The Business Case of a 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 but force it to meet the more costly requirements of public safety. This paper analyzes the viability of a public-private partnership that serves public safety and commercial subscribers from a for-profit provider's perspective. A model is presented that estimates the net present value (NPV) of a wireless network by calculating costs based on the number of cell sites required and revenue based on the projected number of subscribers acquired. The model is applied to both a network that serves only commercial subscribers on 10 MHz of 700MHz spectrum and a public-private partnership that serves commercial subscribers and public safety personnel on 20 MHz of 700MHz spectrum. It is found that NPV is greater for the public-private partnership than for the commercial-only network for any population density, which shows that the value of 10 MHz of spectrum exceeds the cost of meeting public safety requirements. Furthermore, the paper demonstrates that NPV/cell increases with population density, so urban areas are profitable and rural areas are unprofitable. The paper demonstrates that a partnership covering 94% of US population breaks even because the most urban 56% of population subsidizes coverage for the next 38%. If initial deployment is subsidized, a financially sustainable public-private partnership can serve much more than 94%. Additionally, it is shown that allowing urban municipalities to opt-out of the partnership can significantly increase the subsidies required.

Keywords:
Public safety; first responder; homeland security; wireless; public-private partnership; net present value; NPV

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1. Introduction

First responders rely on wireless communications to accomplish their mission and ensure public safety. Unfortunately, recent tragedies and large-scale disasters in the U.S. have highlighted a number of problems with the existing public safety communication infrastructure (National Commission on Terrorist Attacks Upon the United States, 2004; Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina, 2006). Among the problems, the existing public safety infrastructure suffers from a lack of interoperability, being spectrally inefficient, and being limited to narrowband voice functionality. Part of the problem is that this infrastructure is actually thousands of independent systems, built and operated with limited coordination between agencies (Peha, 2005). Deploying a nationwide wireless broadband network serving all public safety users in the U.S. has the potential to address many of these shortcomings (Peha, 2007a). More specifically, building a nationwide broadband network presents an opportunity to introduce data capabilities (e.g. streaming video) to users currently limited to voice-only systems and solves technical interoperability issues by the use of a single technology on the network. Furthermore, deploying a nationwide network may actually save money when compared to the costs of upgrading and maintaining the existing public safety infrastructure (Hallahan & Peha, 2010b), since having many small agencies deploy their own systems has substantially increased the cost of the existing infrastructure (Peha, 2007b).

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 U.S. spectrum policy. Of the recent proposals to create such a nationwide network, there are two fundamentally different approaches: (1) a public-safety-only network that would serve only public safety users, and (2) a joint-use network that would serve both commercial and public safety users on the same spectrum and infrastructure (Peha, 2007a). This paper studies a joint-use network that takes the form of a public-private partnership. In this paper, a public-private partnership has two defining characteristics: (1) there is a profit-maximizing private-sector partner that contributes resources to the enterprise (e.g. money, spectrum, or infrastructure) and accepts the risks in the form of profits or losses, and (2) there is a public-sector partner that contributes resources to the enterprise conditioned on it taking actions designed to meet a social objective. Thus, by modeling optimal behavior from the perspective of the profit-maximizing private-sector partner, this paper determines the extent to which investment of public-sector resources might meet those social objectives, which in this case is the deployment and operation of a broadband wireless network that is capable of meeting the needs of public safety. Indeed, there are a number of challenges facing the establishment of a partnership that serves both public safety and commercial users. In crafting a sensible policy, decision makers must make choices regarding the process by which the partnership is formed (e.g. an auction versus a Request for Proposal (RFP)), the institutions that will be involved (e.g. federal agencies, state and local public safety agencies, and commercial entities) and what their involvement will be (e.g. who is the licensee), and the governance structure for the partnership (e.g. how and when are requirements established and who makes the final decisions: the public safety representatives, the commercial operator, or some third party like a federal agency).

Among the different policy approaches that are possible, the results in this paper are representative of those involving a greenfield network, with both the infrastructure and spectrum shared by public safety and commercial users but with public safety given priority to all capacity during times of emergency. One example of such a policy was the public-private partnership previously proposed by the Federal Communications Commission (FCC, 2007; 2008b; 2008c). In this proposal, a public-private partnership would have been established wherein the commercial partner commits to providing services that meet the needs of public safety in return for access to 10 MHz of public safety spectrum and 10 MHz of commercial spectrum (the D-block) in the 700MHz band. Such a joint-use network would allow the commercial partner to 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 (Bykowsky & Marcus, 2002; Marsh, 2004; Peha, 2007a). 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.

A similar policy was put forth by the FCC (2010b) in their recently released National Broadband Plan (NBP)[1]. This plan proposes auctioning off the D-block for commercial use, but still enabling public safety agencies to enter into incentives-based partnerships (Manner, Newman, & Peha, 2010). The plan also proposes requiring D-block licensees to provide roaming and priority access to public safety users (Hallahan & Peha, 2010a). Thus, incentives-based partnerships between public safety and commercial D-block winners who are building out a greenfield network are also consistent with the analysis presented in this paper. However, this type of partnership would differ from the public-private partnership previously proposed in several ways, namely: incentives-based partnerships could be formed area-by-area as opposed to nationwide (with the FCC's Emergency Response Interoperability Center (ERIC) acting to ensure networks in different areas interoperate) and the incentives-based partnerships could be entered in voluntarily through an RFP process, or some other means, rather than being required as a condition of the commercial D-block license (FCC, 2010a; 2010b; Newman & Peha, 2010).

While each policy will present its own unique set of challenges in terms of defining the appropriate institutions and governance structures, the results presented in this paper do not depend on these details and thus such considerations are outside the scope of this particular paper. However, as discussed by Peha (2008a) there are some criteria that must be satisfied regardless of the policy. Among them, public safety agencies must be able to express their operational needs to whomever makes decisions regarding the design and operation of the network, and these decision makers must operate openly and transparently given the many and diverse groups they represent. The commercial operator or operators need to understand what public safety's technical requirements are before any agreement is reached (Hallahan & Peha, 2008; 2010b) and be provided with the proper incentives to ensure public safety's needs are met (Hallahan & Peha, 2009). When disputes arise between the partners, there must be some mechanism in place to resolve them fairly, and in the event the partnership is not viable long term, there must be some mechanism in place to minimize disruption to public safety's mission.

While it is clear that forming a public-private partnership requires the commitment of a private firm and a number of institutional and governance issues need to be worked out before that is possible, there has also been considerable uncertainty surrounding the financial sustainability of such a partnership. Indeed, the FCC's initial auction failed to attract a commercial partner, magnifying the debate about the potential of the underlying policy and whether or not it should be tried again. In order for policymakers to determine whether or not to proceed with efforts to establish some form of a public-private partnership (e.g. the one proposed by the FCC (2007; 2008b; 2008c), or the incentives-based partnerships proposed in the NBP by the FCC (2010a; 2010b), or something else), it is important to better understand the cost and revenue that would be generated from such a partnership as well as which factors have the most significant impact on these estimates. 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.

To do so, this paper studies the future cash flows (both cost and revenue) for both a public-private partnership operating on 20 MHz of 700MHz spectrum and a commercial-only network operating on 10 MHz of 700MHz spectrum and uses these flows to calculate the network's net present value (NPV). This paper presents an extensible model (which builds on previous work (Hallahan & Peha, 2010b)) that is

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[1] While the NBP proposes policy options which are consistent with the model developed in this paper, it should be noted that the model and analysis presented in this paper were developed and performed before the NBP was released.

used to calculate the number of cell sites required (since deployment and operating costs are roughly proportional to the number of cell sites in a network). This model also calculates the number of public safety and commercial subscribers served by the network in order to estimate future revenue. These 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 this paper studies how the cash flows depend on these parameters. By studying how the cost and revenue change, this paper identifies the conditions under which a partnership is profitable, which can help decision makers as they craft future public-private partnership policy.

This paper also identifies the areas of the U.S. in which a wireless network is profitable. By finding the cells which have a positive NPV, this paper classifies the regions which a for-profit carrier is likely to target for service, and determines whether or not urban areas are more attractive than rural areas. To do so, this paper studies how network cost and revenue depend on the population density of the area being served. It is found that costs tend to increase with population density since costs depend on cell size (which decreases with population density). It is also found 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).

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 expressed interest in opting-out of a network (FCC, 2009). Under the current rules, waivers could be granted to municipalities allowing them to build out a network in their area on the 10 MHz of public safety spectrum. However, it is also conceivable that these waivers could be for the full 20 MHz of combined public safety and commercial spectrum, but this would require additional legislation. In either case, without the ability to serve public safety and commercial subscribers in these urban centers, a nationwide network could become less appealing to a commercial provider. Thus, this paper studies the change in NPV as the fraction of population allowed to opt-out of the partnership is varied.

Section 2 of this paper introduces the model that was developed to calculate the number of cell sites required and subscribers served by a network in order to estimate network cost and revenue. Section 3 discusses the various scenarios studied in this paper and summarizes the numerical values used as inputs to the 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, the conclusions of this paper are discussed in section 5.

2. Model

This paper uses a 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, the model estimates network costs (both upfront and ongoing costs) based on the number of cell sites that is required nationwide under a given set of requirements. To do so, the model calculates the maximum cell size as a function of population density and combines this with zip code level data on the distribution of population density within the U.S. This paper estimates the number of public safety and commercial subscribers served using projections of market penetration, and calculates revenue using estimates of revenue per subscriber based on the experience of past providers. The paper then calculates NPV by discounting the future cash flows over the entire time horizon by a set discount rate.

This section presents the various components of the model in greater detail. Section 2.1 discusses the model's assumptions regarding the amount of population and area covered by a network and the rate at which cells are built to reach this level of coverage. Section 2.2 describes 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 by a network has a significant impact on both cost and revenue. Indeed, both the number of cell sites required (and therefore cost) and the number of subscribers covered (and therefore revenue) are dependent on the amount of area covered. Additionally, the rate at which the area is covered also has an 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; so, the rate of deployment also affects the revenue generated each year.

As discussed in greater detail by Hallahan and Peha (2008), a build-out requirement can be expressed either as a fraction of the U.S. geographic area that is covered by the system or as a fraction of the U.S. population covered. Since the model used in this paper calls for the build-out requirement to be expressed as a fraction of U.S. area covered (not as a fraction of population as the FCC has done), this paper utilizes a method developed by Hallahan and Peha (2008) to convert a fraction of U.S. population covered to a fraction of U.S. geographic area covered using zip code level census data (Peha, 2008b). In the base case, this paper studies a public-private partnership that is designed to cover 99.3% of U.S. population (or about 50% of U.S. area) after 10 years. This level of coverage is consistent with the requirements attached to the commercial license previously auctioned by the FCC (2007). Furthermore, in the base case, this paper assumes that the build out of cell sites each year is constant over the 10 year period.

2.2. Cell Sites and Cost

This paper uses a model (which builds on previous work (Hallahan & Peha, 2008; 2010b)) to calculate the number of cell sites required by a public-safety-grade network under a variety of conditions. The number of cell sites is important given that in a cellular architecture, costs are roughly proportional to the number of cell sites required and in the network proposals this paper considers a cellular architecture is the most cost-effective design.

At a high level, the model finds the total number of cell sites 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. The model assumes that the expected number of cell sites in region $i = A_i / C_i$. The population density in region i is determined using nationwide zip code level population statistics[2] (U.S. Census Bureau, 2000) 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 by Hallahan and Peha (2008), zip code level granularity appears to be reasonable given that the number of cell sites required nationwide is comparable to the number of zip codes.

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[2] This analysis uses Zip Code Tabulation Areas (ZCTAs) which are a set of nationwide tabulation areas created by the U.S. Census Bureau and based on postal zip codes (U.S. Census Bureau, 2000).

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 shown previously by Hallahan and Peha (2008), 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 that 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, a CDMA based system that would be typical of a third generation (3G) network deployment (Etemad, 2004) is modeled. The authors recognize that a future network may be built using emerging technology, such as an OFDM-based fourth generation (4G) cellular standard like LTE, which formed the basis of the analysis performed recently by the FCC (2010a). Nevertheless, portions of this analysis were based on equations derived for today's 3G CDMA-based networks, in part because 3G performance characteristics are more well-established. While the newer technologies will offer some benefits, the authors believe the impact on cell size and therefore total cost will be small relative to the impact of a number of other variables considered in this paper, so results and trade-offs derived using these assumptions are useful for both 3G and 4G deployments.

Consistent with a typical CDMA network, the model used in this paper assumes that the bandwidth allocated is divided into 1.25MHz channels with traffic distributed equally across the channels (Etemad, 2004). Also typical of a CDMA system, this 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 (Etemad, 2004). This model further assumes that the uplink is perfectly power controlled as is typically done when analyzing CDMA systems (Etemad, 2004; Rappaport, 2002). The network has been designed so that cells overlap by 17% (consistent with cells that are hexagonal as opposed to circular) but beyond this level of cell overlap, no fault tolerance is present in the design of this public safety network. This design is no worse than what public safety has today, but the creation of a nationwide public safety network presents an opportunity to add fault tolerance (Peha, 2007a).

As discussed in much greater detail by Hallahan and Peha (2008; 2010b), the model used in this paper uses the following equation to predict the typical radius of a cell in each region:

$$K_5 + 10\log_{10}\left(\frac{K_1}{1-(K_2+K_3)}\right) = K_0 - K_4 + K \qquad \{in\ dB\} \qquad (2.2\text{-}1)$$

Where:

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

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

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

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

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

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

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

And where:

β_{MAX}	Measure of the capacity required to support 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 = 0.6	
Pen	Market penetration as a fraction of population covered	
Num	Number of uplink channels in a sector = uplink bandwidth/channel bandwidth	
$Sect$	Number of sectors per cell = 3	
$\rho_{FR,j}$	First Responder density in the *j*th cell	[km^{-2}]
$\rho_{POP,j}$	Population density in the *j*th cell	[km^{-2}]
$A_{hexagon,j}$	Area of the *j*th cell = 2.59808 r_j^2	[km^2]
r_j	Radius of the *j*th cell	[km]
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]
P_{EIRP}	Transmit power in EIRP (effective isotropic radiated power)	[dBm]
G_{RX}	Receiving antenna gain	[dBi]
$L_{IMPLEMENT}$	Receiver implementation loss margin	[dB]
$L_{RELIABLE}$	Shadowing plus fast fading margin	[dB]
L_{BUILD}	Building penetration margin	[dB]
$L_{SCENARIO}$	Scenario loss margin	[dB]

Many of the variables present in equation (2.2-1) can take a range of numerical values and each is discussed in greater detail by Hallahan and Peha (2008), while the base case values used in the analysis in this paper are summarized in section 3.

Equation (2.2-1) uses the Hata model (Hata, 1980; Parsons, 2000) to predict propagation path loss.[3] The equations used in the Hata model are different for urban, suburban, or rural regions. There is no universally accepted population density threshold which separates these categories; so in this paper, as discussed by Hallahan and Peha (2010b), rural is defined as having less than 100 people per square kilometer and urban as having more than 1900 people per square kilometer, as these values are in line with the values used in similar analysis (Newman, 2008).

For some of the analysis in this paper, it is necessary to study costs as a function of population density, and to do so, Equation (2.2-1) must be modified. Since the Hata model has only three classifications, it was necessary to develop a finer grain propagation model that is a function of

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[3] The Hata model is represented by the terms K, K4 and K5 in equation 2.2-1.

population density. As described in greater detail by Hallahan and Peha (2009), regression analysis was used to find a power-law fit to the Hata model as a function of population density that closely reproduces the results of the original equations in practice. Therefore, instead of the K, K4 and K5 terms in equation (2.2-1), for certain pieces of analysis in section 4, equation (2.2-2) is used:

$$r = 0.0019 \cdot (\rho_{POP})^{-0.194} \cdot e^{0.0692442(PL)} \qquad (2.2\text{-}2)$$

With these equations it is possible calculate the number of cell sites, and from that number it is possible to estimate total infrastructure cost using cost per cell site estimates. This paper estimates both the upfront deployment costs for the infrastructure and recurring annual operating costs. However, this paper only consider costs associated with the installation and operation of cell sites, and not the costs of the core network including mobile switching centers, 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 (Frontline Wireless, 2007), this paper calculates costs and revenues for a commercial provider that adopts a wholesale business model. As such, this paper neglects 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 adjusts 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, this paper considers the cost of towers as an upfront deployment cost. In the base case, this paper uses an estimate of $500 000 per cell site for the upfront cost and $75 000 per cell site for the annual operating cost, as discussed by Hallahan and Peha (2010b). These values are consistent with estimates in similar analysis (Access Spectrum, Columbia Capital III, Pegasus Communications & Telcom Ventures, 2006; Eisenach, 2007; Newman, 2008) but are roughly double the values used in the analysis performed by the FCC (2010a) which were based on different assumptions about the amount of existing infrastructure that is leveraged.

2.3. Subscribers and Revenue

While the previous section focused on calculating the number of cell sites required to cover the 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, the model calculates the number of subscribers by determining the fraction of population that subscribes to the network and calculates revenue using estimates of the revenue per subscriber.

In a public-private partnership, there are two types of subscribers: public safety and commercial users. It is possible calculate the number of both types of users based on the population covered by the network. The model calculates commercial subscribers by looking at projections from a commercial carrier and calculates public safety subscriptions using the linear relationship between first responder density and population density established by Hallahan and Peha (2008).

In the model used in this paper, the market penetration variable, *Pen,* represents the fraction of population covered that the network is designed to serve. This variable can significantly affect the size of the 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 cell sites will be required and thus the more the network will cost. On the other hand, this greater cost is offset by increased revenue due to more subscribers. Thus, before designing the network, the commercial operator must first determine the target market penetration to plan for. 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, it is necessary 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 will be in each year, it is possible to use the experience of a similar market entrant as a guide. In this paper, the actual and projected market penetration for the company Clearwire is studied. Clearwire is a new entrant in the commercial wireless market and is currently in the process of deploying a greenfield nationwide broadband wireless network. Table 1 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 (Butler, 2008).

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%[4]	3.54%	5.67%	7.20%[5]	8.73%[5]	10.26%

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

This paper assumes that the network planner first determines the number of 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 cell sites over a ten-year period. The amount of capacity (and thus commercial penetration) is chosen to maximize profit over that period. The authors 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 it is assumed that this does not occur before year 10. Under these assumptions, this paper finds[6] that a profit-maximizing provider in a public-private partnership operating in 20 MHz should initially design the network to support a market penetration of 8.5%, whereas a commercial-only system operating in 10 MHz should initially design for a market penetration of 3%.

Thus, in the base case, Table 1 is used 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, *Pen*, causing commercial users to see a decline in grade of service beyond design thresholds, it is assumed that this decline in grade of service will deter expansion, and market penetration will remain constant. Therefore, in the base case where *Pen* equals 8.5%, and based on Table 1, this threshold market penetration of 8.5% is achieved in the 9th year.

In addition to commercial subscribers, the public-private partnership is able to serve public safety subscribers as well. As shown by Hallahan and Peha (2008), first responder density is a linear function of population density, and thus it is possible to calculate the number of first responders covered from the

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[4] Year 5 is where the actual and projected data intersect, resulting in a dip in market penetration. Instead a value is used for market penetration that is midway between the market penetration of years 4 and 6.

[5] 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.

[6] Though outside the scope of this paper, by running many simulations with varied target market penetrations, it was found 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.

population covered in a region and the population density for that region. Furthermore, this work makes the optimistic assumption that all public safety agencies will use this network and will subscribe as soon as they are covered. As will be shown in section 4.6.3, even with this assumption, most revenue comes from commercial subscribers, so this assumption has limited impact on the results in this paper. In addition, it is assumed that only one subscription will be purchased for every 2.5 first responders, which is consistent with similar analysis (Eisenach, 2007). This seems reasonable given that not all first responders work on the same shift and therefore radios are typically shared to reduce costs.

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 per month (FCC, 2008d). However, this number represents the industry average for retail customers and since this paper considers a wholesale business model, a value of $10 per subscription per month in the base case is chosen. This number is based on the revenue a major wireless carrier receives from its wholesale operations and is in line with the value used in similar analysis (Eisenach, 2007).

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. Thus, in the base case, this work assumes that each public safety subscription generates $30 in revenue each month for the partnership. This is consistent with a service fee of $50 per month and retail operating costs that equal 40% of retail revenue as suggested in similar analysis (Eisenach, 2007). A monthly service fee of $50 per subscription is in line with the monthly fee of $48.50 per user that the FCC (2008c) proposed as a base rate to be charged to all public safety users by the public-private partnership.

2.4. Net Present Value

Having developed a method to calculate the cost and revenue cash flows for each year into the future, it is now possible to 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. As discussed by Hallahan and Peha (2009), the model calculates a network's NPV using the following equation, which is based on the equation for NPV from Clemen and Reilly (2001):

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

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	[$/month]
R_{COMM}	Monthly revenue per commercial subscription	[$/month]
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	[$]
Opex	Annual cost to operate a cell site	[$/year]
D	Discount rate	
n	Time horizon	[Years]

In the base case, a time horizon of 10 years is chosen 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 by the FCC (2008a) it carried an initial license term of 10 years (although licenses are usually renewed). Additionally, a value of 8% is chosen for the discount rate in the base case, consistent with the value used in similar analysis (Mobile Satellite Ventures, 2008).

3. *Scenarios Analyzed*

This paper studies two different network scenarios where a network scenario is the name given to a distinct set of numerical input values that is analyzed with the 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.

In their initial proposal, the FCC (2007) designated a 10 MHz 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 10 MHz commercial license for the spectrum adjacent to the public safety allocation, which was later auctioned in February 2008. Thus, in the base case, the public-private partnership is allocated 20 MHz of combined commercial and public safety spectrum. For the commercial-only network, only the 10 MHz 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 more stringent public-safety requirements. This means that in addition to the spectrum bandwidth allocated, 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: 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 building penetration margin.

The public safety capacity model, previously developed by Hallahan and Peha (2008), takes the following three parameters as inputs: β_{MAX}, β_{SUM}, $\rho_{\beta RT}$. The values chosen for each of these variables in the base case for a public-private partnership that carries voice and data traffic is discussed in detail by Hallahan and Peha (2008). By definition, β_{SUM} and $\rho_{\beta RT}$ 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 $\rho_{\beta RT}$ 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, a value of 50kbps is chosen for the commercial-only network which is consistent with similar analysis of a commercial network (Newman, 2008). Based on the β_{MAX} equation provided by Hallahan and Peha (2008), a β_{MAX} value of 0.14 is calculated using 50kbps as the input. Additionally, $\rho_{\beta SUB}$ is the measure of the capacity required per commercial subscriber and, in the base case, a $\rho_{\beta SUB}$ value of 0.0029 is calculated as discussed by Hallahan and Peha (2008).

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, a transmit power of about 250mW or 24dBm is chosen (Newman, 2008) compared to the 37dBm chosen for public safety devices in a public-private partnership (Hallahan & Peha, 2008). (This is in contrast to the analysis performed by the FCC (2010a), in which public safety devices transmit at a lower commercial-level power. This design decision by the FCC enables reduced handset costs and lower power requirements but results in additional cell sites being required.) 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, a signal coverage reliability of 90% is chosen for the commercial-only network, down from the 97% level used for the public-private partnership (Hallahan & Peha, 2008; TIA TR8 Working Group 8.8, 1997). Consistent with similar analysis (Newman, 2008), the building penetration margin required for commercial users can be reduced from the 13dB margin used in a public-private partnership (Hallahan & Peha, 2008; Desourdis, Smith, Speights, Dewey, & DiSalvo, 2002), to a 6dB margin which should be sufficient for reliable service in most vehicles (Peha, 2008a).

In Table 2, the inputs used in the model and the numerical values chosen in the base case for each of the two scenarios studied are summarized.

	Input	Pub-Priv	Comm-Only	Units	Description
Link Budget	P_{EIRP}	37	24	dBm	Transmit Power (3W ERP & 0.25W)
	G_{RX}	18	18	dBi	Receiving Antenna Gain
	$L_{RELIABLE}$	12.6	6.9	dB	97% & 90% Coverage Reliability Margin
	L_{BUILD}	13	6	dB	Building Penetration Margin
	$L_{IMPLEMENT}$	4	4	dB	Implementation Losses
	$L_{SCENARIO}$	4	4	dB	Scenario Losses
Propagation	f	776	776	MHz	Transmit Frequency
	h_m	1.5	1.5	m	Height of Mobile Transmitter
	h_b	60	60	m	Base Station Antenna Height
	W	20	10	MHz	Bandwidth of Spectrum Allocation
Capacity	β_{SUM}	2.5	0	--	Measure of PS Emergency Capacity Required
	$\rho_{\beta RT}$	0.0055	0	--	Measure of PS Routine Capacity Required
	β_{MAX}	0.34	0.14	--	Measure of Highest User Datarate Required
	$\rho_{\beta SUB}$	0.0029	0.0029	--	Measure of Commercial Capacity/Subscriber
	Pen	0.085	0.03	--	Commercial Market Penetration
	fract	0.6	0.6	--	Other Cell Interference Fraction
NPV	n	10	10	yrs.	Time Horizon
	D	8%	8%	--	Discount Rate
Cost & Revenue	R_{PS}	30	0	\$/mo.	Monthly Revenue per Public Safety Subscriber
	R_{COMM}	10	10	\$/mo.	Monthly Revenue per Commercial Subscriber
	Capex	500 000	500 000	\$	Upfront Cost to Deploy a Cell Site
	Opex	75 000	75 000	\$/yr.	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. The capacity, propagation, and link budget values are discussed in greater detail by Hallahan and Peha (2008).

4. Results

The goal of this section is to identify the circumstances under which a public-private partnership is viable in an effort to aid decision makers as they craft future policy. Section 4.1 studies the NPV per cell as a function of population density for both a public-private partnership and a commercial-only network, and identifies the regions of the country in which the partnership is profitable and how this profitability compares to a commercial-only network. Section 4.2 studies the NPV of the public-private partnership and shows how this value varies with the coverage build-out requirements. Then, section 4.3 discusses the sustainability of a public-private partnership based on its NPV and how that NPV changes over time. Section 4.4 studies the impact that urban areas opting-out of the partnership will have on the sustainability of the partnership. Finally, sections 4.5 and 4.6 study how these results depend on system characteristics (e.g. public safety capacity and signal reliability requirements) and financial factors (e.g. revenue per subscriber, projections of market penetration, and costs per cell), respectively.

4.1. Regions of Profitability

A number of important questions can be answered by analyzing the NPV per cell site, including determining whether it is more desirable to build out a network in urban areas or rural areas. Also, by studying NPV per cell site, it is possible to determine 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 site, the model first calculates the cost to build out and operate a cell at a given population density, as described in section 2.2. Then, the number of subscribers covered by that cell and the revenue derived from those subscribers are calculated, as described in section 2.3. The NPV for each cell can then be calculated from these cash flows. Fig. 1 is a plot of the NPV per cell as a function of population density for both a public-private partnership and a commercial-only network.

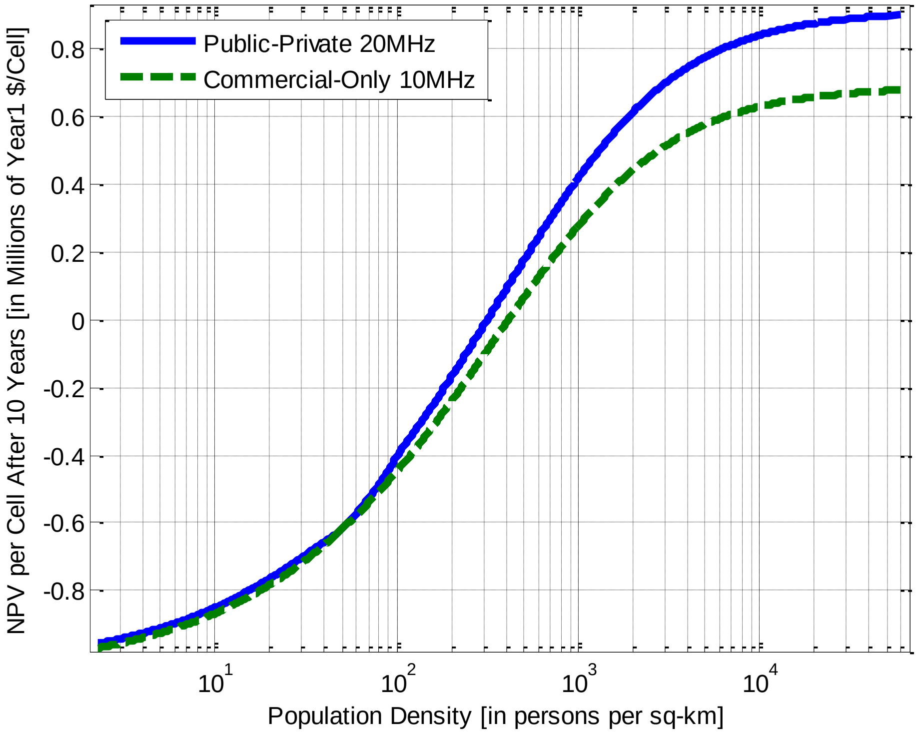


Fig. 1: A plot of the net present value per cell site as a function of population density for a public-private partnership and commercial-only network after 10 years.

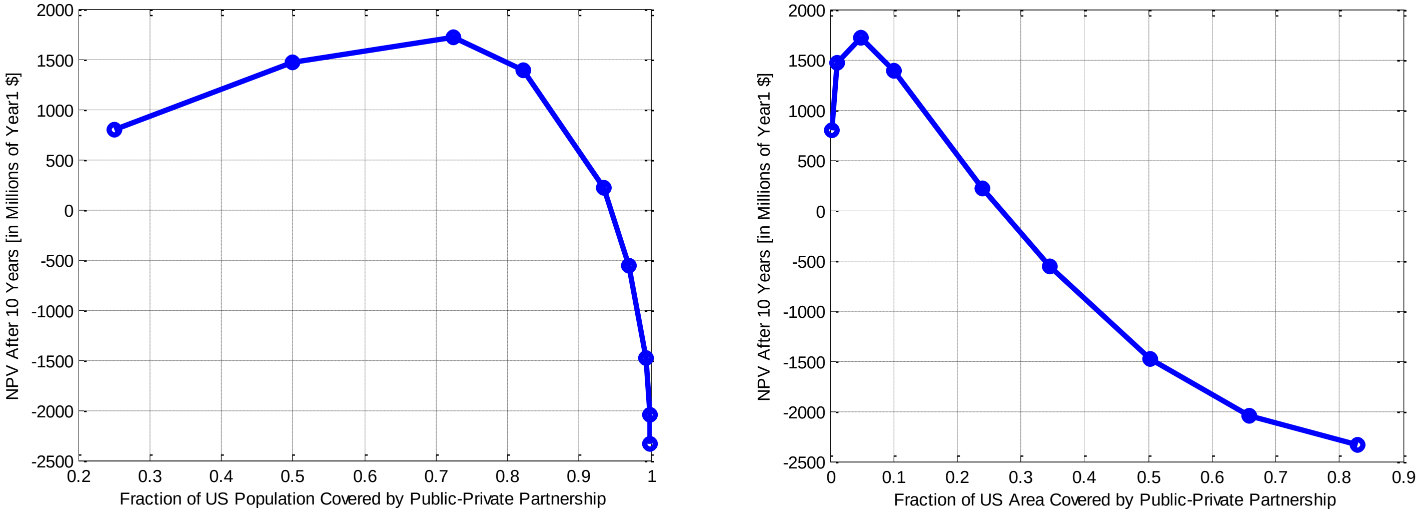
In Fig. 1, it is observed that for all levels of population density the NPV per cell is always greater for a public-private partnership on 20 MHz than for a commercial-only network on 10 MHz. This means that the value of access to additional spectrum and the right to serve both commercial and public safety subscribers on that spectrum are 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.

Fig. 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 studied in this paper, 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 Fig. 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 Fig. 1, the point at which the curves cross the *x*-axis is determined to be at about 320 pop/km^2 and 410 pop/km^2 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/km^2, 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/km^2; 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 by the FCC (2008a). 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. How Build-Out Requirements Affect Profitability

Section 4.1 established the regions in which a public-private partnership is profitable (i.e. NPV/cell > 0) and unprofitable (i.e. NPV/cell < 0). Given the dramatic impact that the population density of the area covered can have on the NPV of the public-private partnership, if the commercial partner was allowed to choose the area covered by the network, many rural areas would go uncovered. Thus, it may be necessary to impose coverage-based build-out requirements on the public-private partnership. To study the impact of these requirements, Figs. 2(a) – 2(b), plots the NPV of a public-private partnership while varying the fraction of U.S. population and fraction of U.S. area covered by the partnership.



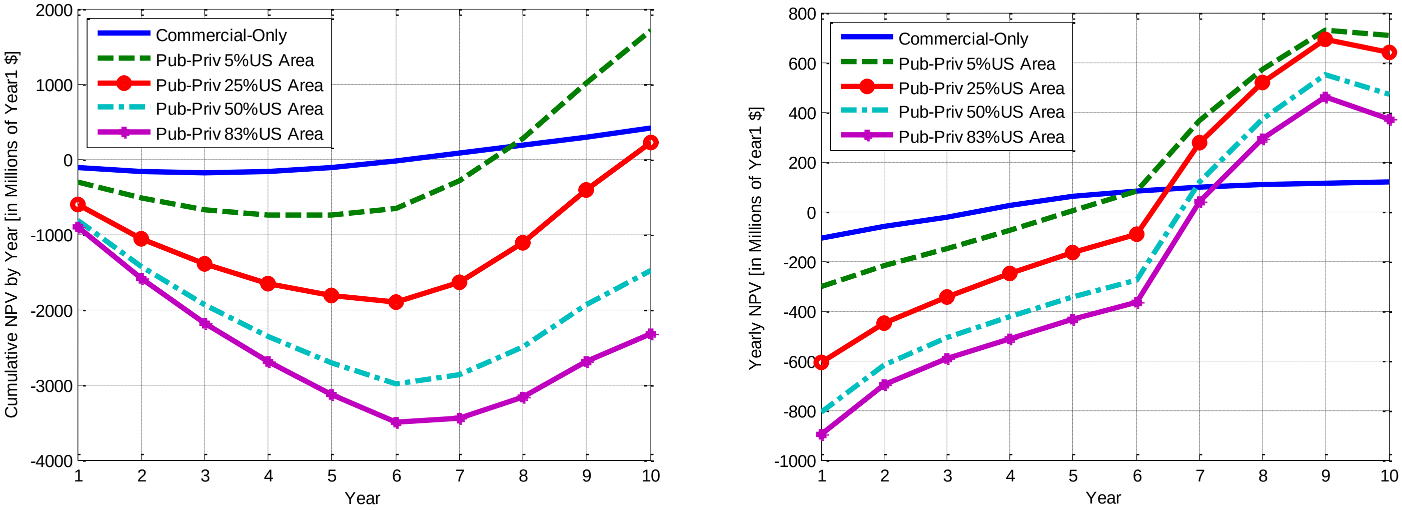
Figs. 2(a) – 2(b): A plot of the net present value of the public-private partnership after 10 years while varying (a) the fraction of U.S. population covered by the partnership and (b) the fraction of U.S. area covered by the partnership.

Fig. 2(a) shows that in the base case (i.e. *x* = 99.3%), the NPV of the public-private partnership is about –$1.5 billion. In order for the partnership to break even after 10 years (i.e. NPV = 0), population coverage must be reduced to about 94%. Moreover, if the population covered is further reduced to about 72%, up to $1.7 billion 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 (Hallahan, 2008). To demonstrate this, Fig. 2(b) shows the same thing as Fig. 2(a), except with area coverage as the *x*-axis instead of population coverage. This plot shows that when population coverage is reduced to 72%, 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 U.S. area covered is between 5% and 50%, there is an approximately linear relationship between fraction of U.S. area covered and the NPV of the partnership (for every 20% less of the U.S. area covered, NPV increases by roughly $1.5 billion).

4.3. The Sustainability of the Partnership

In this paper, three categories are defined 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 terms the partnership is unprofitable and thus unsustainable even if provided an upfront subsidy to cover initial costs.

In the base case, while ignoring any spectrum cost/subsidy, the public-private partnership (covering 99.3% of U.S. population/50% of U.S. area) has an NPV of about –$1.5 billion and the commercial-only network that serves only profitable regions has an NPV of about $400 million 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, Figs. 3(a) – 3(b) is a plot of the cumulative NPV after *x* years for both the public-private partnership (for several levels of area coverage) 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 revenue minus cost) for both networks.



Figs. 3(a) – 3(b): A plot of (a) the cumulative (b) the yearly net present value after *x* years for a public-private partnership (for 4 levels of area coverage) and commercial-only network over the first 10 years.

Fig. 3(a) shows that the commercial-only network breaks even in its 6th year after bottoming out in the 3rd year. Meanwhile, the base case public-private partnership that covers 50% of U.S. area has its lowest cumulative NPV in the 6th year when NPV is about –$3.5 billion, 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 6, 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. Fig. 3(b) reinforces this point, showing 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 $500 million annually in the base case. Given that the partnership does not post annual losses perpetually going forward, it is possible to conclude that the partnership may be profitable in the long term and that it is sustainable in the base case if given an upfront subsidy of at least $1.5 billion. In fact, Fig. 3(b) indicates that even if you vary the build-out coverage requirement from the base case, while the initial subsidy needed may change, the public-private partnership is still likely to be sustainable long term. For instance, if the coverage requirement is increased to 83% of U.S. area, the subsidy needed increases to $2.3 billion but the partnership still has a positive annual NPV of $400 million in year 10.

4.4. The Impact of Urban Areas Opting-Out

As discussed in section 0, recently several municipalities, mostly in densely populated areas, have expressed interest in opting-out of a future partnership and instead obtaining a waiver to use the spectrum themselves. However, as shown 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. This section explores the impact that profitable urban areas opting-out of a partnership can have on the NPV of the partnership by studying two different scenarios: (1) municipalities receive waivers for the 10 MHz of public safety spectrum, and (2) municipalities receive waivers for the 20 MHz of combined spectrum.

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

$$NPV_{10} = NPV_0 - NPV_{OptOut\_PP} + NPV_{OptOut\_CO} \qquad \text{for 10 MHz waivers} \qquad (4.4\text{-}1)$$

$$NPV_{20} = NPV_0 - NPV_{OptOut\_PP} \qquad \text{for 20 MHz waivers} \qquad (4.4\text{-}2)$$

Equation (4.4-1) represents the scenario in which the municipalities that opt-out receive a waiver for the 10 MHz of public safety spectrum, and therefore the public-private partnership operates as a commercial-only network in the areas where the opt-out occurs. Equation (4.4-2) represents the scenario in which the municipalities that opt-out receive a waiver for the full 20 MHz of public safety spectrum, and therefore 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 20 MHz to be granted, additional legislation would need to be passed.

Fig. 4 is a plot of the reduction in NPV of a public-private partnership as a function of the fraction of population covered by the opt-out area where it is assumed that the most urban zip codes across the nation opt-out first.

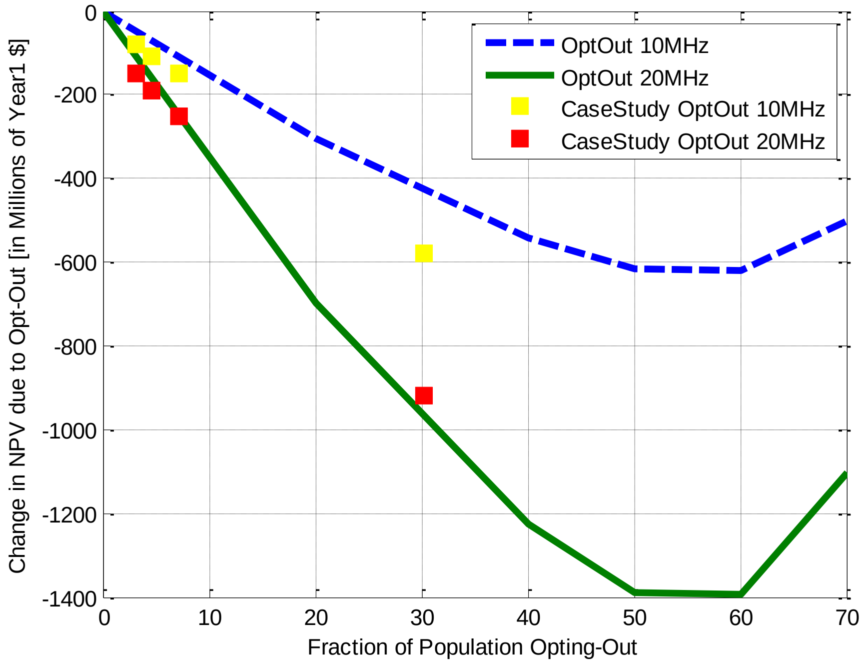


Fig. 4: A plot of the change in net present value of a public-private partnership after 10 years for a range of values for the fraction of population that opts-out.

Fig. 4 establishes the fact that when urban areas opt-out, it always reduces the NPV of the partnership. Additionally, it is observed that for all fractions of population studied, the 20 MHz waiver always results in a greater reduction in NPV than a 10 MHz waiver. When 60% of the population opts-out, the reduction in NPV peaks at –$1.4 billion and –$600 million for the 20 MHz and 10 MHz waiver scenarios, 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 waiver requests submitted have been from urban regions (FCC, 2009).

This is consistent with the results discussed by Hallahan and Peha (2009) wherein the impact of opting-out was analyzed by studying the NPV of a network that covers a collection of zip codes associated with a set of municipalities. In that work, four sets of urban municipalities were defined representing a range of scenarios of municipalities opting-out of a nationwide public-private partnership: Set 1 includes only 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. The first 3 sets represent different combinations of municipalities which have already filed for waivers with the FCC (2009) while Set 4 includes most of the largest municipalities in the U.S. and all are members of a group that submitted a letter expressing interest in having all 20 MHz of the spectrum for the public-private partnership being licensed directly to public safety (Bischoff, 2008; Major Cities Chiefs Association, 2008). These 4 sets of municipalities cover between 8.7 million and 85 million people and Hallahan and Peha (2009) found that the reduction in NPV from these sets opting-out is anywhere from $80 million to $920 million. Additionally, the results from these sets are plotted in Fig. 4 (represented by the 4 case study data points for both a 10 MHz and 20 MHz waiver) and tend to be consistent with their respective opt-out curves.

4.5. The Impact of Link Budget and Capacity Requirements on NPV

As discussed by Hallahan and Peha (2010b), 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. As that work established, the values chosen for the link budget (e.g. signal coverage reliability and building penetration margin) and capacity requirements (e.g. the highest upstream datarate required at the cell-edge) can have a significant impact on the number of cell sites required in a public-private partnership. Therefore, section 4.5.1 quantifies the impact that a range of link budget input values can have on the NPV of a public-private partnership while section 4.5.2 quantifies the impact that a range of public safety capacity requirements can have on NPV.

4.5.1. The Impact of Link Budget Margins on NPV

As discussed in section 2.2, the model used in this paper 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 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, the link margin is defined as the summation of all the gains and losses (in dB) in the link budget, except for the path loss and receiver sensitivity, as shown in equation (4.5-1). In Fig. 5, the link margin is varied 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.

$$LINK_{MARGIN} = P_{EIRP} + G_{RX} - L_{IMPLEMENT} - L_{SCENARIO} - L_{RELIABLE} - L_{BUILD} \qquad (4.5-1)$$

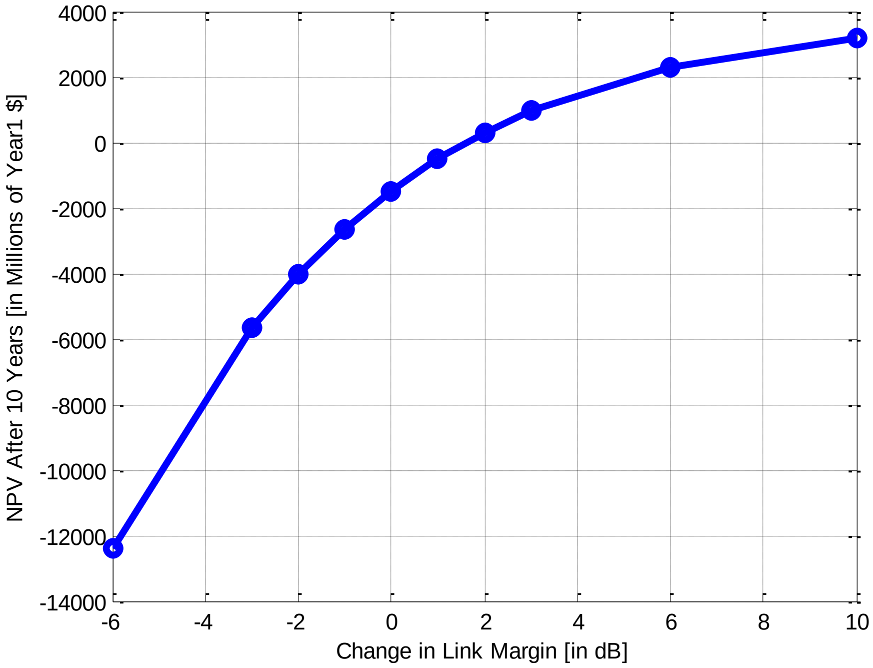


Fig. 5: A plot of the net present value of a public-private partnership after 10 years for a range of link margin values.

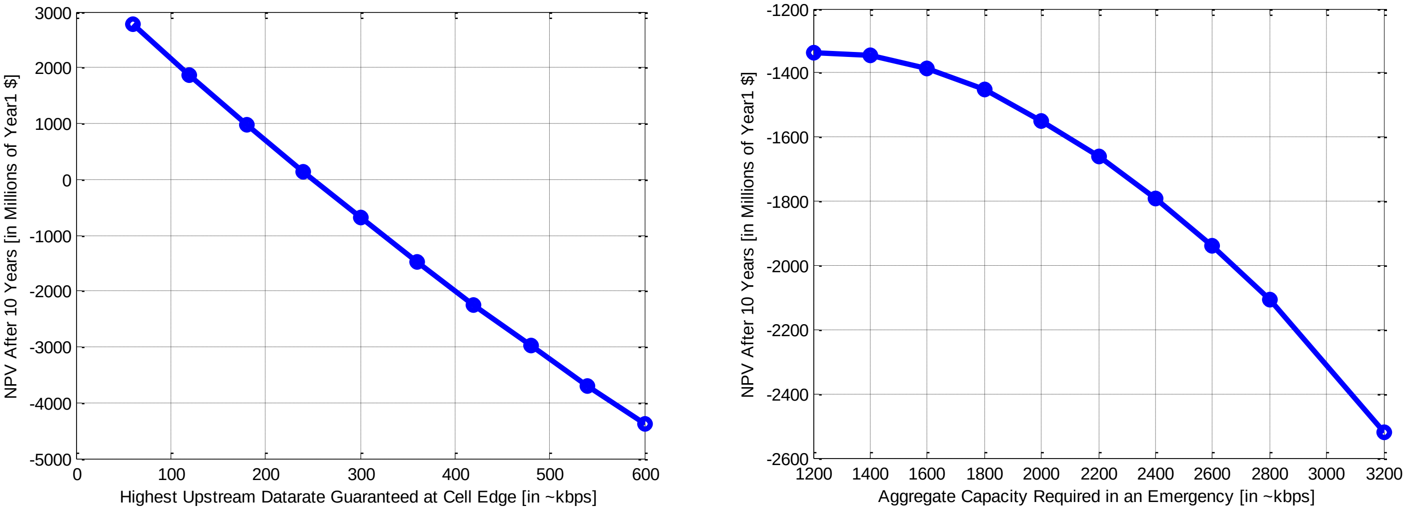
Fig. 5 shows that changing the link margin by more than a few dB considerably changes the NPV of a public-private partnership. This is due to the fact that slight changes to the link budget can have a substantial impact on the number of cell sites required, as found by Hallahan and Peha (2010b). For example, reducing the link margin of a public-private partnership by 6dB could reduce the NPV by about $10 billion while increasing it by 6dB would increase NPV by about $4 billion 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 building penetration margin could yield such a change.

To put this in perspective, a signal coverage reliability level of 95% was proposed first by the Public Safety Spectrum Trust (PSST, 2007) and later adopted by the FCC (2008c), but 97% coverage reliability may be more typical of existing public safety systems (TIA TR8 Working Group 8.8, 1997). Similarly, (PSST, 2007) and later the FCC (2008c) proposed a building penetration margin of 6dB in rural areas, whereas a 13dB building penetration margin is sufficient for coverage within concrete buildings (Desourdis et al., 2002) . In the base case, the more stringent level for these requirements is chosen, but if the signal coverage reliability were reduced to 95%, that would increase the link margin by a little over 2dB as discussed by Hallahan and Peha (2008). This would result in about a $2 billion increase in the public-private partnership's NPV, meaning the partnership would just about break even. Likewise, if a 6dB 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 over $4 billion and become much more attractive to a commercial partner.

4.5.2. The Impact of Capacity Requirements on NPV

As mentioned in section 3, Hallahan and Peha (2010b) previously developed a model of public safety capacity which is characterized by the following three input parameters: β_{MAX}, β_{SUM}, $\rho_{\beta RT}$. Each of these parameters is discussed in much greater detail by Hallahan and Peha (2008), but at a high level, these parameters are measures of the highest user datarate, aggregate capacity, and routine capacity per user required, respectively. Each is dependent on the datarate and E_b/N_o required by first responders.

There is considerable uncertainty surrounding the capacity requirements of public safety on a broadband wireless network and, as was found by Hallahan and Peha (2010b), 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, Figs. 6(a) – 6(b), studies the impact on the NPV of a public-private partnership due to varying the numerical value chosen for the datarate in β_{MAX} and β_{SUM}, respectively, while holding the E_b/N_o and the other capacity values constant.



Figs. 6(a) – 6(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 by Hallahan and Peha (2010b), as the highest upstream datarate required increases, the number of cell sites required in a public-private partnership increases as well. Similarly, Fig. 6(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.

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 observed in Fig. 6(b), increasing aggregate capacity by about 80%, from the base case value of about 1800kbps to 3200kbps, decreases the NPV by over a billion dollars. However, reducing aggregate capacity from the base case value has a diminishing effect, with the NPV leveling off at about –$1.35 billion.

4.6. The Impact of Costs and Revenue on NPV

In addition to the technical requirements of a public-private partnership, the value chosen for financial factors such as the costs per cell site, market penetration, and the revenue per subscriber have a dramatic impact on the NPV of a system. Section 4.6.1 studies the impact on NPV of varying upfront capital and annual operating costs per cell, while sections 4.6.2 and 4.6.3, respectively, study the impact on NPV as the projection used for market penetration and the values chosen for the revenue per commercial and public safety subscriber are varied.

4.6.1. The Impact of Costs per Cell on NPV

After calculating the number of cell sites 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, in the base case, the upfront cost per cell is $500 000 while the annual cost per cell is $75 000. Fig. 7 shows how NPV depends on the value chosen for both the upfront cost per cell and the annual cost per cell.

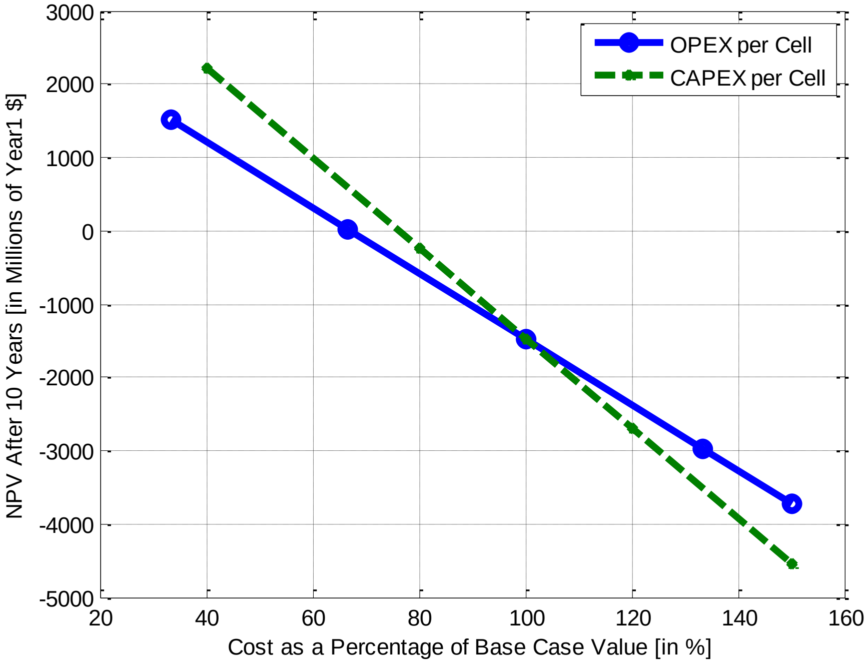


Fig. 7: A plot of the net present value of a public-private partnership after 10 years for a range of values for the upfront capital cost per cell and annual operating cost per cell.

In Fig. 7, 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 every 20% (or $15 000) increase in annual operating cost per cell, there is a billion dollar decrease in the NPV of the partnership. Similarly, for every 20% (or $100 000) increase in the upfront capital cost per cell, there is a $1.25 billion 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.

4.6.2. The Impact of Market Penetration Projections on NPV

In order to calculate the number of commercial subscribers on the network, it is necessary to project the market penetration for the network in the future. As discussed in section 2.3, in the base case the model uses a projection of market penetration based on numbers from Clearwire. In this projection, market penetration is about 1% in year 1, grows slowly for a few years to about 3.5% in year 6, and then grows more rapidly to roughly 10% in year 10. In Fig. 8, the impact that the projection used for market penetration can have on the NPV of the network is investigated. To do so, each year of the base case projection is multiplied by a constant factor, and the impact on NPV is studied as this factor is varied. For comparison purposes, a linear projection is also introduced which, in the base case, has a market penetration of 1% in year 1, 2% in year 2, and so on to 10% in year 10.

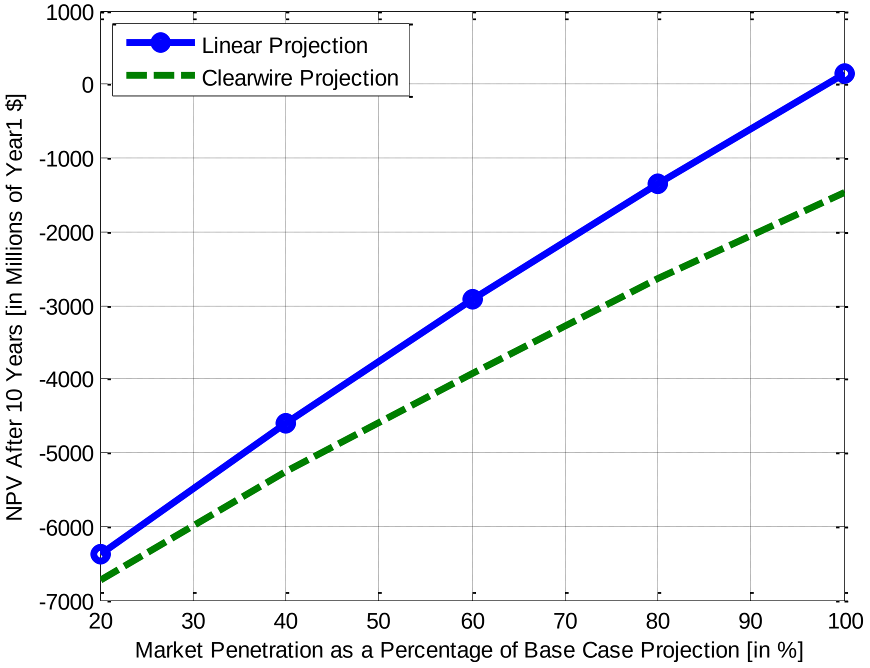


Fig. 8: A plot of the net present value of a public-private partnership after 10 years for a range of projections of market penetration.

Fig. 8 illustrates that the rate at which market penetration grows can have a substantial impact on profitability. More specifically, in the base case the NPV of the partnership would be $1.5 billion greater if market penetration grew at a linear rate rather than the slower Clearwire-based rate. Additionally, for both the linear and Clearwire-based projections, Fig. 8 shows that as market penetration is decreased, the NPV of the partnership decreases at an approximately linear rate. When the market penetration is reduced to only 20% of the base case projection, the NPV of the partnership falls to roughly –$6.5 billion for both projections. The vast range of NPV's possible for the projections studied underscores the risk associated with a public-private partnership. Since it is impossible to be certain of the market penetration the partnership will actually be able to acquire once deployed, it is important for policymakers to understand that deviations from projections could dramatically affect the sustainability of the partnership and the size of subsidy required.

4.6.3. The Impact of Revenue per Subscriber on NPV

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 section 2.3, 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. Fig. 9 shows how NPV depends on the value chosen for the revenue per each type of subscriber.

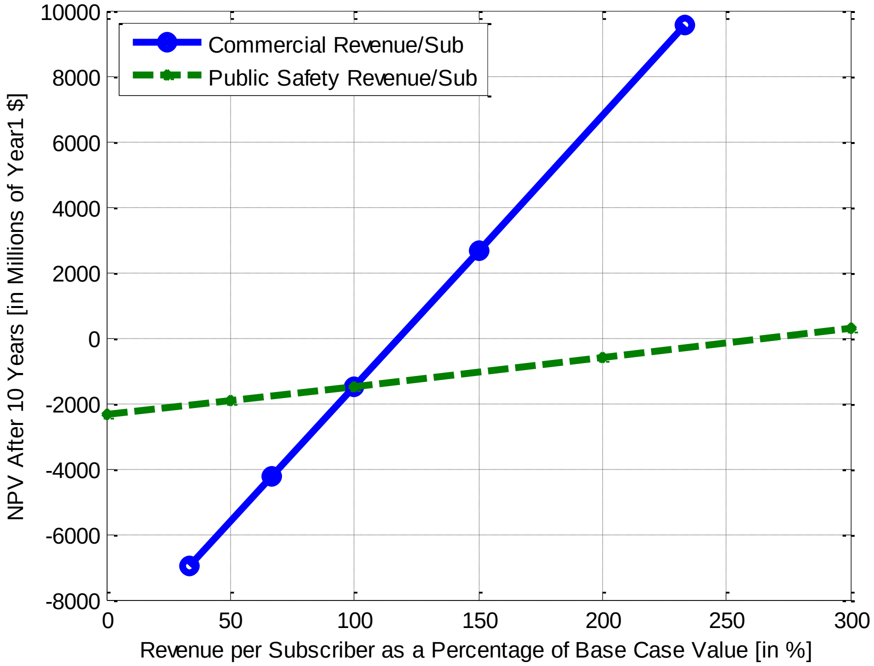


Fig. 9: A plot of the net present value of a public-private partnership after 10 years for a range of values for the revenue per commercial and public safety subscriber.

In Fig. 9, 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 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 about a billion dollars. Instead, the revenue per public safety subscriber needs to increase by 150% from its base case value to $75/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.

5. *Conclusions*

While a wireless broadband network serving all public safety users in the U.S. may represent a significant upgrade over the existing fragmented public safety communications infrastructure (Hallahan & Peha, 2010b; Peha, 2007a), 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 and commercial users. This paper studied a joint-use network in the form of a public-private partnership (which is one proposal considered by the FCC (2007; 2008b; 2008c)). The FCC's 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 financial sustainability of such a public-private partnership.

More recently, the FCC (2010a; 2010b) has proposed another option to enable public safety and commercial users to share a network: incentives-based partnerships built on the D-block and public safety spectrum at 700MHz (Manner, Newman, & Peha, 2010; Newman & Peha, 2010). If public safety has priority access (Hallahan & Peha, 2010a) to the D-block spectrum, as the FCC has proposed, and the commercial partner deploys a greenfield network, such a partnership would be consistent with the model studied in this paper. Moreover, while some of the assumptions underlying the cost estimates in this paper and those performed by the FCC differ (including the amount of existing infrastructure that is leveraged, the air interface technology used, and design choices like handset transmit power), the results based on the model in this paper are still useful since the costs predicted by both analyses are roughly equivalent[7]. However, for either type of partnership to work, a number of institutional and governance issues will need to be resolved beforehand (as discussed in section 0). These considerations are outside the scope of this work since the results in this paper are not dependent on the specific details of the institutional and governance arrangements.

To study the sustainability of a public-private partnership, this paper 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 (Butler, 2008) of penetration as a function of number of years since deployment in a given region. This paper applied the model to both a public-private partnership that serves commercial subscribers in addition to all public safety personnel on 20 MHz of spectrum in the 700MHz band, and a commercial-only network that serves just commercial subscribers on 10 MHz of spectrum in the 700MHz band.

This paper demonstrated that, in the base case, 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 10

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[7] The FCC (2010a) has concluded approximately 44 000 cell sites would be required to cover 99% of the US population at a cost of $12 to 16 billion over 10 years if existing infrastructure is leveraged while Hallahan and Peha (2010b) found that an equivalent greenfield public-private partnership would require roughly 16 000 cell sites and cost roughly $15 billion over 10 years.

MHz of spectrum available in the partnership is always more than the cost to meet public safety's more stringent capacity, signal coverage reliability and building penetration requirements.

Furthermore, this paper demonstrated 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. Indeed, 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 Hallahan and Peha (2010b) found that the cost 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 revenue is insufficient to offset costs. Since a for-profit commercial provider building a greenfield network 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 U.S. population while a public-private partnership would choose to serve about 56% of U.S. population. This is about 1.3% and 1.7% of U.S. area, respectively. Conversely, this means that almost half of the population, primarily in rural and suburban areas, 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, 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 94% and the partnership still breaks even (i.e. NPV = 0). However, even when 94% 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 38% 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 was done in the base case, it was determined that a public-private partnership will require a subsidy on the order of $1.5 billion to meet initial costs, but is likely sustainable in the long run as it generates a positive NPV each year after year 7. In comparison, Hallahan and Peha (2010b) found that a comparable public-safety-only network deployed on 10 MHz of 700MHz spectrum and also covering 99.3% of the population would require about 19 000 cell sites and cost about $9.5 billion to deploy and $1.5 billion annually to operate and maintain. This implies that unless 10 MHz of the partnership spectrum can raise at least eight 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 the analysis by Hallahan and Peha (2008) shows that 83% of U.S. 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 the population covered is not increased should be kept in mind when considering build out coverage requirements.

In order to guarantee at least 99.3% of population and 50% of area are covered if predominately urban regions are granted waivers and allowed to opt-out of a partnership, this paper demonstrated 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 (2009) have come from urban municipalities. 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 for 10 MHz and 20 MHz waivers respectively. However, when the opt-out consists of about 55 urban municipalities, NPV is reduced by $580 million and $920 million for a 10 MHz and 20 MHz 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, it was shown that if about 55 urban municipalities receive 20 MHz waivers, the area of the U.S. covered would need to be reduced from 50% to 38% to compensate.

Besides build-out coverage requirements, this paper demonstrated 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 and capacity requirements. Of the capacity requirements, the highest upstream user datarate 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. Thus, it is important to determine which applications are considered mission-critical by public safety so that the appropriate datarate is guaranteed at the cell-edge. Besides the highest datarate guaranteed, it also matters what the aggregate capacity requirements are during an emergency response. In the base case, decreasing aggregate capacity has little impact while increasing aggregate capacity by 80% will decrease the NPV by more than 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 the 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 by the FCC (2008c), 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 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 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 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 building penetration levels, then 10 MHz 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, projection of market penetration, and cost per cell which also have a significant impact on the NPV of the partnership. This paper demonstrated 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, this paper showed 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 increased by 150% 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. 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 would not 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.

Additionally, the projection used for market penetration can drastically change the NPV of the partnership. For instance, when the market penetration is reduced to only 20% of the base case projection, the NPV of the partnership falls to roughly –$6.5 billion. Given how dramatic the change in NPV can be for the projections studied, it is clear that there is considerable risk associated with a public-private partnership. Thus, it is important for policymakers to understand that the subsidy required and the sustainability of the partnership both depend on projections of the future which are impossible to predict with absolute certainty. Finally, in addition to revenue and market penetration, this paper demonstrated 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.

6. Acknowledgements

The authors gratefully acknowledge the financial support of the MacArthur Foundation.

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