

The Business Case of a Nationwide Wireless Network that Serves both Public Safety and Commercial Subscribers^{*}

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Abstract

Deploying a single nationwide broadband wireless network to serve all public safety users would have great advantages over the existing fragmented public safety systems. A nationwide system could be created to serve both public safety and commercial subscribers, which would allow a provider to exploit important economies of scope but force it to meet the more costly requirements of public safety. In 2007, the U.S. Federal Communications Commission tried to establish a public-private partnership whereby a commercial partner would commit to serving public safety agencies in return for access to valuable spectrum in which it could serve paying customers. No commercial partner emerged from the initial auction, sparking intense debate about the potential of the underlying policy, whether it should be tried again, and if so, how. Thus, this paper considers the viability of a public-private partnership approach from a for-profit provider's perspective. To do so, we present a model to estimate the net present value (NPV) of a wireless network over a 10 year period by calculating costs based on the number of cell sites required and revenue based on the number of subscribers acquired using projections of market penetration each year. We apply this model to both a public-private partnership that serves commercial subscribers in addition to all public safety personnel on 20MHz of 700MHz spectrum, and a commercial-only network that serves just commercial subscribers on 10MHz of 700MHz spectrum.

We find that the NPV/cell is greater for the public-private partnership than for the commercial-only network for any population density in which the cells are deployed. This implies that the value of the additional 10MHz in the partnership is more than the cost to meet public safety's more stringent requirements. Furthermore, we demonstrate that the NPV/cell in both networks increases rapidly with population density such that urban regions are profitable and rural regions are unprofitable. This implies that rural areas are only covered by a network if build-out requirements are imposed on the license. We find that the population covered by a partnership can be increased from 56% (i.e. the region where NPV/cell > 0) to 93% and the partnership still breaks even (i.e. NPV = 0). In this case, the urban 56% of population acts to subsidize the coverage of the unprofitable 37% of population covered. Moreover, we find that if population covered is increased further to 99.3%, a public-private partnership is sustainable if given an upfront subsidy of about \$2B to cover initial costs. However, at this level of population coverage only 50% of area would be covered and thus, many rural agencies would be left out of such a nationwide network. Additionally, we find that urban areas opting-out of the partnership significantly reduces NPV while rural areas opting-out have no negative impact on NPV. Thus, if big cities are allowed to opt-out, this significantly increases the subsidies required to bring coverage to a given fraction of the country.

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1. Introduction

Deploying a nationwide wireless broadband network serving all public safety users in the US has the potential to address many of the shortcomings present in today's fragmented public safety communications infrastructure [1]. There have been a number of proposals for a nationwide public safety network, ranging from a nationwide system that would serve only public safety users, to a system that serves both public safety and the general public on the same infrastructure and spectrum. The proposal being considered in a current Federal Communications Commission (FCC) proceeding [2] [3] [4] calls for a public-private partnership to be established, and for the commercial provider in that partnership to commit to providing services that meet the needs of public safety in return for access to public safety spectrum, and the right to also serve paying customers in that spectrum.

It is clear that forming a public-private partnership requires the commitment of a private firm, but presently there is considerable uncertainty surrounding the sustainability of such a partnership, which may have deterred a partner from coming forward. In order for policymakers to determine whether or not to proceed with the current efforts to establish a public-private partnership or some other form of public-private partnership, it is important to better understand the cost and revenue that should be generated from such a partnership as well as which factors have the most significant impact on these projections. Thus, this paper considers a public-private partnership from a for-profit provider's perspective and analyzes the costs of building out and operating the necessary wireless infrastructure as well as the revenue that could be derived from serving commercial and public safety subscribers.

In section 1.1, we provide background on the current state of public safety communications in the US, while in section 1.2 we present and compare the recent proposals for building a nationwide public safety network. 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

First responders rely on wireless communications to accomplish their mission and ensure public safety. Unfortunately, recent tragedies and large scale disasters have highlighted that the existing public safety communication infrastructure lacks broadband functionality and suffers from a widespread lack of interoperability [5] [6]. Part of the problem is that this infrastructure is actually thousands of independently built and operated systems [7]. Past US spectrum policy of allocating spectrum individually to each of the approximately 50,000 state and local public safety agencies [8] resulted in a fragmented infrastructure consisting of systems deployed independently by most of these agencies. The limited coordination between agencies and the fact that a technical standard has yet to be widely adopted led to systems that are prone to failure when needed most. In addition, this spectrum policy has resulted in the public safety spectrum being substantially fragmented and allocated across 10 bands ranging from 20MHz to 4900MHz [9] [10] with limited spectrum available for broadband communications.

Having many small agencies deploy their own systems has also substantially increased the cost of the existing infrastructure while simultaneously making inefficient use of the

spectrum [7]. However, public safety communication costs could be dramatically lowered by increasing coordination between agencies, deploying systems over larger regions and by taking advantage of commercial wireless broadband technology and architecture [11]. In fact, it has been estimated that the existing infrastructure cost \$100 billion to deploy over the past 20 – 30 years [12], with billions more spent each year to upgrade and maintain this aging infrastructure. However, a nationwide broadband network may actually save money when compared to the costs of the existing public safety infrastructure with estimates of about \$10 billion for the deployment cost of a single 700MHz nationwide network that carries both voice and data traffic [11].

Furthermore, a nationwide public safety wireless network avoids many of the shortcomings of the previous policy [1]. 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. Meanwhile, 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

While a nationwide public safety wireless network has the potential to be an improvement over the existing infrastructure, it also represents a dramatic shift in US spectrum policy. As such, there are a number of outstanding questions as to how to best go about establishing a nationwide network for public safety. In fact, there are two fundamentally different approaches to the creation of such a nationwide network: (1) a public-safety-only network which is a network that would serve only public safety users, and (2) a joint-use commercial and public safety network that would serve both commercial and public safety users on the same spectrum and infrastructure [1].

One proposal for a nationwide 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 only federal public safety users [13]. 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 [14]. Currently, a nationwide public-safety-only network that serves all public safety users, such as an extended IWN [11], does not appear to be a proposal that policymakers are seriously considering.

Instead, a number of proposals calling for a network that serves both commercial and public safety users have received considerable attention [15] [16]. Such a joint-use network would benefit from the fact that a majority of the time, public safety users do not use all of the available capacity on their wireless systems [17] [18]. This is because public safety systems are typically designed for worst-case capacity demand scenarios such as during large-scale emergencies. Thus, if commercial and public safety entities 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 during those infrequent emergencies when it is needed. However, a joint-use network would need to meet the more stringent requirements of public safety users, leading to higher costs than would be expected in a commercial-only network.

In the US, a joint-use commercial and public safety network in the form of a public-private partnership is currently being considered by decision makers. The FCC first advanced their proposal for a partnership in August 2007 [2], and in it a commercial partner would commit to providing services that meet the needs of public safety. In return, the commercial partner gains the right to serve commercial customers as well as public safety customers on both commercial and public safety spectrum. More specifically, in the initial proposal the FCC designated a 10MHz portion of the 700MHz spectrum band specifically for public safety broadband use nationwide and licensed that spectrum to a single public safety representative. Additionally, the FCC created a 10MHz commercial license for the spectrum adjacent to the public safety allocation, which was later auctioned in February 2008. The winner of that auction would have been required to build out a public-safety-grade network on the 20MHz of combined spectrum, which would serve both public safety and commercial users.

No winning bidder emerged from the initial auction, sparking debate about the potential of the underlying policy and whether or not it should be tried again. This led the FCC to reexamine the rules that were attached to the commercial block of spectrum and to consider changes before any re-auction [3] [4]. One proposed change is to reduce the coverage requirements imposed on the commercial provider which may make a partnership more attractive. However, this could result in many areas not being served by a new system [19]. At the same time, several major cities have recently indicated that they are interested in opting-out of any partnership [20]. Without the ability to serve commercial subscribers in these urban centers, a nationwide network could become less appealing to a commercial provider.

1.3. Research Questions

Given the uncertainty surrounding the viability of a public-private partnership and the various changes being proposed, there are a number of questions that should be answered before any policy decisions are made. This paper hopes to inform the current debate by addressing several fundamental questions about the sustainability of a public-private partnership from the point-of-view of a for-profit commercial carrier. We define three categories to describe the viability of a public-private partnership: (1) profitable, which means that under a given set of conditions the partnership is always profitable; (2) sustainable but not profitable, which means that in the short term a partnership is not profitable, but given some level of upfront subsidy the partnership is sustainable in the long run; and (3) unsustainable, which means that in both the short and long term the partnership is unprofitable and thus unsustainable even if provided an upfront subsidy to cover initial costs.

To do so, we study the future cash flows (both cost and revenue) for both a public-private partnership operating on 20MHz of 700MHz and a commercial-only network operating on 10MHz of 700MHz spectrum and use these flows to calculate the network's net present value

(NPV). In this paper, we present an extensible model based on previous work [11] that is used to calculate the number of cell sites required given that deployment and operating costs are roughly proportional to the number of cells in a network. The model also calculates the number of public safety and commercial subscribers served by the network which is used to estimate future revenue. Additionally, the cost and revenue estimates are dependent on the amount of spectrum allocated, the build-out coverage requirements, the design parameters of the network (e.g. aggregate capacity required, signal reliability required, target market penetration), and financial factors (e.g. costs per cell and revenue per subscriber) and thus we study how the cash flows depend on these parameters. By studying how the cost and revenue change, we identify the conditions under which a partnership is profitable, sustainable, and/or unsustainable which can help decision makers as they craft future public-private partnership policy.

In answering questions about network sustainability, we also identify the areas of the US in which a wireless network is profitable. By finding the cells which have a positive NPV, we can classify the regions which a for-profit carrier is likely to target for service, and determine whether or not urban areas are more attractive than rural areas. To do so, we study how network cost and revenue depend on the population density of the area being served. We find that costs tend to increase as population density increases since costs depend on cell size and cell size decreases as population density increases. This is due to the fact that a wireless signal's path loss and network capacity requirements increase as the covered area becomes more urban. We also find that revenue tends to increase as population density increases since revenue depends on the number of subscribers served (and this is greater for cells in more urban areas).

Another question important to policymakers concerns the value of commercial access to the public safety spectrum. The answer to this question will have a significant impact on the auction price set for the commercial license in a re-auction. We answer this question by comparing the NPV of the public-private partnership to the NPV of a commercial-only network. The difference between the two NPV's is the value of commercial access to the additional 10MHz of spectrum. In this case, the NPV differs between the two due to the differing amounts of spectrum available and the differing design requirements typically placed on the two types of networks. While access to additional spectrum will tend to increase the NPV of a network, the fact that going from a commercial-grade to a public-safety-grade network imposes more stringent requirements (e.g. greater aggregate capacity and signal reliability required) will tend to decrease the NPV of a network. Therefore, depending on the requirements placed on the winning bidder, it is possible that access to the additional 10MHz of spectrum may only be attractive to a commercial carrier if the license price is negative (i.e. the winning bidder receives a subsidy of some amount for accepting the license).

Finally, an increasingly important question for policymakers is whether or not to grant waivers to individual cities that wish to opt-out of a nationwide partnership. Presently, there are a number of municipalities which have shown potential interest in opting-out of a network. Indeed, several have officially filed requests with the FCC for a waiver to deploy their own networks on the public-safety portion of the 20MHz of spectrum allocated to the partnership [20]. Under the current rules, waivers could be granted to municipalities allowing them to build out a network in their area on the 10MHz of public safety spectrum. However, it is also

conceivable that these waivers could be for the full 20MHz of combined public safety and commercial spectrum, but this would require additional legislation. Therefore, we have defined several different sets of municipalities that cover a range of potential opt-out scenarios and for each we study both waivers for 10MHz and 20MHz. In our analysis, we compare the NPV for the partnership with and without each set of opt-out cities to determine how the number of cities opting-out changes the overall NPV of the partnership.

By understanding how different parameters impact the partnership differently, policymakers will be better able to craft the requirements that will be placed on the public-private partnership. We therefore investigate which system characteristics have the largest impact on the results. There are many factors which impact the required number of cells for a network (and therefore cost) and these factors often differ between typical public safety and commercial wireless systems. For example, the capacity required in a cell by commercial and public safety subscribers is different at both the individual user level (where first responders tend to require higher data rate applications like video) and in the aggregate (when many first responders must respond to the same emergency and thus are concentrated). Several factors also impact the network's revenue such as market penetration and revenue per subscriber. In general, the following parameters are studied in this paper: the amount of area covered by the partnership, the technical requirements of a public-safety-grade network including coverage reliability and capacity requirements, as well as financial factors such as the revenue per subscriber and costs per cell site.

1.4. Paper Layout

In section 2 of this paper, we introduce the model we developed to calculate the number of cell sites required and subscribers served by a network in order to estimate network cost and revenue. In section 3, we discuss the various scenarios studied and summarize the numerical values used as inputs to this model for each scenario. Section 4 provides the results of the model including an estimate of the NPV of the public-private partnership and how these results change as the input values to the model are varied. Finally, in section 5 we discuss our conclusions.

2. Model

This paper uses an extensible model to calculate the net present value (NPV) of a greenfield public-private partnership under different conditions by estimating future cost and revenue cash flows in a given time horizon. At a high level, our model estimates network costs (both upfront and ongoing costs) based on the number of cell sites that are required nationwide under a given set of requirements. To do so, our model calculates the maximum cell size in each zip code using equations that differentiate regions using population density. To calculate revenue we estimate the number of public safety and commercial subscribers served using projections of market penetration, and derive income using estimates of revenue per subscriber based on the experience of past providers. We then find NPV by discounting the future cash flows over a given time horizon by a set discount rate.

In this section, we explore the various components of this model. In section 2.1, we discuss the amount of population and area covered by a network and the rate at which cells are

built to reach this level of coverage. In section 2.2, we describe in greater detail how the model calculates the number of cell sites required and how network cost is estimated from this number. Section 2.3 describes how the number of subscribers served is estimated and how that number is used to calculate revenue. Finally, section 2.4 discusses how the NPV is calculated from the future cost and revenue cash flows.

2.1. Area Covered and Build-out Timeline

The amount of area covered has a significant impact on both cost and revenue. For one, the number of cells required (and therefore cost) is dependent on the amount of area that is covered. At the same time, the number of subscribers covered (and therefore revenue) is also dependent on the amount of area covered. Similarly, the rate at which the area is covered also has a considerable impact on cost and revenue. This is because the number of cell sites that are deployed each year directly affects that year's capital costs. A rapid roll out will require a much greater upfront capital outlay in the earlier years than a more gradual network deployment. At the same time, no revenue can be generated in a region until service is available there and that requires cells to be deployed; so, the rate of deployment also affects the revenue generated each year. Thus, since we are considering a series of future cash flows which will ultimately be discounted to a present value, the rate of the roll out can have a significant impact on the present value of both cost and revenue cash flows.

In the base case, we adopt the coverage area requirements and build-out timeline attached to the license that was previously auctioned in February 2008 [2]. More specifically, we model a network that will cover 75% of population after 4 years, 95% of population after 7 years, and 99.3% of population after 10 years. Furthermore, we assume that the build-out of cell sites is constant in between each milestone (e.g. if 10,000 cell sites were deployed to reach 75% population coverage by the 4th year, 2,500 were actually deployed in years 1 – 4). Finally, for some of our analysis in section 4, we study build-out requirements that differ from the 99.3% of population used in the base case. In these scenarios, we assume that the build out of cells each year is constant over the 10 year period.

As discussed in [11], 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. Since, our model calls for the build-out requirement to be expressed as a fraction of US area covered (not as a fraction of population as the FCC has done), we have developed a method [11] [21] that uses zip code level census data to convert a fraction of US population covered to a fraction of US geographic area covered. In this case, 75% of US population corresponds to about 6% of US area, 95% of population to 28% of area, and 99.3% of population to 50% of area.

2.2. Cells and Cost

In this paper, we build on the extensible model established in previous work [11] to calculate the number of cell sites required by a public-safety-grade network under a variety of conditions. The number of cells is important given that in a cellular architecture costs are roughly proportional to the number of cell sites required and in the network proposals we consider a cellular architecture is the most cost-effective design. In section 2.2.1, we describe in

more detail how the model calculates the number of cell sites required and in section 2.2.2, we describe how costs are estimated based on the number of cells.

2.2.1. Calculating the Number of Cells

At a high level, we find the total number of cells required by calculating the expected number of cell sites per region for all regions covered by the network. This is done 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 statistics¹ [22] and expected cell size depends on population density because the capacity required in a cell and the appropriate propagation model for a cell are dependent on population density. As discussed in [11], zip code level granularity appears to be reasonable given that the number of cells nationwide is comparable to the number zip codes.

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. As we have shown previously [11], first responder density is a linear function of population density. (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. the maximum allowable path loss) using a link budget which 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. (4) By calculating the radius of a cell using a propagation model that takes as inputs the path loss, frequency of operation, and heights of the mobile and basestation antennas while differentiating between urban, suburban, and rural regions.

In this work, we consider a CDMA based system which would be typical of a 3G network deployment [23]. Consistent with a typical CDMA network, we have assumed that the bandwidth allocated is divided into 1.25MHz channels with traffic distributed equally across the channels [23]. Also typical of a CDMA system, our model considers a network with a frequency reuse factor of 1 (i.e. every cell can operate on each channel) and that all cells in the network have 3 sectors, to limit co-channel interference. This model only considers the uplink as it is assumed to be the limiting link in determining the size of a cell, which is usually the case in a CDMA system where the mobile devices transmit at lower power than basestation and co-channel interference from other mobiles operating on the same channel is present at the basestation [23]. We further assume that the uplink is perfectly power controlled as is typically done when analyzing CDMA systems [23] [24]. In typical CDMA network planning, cells typically overlap by 10 – 30% [23] [25]. We have assumed an overlap of 17%, which would be consistent with cells that are hexagonal as opposed to circular. Beyond this level of cell overlap, we assume no fault tolerance in the design of this public safety network meaning the loss of any

¹ In this analysis, we use Zip Code Tabulation Areas (ZCTAs) which are a set of nationwide tabulation areas created by the Census Bureau and based on postal zip codes [22].

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 [1].

As discussed in much greater detail in [11], our model uses the following equation to predict the typical radius of a cell in each region:

$$K_5 + 10 \bullet \log_{10} \left(\frac{K_1}{1 - (K_2 + K_3)} \right) = K_0 - K_4 + K \quad \{2.2.1-1\}$$

Where:

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

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

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

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

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

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

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

And where:

β_{MAX}	Measure of the capacity required by the highest user datarate guaranteed at cell-edge	
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	
$fract$	Other cell interference as a fraction of same cell interference	
Pen	Market penetration as a fraction of population covered	
Num	Number of uplink channels available in the sector	
$Sect$	Number of sectors per cell	
$\rho_{FR,j}$	First Responder density in the jth cell	[km ⁻²]
$\rho_{POP,j}$	Population density in the jth cell	[km ⁻²]
$A_{hexagon,j}$	Area of the jth cell = 2.59808 r_j^2	[km ²]
r_j	Radius of the jth cell	[km]
h_m	Height of mobile transmitter	[m]
h_b	Height of basestation antenna	[m]
f	Frequency	[MHz]
η	Environmental noise power at the receiver	[W]
$EIRP$	Effective isotropic radiated power	[dBm]
G_{RX}	Receiving antenna gain	[dBm]
$L_{IMPLEMENT}$	Receiver implementation losses	[dB]

$L_{RELIABLE}$	Shadowing plus fast fading margin	[dB]
L_{BUILD}	In-building penetration margin	[dB]
$L_{SCENARIO}$	Scenario loss margin	[dB]

Many of the variables present in equation {2.2.1-1} can take a range of numerical values and each is discussed in greater detail in [11], while the base case values used in our analysis are summarized in section 3.1.

2.2.1.1. Hata Modification

In equation {2.2.1-1}, we use the Hata model [26] to predict propagation path loss. The equations used in the Hata model are different for urban, suburban, or rural regions. This classification is commonly made based on population density [27]. There is no universally accepted population density threshold which separates these categories, so 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 [27].

Using the standard Hata model [26], with appropriate values for frequency, height of basestation antenna, and height of mobile transmitter as described in [11], we calculate radius r as follows

$$r = \begin{cases} 0.0016319 \bullet e^{0.0692442 \bullet PL} & \text{Rural} & \{2.2.1.1-1\} \\ 0.0004588 \bullet e^{0.0692442 \bullet PL} & \text{Suburban} & \{2.2.1.1-2\} \\ 0.0002366 \bullet e^{0.0692442 \bullet PL} & \text{Urban} & \{2.2.1.1-3\} \end{cases}$$

This model is sufficient for most of our work, but in some of our analysis, we would like to study the costs as a function of population density. Since the Hata model has only three classifications, we needed to develop a finer grain propagation model that is a function of population density. In the equations above, only the coefficient before the exponential varies by region. By assigning a population density to each of these coefficients, we have three points through which to fit a curve. Using regression analysis, a power-law fit provides the largest R^2 and produces results that most closely reproduce the results of the original equations in practice. Therefore, instead of equations 2.2.1.1-1 through 2.2.1.1-3, we use the following equation for certain pieces of analysis which will be discussed in section 4.1:

$$r = 0.0019 \bullet \rho_{POP}^{-0.194} \bullet e^{0.0692442 \bullet PL} \quad \{2.2.1.1-4\}$$

2.2.1.2. Commercial Market Penetration

In our model, the market penetration variable, Pen , represents the fraction of population covered that the network is designed to serve. This variable can significantly impact the size of cells in a network since cell size depends on capacity required and capacity required depends on how many subscribers are served. That means the greater the penetration, the more cells will be required and thus the more the network will cost. However, this greater cost is offset by increased revenue due to more subscribers.

In this paper, we assume that the network planner first determines the number cell sites required to provide a given capacity with a fixed bandwidth (with this capacity dependent on the commercial penetration), and then builds out that number of cells over a ten year period. The amount of capacity (and thus commercial penetration) is chosen to maximize profit over that period. We recognize that systems may be designed initially for a given capacity, and then that capacity is later increased through cell splitting, adding additional cell sites to covered areas, or gaining access to additional spectrum, but we will assume that this does not occur before year 10. Under these assumptions, as well as our assumptions regarding the growth rate of market penetration which is discussed in section 2.3.1, we find² that a profit-maximizing provider public-private partnership operating in 20MHz should initially design the network to support a market penetration of 8.5%, whereas a commercial-only system operating in 10MHz should initially design for a market penetration of 3%.

2.2.2. Estimating Costs from Cells

Section 2.2.1 provided the equations to calculate the number of cell sites, and from this number we can estimate total infrastructure cost using cost per cell site estimates. We estimate both the upfront deployment costs for the infrastructure and recurring annual operating costs. However, we only consider costs associated with the installation and operation of cell sites, and not the costs of the core network including mobile switching centers (MSCs), the costs of network planning and administration, or the costs of handset as they are not part of the infrastructure. Furthermore, consistent with one of the proposals for the partnership [16], we calculate costs and revenues for a commercial provider that adopts a wholesale business model. As such, we neglect the costs of operating a commercial retail service, including the costs to acquire subscribers as this would not be necessary as a wholesale provider, and adjust revenue per user accordingly.

There are a variety of factors that contribute to the upfront and recurring costs of a cell site but the dominant capital costs tend to be the costs to purchase and install the equipment, electronics and antennas at the base station while the dominant recurring costs include maintenance, the utilities and backhaul costs. The construction or lease of the tower site itself is also a considerable expense and depends on whether it is necessary to build a new tower or if it is possible to lease space on an existing one. To facilitate comparison with existing analysis, we will consider the cost of towers as an upfront deployment cost. As discussed in [11], in the base case we use an estimate of \$500 thousand per site for the upfront cost and \$75 thousand per site for the operating cost, consistent with estimates in similar analysis [27] [28] [29].

2.3. Subscribers and Revenue

While the previous section focused on calculating the number of cells required to cover a desired area and the area covered by each cell, those same equations can also be used to determine the population covered by each of the cells. From population covered, we calculate the number of subscribers by determining the fraction of population that subscribes to the

² While outside the scope of this paper, we found by running many simulations with varied target market penetrations that 8.5% is the value that maximizes the NPV for a public-private partnership in the base case while 3% maximizes NPV of the commercial-only partner in the base case.

network as discussed in section 2.3.1 and then we calculate revenue using estimates of the revenue per subscriber discussed in section 2.3.2.

2.3.1. Calculating the Number of Subscribers

In a public-private partnership, there are two types of subscribers: public safety and commercial users. We can calculate the number of both types of users based on the population covered by the network. In this section, we first explore how commercial subscribers are calculated by looking at projections from a commercial carrier and then consider how to calculate public safety subscriptions using the linear relationship between first responder density and population density found in [11].

In section 2.2.1.2, we discussed the variable *Pen* which represents the target market penetration that is planned for when deploying the network. However, simply because a given level of penetration is planned for, there is no guarantee that the service provider ever achieves it. In addition, the actual market penetration is zero initially but increases each year and the rate at which this market penetration increases can have a significant impact on revenue. Thus, we need to determine not just what the final market penetration is, but the market penetration by year.

While it is impossible to predict exactly what this market penetration is each year, we can use the experience of a similar market entrant as a guide. In this case, we study the actual and projected market penetration for the company Clearwire. Clearwire is a new entrant in the commercial wireless market and is currently in the process of deploying a greenfield nationwide broadband wireless network. The following table summarizes the yearly market penetration for Clearwire in their first 10 years based on the company’s actual and projected population coverage and subscription data [30].

Year	1	2	3	4	5	6	7	8	9	10
POP Covered	4.6E+06	9.6E+06	1.6E+07	1.7E+07	7.0E+07	1.3E+08	1.5E+08	--	--	1.9E+08
Subscribers	6.2E+04	2.1E+05	3.9E+05	4.6E+05	1.3E+06	4.6E+06	8.5E+06	--	--	2.0E+07
Penetration	1.35%	2.15%	2.42%	2.74%	3.14% ³	3.54%	5.67%	7.20% ⁴	8.73% ⁴	10.26%

Table 1: Clearwire’s actual and projected market penetration for the first 10 years.

Thus, in the base case, we use this table to calculate the number of commercial subscribers the partnership obtains each year by taking the population covered by the network’s cell sites that year and multiplying by that year’s market penetration. However, if utilization ever reaches the maximum capacity designed for, causing commercial users to see a decline in grade of service beyond design thresholds, we assume that this decline in grade of service will deter expansion, and market penetration will remain constant. In a typical system, this might motivate a provider to split cells or acquire additional spectrum, but we assume such things do not happen before year 10. As discussed in section 2.2.1.2, the maximum capacity corresponds

³ Year 5 is where the actual and projected data intersect, resulting in a dip in market penetration. As such, we instead use a value for market penetration that is midway between the market penetration of years 4 and 6.

⁴ There is no projected data available for years 8 and 9, thus the market penetrations for these two years was interpolated from years 7 and 10.

to the set level of commercial penetration, Pen , which the network is designed for when it is deployed. Thus, in the base case where Pen equals 8.5%, and based on Table 1 above, this threshold market penetration of 8.5% is achieved in the 9th year. However, it should be noted that there is no guarantee that the commercial provider will actually achieve this market penetration or at the rate projected. This is an additional risk that is beyond the scope of this paper.

In addition to commercial subscribers, the public-private partnership is able to serve public safety subscribers as well. As discussed in [11], first responder density is a linear function of population density, and thus we can calculate the number of first responders covered from the population covered in a region and the population density for that region. Furthermore, in this work we make the optimistic assumption that all public safety agencies will use this network and will subscribe as soon as they are covered. As we will show in section 4.5.2, even with this assumption, most revenues come from commercial subscribers, so this assumption has limited impact on our results. In addition, we assume only one subscription will be purchased for every 2.5 first responders which is consistent with similar analysis [28]. This seems reasonable given that not all first responders work on the same shift and therefore radios are typically shared to reduce costs.

2.3.2. Estimating Revenue from Subscribers

Given the number of public safety and commercial subscriptions, revenue can be calculated by multiplying the number of each type of subscription by the revenue derived from each subscription. For commercial wireless services, the industry average revenue per user, ARPU, is about 50 dollars per month [31]. However, this number represents the industry average for retail customers and since we are considering a wholesale business model, we chose a value of 10 dollars per subscription per month in the base case. This number is based on the revenue a major wireless carrier receives from its wholesale operations and is inline with the value used in similar analysis [28].

Unlike on the commercial side where the public-private partnership operates a wholesale business model, in this work public safety subscribers are treated as retail customers. The partnership must provide billing and administrative services to its public safety subscribers, but can also expect to charge more than it charges the wholesale customers. In the base case, we assume that each public safety subscription generates 30 dollars in revenue each month for the partnership. This is consistent with a monthly service fee of 50 dollars per month and retail operating costs that equal 40% of retail revenue as suggested in similar analysis [28]. A monthly service fee of 50 dollars per subscription is inline with the monthly fee of \$48.50 per user that the FCC proposed as a base rate to be charged to all public safety users by the public-private partnership [4].

2.4. Net Present Value

Having developed a method to calculate the cost and revenue cash flows for each year into the future, we can now calculate the net present value. Net present value is useful as it allows us to compare different projects with different future cash flows over different time

horizons using just a single number that still accounts for the time value of money. Generally, NPV is calculated using the following equation [32]:

$$NPV = \sum_{i=0}^n \frac{x_i}{(1 + D)^i} \quad \{2.4-1\}$$

Where:

D	Discount Rate	
n	Time Horizon	[Years]
x_i	The Difference between Revenue and Cost in the i th Year	[\$]

In the base case, we have chosen a time horizon of 10 years for the NPV calculations. This seems reasonable, given that the public-private partnership has a build-out timeline of 10 years in the base case, and when it was auctioned it carried an initial license term of 10 years (although licenses are usually renewed) [33]. Additionally, we chose a value of 8% for the discount rate in the base case, consistent with the value used in similar analysis [34].

Substituting in the appropriate expressions for revenue and cost yields:

$$NPV = \sum_{i=0}^n \frac{(12 \cdot (Sub_{PS,i} \cdot R_{PS} + Sub_{COMM,i} \cdot R_{COMM}) - (C_i \cdot Capex + C_{TOT,i} \cdot Opex))}{(1 + D)^i} \quad \{2.4-2\}$$

Where:

$Sub_{PS,i}$	Total Number of Public Safety Subscriptions by the i th Year
$Sub_{COMM,i}$	Total Number of Commercial Subscriptions by the i th Year
R_{PS}	Monthly Revenue per Public Safety Subscription
R_{COMM}	Monthly Revenue per Commercial Subscription
C_i	Number of Cell Sites Deployed in the i th Year
$C_{TOT,i}$	Total Number of Cell Sites Operating in the i th Year
$Capex$	Upfront Cost to Deploy a Cell Site
$Opex$	Annual Cost to Operate a Cell Site

3. Scenarios Studied

In this paper, we study two different network scenarios where a network scenario is the name given to a distinct set of numerical input values that we analyze with our model. While the focus of this paper is on a public-private partnership, it is useful to also study a commercial-only network to establish a basis for comparison. For instance, we can learn what the value of access to the 10MHz of public safety spectrum is by comparing the NPV's of a public-private partnership to that of a commercial-only system. We also study what happens to the NPV of a partnership when urban areas opt-out of a partnership and instead deploy their own networks. To do so, we define 4 sets of municipalities to represent a range of different opt-out scenarios.

In section 3.1, we highlight the differences between inputs used in a public-private partnership and a commercial-only network and then summarize all of the base case numerical values used for the input parameters to each of the scenarios. In section 3.2, we define the 4 different sets of municipalities used to study a broad range of different opt-out scenarios.

3.1. Public-Private Partnership vs. Commercial-Only Network

Compared to a public-private partnership, which must be built to public-safety-grade due to the public safety users that are served by the network, a commercial-only system only needs to meet the less stringent requirements of commercial subscribers. This means that the numerical values used for several of the model inputs in a commercial-only network differ from the values used for a public-private partnership. More specifically, the following inputs differ between the two scenarios: spectrum bandwidth allocated, aggregate capacity required during an emergency, the capacity required for routine public safety traffic, capacity required for the highest datarate application, maximum mobile transmit power, coverage reliability margin and in-building penetration margin [11].

As discussed in section 1.2, the public-private partnership is allocated 20MHz of combined commercial and public safety spectrum in the base case, but for the commercial-only network, only the 10MHz of commercial spectrum is available in the base case. The additional spectrum allocated to the public-private partnership comes with the tradeoff of having to meet public-safety capacity requirements. The capacity model we developed in [11] takes the following three parameters as inputs:

β_{MAX}	Measure of the capacity required by the highest user datarate guaranteed at cell-edge
β_{SUM}	Measure of the aggregate capacity required in a localized emergency per sector
ρ_{BRT}	Measure of the capacity required per first responder due to routine traffic

The values chosen for each of these variables in the base case for a public-private partnership is discussed in detail in [11]. By definition, β_{SUM} and ρ_{BRT} are a function of the emergency and routine capacity required by public safety users. Since no public safety users are supported on the commercial-only network, the value of both β_{SUM} and ρ_{BRT} are set to zero in that scenario. Meanwhile, β_{MAX} is a function of the highest upstream datarate guaranteed at the cell-edge and this datarate likely differs between a network that supports public safety users and one that only supports commercial users. Conceivably, β_{MAX} could be set such that it is sufficient for public-safety-grade real-time video, about 360kbps, or could be set to a much lower value like 10kbps, which is sufficient for voice. In the base case, we have chosen a value of 50kbps which is consistent with similar analysis of a commercial network [27]. Based on the β_{MAX} equation provided in [11], we calculate a β_{MAX} value of 0.14 using 50kbps as the input.

Furthermore, the desire for longer battery life and/or smaller and lighter mobile devices means a typical commercial handset transmits at a lower power than a public safety device. Thus, for a commercial-only network in the base case, we choose a transmit power of about 250mW or 24dBm [27] compared to the 37dBm expected from public safety devices in a public-private partnership [11]. Also, since a commercial-only network is not required to support mission critical applications, a lower level of signal coverage reliability is tolerable. Therefore, in the base case, we choose a signal coverage reliability of 90% for the commercial-only network, which is consistent with [35] and down from the 97% level used for the public-private partnership [11] [35]. Consistent with similar analysis [27], the in-building penetration margin

required for commercial users can be reduced from the 13dB margin used in a public-private partnership [11] [36], to a 6dB margin which should be sufficient for reliable service in most vehicles [37].

In the following table, we summarize the inputs used in the model, the numerical values chosen in the base case for each of the two scenarios studied and we list the section/reference in which the value is discussed.

	Input	Pub-Priv	Comm-Only	Units	Section or Reference	Description
LINK BUDGET	$EIRP$	37	24	dBm	§ 3.1	Transmit Power (3W & 0.25W)
	G_{RX}	18	18	dBi	[11]	Receiving Antenna Gain
	$L_{RELIABLE}$	12.6	6.9	dB	§ 3.1	97% & 90% Coverage Reliability Margin
	L_{BUILD}	13	6	dB	§ 3.1	Building Penetration Margin
	$L_{IMPLEMENT}$	4	4	dB	[11]	Implementation Losses
	$L_{SCENARIO}$	4	4	dB	[11]	Scenario Losses
PROPAGATION	F	776	776	MHz	[11]	Transmit Frequency
	h_m	1.5	1.5	M	[11]	Height of Mobile Transmitter
	h_b	60	60	M	[11]	Base Station Antenna Height
	W	20	10	MHz	§ 3.1	Bandwidth of Spectrum Allocation
CAPACITY	β_{SUM}	2.5	0	--	§ 3.1	Measure of PS Emergency Capacity Req'd
	$\rho_{\beta RT}$	0.0055	0	--	§ 3.1	Measure of PS Routine Capacity Req'd
	β_{MAX}	0.34	0.14	--	§ 3.1	Measure of Highest Datarate Guaranteed
	$\rho_{\beta SUB}$	0.0029	0.0029	--	[11]	Measure of Commercial Capacity/Sub
	Pen	0.085	0.03	--	§ 2.2.1.2	Commercial Market Penetration
	$Fract$	0.6	0.6	--	[11]	Other Cell Interference
NPV	n	10	10	yrs.	§ 2.4	Time Horizon
	D	8%	8%	--	§ 2.4	Discount Rate
Cost & Revenue	R_{PS}	30	0	\$/mo.	§ 2.3.2	Monthly Revenue per Public Safety Sub
	R_{COMM}	10	10	\$/mo.	§ 2.3.2	Monthly Revenue per Commercial Sub
	$Capex$	500,000	500,000	\$	§ 2.2.2	Upfront Cost to Deploy a Cell Site
	$Opex$	75,000	75,000	\$/yr.	§ 2.2.2	Annual Cost to Operate a Cell Site

Table 2: Summary of numerical input values used to analyze the public-private partnership and commercial-only scenarios.

3.2. Opt-out Scenarios

As discussed in section 1.2, we consider the possibility that some urban municipalities may want to opt-out of the public-private partnership and instead deploy their own networks. In order to study what impact, if any, this would have on the sustainability of the partnership, we define 4 sets of municipalities in this section which represent a range of possible opt-out scenarios. For each of these sets, we will consider two possibilities: 1. each of the municipalities included in the set receives a waiver for the 10MHz of public safety spectrum, in which case the

public-private partnership operates as a commercial-only network in the areas where the opt-out occurs; and 2. each of the municipalities included in the set receives a waiver for the full 20MHz of public safety spectrum, in which case the public-private partnership is unable to offer any service in the opt-out areas. It should be noted that in order for waivers for the full 20MHz to be granted, additional legislation would need to be passed.

Each of the 4 sets, which we define below, consists of a distinct set of counties in the US. In some cases, it is the counties that are pursuing waivers. In other cases, cities are requesting waivers. However, even there, city governments generally need to provide communications for their first responders beyond city limits. Thus, we approximate this effect by using county boundaries for all municipalities studied [38]. The 4 distinct sets of municipalities we defined for this paper are summarized below with a detailed list of the municipalities included in each set available in Appendix 7.A.

The first set includes only the 5 counties in New York City and the District of Columbia. This set is meant to represent what would happen if only the two major urban areas which have already deployed a broadband wireless network for public-safety [39,40,41,42] were to opt-out of the partnership.

The second set includes the 5 counties in New York City, the District of Columbia, and the counties which contain the following major cities: Boston, San Jose, San Francisco and Oakland. This set represents what would happen if 6 major cities around the US were to opt-out of the partnership. This list is consistent with the earliest group of cities to file for a waiver with the FCC [20,43,44,45,46,47,48,49].

The third set investigates what happens if the surrounding areas around the urban centers decide to opt-out as well. This set includes all the counties in the second set, but also includes the counties within the National Capital Region that surrounds the District of Columbia, the ten county San Francisco Bay Area which includes San Jose and Oakland, and the three county Metro Boston region. In addition, the 21 counties within the state of New Jersey are added as well. This list is consistent with the broader regions envisioned for coverage by the municipalities included in set 2 (and New Jersey) when they filed for waivers as of the end of June 2009 [20,43,44,45,46,47,48,49].

Finally, the fourth set considers what would happen if the majority of urban municipalities were to opt-out of the partnership. To form this set, we included 55 of the largest municipalities across the US. This set of 55 is consistent with the members of the Major Cities Chiefs Association which represent many of the largest public safety agencies in the country. Furthermore, this association recently sent a letter to the FCC expressing concerns about a commercially run wireless network serving public safety and expressing interest in the possibility of all 20 MHz of spectrum currently earmarked for the public-private partnership being licensed directly to public safety [50] [51]. The complete list of municipalities included in this set is available in Appendix 7.A.

4. Results

The goal of this section is to identify the conditions under which a public-private partnership is profitable, sustainable, and/or unsustainable in an effort to aid decision makers as they craft future public-private partnership policy. In the process, this section addresses several fundamental questions surrounding the viability of the public-private partnership from the point-of-view of a for-profit commercial carrier. We find the answers to these questions by studying the NPV of the public-private partnership under various conditions, which we calculate as described in section 2. It is also useful to compare the NPV of the partnership to the NPV of a commercial-only system but some preliminary steps are required before we can do so.

More specifically, we need to know the fraction of the US that a commercial-only system will cover before we can calculate the NPV of the network. Under current rules, the build out of a public-private partnership must meet certain benchmarks, with a set level of population covered after a set number of years. However, such rules probably would not apply to a commercial-only system and so the area a commercial-only network will cover must be determined. To do so, we identify the areas of the US in which the network proposals we study are profitable. This involves calculating the NPV of a cell as a function of population density, then finding the cells which have a positive NPV. And once we know how much area a for-profit carrier would prefer to serve, we can calculate the NPV for the entire network (as opposed to the NPV of individual cells) assuming all profitable areas are covered.

By comparing the NPV of a public-private partnership to that of a commercial-only system, we can determine the value of access to the 10MHz of public safety spectrum and determine what level of subsidy, if any, would be required to make the public-private partnership attractive. By studying how the NPV of the public-private partnership changes over time, we can see whether or not it is sustainable in the long term.

Additionally, we study how our answers change as we vary the parameters of the public-private partnership. First, we investigate which system characteristics (e.g. public safety signal reliability and capacity requirements) have the largest impact on the results. Similarly, we study which financial factors (e.g. revenue per subscriber and cost per cell) have the largest impact on the results. Finally, we consider what the impact urban areas opting-out of a partnership would have given that a several municipalities have shown interest in using the spectrum on their own.

In section 4.1, we study the NPV per cell as a function of population density for both a public-private partnership and a commercial-only network. In section 4.2, we find the value of access to the 10MHz of public safety spectrum and show how this value varies as the build-out requirements of a public-private partnership varies. Then, in section 4.3, we discuss the sustainability of a public-private partnership based on its NPV and how that NPV changes over time. Then in sections 4.4 and 4.5 we study how these results depends on system characteristics (e.g. public safety capacity and signal reliability requirements) and financial factors (e.g. revenue per subscriber and costs per cell). Finally, in section 4.6 we study the impact that urban areas opting-out of the partnership will have on the sustainability of the partnership.

4.1. Regions of Profitability

We can answer a number of important questions by analyzing the NPV per cell site. This includes determining whether or not it is more desirable to build out a network in urban areas or rural areas. Also, we can figure out what regions of population density a commercial provider would likely target. Or, put another way, when a commercial provider is building out its network, at what point does it stop building additional cell sites if not compelled by license requirements?

To calculate the NPV per cell, we calculate the cost to build out and operate a cell at a given population density, as described above in section 2.2. Then, we calculate the number of subscribers covered by that cell, and calculate the revenue derived from those subscribers as described in section 2.3. The NPV for each cell can then be calculated from these cash flows. In the following figure, we plot the NPV per cell as a function of population density for both a public-private partnership as well as a commercial-only network.

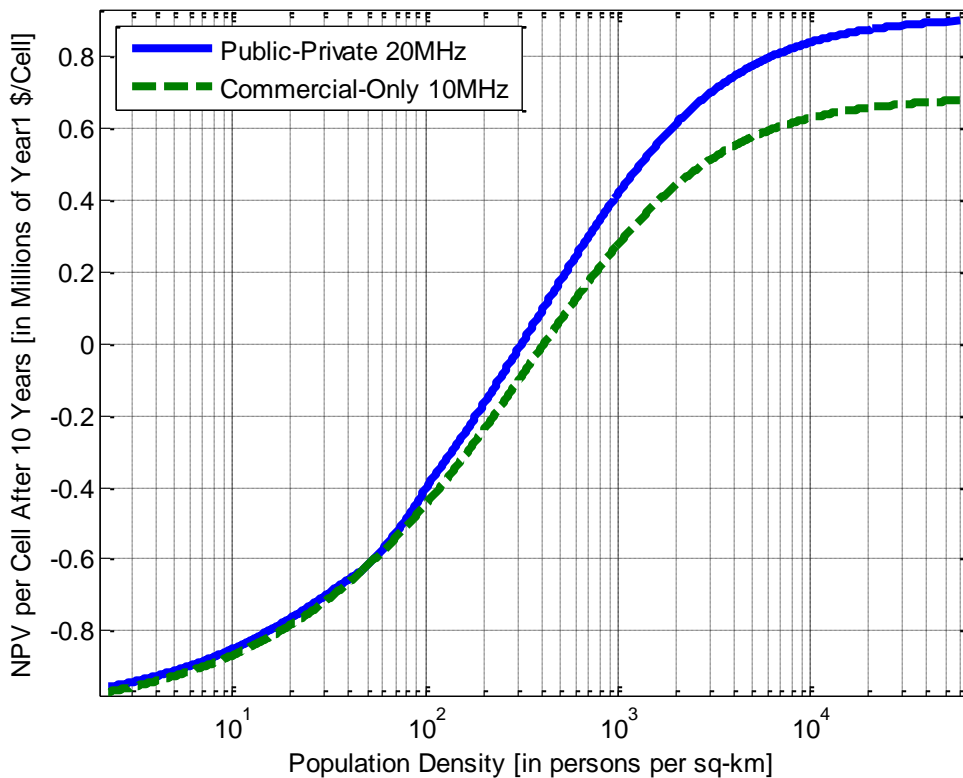


Figure 1: A plot of the net present value per cell site as a function of population density for a public-private partnership and commercial-only network after 10 years.

In Figure 1, we observe that for all levels of population density the NPV per cell is always greater for a public-private partnership on 20MHz than for a commercial-only network on 10MHz. This means that the value of access to additional spectrum and the right to serve both commercial and public safety subscribers on that spectrum is greater than the costs of the additional capacity and signal reliability requirements placed on the network. Thus, there is clearly a business case for a public-private partnership.

Figure 1 also shows that in both the public-private partnership and commercial-only network, the NPV per cell is always an increasing function of population density. While seemingly trivial, there are actually opposing factors at work here. On the one hand, cell sizes tend to increase as the covered area becomes more rural due to better signal propagation characteristics. On the other hand, population density decreases as the covered area becomes more rural meaning that for the same size cell fewer people are covered. However, the rate of increase in cell size is not sufficient to offset the decrease in subscribers due to reduced population density. Thus, in the base case of the scenarios we studied, it is always more profitable to build-out cell sites in more urban areas. Moreover, the difference in profitability between rural and urban cells is large.

In Figure 1, it is important to note the point at which both curves cross the x-axis as this point represents the breakeven population density for a network. More specifically, cells built where the curve is above the x-axis are profitable while ones built below the x-axis are not profitable. By looking closely at Figure 1, the point at which the curves cross the x-axis is determined to be at about 320 pop/km² and 410 pop/km² for a public-private partnership and commercial-only network respectively. Thus, in both scenarios in the base case, rural cell sites are not profitable and cells do not become profitable until they are deployed in regions of at least suburban population density. In order to cover all zip codes with at least 410 pop/km², a network would need to cover at least 52% of the population (i.e. 1.3% of the land area); this is how much of the country a for-profit provider would choose to cover when deploying a commercial-only network. Meanwhile, 56% of the population (i.e. 1.7% of area) would need to be covered to reach all areas with a population density of at least 320 pop/km²; this is the level of coverage a commercial provider would choose for a public-private partnership. In contrast, a public-private partnership was required to cover 99.3% of the population when the license was first auctioned [33]. Requiring the public-private partnership to cover more than 56% of the population, forces the network to cover unprofitable regions of the county.

4.2. Valuing Access to Public Safety Spectrum

From section 4.1, we know the regions in which a commercial-only network will be deployed in order to maximize profit. Thus, we can calculate the NPV for a commercial-only network that only deploys profitable cells and compare it to the NPV of a public-private partnership; the difference between the two NPVs being the value of commercial access to the 10MHz of public safety spectrum. And since section 4.1 demonstrated the dramatic impact that the population density of the area covered can have on the NPV of the public-private partnership, in the following figures, we plot the difference between the NPV of a public-private partnership and the NPV of a commercial-only network while varying the fraction of US population and fraction of US area covered by the partnership.

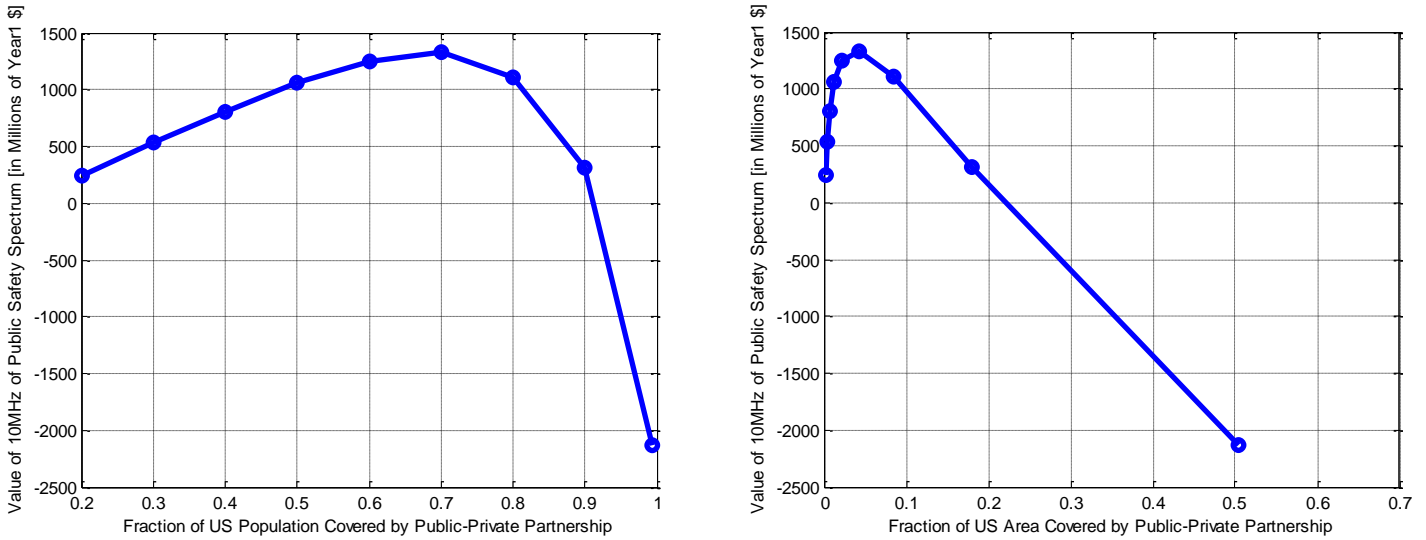


Figure 2(a) and (b): A plot of the value of access to the 10MHz of public safety spectrum calculated by taking the difference in net present value between a public-private partnership and commercial-only network after 10 years while varying (a) the fraction of US population covered by the partnership and (b) the fraction of US area covered by the partnership.

In Figure 2(a), we see that in the base case (i.e. $x = 99.3\%$), access to the 10MHz of spectrum is not attractive to the commercial provider, and the license is worth about negative \$2 billion. However, given that coverage of rural areas is unprofitable, we see that if the population covered by the public-private partnership is reduced to about 93%, the difference between the NPVs of a public-private partnership and a commercial-only network becomes negative 400 million dollars; this represents the point at which the NPV of the partnership goes to zero. However, we see that if the population covered by the public-private partnership is further reduced to about 91%, the difference between the NPVs becomes positive. At this point the government would not have to provide a subsidy, and if the population covered is reduced even further to about 70%, up to a billion dollars could be expected at auction for the license. However, reducing the population coverage to this level dramatically reduces the amount of area covered by the network. To demonstrate this, Figure 2(b) shows the same thing as Figure 2(a), except with area coverage as the x-axis instead of population coverage. This plot shows that when population coverage is reduced to 70%, the area covered would be reduced to about 5% which is down from about 50% of area when 99.3% of population is covered. In fact, when the US area covered is between 5% and 50%, we find that there is an approximately linear relationship between fraction of US area covered and the NPV of the partnership, for every 20% less of the US area covered, NPV increases by \$1.5 billion.

4.3. The Sustainability of the Partnership

In the base case, while ignoring any spectrum cost/subsidy, the public-private partnership has an NPV of about -1.7 billion dollars and the commercial-only network has an NPV of about 400 million dollars after 10 years. While this means that a public-private partnership is not profitable (at least not after 10 years), it may still be sustainable given an upfront subsidy. To explore this further, the following plots show the cumulative NPV after x years for both the

public-private partnership and the commercial-only network and the NPV of each year's set of cash flows (i.e. the present value of each year's net income) for both scenarios.

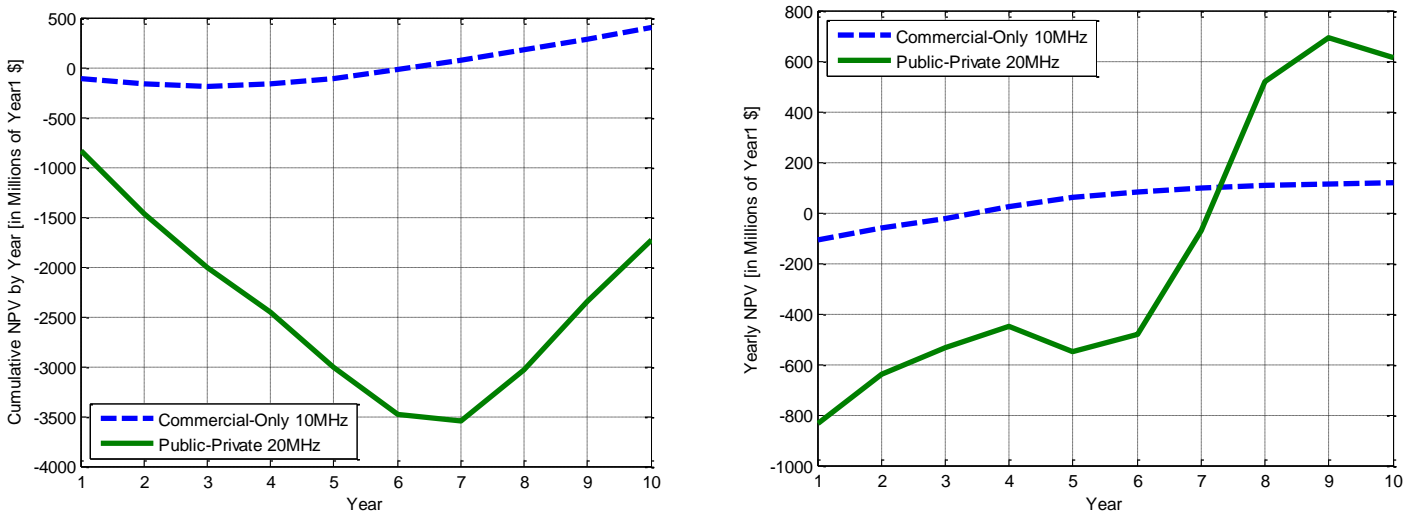


Figure 3(a) and (b): A plot of (a) the cumulative (b) the yearly net present value after x years for a public-private partnership and commercial-only network over the first 10 years.

In Figure 3(a), we see that the commercial-only network breaks even in its 6th year after bottoming out in the 3rd year. Meanwhile, the public-private partnership has its lowest cumulative NPV in the 7th year when NPV is -3.5 billion dollars, but grows steadily thereafter. The NPV becomes increasingly more negative in those early years given the large upfront costs required to build out cell sites. During this time revenue is also increasing due to increasing coverage and market penetration. By year-7, the revenue exceeds the continuing build-out costs plus the costs to operate the deployed cells. If this does not occur, it suggests the network is unsustainable. Figure 3(b) reinforces this point, we see that the public-private partnership started off with a considerably negative cash flow in year-1 due to substantial upfront costs and limited initial revenue. However, the annual NPV trended upward each year after, as revenues outpaced costs, and in year-10, the partnership is expected to have an NPV of about 600 million annually. Given that the partnership does not post annual losses perpetually going forward, we can conclude that the partnership may be profitable in the long term and that it is sustainable if given an upfront subsidy of at least 1.7 billion dollars.

4.4. The Impact of Requirements on NPV

As discussed in [11], there is uncertainty surrounding the requirements that should be placed on a public-private partnership and these requirements have a direct impact on the numeric value chosen for the inputs summarized in section 3.1. As we found previously, the values chosen for the link budget (e.g. signal coverage reliability and in-building penetration) and capacity requirements (e.g. the highest upstream datarate guaranteed at the cell-edge) can have a significant impact on the number of cell sites required in a public-private partnership. Therefore, in section 4.4.1 we quantify the impact that a range of link budget input values can

have on the net present value of a public-private partnership while in section 4.4.2 we quantify the impact that a range of public safety capacity requirements can have on NPV as well.

4.4.1. The Impact of Link Budget Margins on NPV

As discussed in section 2.2.1, our model uses a link budget to calculate the size of cells and thus the number of cell sites required in a network. Among the terms in this link budget, there are parameters that represent the signal coverage reliability and in-building penetration requirements of first responders. When one of the input values to this link budget 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 simplicity, 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 equation below. In the plot that follows, we vary the link margin to study the impact of a number of link budget input values without having to consider each term separately. In this case, the x-axis represents a change in link margin by x dB, with 0 dB being the base case scenario.

$$LINK_MARGIN = EIRP + G_{RX} - L_{IMPLEMENT} - L_{SCENARIO} - L_{RELIABLE} - L_{BUILD} \quad [\text{in dB}]$$

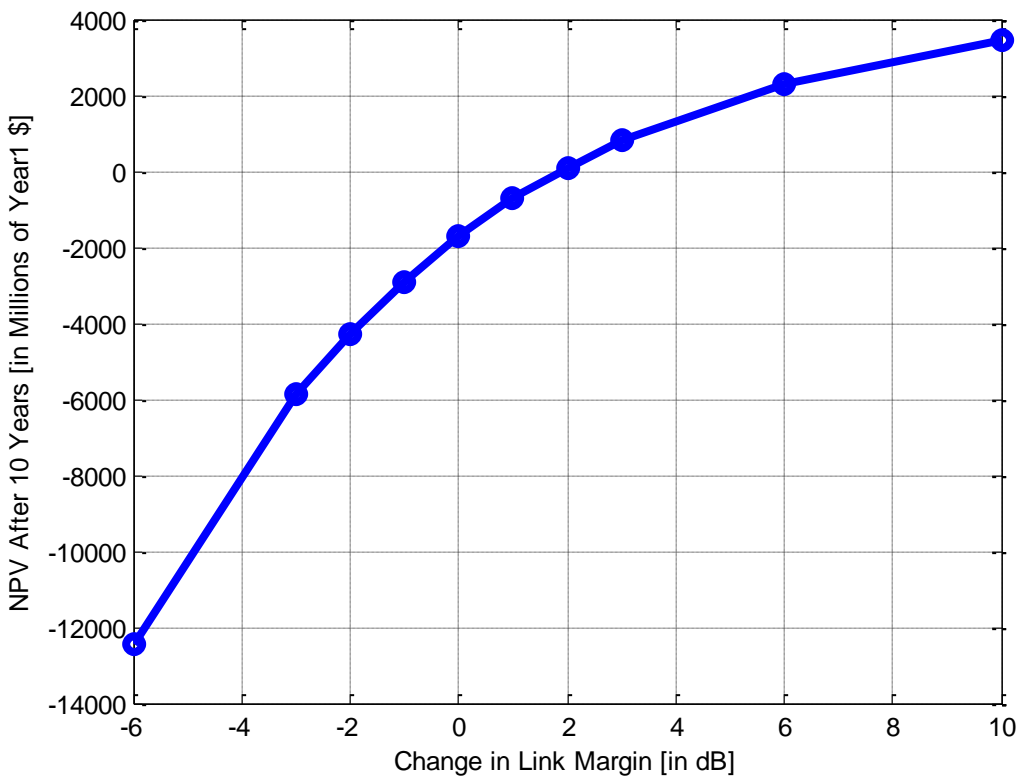


Figure 4: A plot of the net present value of a public-private partnership after 10 years for a range of link margin values.

Figure 4 shows that changing the link margin by more than a few dB considerably changes the NPV of a public-private partnership. This is due to the fact that slight changes to the link budget can have a substantial impact on the number of cell sites required, as found in [11].

For example, reducing the link margin of a public-private partnership by 6dB could reduce the NPV by about eight billion dollars while increasing it by 6dB would increase NPV by about four billion dollars and yield an overall positive NPV for the system. A 6dB increase is relatively large, but there are design choices (e.g. reducing signal coverage reliability from 97% to 90%) that could lead to such a change in link margin. Likewise, a 6dB decrease is large as well, but choices such as substantially increasing the margin for in-building penetration could yield such a change.

More specifically, a signal coverage reliability level of 95% was proposed first by the PSST [52] and later adopted by the FCC [4], but 97% coverage reliability may be more typical of existing public safety systems [35]. Similarly, the PSST [52] and later the FCC [4] proposed a building penetration margin of 6dB in rural areas, whereas a 13dB building penetration margin is sufficient for coverage within concrete buildings [36]. In the base case, we chose the more stringent level for these requirements, but if the signal coverage reliability were reduced to 95%, that would increase the link margin by a little over 2dB as discussed in [11]. This would result in about a two billion dollar increase in the public-private partnership's NPV, meaning the partnership would just about break even. Likewise, if a 6dB in-building penetration margin were adopted for the entire nation instead of the 13dB chosen in the base case, the NPV of the partnership would increase by about five billion dollars and become much more attractive to a commercial partner.

4.4.2. The Impact of Capacity Requirements on NPV

As mentioned in section 3.1, we have previously developed a model of public safety capacity which is characterized by the following three input parameters [11]:

β_{MAX}	Measure of the capacity required by the highest user datarate guaranteed at cell-edge
β_{SUM}	Measure of the aggregate capacity required in a localized emergency per sector
ρ_{BRT}	Measure of the capacity required per first responder due to routine traffic

Each of these parameters is discussed in much greater detail in [11], but at a high level, these parameters are each dependent on the datarate and E_b/N_o required by first responders.

As discussed in [11], there is considerable uncertainty about the capacity requirements of public safety on a broadband wireless network and we found that the value chosen for β_{MAX} and to a lesser degree β_{SUM} , can have a significant impact on number of cell sites required in a network. Therefore, in the figures below, we first study the impact on the NPV of a public-private partnership due to varying the numerical value chosen for the datarate in β_{MAX} while holding the E_b/N_o and the other capacity values constant. Then, we do the same for β_{SUM} , varying the numerical value chosen for the datarate while holding all else constant and studying the impact on NPV.

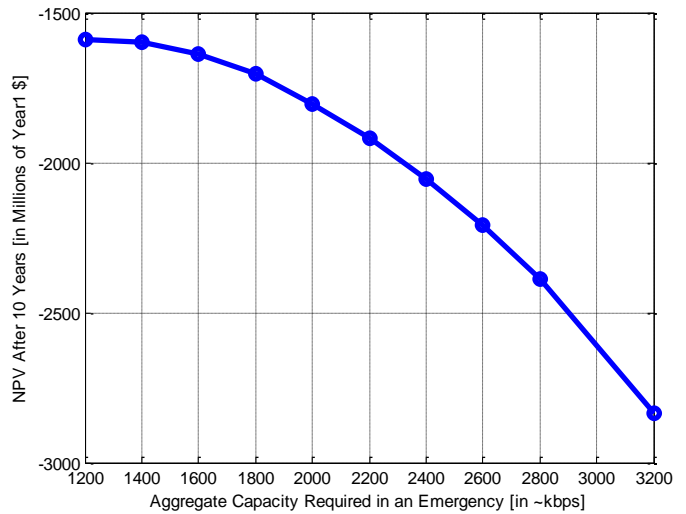
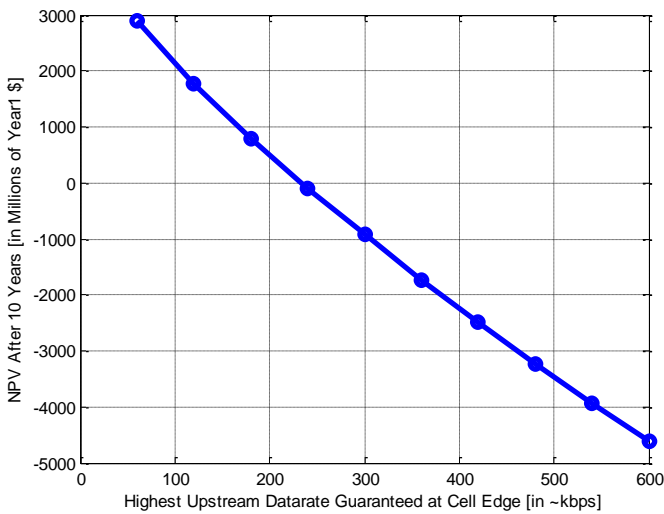


Figure 5(a) and (b): A plot of the net present value of a public-private partnership after 10 years for (a) a range of highest guaranteed upstream datarate values (b) a range of values for the aggregate capacity required during an emergency response.

As discussed in [11], as the highest upstream datarate required increases, the number of cell sites required in a public-private partnership increases as well. Similarly, Figure 5(a) shows that as the value of the highest upstream datarate required increases, the NPV of the public-private partnership decreases at a roughly linear rate. This means that the highest datarate application that the system is designed for can greatly impact the profitability of the network, even if only one user will require that datarate. For example, for every additional 100kbps upstream the network is designed to guarantee at the cell-edge (while keeping all other capacity requirements constant), the NPV of the network decreases by about 1 – 1.5 billion dollars.

In addition, the aggregate capacity required during an emergency response has an impact on NPV, although this impact is not nearly as pronounced as in β_{MAX} . As we can see in Figure 5(b), increasing aggregate capacity by about 80%, from the base case value of about 1800kbps to 3200kbps, decreases the NPV by about a billion dollars. However, reducing aggregate capacity from the base case value has a diminishing effect, with the NPV leveling off at about –1.6 billion dollars.

4.5. The Impact of Costs and Revenue

In addition to the technical requirements of a public-private partnership, the value chosen for financial factors such as the upfront capital and annual operating costs per cell site and the revenue derived from each subscriber have a dramatic impact on the NPV of a system. In section 4.5.1, we study the impact on NPV of varying upfront and recurring costs per cell, while in section 4.5.2 we vary the value chosen for the revenue per commercial and public safety subscriber, and study the impact on NPV.

4.5.1. The Impact of Costs per Cell

After calculating the number of cells required in a network, costs can be estimated using the values chosen for upfront capital cost per cell and annual operating cost per cell. As discussed in section 2.2.2, in the base case, the upfront cost per cell is 500 thousand dollars while the annual cost per cell is 75 thousand dollars. The following figure shows how NPV depends on the value chosen for both the upfront cost per cell and the annual cost per cell.

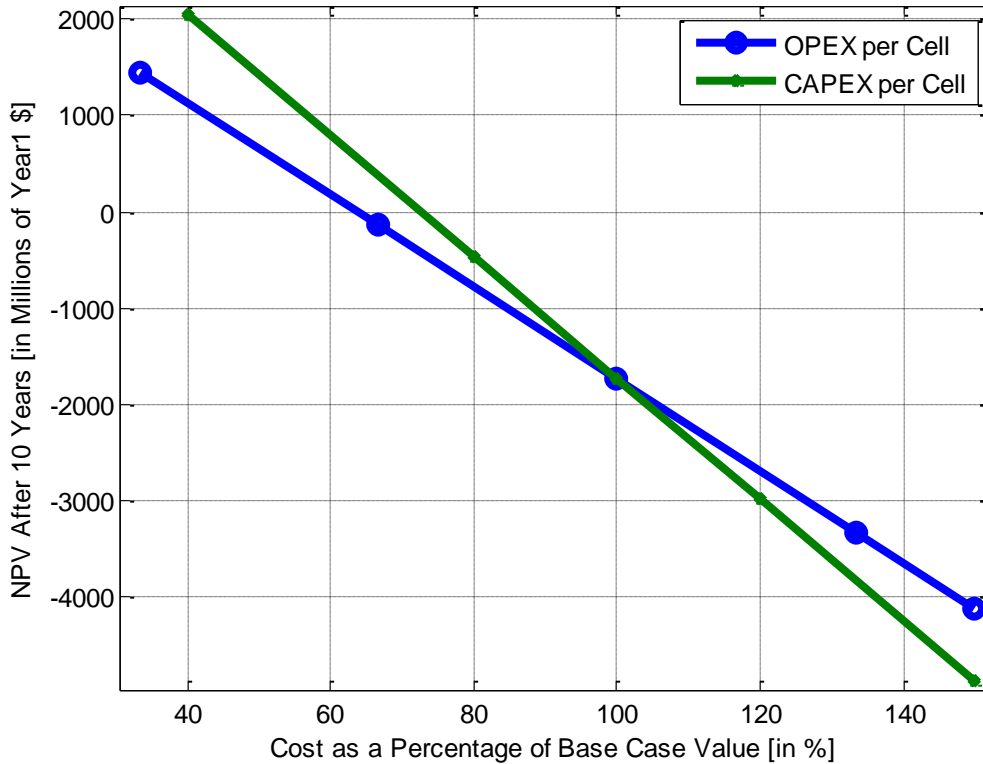


Figure 6: A plot of the net present value of a public-private partnership after 10 years for a range of values for the upfront capital cost per cell and annual operating cost per cell.

In Figure 6, there is a similar impact on NPV from varying both the upfront capital cost per cell and annual operating cost per cell. In both cases, varying the cost value from the base case has a nearly linear impact on NPV. More specifically, for each 20% (or \$15K) increase in annual operating cost per cell, there is a one billion dollar decrease in the NPV of the partnership. Similarly, for each 20% (or \$100K) increase in the upfront capital cost per cell, there is a 1.25 billion dollar decrease in NPV of the partnership. In fact, by reducing either upfront cost by 27% or operating cost by 36%, the partnership will break even. This is significant because there are a number of requirements that could be placed on the partnership which could influence both of these cost values. For instance, requiring structural hardening of cell sites beyond typical industry standards, requiring significant provisions for emergency power such as backup batteries and/or generators, and requiring redundant backhaul facilities at each cell could all impact the upfront and operating costs. Thus, policymakers must carefully

weigh the impact that changes in cost can have on NPV against the benefits the requirement may bring.

4.5.2. The Impact of Revenue per Subscriber

Once the number of subscribers on the network is calculated, revenue only depends on the value chosen for the revenue per subscriber. As discussed in 2.3.2, there are two different values for revenue per subscriber, one for each type of subscriber on the network (public safety and commercial). In the base case, revenue per public safety subscriber is \$30/month while revenue per commercial subscriber is \$10/month. The following figure shows how NPV depends on the value chosen for the revenue per each type of subscriber.

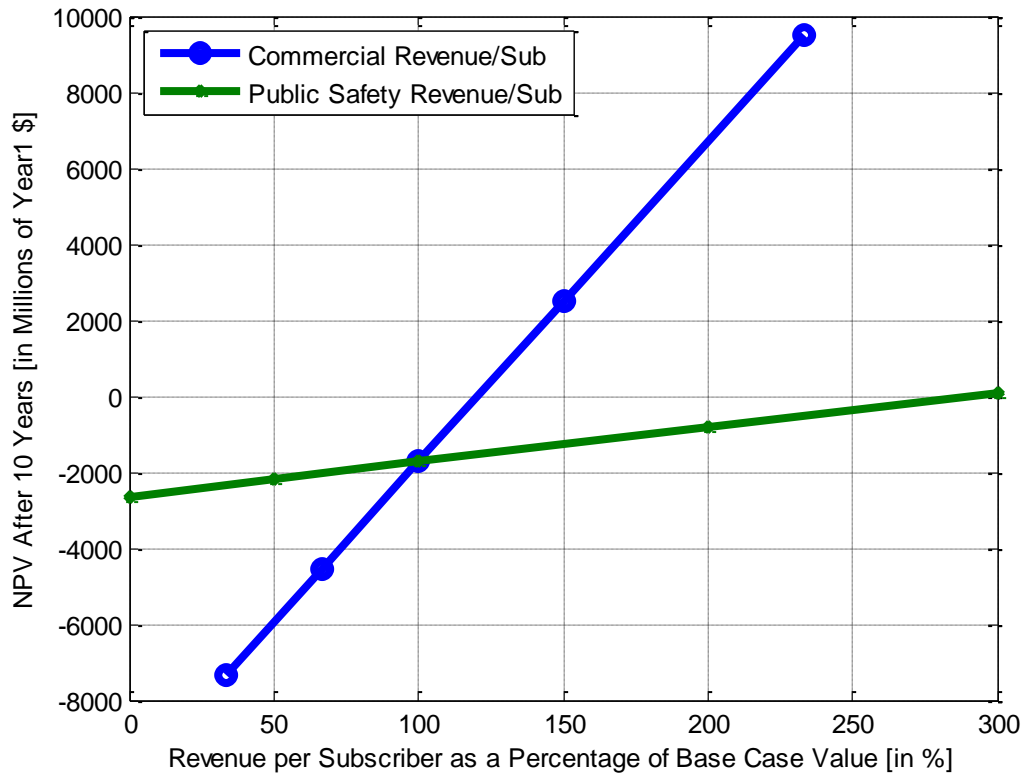


Figure 7: A plot of the net present value of a public-private partnership after 10 years for a range of values for the revenue per commercial and public safety subscriber.

In Figure 7, it is clear that the value chosen for revenue per commercial subscriber has a much more dramatic impact on the NPV than the value chosen for the revenue per public safety subscriber. More specifically, increasing revenue per commercial subscriber by 100% from the base case value (i.e. from \$10/month to \$20/month) results in the NPV for the partnership increasing by about 8 billion dollars and becoming positive. Meanwhile, a 100% increase in the revenue per public safety subscriber (i.e. from \$30/month to \$60/month) only results in an increase in NPV of one billion dollars. Instead, the revenue per public safety subscriber needs to be tripled from its base case value to \$90/month just for the NPV of the network to break even. The fact that public safety revenue makes up a small portion of the partnership’s overall revenue means that there is less incentive for the commercial partner to ensure the public safety

community is well served by the network. Indeed, if all public safety subscribers discontinued their service so that the partnership derives no revenue at all from public safety (i.e. revenue per public safety is set to 0) the NPV is only decreased by about 900 million dollars.

4.6. The Impact of Urban Areas Opting-Out

As we discussed in section 3.2, recently several urban municipalities have expressed interest in opting-out of a future partnership and instead obtaining a waiver to use the spectrum themselves. However, as we showed in section 4.1, a profit-seeking carrier, whether they are deploying a public-private partnership or a commercial-only system, will want to build out the network in the most urban areas first as these are the most profitable. In this section, we explore the impact that profitable urban areas opting-out of a partnership can have on the NPV of the partnership. We study the impact of opting-out from three different angles and in each case, we study the impact of municipalities receiving waivers for 10MHz of spectrum and for all 20MHz.

To do so, we calculate the NPV for a public-private partnership that covers only the area that is opting-out, NPV_{OptOut_PP} and we calculate the NPV for a commercial-only system on 10MHz that covers only the opt-out areas as well, NPV_{OptOut_CO} . Since we know the NPV of a nationwide public-private partnership, NPV_0 , which was calculated in section 4.3, we can calculate the NPV after urban areas opt-out using the following equations:

$$NPV_{10} = NPV_0 - NPV_{OptOut_PP} + NPV_{OptOut_CO} \quad \text{for 10MHz waivers} \quad \{4.6-1\}$$

$$NPV_{20} = NPV_0 - NPV_{OptOut_PP} \quad \text{for 20MHz waivers} \quad \{4.6-2\}$$

These equations are based on the fact that when municipalities opt-out and receive waivers for 10MHz, the commercial partner can still operate a commercial-only system on the remaining 10MHz whereas when the municipalities receive waivers for the full 20MHz there is no spectrum left for the commercial partner to operate on in the opt-out areas.

In section 4.6.1, we consider four opt-out scenarios, each of which consists of a distinct set of urban municipalities, and calculate the change in NPV due to each of these sets of municipalities opting-out of a nationwide public-private partnership. In section 4.6.2, we calculate the change in NPV of a nationwide partnership due to municipalities opting-out as a function of the fraction of population that opts-out. Finally, in section 4.6.3, we consider the impact on a regional public-private partnership if its two urban centers opt-out of the partnership.

4.6.1. The Impact of 4 Opt-Out Scenarios

In section 3.2, we defined four sets of urban municipalities which represent a range of scenarios of municipalities opting-out of a nationwide public-private partnership: Set 1 includes NY and DC; Set 2 includes NY, DC, SF, San Jose, Oakland and Boston; Set 3 includes a broader area around each city in Set 2 and adds the state of New Jersey; and Set 4 includes 55 urban municipalities from across the nation as detailed in Appendix 7.A. For each set, we calculate the NPV for both 20MHz and 10MHz waivers as summarized in the table below.

<i>Summary of Network Opt-Out Statistics</i>							
Scenario	ΔCells	ΔArea Covered	ΔPop Covered	ΔComm Subs	ΔPS Subs	ΔNPV in Millions	
Public-Private w/o Opt-Out	16,900	4.6E+06 km ²	2.8E+08	2.4E+07	480,000	-\$1,700	
Scenario1: 10MHz Opt-Out	-60	- km ²	-	-4.8E+05	-14,400	-\$80	
Scenario1: 20MHz Opt-Out	-180	-1000 km ²	-8.7E+06	-7.4E+05	-14,400	-\$150	
Scenario2: 10MHz Opt-Out	-100	- km ²	-	-7.1E+05	-21,300	-\$110	
Scenario2: 20MHz Opt-Out	-300	-9,700 km ²	-1.3E+07	-1.1E+06	-21,300	-\$190	
Scenario3: 10MHz Opt-Out	-200	- km ²	-	-1.1E+06	-33,500	-\$150	
Scenario3: 20MHz Opt-Out	-550	-34,500 km ²	-2.0E+07	-1.7E+06	-33,500	-\$250	
Scenario4: 10MHz Opt-Out	-900	- km ²	-	-4.7E+06	-140,000	-\$580	
Scenario4: 20MHz Opt-Out	-2,400	-210,000 km ²	-8.5E+07	-7.2E+06	-140,000	-\$920	

Table 3: A table summarizing the change in net present value, number of cells, area covered, population covered, commercial subscribers and public safety subscribers as a result of the 4 different opt-out scenarios.

In Table 3, we can see that the 4 sets considered cover a wide range of area and population that opts-out of a partnership: from 1000 km² and 8.7 million people in Set 1 to 210 thousand km² and 85 million in Set 4. The first observation from this table is that the NPV of the public-private partnership is reduced for all sets opting-out. This reduction is anywhere from 80 million dollars to 920 million dollars and it appears to be very dependent on the amount of population opting-out as well as the population density of the areas opting-out. This means that if the partnership is required to cover 99.3% of population, just 55 urban municipalities opting-out could increase the subsidy required by about 50% and the more urban municipalities that are allowed to opt-out, the greater the initial subsidy would have to be. We also observe that for all sets opting-out, a 20MHz waiver reduces the NPV more than a waiver for only 10MHz. For instance, in Set 4, NPV is reduced by 580 million and 920 million for a 10MHz and 20MHz waiver respectively.

4.6.2. The Impact as a Function of Population Opting-Out

In the previous section, 4.6.1, we consider the impact of opting-out by studying the NPV of a collection of ZCTAs (i.e. zip codes) that are associated with a set of municipalities and we observed that the reduction in NPV is dependent on the population included in the opt-out areas. In this section, we disregard the previously established sets of municipalities and instead study what happens to NPV as the *i*th most urban ZCTAs across the nation opt-out. In the figure below, we plot the reduction in NPV of a public-private partnership as a function of the fraction population covered by the opt-out area.

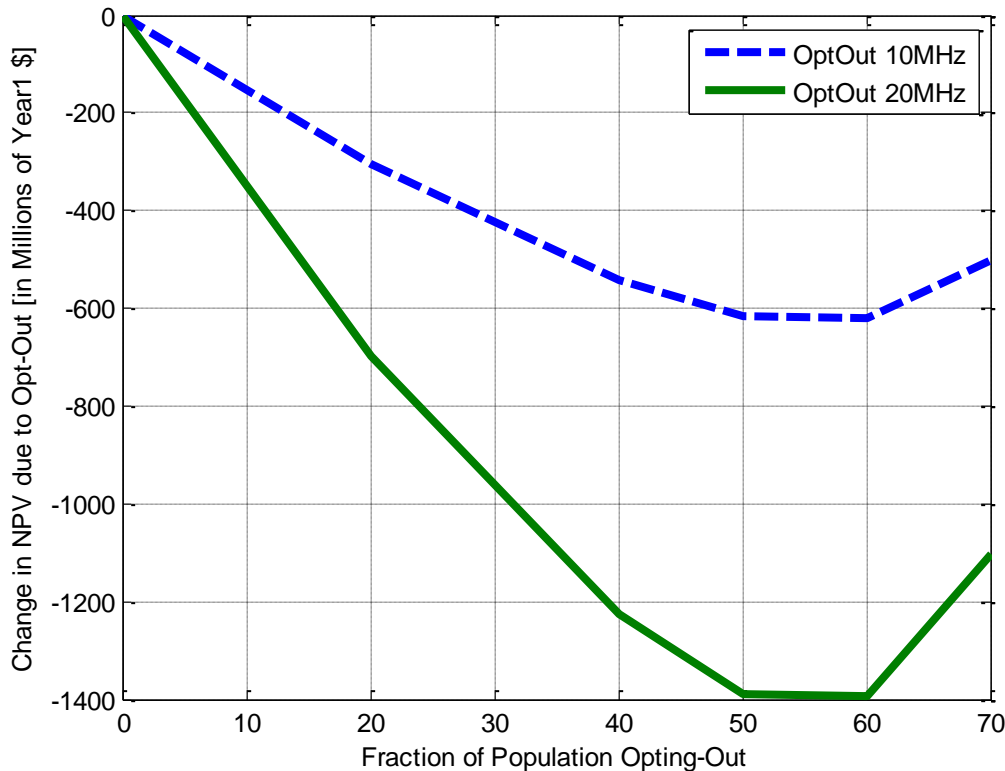


Figure 8: A plot of the change in net present value of a public-private partnership after 10 years for a range of values for the fraction of population that opts-out.

Figure 8 above establishes the fact that when urban areas opt-out, it always reduces the NPV of the partnership. Additionally, we see that for all fractions of population studied, the 20MHz waiver always results in a greater reduction in NPV than a 10MHz waiver. When about 60% of the population opts-out, the reduction in NPV peaks at -1.4 billion dollars and -600 million dollars for the 20MHz and 10MHz waivers respectively. However, after more than 60% of population opts-out, the reduction in NPV begins to decrease due to unprofitable regions beginning to opt-out as well. Thus, while a rural area opting-out has no negative consequence on the partnership, when densely populated areas opt-out it hurts profitability; and to date, the vast majority of waivers submitted have been from urban regions [20].

4.6.3. The Impact on a Regional Public-Private Partnership

In the previous two sections, we have calculated how much an urban area opting-out reduces the NPV of a nationwide public-private partnership. And while all the scenarios studied showed the NPV being reduced, for the scenarios which only consisted of a few municipalities opting-out, the reduction in NPV was less than 200 million dollars; not very much considering the NPV of the nationwide partnership is -1.7 billion before any urban areas opt-out. However, a 200 million dollar reduction in NPV could become much more significant if applied to a regional public-private partnership instead of a nationwide one. And since the FCC recently considered allowing the spectrum to be broken up into multiple regional licenses [4], the impact of urban areas opting-out could be even more significant.

In this section, we study the impact of urban areas opting-out of a regional public-private partnership instead of a single nationwide partnership. To do so, we first model the NPV of a hypothetical regional network, which in this case is a public-private partnership that covers the state of California⁵. Other than limiting the build-out to just one state, this public-private partnership is modeled using all of the base case values chosen for the nationwide public-private partnership and summarized in section 3. Then, we consider a scenario in which the two urban centers of this region (the San Francisco Bay Area⁶ and Los Angeles County) opt-out of the regional public-private partnership. Together these two urban areas make up almost half of the population of California but cover only about 10% of the area. The table below summarizes the statistics of the California regional public-private partnership both with and without the urban areas opting-out.

Scenario	Cells	Summary of Network Statistics					NPV in Millions
		Area Covered	Pop Covered	Comm Subs	PS Subs		
CA Regional w/o Opt-Out	1400	200000 km ²	3.50E+07	3.00E+06	60000	\$ 230	
CA Regional w/ 10MHz Opt-Out	1200	200000 km ²	3.50E+07	2.00E+06	31200	\$ 110	
CA Regional w/ 20MHz Opt-Out	900	160000 km ²	1.80E+07	1.50E+06	31200	\$ 40	

Table 4: A table summarizing the net present value, number of cells, area covered, population covered, commercial subscribers and public safety subscribers of a California regional public-private partnership with and without the opt-out of the SF Bay and LA areas.

In Table 4, we see that a California regional public-private partnership would require 1,400 cells and would serve 3 million commercial subscribers. When the urban areas opt-out, while the number of cells required is only reduced to 1,200 and 900 for the 10MHz and 20MHz waivers respectively (decreases of 14% and 36% each), the number of subscribers is reduced to 2 million and 1.5 million respectively (decreases of 33% and 50% each). And even though the NPV for the partnership remains positive after the urban areas opt-out, the original NPV of 230 million dollars after 10 years is reduced to 110 million and 40 million dollars for the 10MHz and 20MHz waiver scenarios. While the reductions in NPV are inline with the results from Sets 1 and 2 in section 4.6.1, the overall impact on the partnership is more dramatic when a regional partnership is being considered instead of a nationwide one.

5. Conclusions

While a wireless broadband network serving all public safety users in the US may represent a significant upgrade over the existing fragmented public safety communications infrastructure [1] [11], consensus has yet to be reached as to the best policy for achieving such a network. Proposals for a nationwide public safety network range from a nationwide system that would serve only public safety users to a joint-use network that would serve both public safety

⁵ In the latest rules from the FCC [4], it was proposed that the license for California be split into a Northern and Southern region, but for simplicity of analysis, we combine the two halves into a single region.

⁶ In this case, the San Francisco Bay Area is defined as the 10 county Bay Area, which we included in Set 3 in section 4.6.1

and commercial users. In this paper, we studied a public-private partnership which is the proposal currently being considered by the FCC in its most recent proposed rulemaking [2] [3] [4]. This proposal calls for a commercial provider to commit to providing services that meet the needs of public safety in return for access to public safety spectrum, and the right to serve paying customers in that spectrum. However, before a public-private partnership can be formed, a commercial partner must step forward and one has yet to do so. Likely, potential commercial partners have been deterred by the uncertainty surrounding the sustainability of such a public-private partnership.

To study the sustainability of a public-private partnership, we presented a model to estimate the net present value (NPV) of a wireless network over a 10 year period by calculating costs based on the number of cell sites required and revenue based on the number of subscribers acquired each year using projections for future market penetration. Projections of future market penetration are based on estimates by Clearwire [30] of penetration as a function of number of years since deployment in a given region. We applied this model to both a public-private partnership that serves commercial subscribers in addition to all public safety personnel on 20MHz of spectrum in the 700MHz band, and a commercial-only network that serves just commercial subscribers on 10MHz of spectrum in the 700MHz band.

In the base case, we find that the public-private partnership is always more profitable than a commercial-only network in any given part of the country. More specifically, the NPV per cell is greater for a cell in the public-private partnership than a cell in a commercial-only network for any population density in which the cells are deployed. This implies that the value of the additional 10MHz of spectrum available in the partnership is always more than the cost to meet public safety's more stringent capacity, signal coverage reliability and in-building penetration requirements.

Furthermore, we demonstrate that the NPV per cell for both a public-private partnership and commercial-only network increases rapidly with population density, going from unprofitable in rural areas to profitable in urban areas. We find that there is a threshold of about 320 people per square kilometer for a public-private partnership and 410 people per square kilometer for commercial-only: below that, cells have a negative NPV per cell and above that cells have a positive NPV per cell. So while we found in [11] that the costs to cover an additional square mile of rural area with a 700MHz network is low (which is important when considering a public-safety-only approach), in a profit-seeking venture such as the public-private partnership (where NPV matters), covering an additional square mile of rural area is always unattractive because limited rural revenues are insufficient to offset costs. Since a for-profit commercial provider would target profitable regions for service, if no build-out requirements were in place, a commercial-only network would likely only serve about 52% of the population while a public-private partnership would choose to serve about 56% of population. This is about 1.3% and 1.7% of area respectively. Conversely, this means that almost half of the rural population would not be covered by a network because it is unprofitable to do so.

Therefore, the only way that the rural parts of the country are covered by a network is if rural build out is a condition of the spectrum license; effectively having urban areas cross-

subsidize build out in rural areas. In fact, we find that the population covered by a partnership can be increased from 56% (i.e. the fraction of population in which NPV per cell is positive) to 93% and the partnership still breaks even (i.e. NPV = 0). However, even when 93% of population is covered this corresponds to only 27% of area being covered. In this way, the first 56% of the population acts to subsidize the coverage of the next 37% of the population. But in order to increase coverage any further a direct subsidy from the government would be required.

Increasing population covered to 99.3%, as we did in the base case, we find that a public-private partnership will require an initial subsidy on the order of two billion dollars to meet initial costs, but is likely sustainable in the long run as it generates a positive net income each year after roughly year-8. In comparison, we found previously [11] that a comparable public-safety-only network deployed on 10MHz of 700MHz spectrum and also covering 99.3% of the population would require about 19,000 cells and cost about \$9.5 billion to deploy and \$1.5 billion annually to operate and maintain. This implies that unless 10MHz of the partnership spectrum can raise at least seven billion dollars in an auction, the public-private partnership represents a low-cost means of serving public safety when compared to a public-safety-only network. However, 99.3% of population covered only corresponds to 50% of area covered and our analysis in [11] shows that 83% of US area is currently covered by the existing public safety infrastructure. Thus, many rural public safety agencies would gain nothing even from a new nationwide system that covers 99.3% of population. While increasing population covered beyond 99.3% will increase the level of subsidy required, the fact that many rural agencies will be left out if not must be kept in mind when considering build out coverage requirements.

In order to guarantee at least 99.3% of population and 50% of area is covered if predominately urban regions are granted waivers and allowed to opt-out of a partnership, we find that the initial subsidy must be increased. This is due to the fact that urban areas are always the more profitable regions of a public-private partnership, and when these areas opt-out of the partnership, they no longer cross-subsidize the build out of rural areas. Furthermore, the urban areas are more likely to be interested in waivers due to the fact that these municipalities tend to have the scale and budgets necessary to support the build out of their own networks. This is supported by the fact that, to date, the vast majority of waivers filed with the FCC have come from urban municipalities [20]. For instance, when only New York City and Washington D.C. opt-out, the reduction in NPV of the nationwide public-private partnership is about 80 million and 150 million dollars for 10MHz and 20MHz waivers respectively. However, when the opt-out consists of about 55 urban municipalities, NPV is reduced by 580 million and 920 million dollars for a 10MHz and 20MHz waiver respectively. Thus, it is clear that as more urban municipalities are allowed to opt-out, the greater the initial subsidy would have to be to make the partnership sustainable. Alternatively, instead of increasing the subsidy and maintaining 99.3% of population covered, the coverage requirements of the partnership could be reduced to compensate for the urban areas opting-out. More specifically, we find that if about 55 urban municipalities receive 20MHz waivers, the area of the US covered would need to be reduced from 50% to 38% to compensate.

Besides build-out coverage requirements, we find that the NPV of a public-private partnership can be significantly affected by varying a few other key system characteristics such

as the link budget, capacity and hardening requirements. Given that these parameters have such significant impact on the viability of a public-private partnership and that many were not clearly established prior to the 700MHz auction, it is no surprise that a commercial partner never came forward.

Of the capacity requirements, the highest upstream user data rate guaranteed at the cell-edge has a particularly large impact on NPV of a public-private partnership. This impact is roughly linear, for every additional 100kbps that the network is designed to guarantee at the cell-edge the NPV of the network decreases by about 1 – 1.5 billion dollars. Thus, it is important to determine which applications are considered mission-critical by public safety so that the appropriate data rate is guaranteed at the cell-edge. Besides the highest data rate guaranteed, it also matters what the aggregate capacity requirements are during an emergency response. In our base case, decreasing aggregate capacity has little impact while increasing aggregate capacity by 80% will decrease the NPV by about a billion dollars. This implies that aggregate capacity has little impact up to a threshold value, after which point, aggregate capacity has a dramatic impact. In our base case, the value for aggregate capacity was near this threshold; however, the level of aggregate capacity required by public safety has not been well established and warrants further consideration. And while capacity concerns have received some attention recently [4], there has been insufficient work done to define the appropriate values for these requirements in terms of the metrics (e.g. kbps) necessary to design a network and estimate costs. Given the dramatic impact these requirements have, consensus must be reached on them before a public-private partnership can be established.

Unlike capacity requirements, there have been concrete proposals for signal coverage reliability and in-building penetration margins, but little discussion as to whether these proposals were adequate. These design choices have a significant impact on NPV and reducing the requirements from levels typical of existing public safety systems (as we designed for in the base case) can significantly increase the NPV of the partnership. More specifically, if one reduces either the signal coverage reliability or in-building penetration margin of the partnership by 2dB from the base case value, NPV increases by about two billion dollars and the partnership breaks even. On the other hand, if public safety agencies are not willing to use a network with lower signal coverage reliability and in-building penetration levels, then 10MHz of public safety spectrum would have been transferred to commercial service without any substantial benefit to public safety. Thus, and just as is the case with the capacity requirements, it is clear that consensus must be reached on these requirements before a public-private partnership is established.

In addition to the requirements placed on the network, there are a number of financial factors such as the revenue per subscriber and cost per cell which also have a significant impact on the NPV of the partnership. We find that the revenue derived per commercial subscriber has a much more significant impact on NPV than the revenue derived per public safety subscriber. More specifically, we find that the revenue per commercial subscriber need only be increased by 20% from the base case value for the partnership to break even, whereas the revenue per public safety subscriber must be tripled in order for the partnership to break even. The fact that public safety revenue makes up a small portion of the partnership's overall revenue provides less

incentive for the commercial partner to ensure it is meeting the needs of public safety users. In fact, if all public safety subscribers discontinued their service, the NPV is only decreased by about 900 million dollars. On the other hand, this means that the federal government would only need to provide an additional upfront subsidy of about a billion dollars and public safety agencies wouldn't need to pay for subscriptions in the first 10 years; this could serve as a powerful tool to encourage widespread adoption of the partnership by the public safety community. In addition to revenue, we find that both the upfront and annual operating costs per cell have a significant impact on NPV. Thus, policymakers must carefully weigh the benefits of requirements such as cell site hardening and backup power (i.e. requirements that affect cost per cell) against the impact such requirements would have on the NPV of the partnership.

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7. Appendix A – Opt-Out Sets

The following section provides a list of all of the counties that make up the 4 opt-out sets discussed in section 3.2. In addition to the county, we also list the FIP code which is a unique identifier assigned to each county by the federal government [38].

Set 1 includes New York City and the District of Columbia:

- NYC contains 5 counties FIP: 36061, 36047, 36081, 36085, 36005
- District of Columbia FIP: 11001

Set 2 includes New York City, District of Columbia, Boston, SF, San Jose, and Oakland:

- NYC contains 5 counties FIP: 36061, 36047, 36081, 36085, 36005
- District of Columbia FIP: 11001
- Boston is in Suffolk county FIP: 25025
- SF is a consolidated city and county FIP: 06075
- SJ is in Santa Clara county FIP: 06085
- Oakland is in Alameda county FIP: 06001

Set 3 includes New York City, District of Columbia, Boston, SF, San Jose, Oakland, and New Jersey. Also, this set includes the region around several of these cities as follows.

- NYC contains 5 counties FIP: 36061, 36047, 36081, 36085, 36005
- National Capital Region contains
 - District of Columbia FIP: 11001
 - Montgomery and Prince Georges counties in Maryland FIP: 24031, 24033
 - Arlington, Fairfax, Loudoun, Prince William counties; Alexandria city in Virginia FIP: 51013, 51059, 51107, 51153, 51510
- New Jersey contains 21 counties FIP: 34001, 34003, 34005, 34007, 34009, 34011, 34013, 34015, 34017, 34019, 34021, 34023, 34025, 34027, 34029, 34031, 34033, 34035, 34037, 34039, 34041
- The San Francisco Bay Area consists of 10 counties
 - Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Santa Cruz, Solano, Sonoma
 - FIP: 06001, 06013, 06041, 06055, 06075, 06081, 06085, 06087, 06095, 06097
- The Metro Boston Homeland Security Region includes:
 - Boston, Chelsea, Revere, Winthrop which are in Suffolk county FIP: 25025
 - Everett, Somerville and Cambridge are in Middlesex county FIP: 25017
 - Brookline and Quincy are in Norfolk county FIP: 25021

Set 4 includes 55 major urban municipalities across the US. This collection of municipalities is consistent with the members of the Major City Chiefs Association. The municipalities and the county in which they are located are summarized in the following table:

MUNICIPALITY	COUNTY	FIP code
Atlanta, Georgia	Fulton	13121,
Austin, Texas	Travis	48453,
Baltimore City, Maryland	Baltimore City	24510,
Baltimore Co., Maryland	Baltimore Co.	24005,
Boston, Massachusetts	Suffolk county	25025,
Buffalo, New York	Erie	36029,
Charlotte-Mecklenburg, North Carolina	Mecklenburg	37119,
Chicago, Illinois	Cook county	17031,
Cincinnati, Ohio	Hamilton	39061,
Cleveland, Ohio	Cuyahoga	39035,
Columbus, Ohio	Franklin	39049,
Dallas, Texas	Dallas	48113,
Denver, Colorado	Denver city and county	08031,
Detroit Michigan	Wayne	26163,
El Paso, Texas	El Paso Co.	48141,
Fairfax County, Virginia	Fairfax Co.	51059,
Fort Worth, Texas	Tarrant, Parker, Denton	48439,48367,48121,
Honolulu, Hawaii	Honolulu Co.	15003,
Houston, Texas	Harris	48201,
Indianapolis, Indiana	Marion	18097,
Jacksonville, Florida	Duval	12031,
Kansas City, Missouri	Jackson, Clay, Cass, Platte	29095,29047,29037,29165,
Las Vegas Metro, Nevada	Clark	32003,
Long Beach, California	Los Angeles Co.	6037,
Los Angeles City & County, California	Los Angeles Co.	6037,
Louisville, Kentucky	Jefferson	21111,
Memphis, Tennessee	Shelby	47157,
Miami-Dade, Florida	Miami-Dade Co.	12086,
Milwaukee, Wisconsin	Milwaukee Co.	55079,
Minneapolis, Minnesota	Hennepin	27053,
Montgomery Co., Maryland	Montgomery Co.	24031,
Nashville, Tennessee	Davidson	47037,
Nassau Co., New York	Nassau Co.	36059,
New Orleans, Louisiana	Orleans Parish	22071,
New York City, New York	NY, Kings, Queens, Bronx, Richmond	36061, 36047, 36081, 36085, 36005,
Newark New Jersey	Essex	34013,
Oakland, California	Alameda	6001,
Oklahoma City, Oklahoma	Oklahoma	40109,
Philadelphia, Pennsylvania	Philadelphia Co.	42101,
Phoenix, Arizona	Maricopa	4013,
Pittsburgh, Pennsylvania	Allegheny	42003,
Portland, Oregon	Multnomah	41051,
Prince George's Co., Maryland	Prince George's Co.	24033,
Salt Lake City, Utah	Salt Lake, Summit, Tooele	49035,49043,49045,
San Antonio, Texas	Bexar	48029,
San Diego, California	San Diego Co.	6073,
San Francisco, California	San Francisco Co.	6075,
San Jose, California	Santa Clara	6085,
Seattle, Washington	King County	53033,
St. Louis, Missouri	St. Louis City	29510,
Suffolk Co., New York	Suffolk Co.	36103,
Tucson, Arizona	Pima	4019,
Tulsa, Oklahoma	Tulsa	40143,
Virginia Beach, Virginia	Virginia Beach City	51810,
Washington, DC	District of Columbia	11001,

Table 5: A table summarizing the 55 municipalities included in Set 4, the county in which they are located, and the counties' unique identifier (FIP code).