dramatically. This threshold is the point at which many cells are using their entire 7.5MHz, and must therefore be decreased in size. The public-safety-only network at 700MHz shows the same pattern, but it is less pronounced because the network has 10MHz in this scenario. The public-private partnership, with its 20MHz allocation, shows no signs of this within the range of values considered.

6.4.2 The Impact of Commercial Capacity and Market Share

There is considerable uncertainty in the numeric values used in the base case public-private partnership for capacity required per subscriber $\rho_{\beta SUB}$ and fraction of population the partnership can hope to sign up as subscribers, *Pen*. *Pen* is modeled as a fixed percentage of the population covered by a cell that is subscribed to the service. The two input values can have a similar impact on the cell sites required in a network; however, market penetration also has a direct impact on revenue. In the base case, penetration is estimated to be 10% and $\rho_{\beta SUB}$=2.9E-3. The following plot shows the impact of population subscription penetration on the number of cell sites required for three levels estimates of $\rho_{\beta SUB}$.

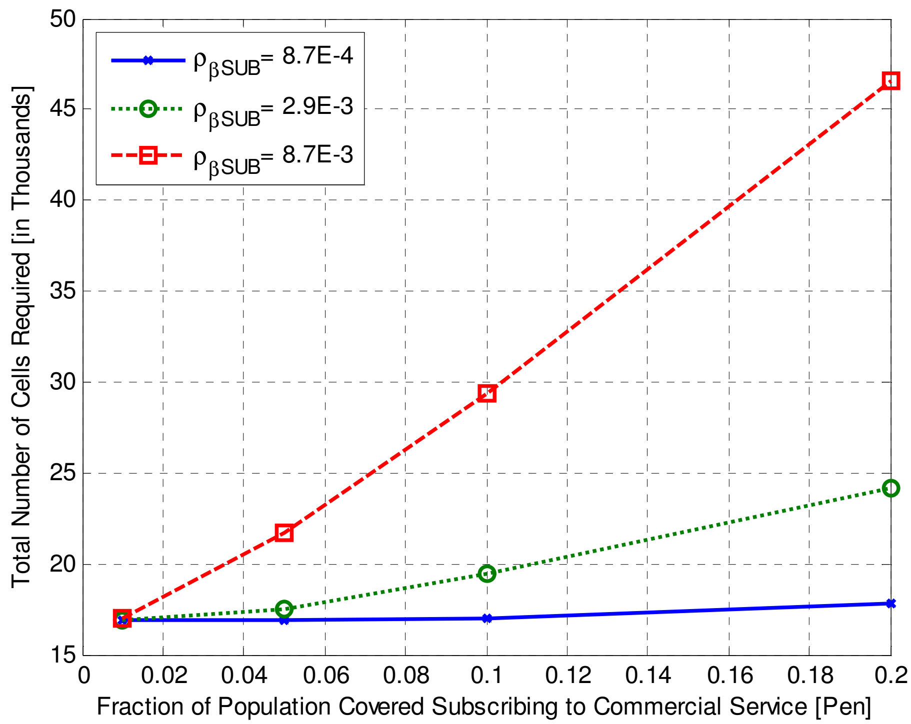

Figure 6.8: A plot of the number of cells required in the public-private partnership for 3 $\rho_{\beta SUB}$ values and a range of market penetrations.

Figure 6.8 shows why a public-private partnership will strive to attain a high enough market penetration for the capacity requirements of commercial users to at least equal the capacity requirements of public safety when responding to a large-scale emergency. For given public safety requirements, this occurs at greater penetration when the capacity requirements per subscriber are lower. Thus, for the curve corresponding to commercial subscribers with low datarates, public safety's emergency capacity requirements always exceed commercial requirements, and increasing commercial penetration has little impact on the number of cell sites required. Thus, increasing penetration increases revenues but not costs, making it highly desirable. On the other hand, for the curve where capacity required per subscriber is great, the number of cells sites required increases roughly linearly with penetration. Thus, increasing penetration at that point may or may not increase profitability.

7 Conclusions

A nationwide broadband network that serves local, state, and federal emergency responders would solve the technical interoperability issues plaguing public safety communication systems today while introducing functionality that will improve emergency response in the future. This network could take the form of a public-safety-only system or a public-private partnership.

Previous work has demonstrated how the fragmented approach to public safety communications in the US has led to infrastructure that is more expensive and uses more spectrum than is necessary [1]. This paper provides further evidence of this by showing that a public-safety-only network using 10MHz of spectrum in the 700MHz band could provide comparable voice services available to public safety today with roughly 1/25th the towers that exist today, and could provide broadband data services throughout the same area as well with roughly 1/5th the towers that exist today. In addition to dramatically reducing the need for costly infrastructure, this nationwide network carrying voice and data could be deployed on less than half of the approximately 23MHz of spectrum used by the existing voice-only infrastructure, whereas public safety organizations are correctly arguing that 23MHz is not enough to support the current fragmented infrastructure, which is why they are receiving spectrum from the 700MHz band. Indeed, it is commonly argued that to support the current fragmented infrastructure public safety needs more than four times the 23MHz of spectrum it currently uses [1].

In this paper, we presented the first version of a fully transparent model to estimate cost of two different approaches to a nationwide network, a public-safety-only network and a public-private partnership, and we applied the model to four base-case scenarios: (1) a public-safety-only network that only serves all public safety personnel (i.e. local, state, and federal) on 10MHz of spectrum in the 700MHz band, (2) a public-private partnership that serves all public safety personnel in addition to commercial subscribers on 20MHz of spectrum in the 700MHz band, and (3&4) two possible designs for a network we have proposed previously [26] and have termed Extended-IWN. This would be a network that extends the current IWN proposal to serve all public safety personnel (not just federal) in either of the two bands that may be used for the federal-only IWN project (168MHz & 414MHz). In each of these scenarios, we consider networks that carry voice only, data only, and both voice and data.

In each of these four scenarios, we have shown that in the base case a nationwide network requires fewer cell sites and therefore costs less than previously estimated. Indeed, we estimate that a 700MHz public-private partnership will require 30 – 50% fewer cell sites while covering a larger fraction of the US as compared to other estimates [30] [36] [37]. Our resulting cost estimate for a public-private partnership is similarly 30 – 50% less than PSST and industry estimates [34] [35] [36] and slightly more than estimates discussed by FCC Chairman Martin [85] [86]. It is difficult to determine the reason for these differences, in part because previous cost estimates have not fully disclosed and justified their underlying assumptions. Indeed, that lack of transparency was part of the motivation for this work.

Given the tremendous inefficiencies of the current fragmented system, as demonstrated above, it is perhaps no surprise that the cost of building an entire nationwide system is comparable to what is likely to be spent in just a few years to upgrade and maintain the existing infrastructure. For example, in the wake of 9/11, the US federal government has dispersed billions of dollars in grants just to address communications issues at the state and local level [90], and billions more will be needed. In fact, the cost to simply upgrade the entire existing infrastructure has been estimated at $18 billion [3]. In contrast, deploying a single 700MHz nationwide network that carries voice and data will cost about $10 billion, while deploying a network carrying only voice will cost substantially less than that at $2 billion.

As an alternative to deployment in the 700MHz band, we have also shown that there are considerable advantages to extending IWN in the manner we have proposed [26]. We show that if 7.5MHz of spectrum is available, it is possible to add broadband data services to the current IWN proposal, to begin serving 1.1 million [4] state and local responders along with their mere 80 thousand federal counterparts [22], and to expand coverage so it is closer to nationwide, at a cost that is comparable to the estimated costs for the current IWN proposal. For example, for Extended-IWN carrying voice and data at 168MHz, we found deployment costs on the order of $6 billion which is comparable to the estimated cost of the federal-only IWN network [22] [87] [88]. In fact, because a lower frequency makes it more cost-effective to cover more area, of the bands considered in this analysis, the IWN frequencies would be best suited for a nationwide network if a block of sufficient bandwidth could be identified. The disadvantage of these bands is that it is more difficult to assign large spectrum blocks, which may produce a system with significantly less capacity than is possible at 700MHz.

We have also shown that these cost estimates can change dramatically by adjusting a few critical input parameters, which include coverage reliability, building penetration margin, total capacity requirements, maximum data rate, and build-out requirements. Since it is impossible to estimate costs until such parameters are firmly set, no commercial company would ever commit to building infrastructure while these parameters remain undecided. Given that many of these critical parameters were not established before the 700MHz auction, and the PSST was free to set them at any level after the auction ended, it is no surprise that no one was willing to make the minimum bid [32].

Capacity requirements can have a particularly large impact on cost. For aggregate emergency and routine capacity requirements, there are threshold values beyond which the number of cell sites required increases dramatically. Understanding whether the capacity required is near these thresholds is critical to estimating both costs and bandwidth needs. Regardless of aggregate capacity requirements, it also matters what the highest datarate application is. By designing a system to support mission-critical video rather than just voice roughly doubles cost, even if only one first responder in a million uses video. Thus, it is important to determine which applications are considered mission-critical by public safety. These capacity requirements have received insufficient attention to reach consensus.

Unlike capacity requirements, there have been concrete proposals for coverage reliability, but little discussion as to whether these proposals were adequate. The PSST proposed a coverage reliability level of 95% and a building penetration margin of 6dB in rural areas [33], but 97% coverage reliability has been recommended for public safety systems [72] and a building penetration margin of 13dB would be more appropriate for coverage within concrete buildings [5]. Such lax standards were undoubtedly welcomed by potential bidders. These standards are probably adequate for commercial subscribers, so the impact on revenues is small. Yet, the impact on costs is great. Increasing the building penetration margin from 6 to 13 dB would increase cost by 60%, while also increasing coverage reliability from 95 to 97% would double costs. Such costly changes should not be taken lightly. On the other hand, if public safety agencies are not willing to use a network with lower coverage reliability standards, then public safety will not benefit from the new network, 10MHz of spectrum will have been shifted from public safety use to commercial use, and an historic opportunity will have been lost. Clearly, further discussion is needed on the actual requirements of public safety.

Unlike the capacity and coverage reliability requirements, the FCC has actually established how much of the US a new nationwide network needs to cover, and the value chosen has been a subject of controversy. In the 700MHz auction, the FCC decided to require the public-private partnership to cover 99.3% of US population [27]. It is impossible to say how much of the US area this would cover without detailed analysis which, to the best of our knowledge, has never been done. The estimate that 63% [33] [81] of the US would be served has been widely cited, although based on our analysis, we suspect the real value is more like 50%. Regardless of whether the correct value is 50% or 63%, it is clear that this build-out requirement falls far short of covering the area served by today's public safety systems. Our analysis shows that 83% of US area is covered today. Thus, under currently proposed build-out requirements, many rural public safety agencies would gain nothing from a new nationwide system. Nevertheless, some have suggested relaxing build-out requirements even further. Of course, this would reduce deployment costs, but not as much as some have predicted. For example, if build-out requirements were changed from 99.3% of US population to 98% of US population, we estimate the cost reduction to be less than $0.35 billion upfront and $0.05 billion annually, whereas the FCC estimated this cost reduction to be $1.6 – 3.1 billion [93]. The actual cost reduction is small because the cost of serving one more square mile actually decreases as coverage area grows.

While we have shown above that capacity requirements can have a significant impact on the cost of a network, carrying voice traffic in addition to data may not increase costs dramatically. For example, for a public-private partnership, we show that going from data-only network to one that carries both data and voice has a negligible impact on the number of cell sites required and therefore cost. This has implications for those who would argue that a nationwide network should offer data services to public safety, but should forego voice services for public safety as a cost-savings measure.

This paper also demonstrates some advantages and disadvantages of a public-private partnership that have previously been discussed only qualitatively [26]. A primary disadvantage is that even though most users are not from public safety, technical requirements must meet public safety's more demanding standards, and this has a cost. For example, designing a public-private partnership for public safety coverage reliability of 97% [72] instead of typical commercial coverage reliability of 90% increases cost by roughly 70%. On the other hand, the sharing of capacity between these disparate users can lead to great cost savings. For example, increasing the public safety data and voice capacity required during a large-scale emergency by 15% beyond our base case had a negligible impact on the cost of the 700MHz public-private partnership, but it increased the cost of the 700MHz public-safety-only network by 15% and the cost of the 414MHz Extended IWN network by 150%.

This work identified a first-cut estimate of the cell sites required for a nationwide, broadband, public-safety-grade wireless network under a variety of scenarios. Further work is required to improve the results presented in this paper and answer additional questions. We will continue to add detail to the cost model by incorporating additional factors, and to refine the numerical values used in the model.

8 References

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Appendix A: Spectrum Allocations for Public Safety Communications

State and local public safety agencies have allocations in bands from 25 to 4,900MHz [5] [6] [7] [8]. These allocations are predominantly for narrowband (NB) voice channels as indicated in the table below. The only spectrum allocated for broadband is the allocation at 4.9 GHz and a portion of the recently allocated 700MHz spectrum.

STATE & LOCAL PUBLIC SAFETY SPECTRUM ALLOCATIONS

Band (MHz)	Band Description	Size (MHz)	NB Channels
25-50	VHF Low Band	6.3	315
150-174	VHF High Band	3.6	242
220-222	220-MHz Band	0.1	10
450-470	UHF Band	3.7	74
470-512	UHF TV Shared	--[i]	--
764-776/794-806	700MHz Band	24	--
806-821/851-866	800MHz Band	3.5	70
821-824/866-869	NPSPAC Band	6	230
Subtotal <1-GHz		**47.2**	
4940-4990	4.9 GHz Band	50	--
Total		**97.2**	

Table A1: Spectrum allocations for non-federal public safety communications

Federal public safety spectrum allocations are also fragmented. Federal agencies have considerable allocations in sub-UHF bands which have significantly better propagation characteristics than the 700MHz band. The following table summarizes the total spectrum allocated for federal use in each band and the subset of that allocation reserved for non-tactical public safety (PS) use [5].

FEDERAL SPECTRUM ALLOCATIONS

Band (MHz)	Band Description	PS (MHz)	TOTAL (MHz)
30-50	VHF Low Band	3.8	6.3
138-150	VHF Mil Band	4	6.75
162-174	VHF High Band	8.25	11.78
220-222	220-MHz Band	0.1	0.1
406-420	UHF Band	8.3	13.9
764-776/794-806	700MHz Band	-	-
Total		**24.45**	

Table A2: Spectrum allocations for federal public safety communications

[i] There are a few spectrum allocations for public safety in the UHF TV band, but these allocations are not nationwide and are only available in select urban areas

Appendix B: Derivation of Receiver Sensitivity

As discussed in section 2, in a CDMA system, we can express the minimum acceptable received signal power, s_i, for the ith user to support the desired datarate, R_i, in the following form [42] [43]:

$$s_i \equiv \left(\frac{E_b}{N_o}\right)_i \bullet \frac{R_i}{W} \bullet (\eta + I_{SC,i} + I_{OC,i}) \quad \text{(B-1)}$$

Where:

s_i	= minimum acceptable received signal power of the ith user in the sector	(W)
W	= channel bandwidth	(Hz)
R_i	= datarate or information bit rate desired by the ith user in the sector	(bps)
$(E_b/N_o)_i$	= bit energy to noise ratio required for operation at datarate R_i	
η	= environmental noise (predominantly thermal noise) power at the receiver	(W)
$I_{SC,i}$	= cochannel interference power to the ith user due to users from the same sector	(W)
$I_{OC,i}$	= cochannel interference power to the ith user due to users from other sectors	(W)

DERIVATION OF EQUATION (2.3-2):
From equation (B-1), we can derive an expression for the receiver sensitivity that must be designed for in a cell based on the capacity requirements of public safety.

Ignoring other cell interference for a moment, we define P as the summation of power received at the base station on each channel due to all users in the sector.

$$P \equiv I_{SC,i} + s_i = \sum_{j=1}^{N} s_j = s_1 + s_2 + ... + s_{N-1} + s_N \quad \text{(B-2)}$$

Substituting P into equation (B-1), the equation for the receiver sensitivity of the ith receiver can be expressed as:

$$s_i \equiv \left(\frac{E_b}{N_o}\right)_i \bullet \frac{R_i}{W} \bullet (\eta - s_i + s_1 + s_2 + ... + s_{N-1} + s_N) = \left(\frac{E_b}{N_o}\right)_i \bullet \frac{R_i}{W} \bullet (\eta + P - s_i)$$

$$\Rightarrow s_i = (\eta + P) \bullet \left(\frac{E_b}{N_o}\right)_i \bullet \frac{R_i}{W} \Bigg/ \left[1 + \left(\frac{E_b}{N_o}\right)_i \bullet \frac{R_i}{W}\right] \quad \text{(B-3)}$$

For clarity, we introduce the term: $\beta_i \equiv \left(\frac{E_b}{N_o}\right)_i \bullet \frac{R_i}{W} \Bigg/ \left[1 + \left(\frac{E_b}{N_o}\right)_i \bullet \frac{R_i}{W}\right]$ (B-4)

Thus, equation (B-3) becomes:

$$s_i \equiv \beta_i \bullet (\eta + P) \quad \text{(B-5)}$$

Now, solving for P and simplifying:

$$P \equiv \sum_{j=1}^{N} s_j \equiv \sum_{j=1}^{N} \beta_j \bullet (\eta + P) = (\eta + P)\sum_{j=1}^{N} \beta_j \quad \Rightarrow P = \eta \frac{\sum_{j=1}^{N} \beta_j}{(1 - \sum_{j=1}^{N} \beta_j)} \tag{B-6}$$

Substituting for P in equation (B-5), the receiver sensitivity for the ith receiver becomes:

$$s_i \equiv \beta_i \bullet \left(\eta + \eta \frac{\sum_{j=1}^{N} \beta_j}{(1 - \sum_{j=1}^{N} \beta_j)} \right) = \beta_i \bullet \eta \left(1 + \frac{\sum_{j=1}^{N} \beta_j}{(1 - \sum_{j=1}^{N} \beta_j)} \right) \tag{B-7}$$

Using the following identity: $1 + \frac{X}{1 - X} = \frac{1}{1 - X}$, equation (B-7) can be reduced to:

$$s_i \equiv \frac{\beta_i \bullet \eta}{1 - \sum_{j=1}^{N} \beta_j} \tag{B-8}$$

As explained in section 2, it is common in a CDMA system to state the interference due to other sectors, $I_{OC,i}$, as a fraction of same sector interference, $I_{SC,i}$ [42]. However, we have designed for an emergency response that is localized within a cell, and we assume that all other cells are only carrying routine public safety traffic. Thus, $I_{OC,i}$, is assumed to be a fraction of interference due to routine traffic in the same sector. The receiver sensitivity that a sector must be designed for can be calculated using the following equation:

$$s \equiv \frac{\beta_{MAX} \bullet \eta}{1 - \left(\sum_{k=1}^{n} \beta_k + (1 + fract) \sum_{l=1}^{m} \beta_l \right)} \tag{B-9}$$

Where:

β_{MAX} Is the largest β_i value of any active user.

$\sum_{k=1}^{n} \beta_k$ Is the sum of the β_i terms for all n users that are responding to a large-scale emergency within a sector per channel.

$\sum_{l=1}^{m} \beta_l$ Is a measure of the capacity required by routine traffic per channel in a sector.

fract Is a fraction of interference due to routine traffic which represents the other sector interference, $I_{OC,i}$.

Appendix C: Police, Fire, and EMS vs. Population Regression Analysis

We performed a linear regression to predict the first responders per unit area based on population density using MSA level employment and population statistics. In the US, there are 370 MSAs[ii] which cover a population of about 250 million (83% of US population) corresponding to an area of 2.5 million km^2 (25% of US area). There are 400,000, 140,000 and 120,000 police officers, firefighters and EMS personnel employed in MSAs respectively [59] [60] [61].

The following table provides a summary of the results of the linear regression as explained in section 3. The following figures illustrate police, firefighter, and EMS personnel density plotted against population density along with the regression line.

	Parameter	Coefficient	Standard Error	t Stat	P-value
Police:	Intercept	-0.032	0.0106	-3.03	0.0027
(3.1-1)	Population Density [1/km^2]	0.0024	0.00006	39.6	<0.0001
Fire:	Intercept	0.022	0.0109	2.04	0.0426
(3.1-2)	Population Density [1/km^2]	0.00081	0.00005	16.1	<0.0001
EMS:	Intercept	0.0187	0.0056	3.36	0.0009
(3.1-3)	Population Density [1/km^2]	0.00052	0.00002	25.34	<0.0001

Table C1: MSA Level First Responder Density vs. Population Density Regression Parameters

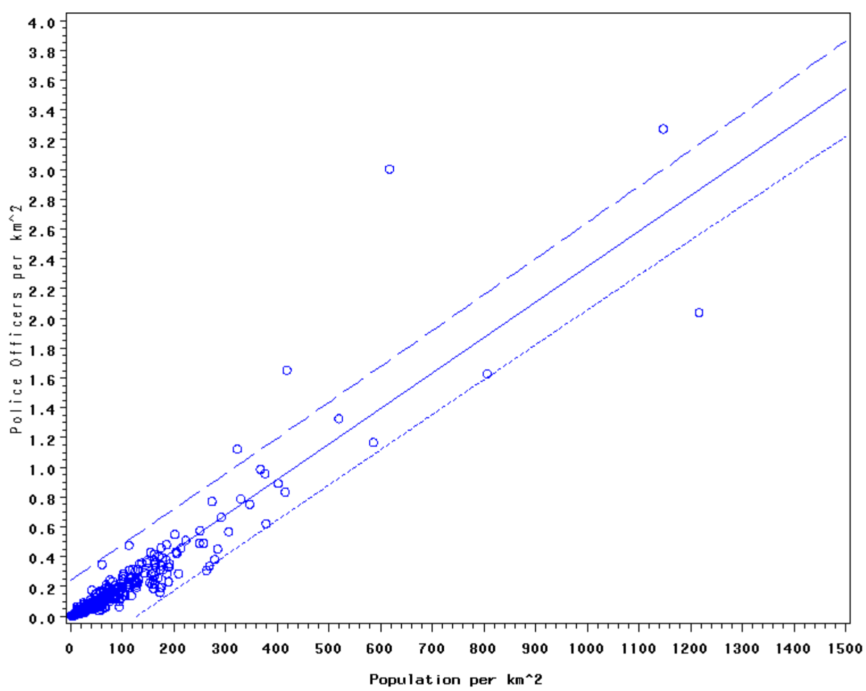

Figure C1: MSA Level Police Density vs. Population Density plotted with the Mean Linear Regression Line and the 95% Prediction Interval.

[ii] The US Office of Management and Budget (OMB) is responsible for defining metropolitan statistical areas (MSA) based on Census Bureau data. Each MSA must include at least one urbanized area of 50,000 or more inhabitants.

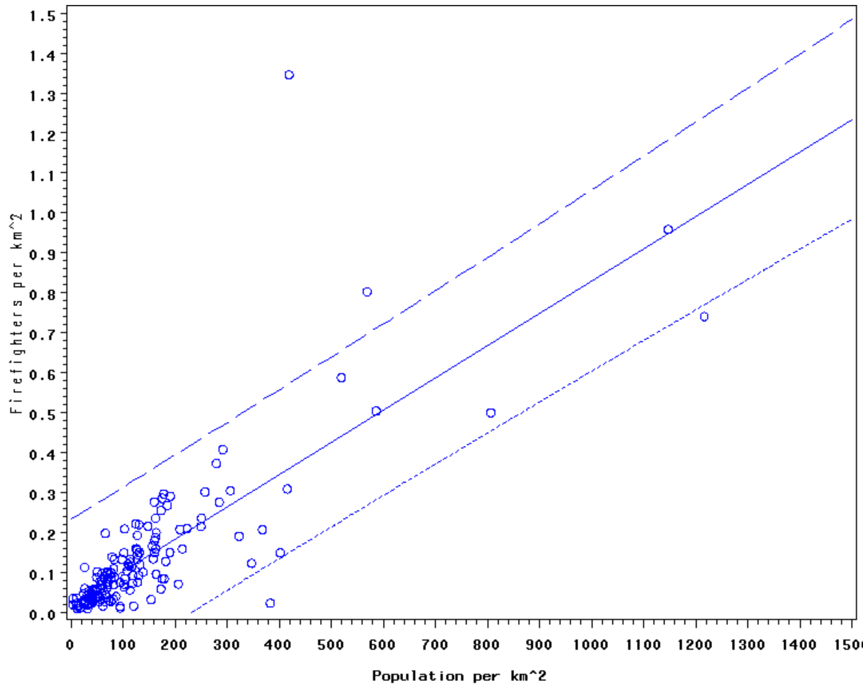

Figure C2: MSA Level Firefighter Density vs. Population Density plotted with the Mean Linear Regression Line and the 95% Prediction Interval.

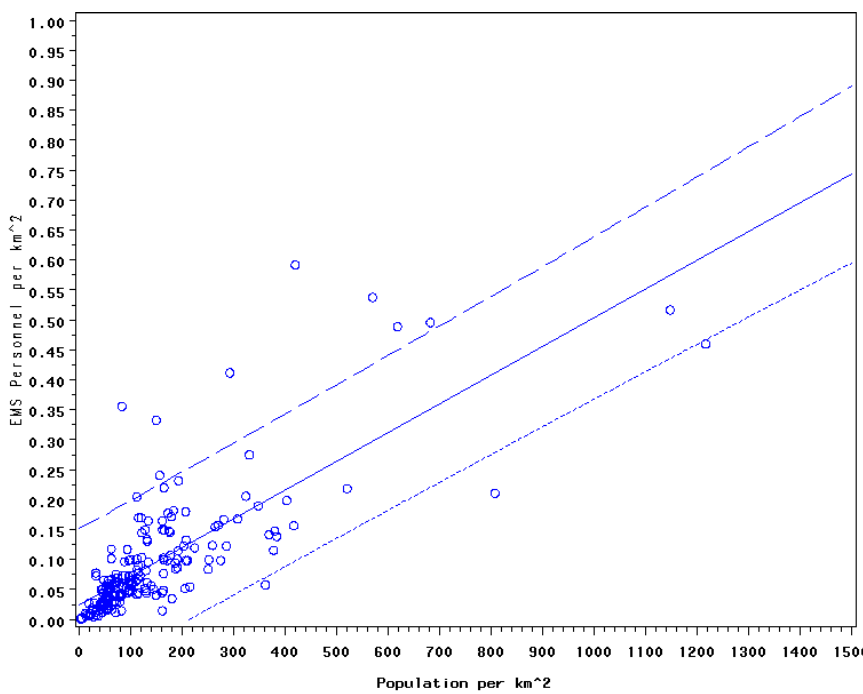

Figure C3: MSA Level EMS Density vs. Population Density plotted with the Mean Linear Regression Line and the 95% Prediction Interval.

Appendix D: Penetration Attenuation Measurements for Common Building Materials

As explained in section 3, designing for coverage inside buildings requires adding a building penetration margin to the link budget. Penetrating different building materials requires using a different level margin. The following table summarizes attenuation characteristics of common building materials.

Material	MIN Attenuation (dB)	Typical Attenuation (dB)	MAX Attenuation (dB)	Source
Ceiling Duct	1.0	-	8.0	[79]
Foil Insulation	-	3.9	-	[79]
Metal Stairs	-	5.0	-	[79]
Concrete Wall	8.0	-	15.0	[79]
Loss from One Floor	13.0	-	33.0	[79]
Loss from Two Floor	18.0	-	50.0	[79]
Aluminum Siding	-	20.4	-	[79]
Thick (25cm) Concrete w/ Large Windows	4.0	4.0	5.0	[5]
Thick (25cm) Concrete w/ Large Windows & Large Incidence Angle	9.0	11.0	12.0	[5]
Thick Concrete w/ No Windows	10.0	13.0	18.0	[5]
Double (2 x 20cm) Concrete	14.0	17.0	20.0	[5]
Thin (10 cm) Concrete	3.0	6.0	73.0	[5]
Brick Wall, Small Windows	3.0	4.0	5.0	[5]
Steel Wall (1 cm) w/ Large Windows	9.0	10.0	11.0	[5]
Glass Wall	1.0	2.0	3.0	[5]

Table D1: Minimum, Maximum, and Typical measurements of signal attenuation for common building materials.