

Quantifying the Costs of a Nationwide Public Safety Wireless Network

Ryan Hallahan^{*} and Jon M. Peha[†]
Carnegie Mellon University

Abstract

The existing US public safety wireless infrastructure consists of thousands of disparate systems built by separate local agencies. Problems with interoperability, cost, spectral efficiency, and limited functionality plague these systems but could be significantly reduced through the deployment of a single nationwide network that serves all public safety personnel. Two major efforts towards such a nationwide network are the federal-government-only Integrated Wireless Network (IWN) and an FCC-led effort to create a public-private partnership in the 700MHz band; the future of both projects is uncertain due in part to concerns surrounding cost. This paper presents a model to estimate cost for two fundamental approaches to a nationwide network: 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 network scenarios which differ in the amount and band of spectrum allocated as well as the number and type of subscribers (public-safety-only vs. commercial and public safety) under three traffic scenarios: voice-only, data-only, and voice and data. We demonstrate that the nation's many small systems could be replaced with a single nationwide network with a small fraction of the tower sites and spectrum. The cost of building this new infrastructure is comparable to what is likely to be spent in just a few years on upgrading and maintaining the existing infrastructure. In addition, we show that these cost estimates are highly dependent on some key system design parameters including the public safety capacity required and signal coverage reliability, which must therefore be well-defined in advance.

Keywords:

Public safety; first responder; wireless; spectrum; cost estimate; homeland security

^{*} Ryan Hallahan, Department of Engineering and Public Policy, Carnegie Mellon University; hallahan@cmu.edu, <http://www.contrib.andrew.cmu.edu/~rhallaha/>

[†] Jon M. Peha, Professor of Electrical Engineering and Public Policy, Carnegie Mellon University; peha@cmu.edu, <http://www.ece.cmu.edu/~peha>

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1 Introduction

Recent tragedies in the United States have demonstrated many of the deficiencies of the current public safety systems across the nation and the severe consequences that occur when these systems fail (National Commission on Terrorist Attacks Upon the United States, 2004; Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina, 2006). Among the problems, the existing infrastructure is expensive, spectrally inefficient, limited in functionality and lacks interoperability. The potential deployment of a nationwide public safety wireless system presents an opportunity to alleviate these problems (Peha, 2007), but there is considerable uncertainty surrounding the cost of the current proposals. In this paper, we provide an analysis of the costs of two fundamentally different approaches to a nationwide network while investigating the factors that have the greatest impact on cost.

In the wake of these tragedies, the lack of interoperability between systems (i.e. the ability to communicate across agencies) has been the focus of increased attention from both the academic community (Brito, 2007; Faulhaber, 2007; Mayer-Schoenberger, 2002; Weiser, 2007) and federal government (National Task Force on Interoperability [NTFI], 2003; SAFECOM, 2006a; U.S. Department of Homeland Security [DHS], 2007). And while there are a variety of ways to improve interoperability by itself (Weiser & Hatfield, 2007), such as patching together the existing public safety systems¹ or deploying new networks based on newer narrowband technologies such as Project 25 (P25)², doing so is limited in its effectiveness, and would only address one of several problems plaguing the existing infrastructure.

Deploying a nationwide public safety wireless network can inherently solve technology-based interoperability by employing a coherent architecture and a single equipment standard in the design. By avoiding the shortcomings of the previous fragmented approach to public safety (Peha, 2007), a nationwide network can also address many problems which interoperability-specific solutions do little to alleviate, and often exacerbate (Peha, 2005). Instead of allocating spectrum individually³ to more than 50 000 state and local public safety agencies across the country (Booz-Allen & Hamilton, 1999) who deploy networks independently and with limited coordination between neighboring agencies (Peha, 2005), there is a single nationwide network to be designed and deployed. A single network makes it possible to exploit significant economies (to reduce costs and increase spectral efficiency) and use broadband technologies to introduce new functionality (such as streaming video to users who previously had to rely on voice-only systems).

Currently, there are two fundamentally different approaches to the creation of a nationwide public safety wireless network: 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 (Peha, 2007).

An example of a public-safety-only network is the Integrated Wireless Network (IWN). This is a program by the U.S. Departments of Justice, Treasury, and Homeland Security to provide 80 000 federal public safety users across the nation with mission critical voice service (Office of the Inspector General, 2007). The current design for IWN (General Dynamics C4 Systems, 2009) is based on the Project 25 narrowband technology which will not support broadband data applications. Additionally, it

¹ Existing systems can be patched together either by using gateways to bridge disparate networks or by using multiband radios that can operate on a range of frequencies and standards (Weiser & Hatfield, 2007).

² Project 25 is a narrowband wireless technology designed for public safety systems. One of its stated goals is to improve interoperability. Phase I of the Project 25 standard operates on 12.5 kHz channels enabling voice or low speed data service of approximately 10kbps (Association of Public-Safety Communications Officials [APCO]).

³ The fragmented approach to spectrum allocation has led to public safety spectrum being spread across 10 bands ranging from 20MHz to 4900MHz (Desourdis, Smith, Speights, Dewey, & DiSalvo, 2002; Doumi, 2006; Public Safety Wireless Advisory Committee [PSWAC], 1996).

is expected that the network will use spectrum from the federal allocations around 168MHz and/or 414MHz as most of the agencies that would use this network have their existing land mobile radio (LMR) operations concentrated in these two bands (Hoffman, Matheson, Najmy, & Wilson, 2006). By extending this system to support broadband data applications and to 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 (Peha, 2006).

In addition to 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 (Federal Communications Commission [FCC], 2007). Since public safety communication systems are designed for worst-case capacity demand scenarios and most of the time these large-scale emergencies are not taking place, there is usually unused capacity available on these networks (Bykowsky & Marcus, 2002; Marsh, 2004; Peha, 2007). This implies that if public safety were to share spectrum with a commercial partner, most of the time the commercial partner could use some public safety spectrum to serve commercial subscribers while allowing the public safety partner access to both the public safety spectrum and commercial spectrum in the rare emergencies when it is needed.

In August 2007, in the wake of an innovative proposal (Cyren Call Communications, 2006), the FCC (2007) licensed 10 MHz of 700MHz spectrum nationwide to a single representative of public safety specifically for broadband use. Later, in February 2008, the FCC (2008a) auctioned a nationwide 10 MHz commercial license for the spectrum adjacent to the public safety allocation. The winner of this commercial license would have been obligated to build a nationwide public-safety-grade network in exchange for access to the 20 MHz of combined spectrum (Federal Communications Commission [FCC], 2007). This auction concluded without a winning bidder, which can be attributed, at least in part, to the considerable uncertainty about the requirements that would be placed on the network (Peha, 2008; Public Safety Spectrum Trust [PSST], 2007) and has led the FCC (2008b; 2008c) to consider changes to the rules that were attached to the commercial block of spectrum before it is re-auctioned.

The substantial uncertainty surrounding the cost of a nationwide public-safety-grade network is a significant impediment to its deployment. Thus, this work addresses the following two fundamental questions: (1) what will a nationwide wireless network for public safety cost with each of the two approaches under consideration, and (2) what impact do system characteristics and policy approaches have on this cost? By understanding these costs better and understanding what factors have the greatest impact on them, we can better enable policymakers to determine if any of the proposals currently being considered are feasible. By comparing these results to the status quo, we can identify what, if any, cost savings these proposals present when compared to supporting the existing infrastructure.

A few other studies have been done on the cost of a nationwide wireless network, all produced or funded by stakeholders in the debate (Access Spectrum, Columbia Capital III, Pegasus Communications & Telcom Ventures, 2006; Eisenach, 2007; Mobile Satellite Ventures, 2008). Their results vary, and are hard to assess because the analysts do not reveal all of the essential details of their assumptions, and in a few cases make assumptions which we believe are problematic. In contrast, this paper presents a transparent model with assumptions explicitly stated.

Additionally, while most of the previous studies consider only a single network proposal, in this paper we present an extensible model that is used to compare fundamentally different approaches to a nationwide network (i.e. a public-safety-only network versus a public-private partnership). More specifically, we analyze four distinct network scenarios in this paper: three public-safety-only networks that serve all public safety personnel (i.e. local, state, and federal) on (1) 10 MHz of 700MHz spectrum, or (2&3) 7.5 MHz in either of two possible federal bands (168MHz & 414MHz) as extended versions of

the IWN program, and (4) a public-private partnership that serves commercial subscribers and all public safety personnel on 20 MHz of 700MHz spectrum.

For this analysis, we focus on the number of cell sites required by a network because this number is roughly proportional to both the upfront cost and operating cost of that network. Many factors affect the number of cell sites required for a network and in this paper we study how this number changes as the following system parameters are varied: (1) the frequency and bandwidth of the spectrum allocated, (2) the amount of area covered, (3) the level of signal reliability required, and (4) the amount of communications capacity required.

Many of these factors often differ between typical public safety and commercial wireless systems. For example, while commercial cellular systems are built so that most areas where paying customers reside, work, and travel are served, public safety users need coverage wherever emergencies can occur. In addition, both the capacity and signal reliability levels required in a cell by commercial cellular users are typically not as strict as the levels is required by first responders. Given these differences, when deploying 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.

In addition to cost, there are a number of other challenges associated with establishing a nationwide wireless network for public safety. For example, where the federal government plays a substantial role, its effectiveness depends on its ability to gather meaningful input from local public safety agencies (Peha, 2007), harmonize the views of multiple federal agencies (which has proven problematic with IWN (U.S. Government Accountability Office [GAO], 2008)), and address the routine challenges of keeping a very large-scale project on time and within budget. Similarly, where local governments play a substantial role, their effectiveness depends on the extent to which their incentives under the national plan are aligned with their own local resources and budget, and whether enough of the benefits of the new system are dispersed to local agencies to overcome their reliance on costly legacy systems. For example, if a new system freed up \$10 billion worth of spectrum previously used by local agencies, but those local agencies received none of the benefit, this would not increase their participation. While we recognize their importance, most non-cost considerations are outside the scope of this particular paper, and our analysis does not depend on the specific details of who pays for the deployment of a system, who operates it, or what oversight and governance structures are put in place. As a result, we show the relative merits with respect to cost that can be achieved with different approaches, provided that issues of management and governance can be adequately addressed.

In section 2 of this paper, we introduce the model we developed to calculate the number of cell sites required in a nationwide wireless network. This model takes several variables as inputs and section 3 provides a review of the four network scenarios we study, the numerical value chosen for the inputs that are specific to each scenario, and a summary of all the numeric values used as inputs to the model. Section 4 provides the results of the model with an estimate of the number of cell sites required and cost for each scenario studied. Section 5 investigates how these results change as the input values are varied. Finally, section 6 provides a discussion of our conclusions.

2 Model Development

In this section, we introduce the framework of the 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 in section 2.1, which introduces the important concepts used and discusses the major assumptions made. The next four sections describe the major components of the model: section 2.2 discusses the capacity required in a cell, section 2.3 derives a receiver sensitivity

equation, section 2.4 presents the link budget used, and section 2.5 describes the propagation model used. Section 2.6 shows how all four components relate to form a system of equations that are solved for the input values summarized in section 3.

2.1 Model Overview

For the network approaches we study, the most cost-effective design is based on a cellular architecture. Costs in a cellular architecture are highly dependent on the number of cell sites required. 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 population statistics (U.S. Census Bureau, 2000). Expected cell size depends on population density because both 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: (1) by calculating the capacity required in each cell as a function of first responder density (i.e. the number of first responders per area), (2) by calculating the minimum received signal power required for the capacity required (i.e. receiver sensitivity), (3) by calculating the maximum amount of signal power that can be lost in the path between transmitter and receiver (i.e. path loss) using a link budget, and (4) by calculating the radius of a cell based on the path loss using a propagation model.

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 be located 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 4, the number of cell sites required in a nationwide network is comparable to the number zip codes.

In this work, we consider a code division multiple access (CDMA) based system which would be typical of a 3G network deployment (Balachandran, Budka, Doumi, & Kang, 2004; Etemad, 2004). Consistent with a typical CDMA network, we have assumed that the bandwidth allocated under each proposal is divided into 1.25 MHz channels (Etemad, 2004) with traffic distributed equally across the channels. Also typical of a CDMA system, we model a network with a frequency reuse factor of 1 (i.e. every sector can operate on each channel) and that all cells in the network have 3 sectors, to limit co-channel interference. This paper focuses on the uplink as it is assumed to be the limiting link in determining the size of a cell. This is usually the case in a CDMA system where mobile devices have lower transmit power limits than base stations and co-channel interference from other mobiles operating on the same channel is present at the base station (Etemad, 2004). We further assume that the uplink is perfectly power controlled as is typically done when analyzing CDMA systems (Etemad, 2004; Rappaport, 2002). Perfect power control means that the transmit power of a mobile device is controlled so that the power received at the base station from the mobiles communicating with it is no greater than that necessary for adequate communications.

When calculating cell area as a function of radius, one must account for the fact that cells typically overlap by 10 – 30% (Etemad, 2004; UMTSWorld.com, 2003b). 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 (Peha, 2007).

2.2 Capacity Model

The capacity required in a cell can have a significant impact on the size of that cell. 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 U.S., there is a lack of empirical evidence for the 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 network while the actual numerical values used in our simulations are discussed in (Hallahan & Peha, 2008) and summarized 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 traffic 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 terrorist bombing, etc.) similar to what has been done in existing analysis (Spectrum Coalition for Public Safety, 2005; Ring, 2002).

The magnitude and nature of a large-scale emergency and the subsequent response may vary depending upon where in the U.S. it 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 while areas with higher population density may require more first responders to protect the affected population. As shown in (Hallahan & Peha, 2008), we have observed a linear relationship between population density and the density of first responders (i.e. law enforcement, fire protection and emergency medical personnel) in the U.S. The following figure depicts the model we developed to determine the capacity required in a cell as a function of the population density in that cell.

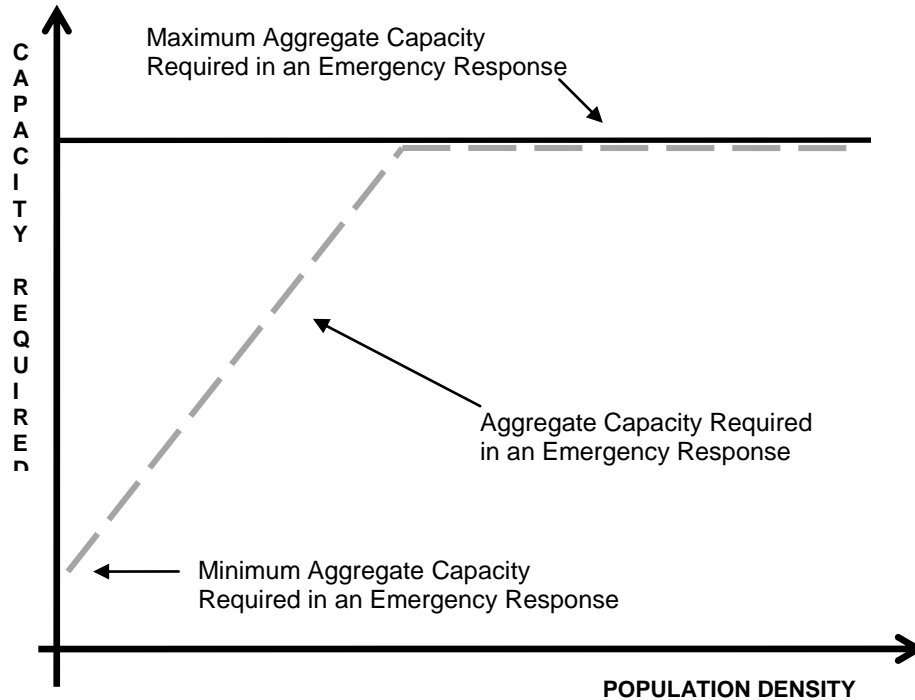


Figure 1: The capacity required in a cell as a function of the population density in that cell.

In Figure 1, 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 as discussed in (Hallahan & Peha, 2008). 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 (Hallahan & Peha, 2008) and summarized section 3.

For the second source of public safety traffic, we propose that the routine capacity required in a cell varies linearly with population covered by that cell. We calculate the population covered by a cell as the product of the population density in the cell and the area 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.

2.3 Receiver Sensitivity

In a wireless system, the strength of a signal decreases as it travels from transmitter to receiver. 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 can have a significant impact on the size of the cell.

In a CDMA system, the receiver sensitivity is dependent upon the instantaneous noise and interference environment (which is related to the capacity required), however, in link budget analysis, receiver sensitivity is often stated as a constant value. This may be reasonable in some systems where capacity requirements are constant across cells but this is not true in our model, so we derive the following equations appropriate for a CDMA system based on previous work by (Etemad, 2004; Rappaport, 2002).

In a CDMA system, we can express the minimum acceptable received signal power, s_i , for the i th user to support the desired datarate, R_i , in the following form:

$$s_i = \left(\frac{E_b}{N_o}\right)_i \cdot \frac{R_i}{W_C} \cdot (\eta + I_{SC,i} + I_{OC,i}) \quad (2.3-1)$$

Where:

s_i	Minimum acceptable received signal power of the i th user in the sector	[W]
$I_{SC,i}$	Co-channel interference power to the i th user from users in same sector	[W]
$I_{OC,i}$	Co-channel interference power to the i th user from users in other sectors	[W]
η	Environmental noise power at the receiver	[W]
R_i	Datarate desired by the i th user in the sector	[bps]
W_C	Channel bandwidth = 1.25MHz	[Hz]
$(E_b/N_o)_i$	Bit energy to noise spectral density ratio required for operation at R_i	

Since the environmental noise power present at the receiver, η , 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 as discussed in (Hallahan & Peha, 2008): (1) an equation for thermal noise (Stallings, 2005) which is the dominant source of environmental noise at frequencies above 400MHz (TIA TR8 Working Group 8.8, 1997), and (2) an equation which includes an adjustment factor to the thermal noise equation so that it is valid at frequencies below 400MHz (TIA TR8 Working Group 8.8, 1997). Both equations are dependent upon the base station's noise figure, values which typically range from 3 – 8 dB (Dobkin, 2005; Etemad, 2004; Miller, 2006; Newman, 2008).

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, s_i , for the i th user in the sector, we define the receiver sensitivity of a sector, S , as the largest value of s_i in that sector.

In section 3, we discuss the datarate and E_b/N_o desired by the most demanding user in the sector. Thus, the only unknowns left 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 on a channel requires the power received at the base station on that channel to increase. Since it is a shared channel, a user considers all of the power

received at the base station 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 the power from all signals received per channel at the base station due to the two sources of public safety traffic. 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, $I_{SC,i}$ and values tend to range from 0.5 – 0.8 (Etemad, 2004; Rappaport, 2002). However, we have designed for an emergency response that is localized within a cell, and we assume that all other cells are carrying only routine public safety traffic. Thus, $I_{OC,i}$ is assumed to be a fraction of the same-sector interference due to routine traffic and we calculate the receiver sensitivity in a public-safety-only cell, S_{PSO} , as follows⁴:

$$S_{PSO} = \beta_{MAX} \cdot \eta / (1 - [\sum_{k=1}^n \beta_k + (1 + fract) \cdot \sum_{l=1}^m \beta_l]) \quad (2.3-2)$$

Where:

$\beta_i \equiv \left(\left(\frac{E_b}{N_0} \right)_i \cdot \frac{R_i}{W_c} \right) / \left(1 + \left(\frac{E_b}{N_0} \right)_i \cdot \frac{R_i}{W_c} \right)$ is a measure of the capacity that user i requires.

β_{MAX} is the largest β_i value of any user in a sector.

$\sum_{k=1}^n \beta_k$ is a measure of the aggregate emergency capacity required per channel in a sector.

$fract$ is other cell interference as a fraction of same cell interference = 0.6.

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

Similarly, we calculate the receiver sensitivity in a public-private partnership cell, S_{PPP} , as follows:

$$S_{PPP} = \beta_{MAX} \cdot \eta / (1 - [(1 + fract) \cdot (\sum_{q=1}^p \beta_q + \sum_{l=1}^m \beta_l)]) \quad (2.3-3)$$

Where:

$\sum_{q=1}^p \beta_q$ is a measure of the commercial capacity required 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. Since the capacity required is distributed across the available channels in a sector, we define the following equations for the j th cell:

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

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

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

Where:

β_{SUM} Measure of the aggregate capacity required in a localized emergency per sector

$\rho_{\beta RT}$ Measure of the capacity required per first responder due to routine traffic

$\rho_{\beta SUB}$ Measure of the capacity required per commercial subscriber

⁴ A more detailed derivation is available in (Hallahan & Peha, 2008).

Num	Number of uplink channels in a sector = uplink bandwidth / channel bandwidth	
Pen	Market penetration as a fraction of population covered	
$Sect$	Number of sectors per cell = 3	
$\rho_{FR,j}$	First responder density in the j th cell	[km ⁻²]
$\rho_{POP,j}$	Population density in the j th cell	[km ⁻²]
$A_{hexagon,j}$	Area of the j th cell = $2.59808 r_j^2$	[km ²]
r_j	Radius of the j th cell	[km]

As discussed in section 2.2, a public-private partnership 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 j th cell of a public-safety-only network is given by equation (2.3-7) below, while the receiver sensitivity in the j th cell of a public-private partnership is the larger of equations (2.3-7) and (2.3-8):

$$S_{PSO,j} = \frac{\beta_{MAX} \cdot \eta}{1 - \left[\frac{\beta_{SUM}}{Num} + (1 + fract) \cdot \left(\frac{A_{hexagon,j} \cdot \rho_{FR,j} \cdot \rho_{\beta RT}}{Num \cdot Sect} \right) \right]} \quad (2.3-7)$$

$$S_{PPP,j} = \frac{\beta_{MAX} \cdot \eta}{1 - \left[(1 + fract) \cdot \frac{A_{hexagon,j} \cdot \left((Pen \cdot \rho_{POP,j} \cdot \rho_{\beta SUB}) + (\rho_{FR,j} \cdot \rho_{\beta RT}) \right)}{Num \cdot Sect} \right]} \quad (2.3-8)$$

2.4 Link Budget

In a wireless channel, a number of factors can affect the strength of a signal as it travels from transmitter to receiver. Factors that increase the signal strength are referred to as gains while those that decrease are losses. Meanwhile, a link budget is a calculation which takes into account all of these gains and losses to determine the net impact on a signal at the receiver. These gains and losses can greatly affect the size of a cell and this section will discuss a link budget appropriate for a public-safety-grade wireless network while the values chosen are summarized in section 3.

For a cellular system, the power received at the base station, S , is equal to the initial transmit power at the handset, P_{EIRP} , plus the gain of the receiving antenna, G_{RX} , minus the summation of any losses (with all terms expressed in dB). The link budget used for this model is given by equation (2.4-1) below and is based on the link budgets in (Desourdis, Smith, Speights, Dewey, & DiSalvo, 2002; Etemad, 2004; Miller, 2006; Smith & Collins, 2007):

$$PL = P_{EIRP} + G_{RX} - L_{IMPLEMENT} - L_{SCENARIO} - L_{RELIABLE} - L_{BUILD} - S \quad (2.4-1)$$

Where:

PL	Propagation path loss	[dB]
P_{EIRP}	Transmit power in EIRP (effective isotropic radiated power)	[dBm]
S	Receiver sensitivity	[dBm]
G_{RX}	Receiving antenna gain	[dBi]
$L_{RELIABLE}$	Shadowing plus fast fading margin	[dB]
L_{BUILD}	Building penetration margin	[dB]
$L_{IMPLEMENT}$	Receiver implementation loss margin	[dB]
$L_{SCENARIO}$	Scenario loss margin	[dB]

Expressing transmit power, P_{EIRP} , in EIRP in the link budget is a common way of combining any gains or losses internal to the transmitter (e.g. transmitting antenna gain) with the transmitter power. The power limit currently imposed on the 700MHz band in the U.S. by the FCC is 3 W ERP, or 36.9 dBm EIRP, for portable devices (Broadband transmitting power limits, 2007). These power limits are likely comparable to the transmit powers used in systems in the 168MHz and 414MHz federal bands as well. 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. In a public-private partnership, commercial handsets may be designed to transmit at a lower power⁵ (and thereby choosing to accept a signal reliability that is below what public safety requires), however, such a decision falls outside the scope of our model.

The receiving antenna gain, G_{RX} , is a measure of how effectively the antenna captures more power in certain directions than in others and is usually the most significant gain on a radio link. Typically, in a 3-sector cell, panel antennas are used that range in gain from about 12 – 18 dB (Etemad, 2004; Newman, 2008; Smith & Collins, 2007; UMTSWorld.com, 2003a).

The reliability margin, $L_{RELIABLE}$, 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 between transmitter and 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. In system planning, reliability is usually expressed as either coverage area reliability or cell-edge signal reliability. Coverage area 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. We have used the method presented in (TIA TR8 Working Group 8.8, 1997) to convert the 97% coverage area reliability value to a value of 89% cell-edge signal reliability. The equation to calculate the coverage reliability margin for a given level of cell-edge signal reliability is provided in (Miller, 2006). This equation depends on the value chosen for the standard deviation of shadowing, σ_L , which typically ranges from 4 – 10 dB (Desourdis, Smith, Speights, Dewey, & DiSalvo, 2002; Hess, 1998; Miller, 2006). We have used a value of $\sigma_L = 5.6$ dB as recommended in (TIA TR8 Working Group 8.8, 1997) which yields a margin of 12.6 dB for 97% coverage area reliability. In contrast, 95% coverage area reliability requires only 83% cell-edge signal reliability and a margin of 10.3 dB.

Similarly, the building penetration margin, L_{BUILD} , determines how reliable communications are within indoor environments. This margin is necessary to account for a signal being attenuated as it penetrates building walls and is dependent upon the type of material used to construct the walls of the buildings in which users want to operate. A margin of 13 dB should be sufficient for reliable signal penetration of a single-walled-concrete building (Desourdis, Smith, Speights, Dewey, & DiSalvo, 2002; Public Safety Wireless Network [PSWN] Program, 2002).

The implementation margin, $L_{IMPLEMENT}$, includes any losses due to the signal being attenuated as it travels through cabling between the receiving antenna and base station and losses due to mismatches and connectors at the base station. The scenario margin, $L_{SCENARIO}$, estimates losses due to receiver orientation and polarization mismatches as well as signal obstruction due to the body of the user. Typical values range from 2 – 5 dB for both implementation losses and scenario losses (Etemad, 2004; Miller, 2006; Smith & Collins, 2007; UMTSWorld.com, 2003a).

⁵ By comparison, a typical commercial handset transmits at about 24 dBm.

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, f , base station antenna height, h_b , the height of the mobile radio, h_m , and the distance of separation between the transmitter and receiver, r . For this paper, we use the Hata propagation model (Hata, 1980; Parsons, 2000; Seybold, 2005) as it is arguably the most commonly used model in the wireless industry for large-scale network planning and our work is interested in the size of a cell averaged over many similar locations. A similar analysis (Mobile Satellite Ventures, 2008) used the Walfisch-Ikegami propagation model. While the Walfisch-Ikegami model is commonly used to analyze built-up urban environments (Blaunstein, 2004; Mishra, 2004; Smith & Collins, 2007), the Hata model has broader applicability (i.e. can be applied to both urban and rural environments). Thus, we believe our use of the Hata model leads to more accurate results in rural areas.

The equations used in the Hata model are different for urban, suburban, or rural regions. This classification is commonly made based on population density (Newman, 2008). There is no universally accepted population density threshold which separates these categories. The dividing line between rural and suburban varies from 80 to 500 people per square kilometer and the dividing line between suburban and urban varies from 1000 to 10 000 people per square kilometer (Access Spectrum, Columbia Capital III, Pegasus Communications & Telcom Ventures, 2006; Newman, 2008; Pozzi & Small, 2002; Public Safety Spectrum Trust [PSST], 2007). We have defined rural as having less than 100 people per square kilometer and urban as having more than 1900 people per square kilometer and these values are in line with the values used in similar analysis (Newman, 2008).

2.6 Solving the System of Equations

In our model, we use the following equation (2.6-1) to predict the average radius of a cell in each region. This equation is derived by plugging the expression for receiver sensitivity (i.e. equations 2.3-7 & 2.3-8) and propagation path loss⁶ into the link budget from section 2.4 (i.e. equation 2.4-1).

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

Where:

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

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

$$K_2 = \begin{cases} \beta_{SUM}/Num & \text{Public Safety Emergency Traffic} \\ (1 + fract) \cdot \frac{A_{hexagon,j} \cdot Pen \cdot \rho_{POP,j} \cdot \rho_{\beta SUB}}{Num \cdot Sect} & \text{Commercial Traffic} \end{cases}$$

$$K_3 = (1 + fract) \cdot \frac{A_{hexagon,j} \cdot \rho_{FR,j} \cdot \rho_{\beta RT}}{Num \cdot Sect} \quad \text{Public Safety Routine Traffic}$$

$$K_4 = 69.55 + 26.16 \log_{10} f - 13.82 \log_{10} h_b - [(1.1 \log_{10} f - 0.7)h_m - (1.56 \log_{10} f - 0.8)]$$

$$K_5 = [44.9 - 6.55 \log_{10} h_b] \cdot \log_{10}(r_j)$$

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

⁶ The Hata model from section 2.5 is represented by the terms K, K4 and K5 in equation 2.6-1.

3 Deployment Scenarios

Given the extensible design of our model, we can study a range of network approaches by manipulating the values chosen as inputs to the equations presented in section 2. This section first provides an overview of the four network deployment scenarios studied in sections 4 and 5 (a network deployment scenario is simply a distinct set of numerical input values analyzed), then identifies the numerical values which differ between scenarios. This section concludes with a summary table of the input values used in our analysis.

The four network deployment scenarios we study in this paper are based on the nationwide network approaches discussed in section 0. Three scenarios are public-safety-only networks operating in the 168MHz, 414MHz, and 776MHz bands respectively and the fourth is a public-private partnership that would use public safety and commercial spectrum at 776MHz. For each of the four network deployment scenarios, 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.

The capacity parameters β_{SUM} , β_{MAX} , and ρ_{BRT} are used in the calculation of receiver sensitivity as discussed in section 2 and the numerical values for these inputs differ depending on the type of traffic the network carries (i.e. voice-only versus data-only). Thus, in this paper we study 12 different combinations of input values (3 different traffic types for each of the 4 different network deployment scenarios). The value of β_{SUM} depends on the aggregate capacity required by all public safety personnel in a given cell who are responding to a large-scale emergency. The values of β_{MAX} and ρ_{BRT} depend on the capacity required to support the public safety user who operates at the highest datarate and the capacity required to support routine public safety traffic respectively.

Determining appropriate β_{SUM} , β_{MAX} , and ρ_{BRT} values is difficult and further research and discussion on these numbers is required. This is because public safety usage of broadband systems is not well understood and previous work has focused on hypothetical emergency response scenarios (Ring, 2002; SAFECOM, 2006b; Spectrum Coalition for Public Safety, 2005) with only limited information available about traffic on existing broadband networks (National Telecommunications and Information Administration [NTIA], 2007). In addition, the public safety user population is not well defined and it is unclear exactly how many public safety users the network should be designed to support. In this work, the network is designed to support all local, state and federal first responders defined as law enforcement, fire protection, and emergency medical personnel⁷.

As discussed in (Hallahan & Peha, 2008), the values for the data-only case are based on the analysis by the Spectrum Coalition for Public Safety (2005) which details a hypothetical large-scale emergency in Washington D.C. involving federal, state, and local public safety personnel responding to a 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, and email access. For this scenario, at most an aggregate capacity of about 1500 kbps upstream is required in a sector with approximately 60% of the traffic as high-datarate (i.e.

⁷ Altogether, there are over 1.1 million employed law enforcement, fire protection, and emergency medical personnel in the U.S. (U.S. Department of Labor, 2008a; 2008b; 2008c). This user population could be significantly expanded by including a broader segment of the public safety community or including users from related fields such as the critical infrastructure industry.

360kbps) real-time video, 35% is 60kbps data transfer, while the remaining 5% is low-datarate (i.e. 10kbps). For routine traffic in the base case, we assume the mean amount of data uploaded per first responder per hour worked is 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. As discussed in (Hallahan & Peha, 2008), we calculate the capacity due to routine data traffic as 4.2 kbps/first responder.

As discussed in (Hallahan & Peha, 2008), the same number of first responders are present in the data-only case and the voice-only case. We design for 5% to be active simultaneously during the busiest time. This results in 32 low-datarate (i.e. 9.6kbps) real-time voice streams active during the busiest time, which in the worst-case occurs when the data-only traffic is at its peak. Thus, the value of β_{SUM} in the data and voice case is the sum of the β_{SUM} values in both the data-only and voice-only cases, while the β_{MAX} for the data and voice case is the larger of the β_{MAX} values from the data-only and voice-only case. For routine traffic in the base case, we assume the mean percentage of time that a first responder spends talking while on duty is 1% and, as discussed in (Hallahan & Peha, 2008), we calculate the capacity due to routine voice traffic as 0.1 kbps/first responder.

In addition to public safety traffic, a public-private partnership will need to accommodate traffic from commercial users. For commercial traffic in the base case, we assume the mean amount of data uploaded per commercial subscriber per month is 200 MB. As discussed in (Hallahan & Peha, 2008), for the commercial capacity per subscriber, $\rho_{\beta SUB}$, we calculate a value of 2.4 kbps/subscriber. Additionally, we have defined Pen (i.e. the commercial provider's market penetration) as a constant 10% of population covered by the network as discussed in (Hallahan & Peha, 2008).

In addition to the datarate required, the value of E_b/N_o depends on the bit error rate (BER) requirements of the application. There is no consensus on what acceptable BER values are for the various public safety applications that will be deployed and more work is needed in this area. These values depend on a variety of factors including the modulation scheme employed and level of forward error correction (FEC) used (Rosenberg & Kemp, 2003). In the absence of widely accepted values, we have chosen an E_b/N_o value of 6dB for real-time voice and 2.5dB for data transfer, which are in line with values used for a commercial network (Etemad, 2004).

Below we highlight the input values (i.e. frequency, bandwidth, and capacity requirements) that differ between deployment scenarios.

Public-Safety-Only Scenario (PS-Only): is a public-safety-only scenario on 10 MHz of spectrum at 776MHz with all other inputs using the base case estimate values discussed in (Hallahan & Peha, 2008).

Public-Private Partnership Scenario (PubPriv): is public-private partnership on 20 MHz of spectrum at 776MHz. This is the only proposal we analyze that serves commercial subscribers and depends on the fraction of population that subscribes to the network, Pen , and capacity required per commercial subscriber, $\rho_{\beta SUB}$, as discussed in (Hallahan & Peha, 2008).

Extended IWN Scenarios (IWN168 & IWN414): are public-safety-only scenarios in each of the two potential federal bands (168MHz and 414MHz). The 168MHz band is currently divided into at least 240 narrowband channels (Hoffman, Matheson, Najmy, & Wilson, 2006), and it is unclear whether or not sufficient contiguous spectrum can be freed for a broadband deployment. Currently, both bands contain roughly 12 MHz of federal spectrum, however, only about 8 MHz in each band is used for public safety (Desourdis, Smith, Speights, Dewey, & DiSalvo, 2002; Hoffman, Matheson, Najmy, & Wilson, 2006). Our analysis assumes that in both of these bands, a 7.5 MHz contiguous spectrum allocation can be identified across the nation.

The table below summarizes all of the base case numerical values used for the input parameters in each of the four network deployment scenarios and for each of the three traffic types. 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 chosen. Indeed, in section 5 we study how results change as several of these numerical values are varied from the base case.

Network Scenario Input Values							
Input	PS-Only	Pub-Priv	IWN 168	IWN 414	Units	Input Description	
LINK BUDGET	P_{EIRP}	37	37	37	37	dBm	Transmit Power (3W ERP)
	G_{RX}	18	18	18	18	dBi	Receiving Antenna Gain
	$L_{RELIABLE}$	12.6	12.6	12.6	12.6	dB	97% Coverage Area Reliability Margin
	L_{BUILD}	13	13	13	13	dB	Building Penetration Margin
	$L_{IMPLEMENT}$	4	4	4	4	dB	Implementation Losses
	$L_{SCENARIO}$	4	4	4	4	dB	Scenario Losses
PROPAGATION	F	776	776	168	414	MHz	Transmit Frequency
	h_m	1.5	1.5	1.5	1.5	m	Height of Mobile Transmitter
	h_b	60	60	60	60	m	Base Station Antenna Height
	W	10	20	7.5	7.5	MHz	Bandwidth of Spectrum Allocation
CAPACITY	ρ_{BSUB}	--	0.0029	--	--	--	Measure of Commercial Capacity/Subscriber
	Pen	--	0.1	--	--	--	Commercial Market Penetration
	$Fract$	0.6	0.6	0.6	0.6	--	Other Cell Interference Fraction
	N_f	4	4	4	4	dB	Receiver Noise Figure
BUILD OUT	US_Area	0.83	0.83	0.83	0.83	--	Fraction of the U.S. Area Covered
	US_Pop	0.99998	0.99998	0.99998	0.99998	--	Fraction of the U.S. Population Covered
TRAFFIC: Data-Only	β_{SUM}	1.6	1.6	1.6	1.6	--	Measure of PS Emergency Capacity Req'd
	β_{MAX}	0.34	0.34	0.34	0.34	--	Measure of Highest User Datarate Req'd
	ρ_{BRT}	0.00520	0.00520	0.00520	0.00520	--	Measure of PS Routine Capacity/User Req'd
TRAFFIC: Voice-Only	β_{SUM}	0.94	0.94	0.94	0.94	--	Measure of PS Emergency Capacity Req'd
	β_{MAX}	0.03	0.03	0.03	0.03	--	Measure of Highest User Datarate Req'd
	ρ_{BRT}	0.00028	0.00028	0.00028	0.00028	--	Measure of PS Routine Capacity/User Req'd
TRAFFIC: Data & Voice	β_{SUM}	2.5	2.5	2.5	2.5	--	Measure of PS Emergency Capacity Req'd
	β_{MAX}	0.34	0.34	0.34	0.34	--	Measure of Highest User Datarate Req'd
	ρ_{BRT}	0.00550	0.00550	0.00550	0.00550	--	Measure of PS Routine Capacity/User Req'd

Table 1: A summary of the base case numeric input values for each of the 4 network scenarios studied. Each of these values is discussed in greater detail in (Hallahan & Peha, 2008).

4 Results: Cell Sites Required and System Cost

In this section, we use the model described in section 2 to calculate the number of cell sites required in each of the four base case network scenarios with the three types of traffic presented in section 3. We also calculate how much it would cost to deploy and operate each network in the base case using estimates of the upfront deployment cost and annual operating cost of a cell site.

In these estimates, we only consider costs associated with the installation and operation of cell sites and not the costs of the backbone network components (e.g. mobile switching centers), or the costs

of network planning and administration. Also, handset costs are not part of the infrastructure and are therefore not included. The dominant sources of upfront capital costs are the cost of the base station electronics, antennas, backup power systems and the cost to install the equipment and mount the antennas. The main recurring costs include maintenance, utilities, and backhaul costs. Another major cost is the construction or lease of the tower site itself and to facilitate comparisons with existing analyses, we consider the cost of towers as an upfront deployment cost.

In similar analyses, the average upfront cost of a cell site ranges from \$200 000 – \$600 000 (Access Spectrum, Columbia Capital III, Pegasus Communications & Telcom Ventures, 2006; Eisenach, 2007; Newman, 2008) while the average operating cost has been estimated to range from \$50 000 – \$100 000 per year (Newman, 2008). In this paper, we calculate costs for each of the base case scenarios using an estimate of \$500 000 per site in upfront deployment cost and \$75 000 per site in annual operating cost.

As an illustrative example, we calculate the total cost to deploy and operate each scenario over a ten year time period. In this case, we have assumed that for a given scenario, cell sites are deployed at a constant rate such that the same number of cell sites is built each year over the ten year period (actual build-out rates depend on many factors (Hallahan & Peha, 2009) which are outside the scope of this paper). In this example, we did not discount the future cash flows as the discount rate used may depend on who is doing the borrowing and the risk associated with the project, both of which are considerations that are outside the scope of this paper.

The table below summarizes the results of the model simulations for the four base case network scenarios and the three types of public safety traffic discussed in section 3.

Network Scenario:	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
VOICE TRAFFIC ONLY				
Total Number of Cells Required	3,700	1,000	1,900	10,300
Upfront Deployment Cost in Millions	\$1,900	\$500	\$950	\$5,200
Operating Cost in Millions/Year	\$280	\$75	\$140	\$770
10 Year Total Cost in Millions	\$3,400	\$910	\$1,700	\$9,400
DATA TRAFFIC ONLY				
Total Number of Cells Required	18,200	6,200	10,700	19,000
Upfront Deployment Cost in Millions	\$9,100	\$3,100	\$5,400	\$9,500
Operating Cost in Millions/Year	\$1,400	\$470	\$800	\$1,400
10 Year Total Cost in Millions	\$16,600	\$5,700	\$9,800	\$17,300
DATA & VOICE TRAFFIC				
Total Number of Cells Required	22,200	12,300	18,400	19,400
Upfront Deployment Cost in Millions	\$11,100	\$6,200	\$9,200	\$9,700
Operating Cost in Millions/Year	\$1,700	\$900	\$1,400	\$1,500
10 Year Total Cost in Millions	\$20,300	\$11,200	\$16,800	\$17,700

Table 2: A summary of the total number of cell sites required, the upfront deployment costs, the recurring annual costs, and the total costs calculated over a 10 year period in the base case for each of the 4 network scenarios and 3 traffic types studied.

Our results are roughly 30% to 50% less than other recent estimates written or funded by stakeholders (Access Spectrum, Columbia Capital III, Pegasus Communications & Telcom Ventures, 2006; Cyren Call Communications, 2006; Eisenach, 2007; Mobile Satellite Ventures, 2008). For instance, some analysts have estimated that a public-private partnership on 20 MHz of 700MHz spectrum that covers 75% of the contiguous U.S. (CONUS) (or 64% of the U.S.) would require 33 000 (Eisenach, 2007) to 37 000 (Cyren Call Communications, 2006) cell sites and some have estimated that such a network would cost \$15 – \$20 billion to build (Eisenach, 2007; Jackson, 2008b; 2008d). Our estimate is greater than but more in line with estimates of \$5 – \$8 billion presented by FCC Chairman Martin in congressional testimony (Jackson, 2008c; 2008a). It is impossible to fully explain differences between these estimates and our results since previous analysts have not made all their assumptions transparent as we do in this paper. Since these analysts worked for stakeholders who were filing comments with the FCC, their assumptions may have been viewed as proprietary and therefore withheld.

To put these estimates in perspective, our analysis in (Hallahan & Peha, 2008) showed that the existing public safety wireless infrastructure consists of 98 – 136 thousand tower sites nationwide. Most of them offer only voice services. Therefore, 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 roughly 1/25th the towers. This huge disparity is due in large part to the fragmented approach to public safety communications wherein many thousands of individual agencies build their own separate systems (Peha, 2005).

Today's systems are so inefficient that abandoning sunk investments and building new infrastructure can save money in the long run. A nationwide public-safety-only interoperable voice system would cost about \$2 billion upfront and about \$300 million per year to operate, which is small even compared to what the U.S. spends on regular upgrades to the existing non-interoperable voice systems. For example, from 2003 – 2006 DHS disbursed \$2.1 billion in federal grants to improve interoperability in the existing state and local infrastructure (Chertoff, 2006), and this is just a small fraction of what is spent on these existing systems. Indeed, among those localities that have received federal funds for system upgrades, federal grants represent only 3% – 8% of their total funding needs (U.S. Conference of Mayors, 2004). Moreover, 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 in addition to the already sunk costs (Booz-Allen & Hamilton, 1999; Evans, 2003; Information Technology Industry Council, 2005), which is more than the cost of deploying a single nationwide broadband network.

Table 2 also shows that 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 but going from data-only to both data and voice has a much smaller impact. For example, in the public-safety-only network at 776MHz, going from voice-only to data-only requires about 5 times as many cell sites while going from data-only to data and voice requires increasing the number of cell sites by just 20%. This means forgoing voice services on a broadband data network will not present significant cost savings as some have argued.

Additionally, Table 2 shows the effect frequency can have on cost and why the low-frequency spectrum used for IWN is so valuable when building a nationwide network. For example, with all other factors held constant, the Extended IWN networks at 168MHz require roughly 30%–50% fewer cell sites and cost roughly 30%–50% less than a comparable network operating at 414MHz. In fact, if the requisite spectrum blocks can be identified, extending IWN to serve all local, state, and federal public safety users with interoperable voice and data services could cost as much as serving only federal users

on a new primarily-voice system. More specifically, we estimate that a base case Extended IWN network at 168MHz that is designed for data and voice traffic will cost about \$6 billion to deploy and a billion dollars to operate annually while recent estimates place the costs of the IWN network as currently proposed at anywhere from \$5–\$30 billion to deploy and operate for 15 years (Dizard, 2005; Hsu & Babington, 2007; Office of the Inspector General, 2007).

5 Results: The Impact of Varying Requirements

As discussed in section 2, there are several design choices that must be made when planning a nationwide wireless network: how much of the country the network must cover, the reliability of the signal within the coverage area, the aggregate capacity available in a cell and the highest data rate supported at the cell edge. These choices directly affect the numeric value chosen for the inputs presented in Table 1 and this section studies how results change as several of these numeric values are varied. Respectively, sections 5.1, 5.2, 5.3, and 5.4 quantify the impact build-out requirements, indoor/outdoor coverage reliability requirements, link budget input values, and public safety capacity requirements have on the number of cell sites required in each of the four base case network scenarios carrying data and voice traffic.

5.1 Build-out Requirements

We define the build-out requirement as the fraction of U.S. area or population that must be covered by the network. In the 700MHz auction, the FCC (2007) required the public-private partnership to cover 99.3% of U.S. population. This fraction of population coverage has been estimated to require coverage of only about 64% of U.S. area (or 75% of CONUS area) (Cyren Call Communications, 2006; Public Safety Spectrum Trust [PSST], 2008). In the most recent proposal by the FCC (2008c), the population build-out requirement has been reduced even further and regional licenses have been introduced in an attempt to make the partnership more attractive to a commercial partner. Indeed, a re-auction under these proposed rules could result in only about 6% of the U.S. area being covered after 15 years (depending on how many regional licenses receive winning bids) (Hallahan, 2008). Even if all regional licenses receive winning bids, the licensees would still only be required to cover about 38% of U.S. area (Hallahan, 2008). In contrast, our analysis in (Hallahan & Peha, 2008) revealed that approximately 83% of U.S. land area is currently covered by at least one public safety wireless system.

The following two figures show how the number of cell sites required in a network changes as the network's area and population coverage requirements are varied.

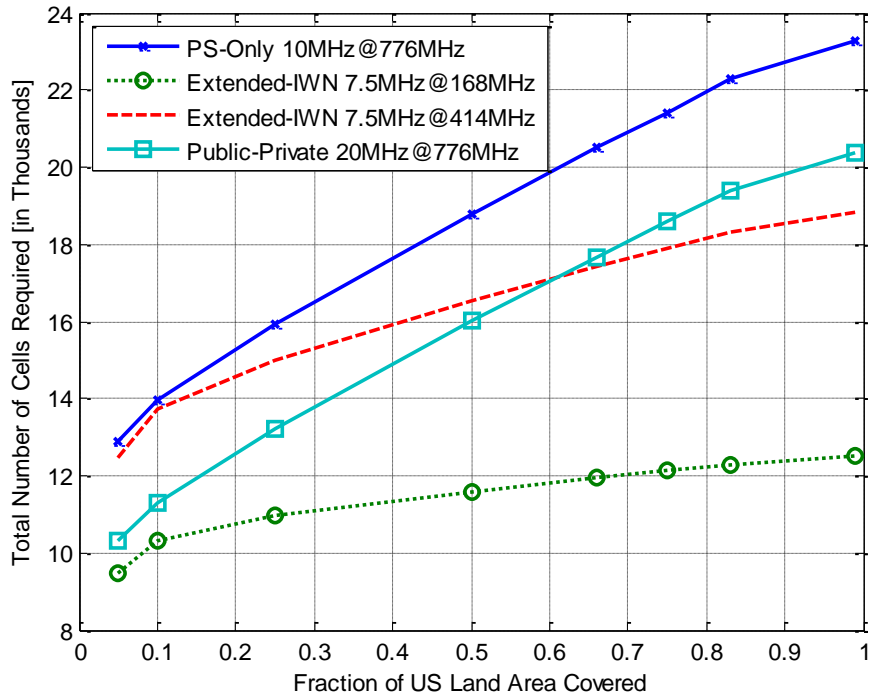


Figure 2: A plot of the number of cell sites required in each of the 4 base case network scenarios for a range of fractions of U.S. land area covered.

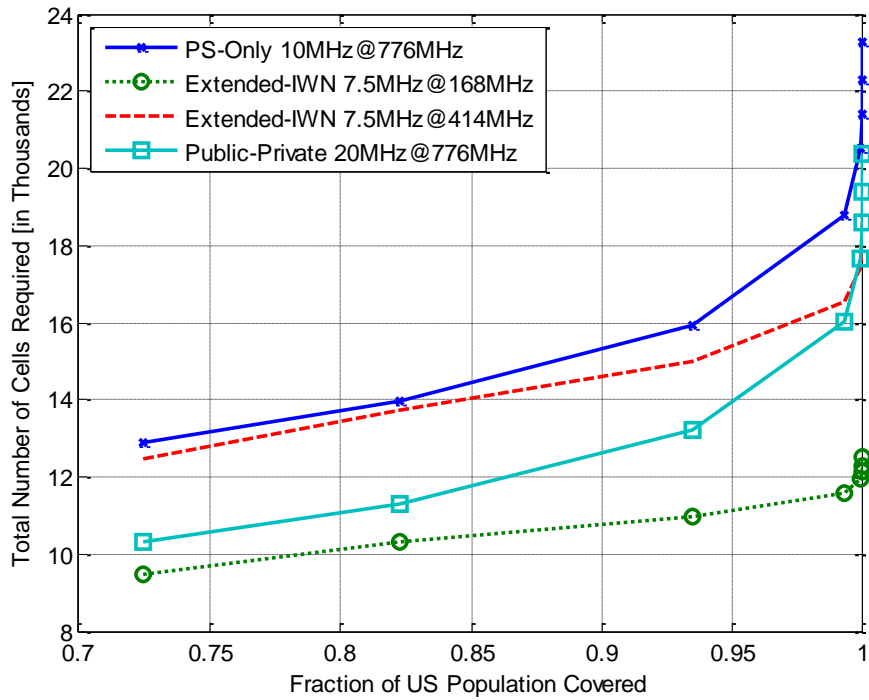


Figure 3: A plot of the number of cell sites required in each of the 4 base case network scenarios for a range of fractions U.S. population covered.

Figure 2 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. Meanwhile, Figure 3 demonstrates that covering the last 5% of the U.S. population is most costly because this population is spread over about 70% of the U.S.

5.2 Indoor and Outdoor Coverage Reliability

In section 2, we discussed building penetration and coverage area reliability margins and how they are used to ensure adequate communications reliability for public safety users throughout the cell. For a public-private partnership, the FCC(2008c) recently proposed requiring 95% outdoor coverage area reliability within each cell and building penetration margins that vary depending on the type of area being covered (for about 90% of the U.S. these building penetration margins would be sufficient for coverage within vehicles (Peha, 2008)). Both of these proposed requirements are in line with the guidelines put forth by the public safety licensee, the PSST (2007). However, in the base case we design the network for 97% coverage area reliability, as recommended for a public-safety-grade system⁸ (TIA TR8 Working Group 8.8, 1997), and for adequate coverage in buildings with attenuation characteristics no worse than single-wall concrete. The following two plots show how the number of cell sites required increases as the coverage area reliability requirements and building penetration margins are increased in the four base case network scenarios carrying data and voice traffic.

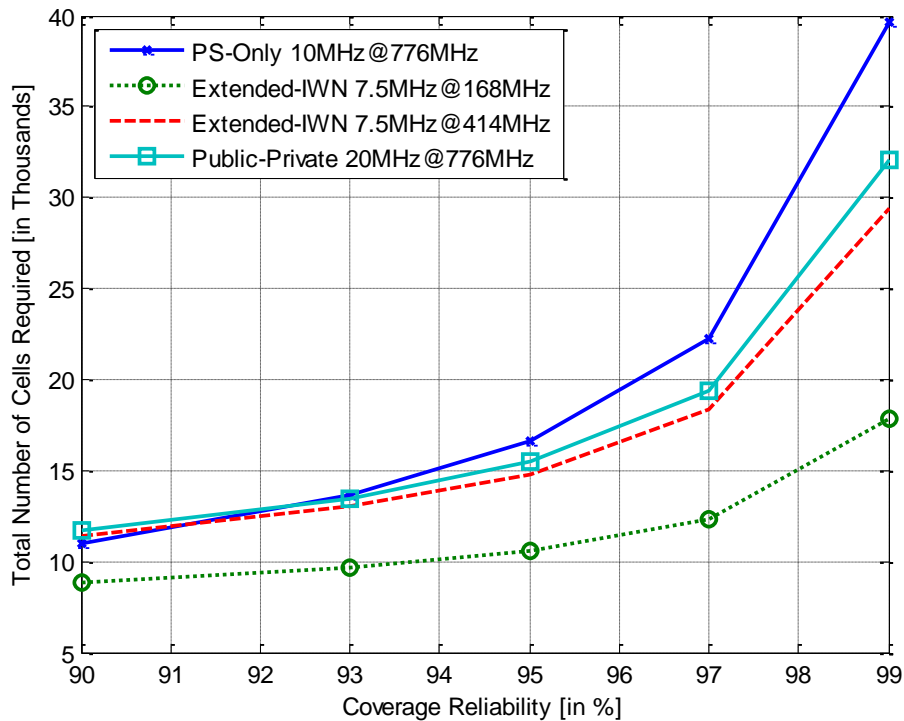


Figure 4: A plot of the number of cell sites required in each of the 4 base case network scenarios for a range of coverage area signal reliability levels.

⁸ By comparison, 90% coverage reliability is more typical of a commercial system.

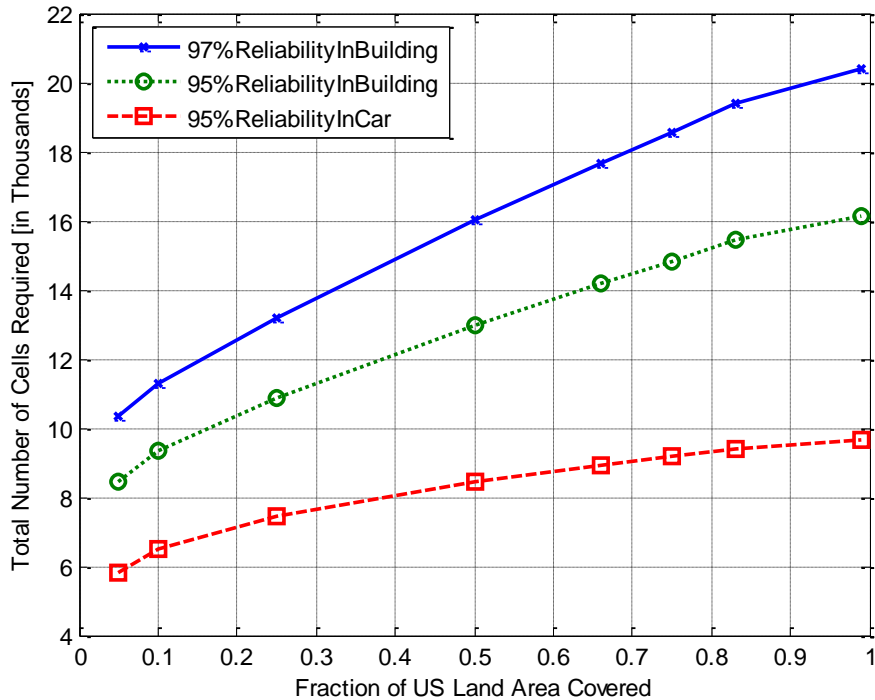


Figure 5: A plot of the number of cell sites required in a public-private partnership at 776MHz for three levels of indoor/outdoor coverage reliability.

These two plots demonstrate that increasing coverage area reliability margins, building penetration margins, or both can significantly increase the number of cell sites required. In Figure 4 for example, a public-private partnership designed for 97% coverage area reliability will require approximately 30% more cell sites than the same network designed to 95% coverage area reliability. Similarly, Figure 5 shows that in a public-private partnership, increasing the requirements from 95% coverage area reliability in-car to 95% coverage area reliability indoors increases cost by about 60% and increasing to 97% coverage area reliability indoors coverage roughly doubles cost.

These plots also illustrate 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 area reliability from 90% to 97%, and according to Figure 4, this would increase the cost of the network by roughly 70%.

5.3 Link Budget Values

In our 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 regardless of which input value is actually changed. 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, as shown in the following equation. By varying the link margin as depicted in the plot below, we are able to study a range of link budget input values without considering each term separately.

$$LINK_{MARGIN} = P_{EIRP} + G_{RX} - L_{IMPLEMENT} - L_{SCENARIO} - L_{RELIABLE} - L_{BUILD} \quad \{in \text{ dB}\}$$

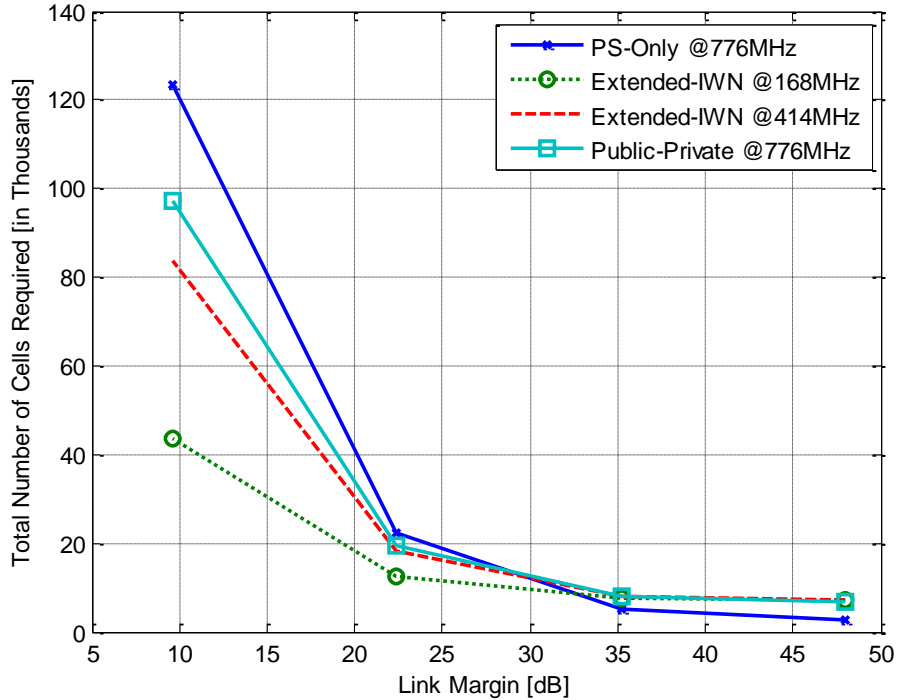


Figure 6: A plot of the number of cell sites required in each of the 4 base case network scenarios for a range of link margin values.

Figure 6 shows that changing the link margin by more than a few dB has a substantial impact on the number of cell sites required. For example, a network with a link margin of 10 dB (versus about 22 dB in the base case) could require up to 120 thousand sites. A 12 dB decrease in link margin is large, but there are design choices that could lead to such large changes, such as forcing public safety handsets to transmit at the lower powers that are typical of commercial handsets or substantially increasing the building penetration margin.

5.4 Public Safety Capacity Requirements

The capacity required by public safety users differs from the capacity required by commercial users. On a broadband wireless network, these 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 communicate during an emergency concentrated within a single cell. As discussed in section 2.2, public safety's capacity requirements are not yet well understood and more study on this topic is needed.

In the absence of an established model, we developed a model of public safety capacity that is characterized by three input parameters: β_{SUM} , β_{MAX} , and ρ_{BRT} . As discussed in sections 2.3 and 3, these parameters are a function of the data rate and E_b/N_0 required. In this section, we study the impact of varying the numerical value chosen for the data rate in each of these inputs independently while holding the E_b/N_0 value constant.

The aggregate capacity required to support public safety users during a large-scale emergency is dependent on the scale of the emergency planned for and the type of applications used during the response; neither of which are well established. The figure below is a plot of the number of cell sites required for a range of aggregate capacity values (in kbps).

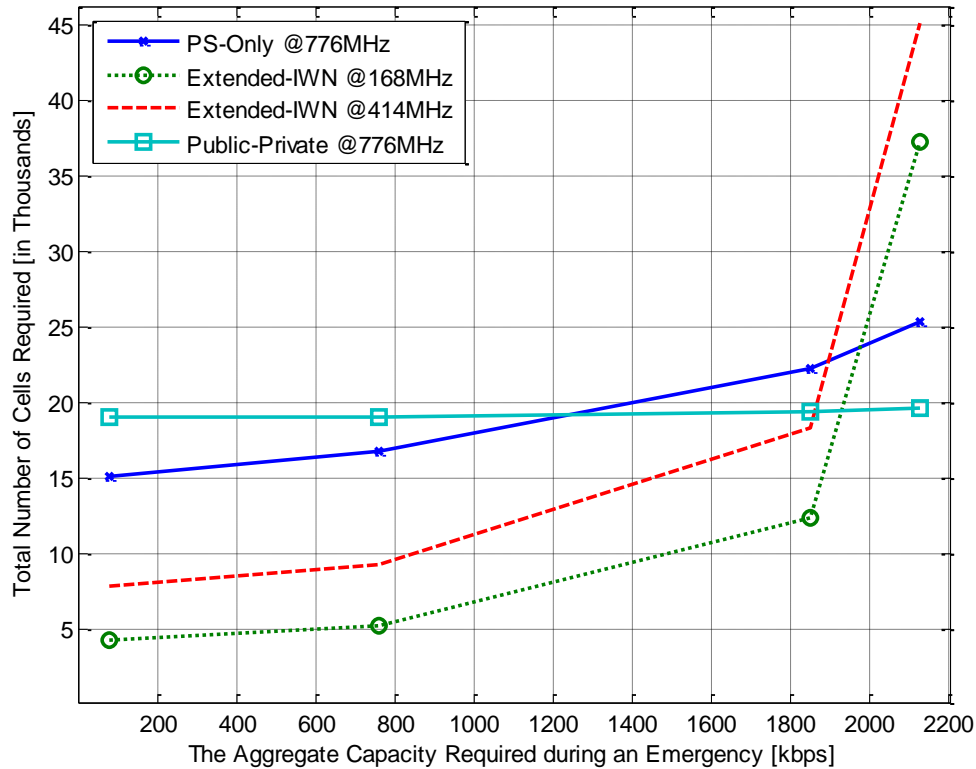


Figure 7: A plot of the number of cell sites required in each of the 4 base case network scenarios for a range of aggregate capacity values.

Figure 7 illustrates a major advantage of sharing public safety and commercial spectrum and infrastructure. For the public-private partnership, the capacity required in an emergency has little impact on the number of cell sites required because in the base case, 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 in Figure 7, the capacity required in an emergency does not matter much until it reaches a certain threshold, beyond which the number of cell sites required increases rapidly. This threshold is at about 2100 kbps, which is approximately 15% more capacity than the voice and data base case. The dramatic impact that values near this threshold can have illustrates why public safety capacity requirements deserve considerable study.

In the following two plots we study the impact of varying the highest user data rate required and the routine capacity required.

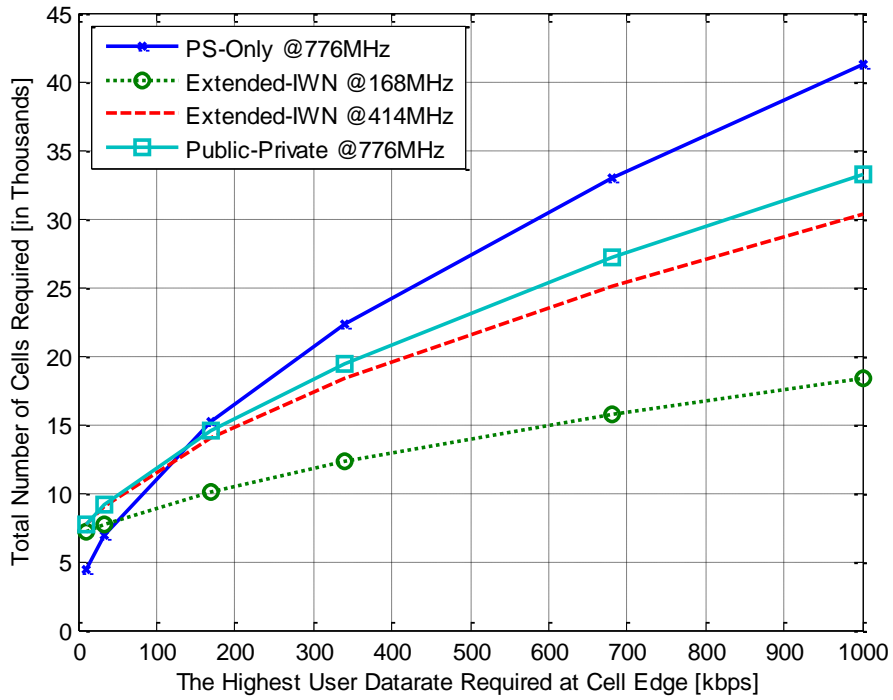


Figure 8: A plot of the number of cell sites required in each of the 4 base case network scenarios for a range of values of the highest user datarate required.

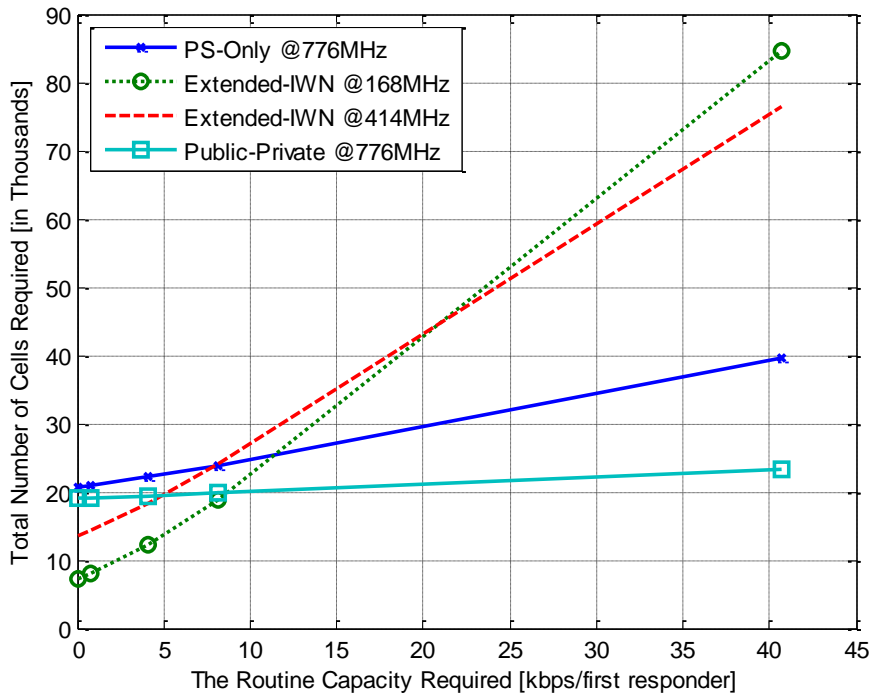


Figure 9: A plot of the number of cell sites required in each of the 4 base case network scenarios for a range of values of the routine capacity required per first responder.

Figure 8 shows that as the value of highest user datarate required increases, the number of cell sites required in each of the scenarios increases considerably. Thus, the highest-datarate application the system is designed for can dramatically affect 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) approximately doubles the number of cell sites required in a public-private partnership.

Figure 9 shows that as the value of routine capacity required is increased the number of cell sites required increases roughly linearly. For the extended IWN scenarios, the rate of this increase is much more dramatic due to the smaller bandwidth allocation (i.e. 7.5 MHz). The public-safety-only network at 776MHz shows the same pattern, but it is less pronounced because the network has 10 MHz in this scenario. The public-private partnership, with a 20 MHz allocation, varies little within the range of values considered.

6 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 U.S. has led to infrastructure that is more expensive and uses more spectrum than is necessary (Peha, 2005). This paper provides further evidence of this by showing that a public-safety-only network using 10 MHz 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 with roughly 1/5th the towers that exist today. In addition to dramatically reducing the need for costly infrastructure (as costs are roughly proportional to the number of cell sites required), this nationwide network carrying voice and data could be deployed on less than half of the approximately 23 MHz of spectrum used by the existing voice-only infrastructure.

In this paper, we presented the first version of a fully transparent model to estimate costs of a public-safety-only network and a public-private partnership under four base case scenarios: (1) a network that only serves all public safety personnel (i.e. local, state, and federal) on 10 MHz of spectrum in the 700MHz band, (2&3) an extension of the current IWN proposal to serve all public safety personnel (not just federal) on 7.5 MHz of spectrum in either of two possible federal bands (168MHz & 414MHz), and (4) a public-private partnership that serves all public safety personnel in addition to commercial subscribers on 20 MHz of spectrum in the 700MHz band. For each of these scenarios, we study networks that carry only voice, only data, and both voice and data.

In all four network scenario base cases, we have shown that a nationwide network requires fewer cell sites and therefore costs less than previously estimated. Indeed, when compared to other estimates written or funded by stakeholders, we estimate that a 700MHz public-private partnership will require roughly 30% – 50% fewer cell sites (Access Spectrum, Columbia Capital III, Pegasus Communications & Telcom Ventures, 2006; Cyren Call Communications, 2006; Eisenach, 2007; Mobile Satellite Ventures, 2008) and cost roughly 30% – 50% less (Eisenach, 2007; Jackson, 2008b; 2008d) while covering a larger fraction of the U.S.. However, our estimates are slightly more than the estimate presented by FCC Chairman Martin (Jackson, 2008c; 2008a). It is difficult to explain these differences because previous cost estimates have not fully disclosed their assumptions, whereas our model is fully transparent.

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 U.S. federal government has dispersed billions of dollars in grants just to address communications issues at the state and local level (Chertoff, 2006), and billions more will be needed. In fact, the cost to upgrade the entire existing infrastructure has been estimated at \$18 billion (Booz-Allen & Hamilton, 1999). In contrast, we found that deploying a single 700MHz nationwide network that carries voice and data will cost about \$10 billion, while a voice-only network would cost \$2 billion. While a nationwide network may represent a cost savings in the long run if agencies can transition to it, until that transition occurs, both the existing systems and the nationwide network must be operated. In the short term, this will lead to increased costs, some of which may be borne by local agencies which have constrained budgets that may not be able to handle large upfront expenditures, even if it leads to long term savings.

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 previously (Peha, 2006). We show that if 7.5 MHz of spectrum is available, it is possible to add broadband data services to the current IWN program, to begin serving over a million state and local first responders (U.S. Department of Labor, 2008a; 2008b; 2008c) along with their mere 80 thousand federal counterparts (Office of the Inspector General, 2007), and to expand coverage so it is closer to nationwide, at a cost that is comparable to the estimated costs for the current IWN program. 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 (Dizard, 2005; Hsu & Babington, 2007; Office of the Inspector General, 2007).

We have also shown that these cost estimates can change dramatically by adjusting a few critical input parameters, which include coverage area signal reliability, building penetration margin, aggregate capacity required, highest user datarate required, and population/area 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. Thus, it is no surprise that no one was willing to meet the minimum bid in the most recent 700MHz auction (Peha, 2008).

Capacity requirements can have a particularly large impact on cost, but have received little study to this point. For both routine capacity and aggregate capacity required in an emergency, 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 that the network must support. By designing a public-private partnership to support mission-critical video rather than just voice roughly doubles cost, even if only one first responder in a million uses video. Thus, more emphasis should be placed on determining which applications are considered mission-critical by public safety.

Unlike capacity requirements, there have been concrete proposals for coverage reliability, but little discussion as to whether these proposals were adequate. The FCC (2008c), in line with the recommendations of the PSST (2007), has proposed a coverage area signal reliability level of 95% and a building penetration margin of 6dB in rural areas. In contrast, 97% coverage area signal reliability has been recommended for public safety systems (TIA TR8 Working Group 8.8, 1997) and a building penetration margin of 13 dB would better provide coverage within concrete buildings (Desourdis, Smith, Speights, Dewey, & DiSalvo, 2002). Such lax standards are undoubtedly welcomed by potential bidders and these standards are probably adequate for commercial subscribers, so the impact on revenues is

small. Yet, the impact on cost is great. Increasing the building penetration margin from 6 dB to 13 dB would increase cost by about 60%, while also increasing coverage area signal reliability from 95% to 97% would roughly 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, 10 MHz 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.

As for build-out requirements, our analysis in (Hallahan & Peha, 2008) showed that approximately 83% of U.S. area is covered by at least one public safety wireless system while the build-out requirements specified in the 700MHz auction would likely require only 50% of U.S. area be covered by a new nationwide system. So while the previously established requirements would provide no coverage to much of the country that is currently covered, nevertheless, the FCC (2008c) has suggested relaxing build-out requirements even further (Hallahan, 2008). Of course, as discussed in (Hallahan & Peha, 2008), this would reduce deployment costs, but not as much as some have predicted (Federal Communications Commission [FCC], 2008b; Mobile Satellite Ventures, 2008). 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 minimal 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 (Peha, 2006). A primary disadvantage is that even though most users are commercial, 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-grade coverage area signal reliability of 97% (TIA TR8 Working Group 8.8, 1997) instead of 90% (which may be more typical of a commercial system) increases cost by roughly 70%. On the other hand, the sharing of capacity between these disparate user groups can lead to great cost savings (Hallahan & Peha, 2009). For example, increasing the aggregate capacity required by public safety during a large-scale emergency by 15% beyond our voice and data base case had a negligible impact on the cost of the 776MHz public-private partnership, but it increased the cost of the 776MHz public-safety-only network by about 15% and increased the cost of the 414MHz Extended IWN network by roughly 150%.

This paper presented estimates of the number of cell sites required for a nationwide, broadband, public-safety-grade wireless network under a variety of network deployment scenarios. In the absence of a more established model, this work presented rough estimates of public safety's capacity needs, but further study is needed in this important area. Additionally, this model considered only costs associated directly with a cell site and does not yet include backbone costs, replacement costs, or handset costs. We will continue to add detail to the cost model by incorporating additional factors, and to refine the numerical values used in the model in future work.

In addition to cost, there are a number of other challenges associated with establishing a nationwide wireless network for public safety which are outside the scope of this paper. Indeed, our analysis does not depend on the details of who pays for or operates the system, or the oversight and governance structures that are put into place. Thus, we have shown the relative merits with respect to

cost that can be achieved with different approaches, provided that the management and governance issues can be addressed and the benefits can be sufficiently dispersed across all local, state and federal decision makers to yield adequate incentives.

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