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Research Article

Examining the Viability of Broadband Wireless Access under Alternative Licensing Models in the TV Broadcast Bands

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One application of cognitive radios is to provide broadband wireless access (BWA) in the licensed TV bands on a secondary access basis. This concept is examined to see under what conditions BWA could be viable. Rural areas require long range communication which requires spectrum to be available over large areas in order to be used by cognitive radios. Urban areas have less available spectrum at any range. Furthermore, it is not clear what regulatory model would best support BWA. This paper considers demographic (urban, rural) and licensing (unlicensed, nonexclusive licensed, exclusive licensed) dimensions. A general BWA efficiency and economic analysis tool is developed and then example parameters corresponding to each of these regimes are derived. The results indicate that an unlicensed model is viable; however, in urban areas spectrum needs can be met with existing unlicensed spectrum and cognitive radios have no role. In the densest urban areas, the licensed models are not viable. This is not simple because there is less unused spectrum in urban areas. Urban area cognitive radios are constrained to short ranges and many broadband alternatives already exist. As a result the cost per subscriber is prohibitively high. These results provide input to spectrum policy issues.

1. INTRODUCTION

Cognitive radios (CRs) have the potential for providing broadband wireless access (BWA) as an alternative to existing broadband options. In the Notice of Proposed Rule Making, *Unlicensed Operation in the TV Broadcast Bands*, the FCC proposed both low- and high-power cognitive radio alternatives in the TV bands [1]. The latter can provide BWA via outdoor access points (AP) to individual customers. A standard for BWA in the TV bands is already being developed by the IEEE in the event when such rules are made [2]. In urban areas, CR-based BWA is a potential competitor to cable, DSL, and wireless options in the unlicensed bands [3]. In rural areas, the better propagation at TV-band frequencies below 1 GHz may provide a low-cost option for BWA. In this paper, we test these potential outcomes via a combined technical and economic analysis tool for BWA. Unlike more technical analysis (e.g., see [2]), we examine the economics of providing CR-based BWA in urban and rural environments. In urban environments, there is relatively little unused spectrum in the TV bands. However, customer density is high, so the system can operate using short-range access points (APs) and have large reuse. In rural areas, the available spectrum is greater. However, APs need to use longer ranges to efficiently cover the sparse customers. Long-range transmitters may find many channels excluded because of potential interference with distant TV coverage areas.

A further nuance to CR BWA deployment is the regulatory regime under which it operates. Access to the TV spectrum is controversial [4] and several alternatives have been proposed [5], that is, commons and property rights models. To capture this range, we examine several unlicensed and licensed regimes. In an unlicensed regime, spectrum is free, but the CR must contend with other users who may or may not have compatible architectures. In an exclusive licensed regime, the CR BWA operator must pay for the spectrum and can plan efficient use of the spectrum. In between is a nonexclusive licensed regime where different licensed CR operators pay for access to the spectrum and may be required to cooperate with each other. We do not dwell in this paper on the likelihood or mechanism through which any of these regimes would be realized. Rather, we investigate the impact of each of these regimes on the economics and spectrum needs of BWA.

In this paper, we develop a general purpose BWA spectrum requirements and economics tool. With this tool, we examine the network cost for deploying a BWA network in the six combinations of demographics (urban, rural) and licensing (unlicensed, nonexclusive licensed, exclusive licensed). For each of these regimes, parameters are estimated. The resulting spectrum requirements and cost of each regime indicates its relative viability. This paper extends [6], by providing sensitivity analysis of key parameters. We start by providing an overview of the BWA communication architecture and a description of each regime.

2. COMMUNICATION ARCHITECTURE

The primary purpose of the BWA system is to provide connectivity between the user stations and the Internet. The BWA system consists of one or more access points (AP) that communicate with fixed user stations. Multiple APs may be needed to provide sufficient coverage or to provide sufficient capacity similar to a cellular system. The AP may consist of one or more antennas each covering different directions. Radio channels are reused over the coverage area.

The user traffic from each AP needs to be backhauled to a single or a small number of Internet gateways. The backhaul channels can be wired or wireless. Thus the spectrum requirements can be divided into access spectrum between users and the AP and backhaul spectrum between the AP and the Internet gateways.

The APs communicate to users over links that may pass through or around man-made clutter, vegetation, and terrain. For such links, frequencies below 3 GHz are most suitable [7]. However spectrum below 3 GHz is less plentiful compared to higher frequency spectrum. Since TV bands are below 1 GHz and potentially have large tracts of unused spectrum, they are especially suitable. The backhaul links are more likely to be line of site since APs are mounted higher and the Internet gateways can have dedicated towers. Such links can be provided using higher frequencies, above 3 GHz, where unlicensed spectrum is plentiful and dedicated high-capacity microwave links are available. For instance, this is the approach used in the Philadelphia municipal BWA system [8]. Therefore, in this paper we assume that the backhaul spectrum needs (if any) are met with the readily available higher frequencies and we focus on the access spectrum needs.

For this paper, the BWA system uses unused spectrum in the TV bands for its access spectrum. We focus on the United States, however the analysis framework applies more broadly to other countries as well. The BWA system must avoid interfering with the licensed broadcast uses of the spectrum. The APs in the BWA system use any of a number of techniques to identify unused spectrum. To be specific, we assume that they use a combination of geolocation and access to a database as described in [9]. The user stations are controlled by the AP and only transmit as permitted by the AP.

3. SIX REGIMES

We describe the six regimes and six factors which distinguish them. The six regimes we consider vary across demographic (urban, rural) and licensing (unlicensed, nonexclusive licensed, exclusive licensed) dimensions.

3.1. *Demographic and licensed regimes*

We explore two aspects that follow from this cognitive radio usage of the spectrum. First, the available spectrum varies from place to place. Areas that have fewer licensed users will have more potential spectrum for BWA. The question is whether the available spectrum is sufficient for a viable BWA system. To explore this aspect, we will investigate rural and urban areas. As a limit, we consider two extremes: New York City, one of the busiest television broadcasting regions in the country; and Buffalo County South Dakota, noted as being sparse. (Buffalo county, SD was chosen since it has the lowest median per capita income among all US countries. It is a candidate for using BWA to close the digital divide.)

The second aspect to BWA access to the TV spectrum is that the licensing regime for this secondary access has not been finalized and we seek to understand how different licensing regimes could impact the BWA service. Unlicensed access to the spectrum enables many users and potentially uncoordinated services to be offered. Barriers to new entrants are low and the BWA radio would need to resolve the uncoordinated contention for radio resources. At the other extreme, the BWA may be given licensed and exclusive access to the spectrum not being used by primary users. This reduces competition at both a service level from other BWA providers and a radio resource level from other contending users. However, the exclusive access may require the BWA provider to pay for the license, which would increase the BWA service cost. As a third option, we consider offering multiple licenses (nonexclusive licensing). These licenses could take several forms, ranging from permission to access the entire available unused spectrum to divide the spectrum into specific blocks, which are licensed and used on an exclusive basis. For our purposes, we consider this range of options equivalent if the number of licensees is small. A small number of licensees will be motivated to cooperate and provide de facto divisions of spectrum in the case that no specific exclusive block license is provided. The nonexclusive license regime may require the BWA operator to pay for the license.

3.2. *Six factors*

For the purposes of our analysis, the six regimes differ in six factors: population density, transmission range, available spectrum, traffic per person, spectral efficiency, and cost of spectrum. These are divided along demographic and license axis.

Urban and rural areas, by definition, differ in population density. An urban area can have densities over 4,000 people per square kilometer and a rural area under 10 people per square kilometer [10].

Generally, to be more efficient, rural systems will require APs to have longer range in order to efficiently reach the population. In urban areas, the AP can be mounted on existing structures and, as described later, a short range such as 500 m is both achievable and sufficient. In rural

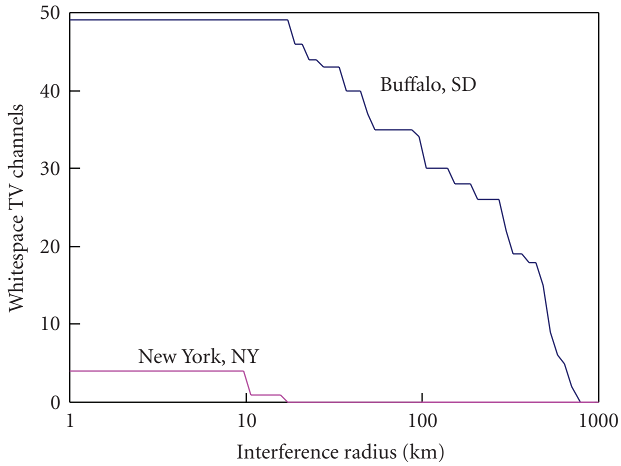


Figure 1: The number of 6 MHz TV channels available for cognitive radio use as a function of potential interference. Computed for New York City (Times Square) and Buffalo County, SD (geographic center).

areas, APs will be mounted on higher towers to achieve longer ranges. As an example, 10 km would be a reasonable target. The choice of range depends on the availability of spectrum in the vicinity of the BWA transmitters. Longer transmission range requires spectrum to be available over longer distances. This issue is addressed below. Population density and transmission range together affect the number of people captured by a single AP. However, their affects are counterbalancing. As an example, rural areas may have 400 times smaller density, D, while the range, r, can be 20 times larger so that r^2 is 400 times larger. In this case, they would exactly counterbalance each other so that a rural AP and an urban AP capture the same population.

A key factor in BWA viability is the availability of spectrum. The appendix describes a method for estimating the unused spectrum, also known as "whitespace." Figure 1 shows the availability of unused TV channels as a function of the interference radius of the CR. The interference radius can be significantly larger than the transmission range of the CR due to TV receivers' sensitivity to interference. The appendix estimates that the interference range is 10 times the transmission range. From Figure 1, a transmission range of 500 m (5 km interference range) in New York would yield 4 unused channels (24 MHz). In Buffalo, SD a transmission range of 10 km (100 km interference range) would yield 32 unused channels (192 MHz). The exclusive licensed model would make this spectrum available to the BWA operator. The unlicensed and nonexclusive licensed model would divide the spectrum between different operators.

The unlicensed model can be supported by other unlicensed spectrum below 3 GHz. There is 109.5 MHz of useful spectrum, that is, 26 MHz at the 902–928 MHz and 83.5 MHz at 2.4–2.4835 GHz. Other unlicensed spectrum is available but it is not useful for this application because of the small size of the bandwidth block, limits on power, or limits on usage.

The traffic per person, U, represents the total traffic demanded on the BWA system divided by the total population. It is affected by both the licensing and demographic regimes. In urban areas, BWA is one of several existing broadband delivery modes. In rural areas the major competitor is satellite. Compared to satellite, BWA has the potential to provide significantly lower delays and greater bandwidth. As a result, BWA's relative market share for broadband access will be more in rural areas than in urban areas. If unlicensed or nonexclusive licenses are used, then there will be lower barriers to entry for BWA competitors and the market share for each BWA provider will be less. The traffic per person affects the amount of spectrum required. More user traffic per person requires more spectrum.

Spectral efficiency, E, captures the ratio of system traffic to required spectrum to carry that traffic. It will depend on whether unlicensed or licensed access will be granted. With unlicensed spectrum, the BWA operator must contend with other uncoordinated spectrum users. More robust but less efficient transmission schemes are required in this case, which lowers the spectral efficiency and accordingly increases the required spectrum. Though the unlicensed approach may require more spectrum, unlicensed spectrum promotes competition and supports multiple service providers without requiring any additional spectrum. Moreover, unlicensed spectrum promotes innovation since it presents lower barriers to diverse new services and applications. Further, in the future if the BWA service becomes less viable, then the unlicensed spectrum will already be available for other uses, providing a natural technology evolution path without protracted spectrum reassignment periods. Thus increased spectrum requirements are traded against the reduced administrative burden and operator flexibility when using unlicensed access.

Spectrum cost depends on the licensing and demographic regimes. Unlicensed spectrum has no direct cost to the BWA operator. Based on recent history, the licensed regimes will require the BWA operator to pay some cost in proportion to the population and the bandwidth of the spectrum. This cost has been determined through spectrum auctions. In these auctions, the cost of rural spectrum is often much lower than urban spectrum. Lower spectrum cost tends to lead to more spectrum usage; however, more spectrum is available.

To make the different regimes and factors concrete, the next section develops a tool for assessing the persubscriber cost and required spectrum.

4. SPECTRUM REQUIREMENTS

We now present three approaches to determine the required spectrum. When deploying a network, two major design constraints dominate design—cost and usage. Engineering the design of a network generally requires minimizing the cost of the system, while ensuring the operational demands can adequately be maintained. We use these principles to inform our approach in defining the overall spectrum requirements.

The first approach is based on a required service data rate. The amount of spectrum required at an AP to provide this rate to a user is a lower bound on the required spectrum.

We denote this as the minimum service rate spectrum requirements (MSR). The second approach is based on minimizing the number of APs. Fewer APs lowers the system cost, while requiring more spectrum to be able to carry the greater traffic load on each AP. We denote this as the minimum system cost spectrum requirement (MSC). MSR and MSC set upper and lower bounds on the required spectrum. Within these bounds, an operator will minimize the overall cost to build their system. The third approach analyzes the total capacity required by the system to carry every user's average traffic load. In principal this capacity can be provided with any amount of spectrum. However, to have sufficient total capacity there is a trade off between the amount of spectrum and number of APs. As the amount of spectrum decreases, the number of APs and the cost of the system increase. Thus it becomes a tradeoff between available spectrum and cost of providing the service. Based on the value placed on the spectrum used, we can determine a spectrum that minimizes the total cost of the BWA deployment and spectrum. We denote this as the minimum total cost spectrum requirements (MTC).

4.1. Key factors

The key factors in the model are described in detail in this section.

Spectrum efficiency factors

A number of wireless technologies are in place today for providing BWA. The IEEE 802.11a/b/g family of protocols provides a range of communication capabilities with rates from 1 up to 54 Mbps. The 802.16 family of protocols provide data rates up to 134 Mbps. These technologies can use more or less spectrum to increase or decrease communication rates. The 802.16 standards work at a variety of spectral bandwidths with proportional variations in channel rates. An AP with more than one wireless interface working on different channels will also have more capacity. Two or more interfaces will yield a proportional two or more factor increase in capacity. These observations suggest that a single AP can use whatever spectrum is made available to it and the useable channel rate is proportional to the spectrum assigned. We denote the ratio of channel rate to spectrum assigned as the spectral efficiency. Given these observations, an AP can provide a rate $B = SE$, where B is the data rate (in bps), S is the spectrum (in Hz), and E is the spectral efficiency (in bps/Hz).

The spectral efficiency is a function of several factors $E = e_{\text{modulation}}\, e_{\text{reuse}}\, e_{\text{protocol}}\, e_{\text{loading}}\, e_{\text{sharing}}$. The modulation efficiency, $e_{\text{modulation}}$, is the ability of a modulation scheme to produce a bit rate in a given channel bandwidth, in (bps/Hz). The reuse efficiency factor, $e_{\text{reuse}} \leq 1$, accounts for the fact that channels may not be used at every AP due to cochannel interference between adjacent AP. The protocol efficiency factor, $e_{\text{protocol}} \leq 1$, accounts for the overhead of packet headers and channel access. The loading efficiency factor, $e_{\text{loading}} \leq 1$, accounts for the level to which a channel can be loaded in the long term and still experience good performance. Too high a loading leads to excessive queuing and delays. The minimum service rate model considers only the peak rate and so loading is not relevant ($e_{\text{loading}} = 1$). The sharing factor, $e_{\text{sharing}} \leq 1$, accounts for additional overhead to resolve contention between the different coexisting operators in the same band.

Access point cost

The cost of building the BWA network infrastructure and paying for it depends on the cost of the AP and the cost of terminating to the Internet. For these costs, we consider the net present value costs with discount factor d (A discount factor of d means that a cost of x dollars y years in the future has NPV of $x(1-d)^y$. Given an ongoing cost stream of x dollars per year and discount factor of d, the NPV of this stream is x/d.).

For the AP, this is the initial cost of the hardware and installation, and the discounted cost of the future maintenance and operations expenses

$$K_{\text{ap}} = k_f + \frac{k_{\text{om}}}{d}, \tag{1}$$

where k_f is the initial fixed hardware and installation costs and k_{om} is the annual operations and maintenance costs.

Traffic per person

Active BWA users can generate significant traffic. However, these users may be a fraction of the total population depending on a number of factors. Let U be the traffic per person where $U = u_{\text{traffic}}\, u_{\text{active}}\, u_{\text{takeup}}\, u_{\text{mrktshr}}\, u_{\text{operator}}$. The traffic per active user, u_{traffic}, is the average usage of such a user over the busy hour in bps. It includes the total of uplink and downlink traffic. The active user factor, $u_{\text{active}} \leq 1$, is the average fraction of users that are active during the busy hour. The take up factor, $u_{\text{takeup}} \leq 1$, is the ratio between the number of broadband users and the total population. The market share factor, $u_{\text{mrktshare}} \leq 1$, is the fraction of broadband users that are users of BWA. The operator factor, $u_{\text{operator}} \leq 1$, is the fraction of the BWA market captured by one BWA operator. A BWA operator has $u_{\text{takeup}}\, u_{\text{mrktshare}}\, u_{\text{operator}}$ customers (as a fraction of the total population) which are generating $u_{\text{traffic}}\, u_{\text{active}}$ bits per second of traffic on average in the busy hour.

4.2. Minimum service rate spectrum requirements

Broadband service providers often specify a service rate that they are providing to users, such as 1.5 Mbps DSL or a 27 Mbps Cable modem. This rate is the peak rate at which users can exchange data with their service provider. This rate is typically shared among different users and individual users can have average rates that are only a fraction of this carrier specified rate. However, this specified rate is often a criterion in comparing different service offerings. The minimum service rate spectrum requirements model relates a specified minimum service rate offered to users, denoted as the user bandwidth, B_U, and the spectrum required to provide this bandwidth at each AP. Given a total spectrum S, the user bandwidth per AP is $B_{AP} = SE$. This bandwidth must be shared by all users in practice, but defines the peak usable rate any customer could hope to achieve. Thus the required spectrum is

$$S_{MSR} = \frac{B_U}{E} \quad \text{(MSR spectrum requirement)}, \tag{2}$$

where S_{MSR} is the required spectrum (in Hz, Hertz), B_U is the user bit rate per user (in bps, bits per second), and E is the spectral efficiency of the radio system (in bps/Hz). The MSR spectrum requirement does not depend on the number of APs or user traffic for the covered area.

4.3. Minimum system cost spectrum requirements

We define the maximum spectrum that can be usefully exploited to carry a given traffic load per user. As will be seen in Section 4.4, the NPV cost of the BWA system decreases with additional spectrum. To a first order, more spectrum means that each AP can carry more load and so fewer APs are needed, which lowers the overall system cost. However, coverage requires a minimum number of APs (N_{min}) to provide service over the metropolitan area, A:

$$N_{min} = \frac{A}{\pi r^2}, \tag{3}$$

where πr^2 is the maximum coverage area of an AP. The minimum cost system will have N_{min} APs. How much spectrum is required for these few APs? If U is the average traffic per person in the busy hour and D is the population density, then a single AP captures at most $UD\pi r^2$ traffic. The bandwidth capacity per AP is SE. Thus,

$$S_{MSC} = \frac{U \cdot D \cdot \pi r^2}{E} \quad \text{(MSC spectrum requirement)}. \tag{4}$$

This incorporates the number of APs and required traffic capacity.

4.4. Minimum total cost spectrum requirements

The MSR and MSC spectrum requirements are sufficient if spectrum cost is not considered. The required spectrum is simply the maximum of S_{MSR} and S_{MSC}. The second is more important since the minimum system cost is typically reached with a large S_{MSC}. However, there may be limited spectrum available. Even if unlimited spectrum is available, there may be a cost to this spectrum. In this case, the BWA operator will trade the savings in fewer APs against the cost of more spectrum.

We first introduce a system cost model. We then introduce the spectrum cost and determine what spectrum is required to minimize the total cost of the system and spectrum. The costs only consider the system and spectrum costs. The customer costs of Internet backhaul, marketing, billing, customer service, and customer premises equipment are a significant portion of the service cost. However, these costs are independent of the spectrum and so are not included.

System cost

The system cost, to a first order, is proportional to the number of APs. For a total spectrum, S, the data rate per AP is again SE. It follows that to provide UP total capacity to a total population, P, requires the following number of APs:

$$N = \frac{UP}{SE}. \tag{5}$$

Thus the system cost per person is

$$K_{Sys}(S) = \frac{NK_{ap}}{P} = \frac{UK_{ap}}{SE}. \tag{6}$$

This shows that the cost of the system is directly proportional to the traffic generated per user.

The system cost decreases monotonically as S increases. However, the number of APs is lower bounded by N_{min} and so the cost is minimized at S_{MSC} as computed earlier. Additional spectrum only serves to increase the data rates experienced by users without changing the system costs.

Spectrum cost

Spectrum is valued in a number of ways. In this study, we use K_S to denote the cost of one unit of spectrum (e.g., one MHz) for an area divided by the population of that area (dollars per MHz pop). The total system and spectrum cost per person is then

$$K_T(S) = K_{Sys}(S) + K_S S. \tag{7}$$

The amount of spectrum that minimizes this cost can be found by standard minimization techniques with the result

$$S_{MTC} = \left(\frac{UK_{ap}}{EK_S}\right)^{1/2} \quad \text{(MTC spectrum requirement)}. \tag{8}$$

This requirement incorporates the user traffic, spectrum efficiency, and cost factors. However, the square root decreases the sensitivity to these factors.

4.5. Variable sensitivity

The three spectrum models are sensitive to the variables that are assumed. All of the models depend on the spectrum efficiency, E, and its constituting factors. The first two models are directly sensitive. A factor of two change in the spectrum efficiency yields a factor of two change in the required spectrum. The last two models depend on the user bandwidth, U, and its constituting factors. The relationship is linear for the MSC model and sublinear for the MTC model.

The required user bandwidth, B_U, affects only the MSR model and the effect is linear. The max population covered by an AP, $D\pi r^2$, affects only the MSC model and the effect is linear. However, D and r tend to have a negative correlation that reduces the impact of these factors. The cost factors only affect the MTC model and have a sublinear relationship.

Table 1: Output variables.

Variable	Description
S	Total spectrum required for all BWA operators
N	Total number of APs per 1000 km^2 for all BWA operators
B_{AP}	Bandwidth capacity provided by each AP
$K_{Sys}(S)$	System cost per subscriber
$K_T(S)$	Total cost per subscriber

Table 2: Output spectrum requirements.

Variable	Description
S_{MSR}	Spectrum required to provide a minimum service rate
S_{MSC}	Spectrum required to minimize system cost
S_{MTC}	Spectrum required to minimize total system cost

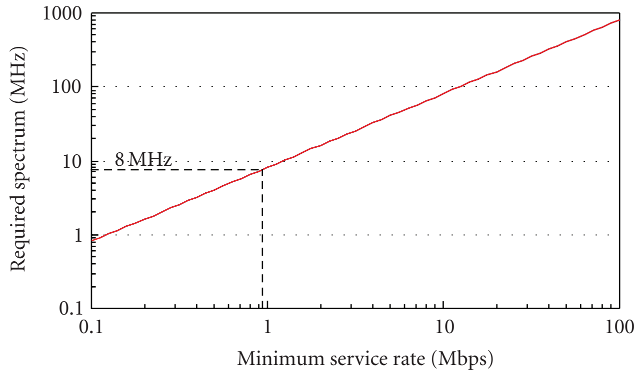
4.6. Analysis outputs

The analysis can be summarized via the output variables and output spectrum requirements in Tables 1 and 2. The spectrum is the required spectrum according to each model. The number of APs is based on assuming an area of A = 1000 km^2. This area is large compared to most cities and small compared to most rural areas, but it provides a common point of reference. The number of APs indicates the system infrastructure required. The spectrum and number of APs as computed in the previous section are per operator. In order to correctly reflect the total spectrum and number of APs, we need to incorporate the number of BWA operators. If S and N are the per operator requirements, then S/u_{operator} and N/u_{operator} are the total requirements for all BWA users. The bandwidth capacity per AP indicates the bandwidth required to provide sufficient traffic capacity. It is always at least B_U. Though the models considered cost factors to different degrees, we compute the system and total costs for each method. Cost per person is converted to cost per subscriber to give a better indication of what costs will be from a network operator's perspective. If K is a cost per person, then $K/(u_{\text{takeup}}\, u_{\text{mrktshr}}\, u_{\text{operator}})$ is the cost per subscriber. We reiterate that these costs consider network costs and do not include customer equipment and marketing costs.

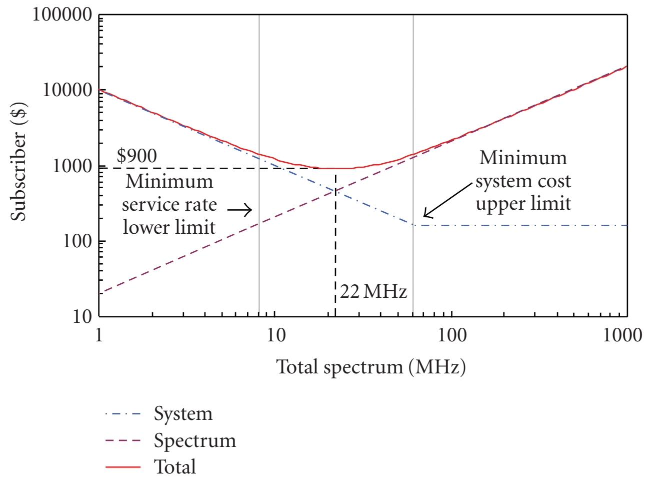
As a final comparison, we consider a startup system model. The startup system model uses spectrum as determined by the minimum service rate model, S_{MSR}, and enough APs to provide coverage, that is, $N_{\min}$. This system does not consider the user traffic. It is the lowest cost system that could be built and start to provide service. The cost per subscriber is calculated as described above. However, this is the cost per eventual subscriber since the startup system would need to invest in additional APs in order to have enough capacity to carry these subscribers' traffic.

4.7. Analysis summary

The interaction between the different models is seen in Figure 2. In Figure 2(a), the relationship between the minimum bandwidth per user and the required spectrum is plotted. For a given minimum required user bandwidth (e.g., 1 Mbps), the minimum required spectrum is plotted (e.g., 8 MHz). In Figure 2(b) this sets a lower limit on the required spectrum. The minimum system cost sets an upper limit on the usable spectrum (e.g., 63 MHz). The minimum of the total cost within this range sets the overall minimum cost and spectrum requirements (e.g., $900, 22 MHz).



(a)



(b)

Figure 2: Example derivation. The minimum service rate spectrum requirements (a) sets a lower limit on the required spectrum (8 MHz). The "knee" in the system cost (b) sets the upper limit on the usable spectrum (63 MHz). The minimum total cost determines the persubscriber cost and required spectrum ($900, 22 MHz).

5. EXAMPLE APPLICATION: INPUT VARIABLES

This section describes the input variables used in Section 6. Many of the variables are based on the recent project to provide a municipal wireless network in Philadelphia, USA [8, 11].

5.1. Spectrum efficiency factors

A number of wireless technologies are in place today for providing BWA. Cellular technologies are also available. So-called CDMA 2000 and W-CDMA are third-generation

Table 3: Modulation efficiency of several wireless technologies.

Technology	Channel bandwidth (MHz)	Channel rate (Mbps)	Efficiency (bps/Hz)
802.11b (WiFi) [13]	22	11	0.5
802.11a [13]	20	54	2.7
802.16 [12]	28	134	4.8
CDMA-2000 EVDO [23]	1.25	3.1	2.5

technologies with data rates in the few megabits per second range.

Table 3 lists the modulation efficiency of a few wireless technologies including wireless LAN (802.11b, 802.11a), wireless MAN (802.16), and third generation cellular (CDMA-2000 EVDO release 0). Spectral efficiencies range from 0.5 to about 5 bps/Hz [12, 13]. These efficiencies are best case efficiencies. For instance 802.11a can only achieve its highest rate within about 10 meters of the access point, whereas it can achieve lower rates to significantly further distances. To account for this we downgrade the best available efficiency by 50% in $e_{\text{modulation}}$.

These rates are so-called channel rates and do not include wireless protocol overhead, which reduces the usable capacity. For instance, 802.11b has a maximum channel rate of 11 Mbps, while the maximum usable capacity is about 3.5 Mbps. Overhead from other protocols (e.g., TCP/IP/LLC) can reduce capacity further to below this rate. In other words, the true capacity is about 30% of the channel rate [14]. Similar overhead can be observed in other protocols.

Beyond protocol inefficiencies, Internet applications generally perform better when the loading on the channel is below full capacity. As the load approaches capacity, queuing delays can develop that degrade the performance. For real-time applications, such as voice, low delays are critical. For more bursty applications such as Internet browsing, delays are less critical. However, an average load below capacity is necessary to avoid significant periods of congestion. With such traffic, a high load, for example 50%, can result in acceptable performance. This loading is the average over the peak busy hour. Typical wireless access networks have much lower loading over the day [15, 16]. Nevertheless, busy-hour provisioning is necessary to provide adequate service.

The maximum raw channel rates are best-case rates for dedicated spectrum. In shared or unlicensed environments, the available channel rates are below these maximum rates since the lower rates are more robust to radio noise and interference. The ratio of the lower rate used for the purposes of providing more robust coverage to the maximum rate is the sharing efficiency, e_{sharing}. If dedicated spectrum is provided to a single operator to provide BWA, then $e_{\text{sharing}} = 1$. We assume that the nonexclusive licenses are well organized so that $e_{\text{sharing}} = 1$. Non-cooperative operators can choose interfering channels. Even if cooperating, different operators may cover the same area multiple times using incompatible channel assignments. Besides other BWA operators, there may be other services and applications that are not amenable to coordination. Because of these inefficiencies more robust modulation is necessary. The 802.11 standards are designed to operate in unlicensed environments, while the 802.16 standards are designed for unlicensed and licensed with the most efficient protocols designed for licensed. The maximum current 802.11 efficiency (2.7 bps/Hz) is approximately half of the maximum 802.16 efficiency (4.8 bps/Hz). The resulting sharing efficiency in shared unlicensed spectrum is $e_{\text{sharing}} = 0.5$.

The spectral efficiency above assumes that an operator assigns different frequency channels to its nearby APs in order to avoid interference. A simple strategy to achieve this is to divide the spectrum into subbands and assign the spectrum in a nonconflicting pattern. This pattern can be repeated over the coverage area so that channels are reused many times. This strategy is applied in cellular and wireless LAN deployments. Cellular systems use a variety of reuse patterns depending on the technology. For instance, the entire spectrum is assigned to each AP in CDMA cellular systems. This is traded against a lower net spectral efficiency. Since WLAN technologies are most similar to the BWA technologies, we will follow their reuse strategy, that is, a reuse of three. Every AP would then have at most one third of the total spectrum available.

In this study, we will assume a radio technology similar to 802.16 that can utilize a variety of spectral bandwidths, has a modulation efficiency of about $e_{\text{modulation}} = 2.5$ bps/Hz, a protocol efficiency of $e_{\text{protocol}} = 0.30$, and typically transmits at one half of the maximum channel rate, $e_{\text{loading}} = 0.50$. In the minimum service rate model, $e_{\text{loading}} = 1.00$. Channels are reused in a pattern of three channels, $e_{\text{reuse}} = 0.33$. The sharing factor depends on whether channel access is unlicensed, $e_{\text{sharing}} = 0.5$, or licensed, $e_{\text{sharing}} = 1.00$.

5.2. *Access point costs*

The access point costs can be divided into (a) costs that are independent of the coverage and total usable bandwidth per AP; (b) costs that depend on the coverage per AP; and (c) costs that depend on the usable bandwidth per AP. The model AP is based on the configuration to achieve the minimum number of APs (i.e., have the maximum coverage). It consists of a broadband wireless radio; a set of 3 to 6 directional antennas either attached to an existing structure or on a mast; additional radios as necessary for wireless backhaul; and connections to power. As the coverage decreases, it is possible to use lower power and less expensive amplifiers. As the user bandwidth per AP decreases, the AP can use fewer channels and fewer antennas to achieve its capacity goal. This reduces the hardware and installation cost. For simplicity we assume that the NPV cost of an AP is independent of these capacity and coverage factors. For instance, a rural AP will consist of a taller more expensive mast than an urban AP. However, the site costs in urban environments are higher. Based on data from Philadelphia, the average installed cost of an AP is $5,000. The initial total estimated capital cost in Philadelphia is $10 M, while the total annual operating expenses are $8 M. If we assume these costs are proportional to the number of AP, the annual operating costs per AP are 80% of the initial capital costs, or $4,000 per AP. Given a discount factor of 20%, this indicates that the NPV cost of each AP is K_{AP} = $25,000.

5.3. Traffic per person

A BWA system might provide service to a variety of users including residential, commercial, and municipal. The users might access the BWA system for communication, web-browsing, and media download applications. There may be other embedded users including sensors, transaction processing devices (e.g., parking meters), security video cameras, and remotely controlled devices (e.g., sprinklers). For simplicity, we consider a single typical subscriber which generates traffic at a rate of u_{traffic} during the busy hour. This traffic is the total of uplink and downlink bandwidths since the capacity of many wireless protocols can be divided as needed between up and down links. Separate up and down link analysis is unnecessary. Applications such as voice over IP use 10's of kilobits per second (kbps). Web browsing alternates between brief periods of high data rate downloads and longer periods of viewing the content. Streaming video or audio can be many 100's of kbps. A remote video camera can generate 300 kbps. These rates are growing over time. These observations suggest that an active user in the near future could generate 100 kbps of traffic on average during the busy hour.

Users access the Internet at different times of the day. In any given busy hour, only a fraction of the users may be actively using the system. Internet access is a regular part of many users' daily activity and as many as 50% of the users might be active during the busy hour.

Not every person in the population corresponds to a user. Some people will not be able to afford or will not have the need of a broadband service. Household members might share the service. A household consists of 2.5 people on average, suggesting that the take up rate is at most 100/2.5 = 40 lines per 100 people. The take up rate was 17 broadband lines per 100 people at the beginning of 2006 and has been growing steadily [17]. We extrapolate that, in the near future, the take up rate will approach 25 broadband lines per 100 people.

Given the set of broadband users, only a fraction will use a BWA service depending on the market share of the BWA service provider. In rural areas, the primary competition to BWA will come from satellite service and existing Wireless ISPs based on the 2.4 GHz unlicensed bands. Because of better coverage and more bandwidth, we expect the BWA to have a competitive advantage over these alternatives capturing a majority of the broadband users. The market share in this case is 50%. In urban areas, there are additional competitors such as DSL and Cable. These are already entrenched. The BWA service will have lower market share against these four competitors. The market share in this case is 20%. This market share is for a single BWA operator. If nonexclusive licenses or unlicensed access regimes are used, then each BWA operator will enjoy half of this market share.

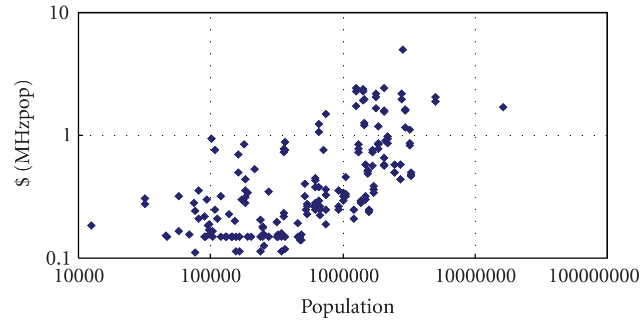


Figure 3: Normalized spectrum cost as a function of population for full BTAs auctioned in the PCS broadband auction.

In this study, we assume an active user that generates u_{traffic} = 100 kbps in the busy hour. Half of these users are active in the busy hour, u_{active} = 0.50 and a fraction of the population that is a user, u_{takeup} = 0.25. The market share will vary from $u_{\text{mrktshare}}$ = 0.20 to $u_{\text{mrktshare}}$ = 0.50 depending on the regime. The operator fraction is u_{operator} = 1.00 for the licensed exclusive regime and u_{operator} = 0.50 for the licensed nonexclusive and unlicensed regimes.

We note the difference between our factors here and the industry "over subscription factors." A typical wireless Internet service provider (WISP) will share an 11 Mbps link between 100 users [18]. The over subscription factor of 100 is based on implicit assumptions about the average traffic per user. In our model we make these assumptions explicit. To compete with a WISP, the BWA service provider must provide at least Mbps service to customers. We assume B_U = 1 Mbps. This is the same target as in Philadelphia.

5.4. Spectrum cost

The cost of the spectrum can be estimated from recent FCC auctions. The PCS broadband auction was both recent and appropriate for a BWA service [19]. Figure 3 shows the normalized cost (in $/MHz pop) as a function of the licensed basic trading area (BTA) population (only includes full BTAs for the full license size that actually were sold). Clearly, less populated BTAs tend to have lower spectrum costs than more populated areas. If we use BTAs with populations less than 100,000 to represent rural areas and BTAs with populations more than 1,000,000 people to represent urban areas, then we can estimate the relative spectrum cost. The average normalized cost for the rural areas is $0.21 and for urban areas is $1.01, or approximately $0.2 and $1.0, respectively.

5.5. Transmission range

A BWA system requires a minimum number of APs to provide sufficient signal to reach the intended coverage area. We assume frequencies are in the TV bands; the APs use high gain antennas; in urban areas the APs are not placed on high towers, the subscriber equipment uses an outdoor antenna; and the transmit power is at least 1 W.

What kind of coverage can be expected under these assumptions? Wireless links using 802.11 typically have

Table 4: Regime independent input variables used in the model.

Variable	Value	Description
$e_{\text{modulation}}$	2.5 (bps/Hz)	Modulation efficiency
e_{reuse}	0.33	Frequency reuse factor
e_{protocol}	0.30	Protocol efficiency factor
e_{loading}	0.50	Network loading factor
k_f	\$5,000	Fixed cost of an AP
k_{om}	\$4,000	Annual operations and maintenance cost per AP
d	20%	Discount factor for NPV calculation
B_U	1 Mbps	Minimum data bandwidth per user
u_{traffic}	100 kbps	Traffic rate of active user in busy hour
u_{active}	0.50	Fraction of users active in busy hour
u_{takeup}	0.25	Take up fraction for broadband service

specified outdoor ranges of 100 m or more [20, 21]. Experiments have shown point-to-point links at distances of many 10’s of kilometers under line-of-site conditions with high-gain antennas [21, 22]. Under more typical conditions with APs placed on rooftops, the range can approach a few kilometers. These data suggest that in urban areas high-gain antennas placed at modest heights should enable ranges up to 500 m. In rural areas high towers and less urban clutter can enable transmission ranges of 10 km. We emphasize that the range limit is not purely a question of meeting the radio link budget. A CR-based operator will use shorter ranges than possible in order to avoid interference with TV reception areas as described in the appendix. In any case, these ranges are only a direct factor for the minimum system cost model. For the other models, the number of access points is greater than $N_{\min}$ and the transmission range is set by other factors than this minimum.

5.6. Model variables

The input variables that are independent of the regime are summarized in Table 4. Five variables depend on the regime. They are summarized in Table 5.

6. EXAMPLE APPLICATION: OUTPUT VARIABLES

Based on the input variables derived in the previous section, we apply the spectrum requirement and cost analysis to provide some insights into the effect of each regime. The output of the model is shown in Tables 6 and **??** and plotted in Figure 4.

6.1. Rural areas

Rural areas have the potential to go to low system cost per subscriber and exploit more than 300 MHz of bandwidth if unlicensed. Given the more than 100 MHz of existing unlicensed spectrum at 900 MHz and 2.4 GHz, the addition of 100 MHz to 200 MHz can push the per subscriber cost below \$200 per subscriber.

If an exclusive license is used, then the total cost must be considered if the operator must pay for the license. An exclusive license would allow an operator to have a total cost around \$250. About 80 MHz would be required to achieve that price. Many rural areas have this volume of spectrum available. The nonexclusive license would require more spectrum and would have a total cost over \$300, mainly because of the duplication of infrastructure implied by having multiple operators.

In all scenarios, the effective per AP bandwidth shared by subscribers would be 7 to 20 times the minimum requirement of 1 Mbps. A startup system (Table 6) could be built for less than \$100 per eventual subscriber if licensed, but further investments would be needed to have the necessary capacity.

6.2. Urban areas

In urban areas, an unlicensed approach requires more than 100 MHz in order to have a price below \$400 per subscriber. This much unlicensed spectrum already exists below 3 GHz. In New York City the available whitespace bandwidth is 24 MHz. Going from the 110 MHz of existing spectrum to the maximum useful spectrum of 127 MHz would yield a 14% reduction in cost. This modest savings must be weighed against the added cognitive radio complexity to use the whitespace bandwidth. This result follows from the relatively short range of each AP and the low market share. As a result, each AP can at best capture relatively few customers. Lack of bandwidth is not directly the constraint. Longer range AP could be used and that would increase the number of customers captured per AP. However, only modest increases are possible in urban areas such as New York before no channel would be available (see Figure 1). The unlicensed spectrum here is similar to the 80 MHz of access spectrum used in the Philadelphia model. The cost per subscriber is higher than Philadelphia. In our sample model, we are assuming only a 20% market share for BWA split between two operators. The Philadelphia model is more optimistic. For instance, if the market share is the same but the operator share rises to 100%, the required spectrum remains the same, but the system cost is half.

Licensing helps by reducing the required bandwidth to 22 MHz, an amount of white space available in many markets. However, the persubscriber total costs are at best \$900 and unlikely to be viable. BWA via TV spectrum is a late comer to the urban broadband market. The lack of viability follows from its likely low market share. As shown in Figure 5, it would require a market share of 65% of the broadband market to drop below \$500 per subscriber. Such high market share is unlikely given the existing broadband competitors. Even the startup system has a minimum cost of around \$250. Recall that the total cost as described here does not include additional costs such as the subscriber equipment and its installation.

Table 5: Regime-dependent input variables.

Regime		Sharing efficiency e_{sharing}	Spectrum cost (\$/MHz-pop) K_S	Operator share u_{operator}	Market share u_{mktshare}	Density pp/km^2 D	TX range r
Rural	Unlicensed	0.5	0	50%	50%	10	10 km
	Licensed nonexclusive	1.0	0.2	50%			
	Licensed exclusive	1.0	0.2	100%			
Urban	Unlicensed	0.5	0	50%	20%	4,000	500 m
	Licensed nonexclusive	1.0	1.0	50%			
	Licensed exclusive	1.0	1.0	100%			

Table 6: Spectrum requirements and cost of a startup system.

	Regime	S MHz	N per 1000 km^2	B_{ap} Mbps	K_{Sys} \$/sub	K_T \$/sub
Rural	Unlicensed	8	3	1	\$127	\$127
	Licensed nonexclusive	4	3	1	\$127	\$140
	Licensed exclusive	4	3	1	\$64	\$70
Urban	Unlicensed	8	1273	1	\$318	\$318
	Licensed nonexclusive	4	1273	1	\$318	\$480
	Licensed exclusive	4	1273	1	\$159	\$240

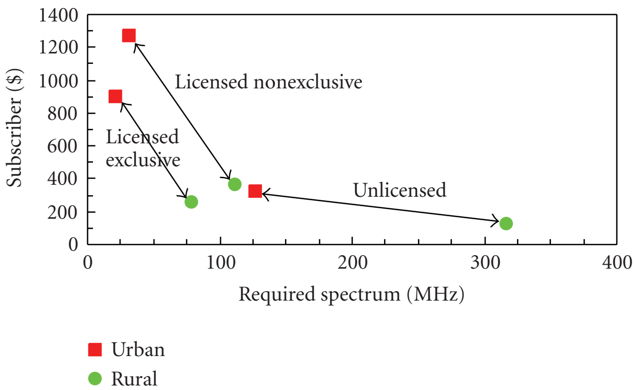


Figure 4: Required spectrum and cost per subscriber in the six regimes.

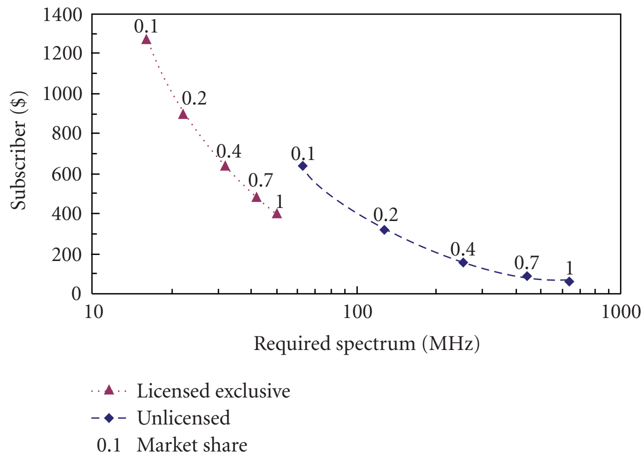


Figure 5: Effect of market share on per subscriber cost and required spectrum in the urban area.

7. CONCLUSIONS

In this paper, we have presented a general analysis framework for investigating the spectrum and cost issues associated with building out a broadband wireless access network. Specifically, we have examined under what conditions cognitive radios could be viable to provide broadband wireless access (BWA) in the licensed TV bands. We explored this issue along demographic (urban, rural) and licensing (unlicensed, nonexclusive licensed, exclusive licensed) dimensions. We developed a general BWA efficiency and economic model for this analysis and derived parameters corresponding to each of these regimes. The results indicate that in rural areas an unlicensed model is viable and the additional spectrum would be useful despite existing unlicensed spectrum. A licensed model is also viable, although at a higher cost. In the densest urban areas no model is economically viable. This is not simple because there is less unused spectrum in urban areas. Urban area cognitive radios are constrained to short ranges and many broadband alternatives already exist. As a result either there is already sufficient unlicensed spectrum or the cost per subscriber is prohibitive. An exclusive license is a better choice than nonexclusive licenses. It results in lower cost per subscriber and less required spectrum. The potential for monopoly behavior is unlikely, given the competition from other broadband access technologies. These results are based on one set of input variables for the model. The model can be easily manipulated to account for other scenarios or different assumptions. These results provide useful input for a variety of spectrum policy issues.

Table 1: Output results in each regime.

Rural

(a)

Model	S MHz	N per 1000 km^2	B_{ap} Mbps	K_{Sys} \$/sub	K_T \$/sub
MSR	16	125	1	\$2,500	\$2,500
MSC	317	6	10	\$127	\$127
MTC	n/a	n/a	n/a	n/a	n/a

(b)

Model	S MHz	N per 1000 km^2	B_{ap} Mbps	K_{Sys} \$/sub	K_T \$/sub
MSR	8	125	1	\$2,500	\$2,513
MSC	159	6	10	\$127	\$381
MTC	112	9	7	\$180	\$360

(c)

Model	S MHz	N per 1000 km^2	B_{ap} Mbps	K_{Sys} \$/sub	K_T \$/sub
MSR	4	125	1	\$2,500	\$2,506
MSC	159	3	20	\$64	\$318
MTC	79	6	10	\$127	\$254

Urbal

(d) Unlicensed

Model	S MHz	N per 1000 km^2	B_{ap} Mbps	K_{Sys} \$/sub	K_T \$/sub
MSR	16	20000	1	\$2,500	\$2,500
MSC	127	2547	4	\$318	\$318
MTC	n/a	n/a	n/a	n/a	n/a

(e) Licensed Non-Exclusive

Model	S MHz	N per 1000 km^2	B_{ap} Mbps	K_{Sys} \$/sub	K_T \$/sub
MSR	8	20000	1	\$2,500	\$2,662
MSC	63	2547	4	\$318	\$1,588
MTC	32	5085	2	\$636	\$1,271

(f) Licensed Exclusive

Model	S MHz	N per 1000 km^2	B_{ap} Mbps	K_{Sys} \$/sub	K_T \$/sub
MSR	4	20000	1	\$2,500	\$2,581
MSC	63	1273	8	\$159	\$1,428
MTC	22	3596	3	\$449	\$899

APPENDIX

AVAILABLE TV WHITESPACE

The TV Whitespace was assessed for this paper using a FCC transmitter location database [24]. For each area of study, a location was determined: 40 : 46 N, 73 : 58 W for New York City and 44 : 03 N, 99 : 11 W for Buffalo County, SD. Using the database, every TV transmitter was identified within 1000 km. For each transmitter, the database identifies the distance to the Grade B signal contour (The Grade B contour is a regulatory concept that corresponds to the approximate range of a TV signal.). For channels whose contour encompasses the location, the distance is zero. For each channel the closest signal contour is identified. Since TV receivers are sensitive to both cochannel and adjacent channel interference, for each channel the closest signal contour on the same or adjacent channel is identified (noting that some channels such as 13 and 14 are adjacent in number but not frequency). This distance is the interference distance for that channel. For any given distance, d, $n(d)$ counts the number of channels whose interference distance exceeds d. This function is plotted in Figure 1. This is not intended to be a definitive assessment. It is not based on actual measurements and does not include existing secondary uses such as wireless microphones. However, it does suggest the relative viability of cognitive radio use in rural and urban environments.

How far must a BWA transmitter be from a TV receiver at the edge of its coverage area? A cognitive radio that is transmitting at a maximum range d, can potentially interfere with TV receivers that are much farther than d away. The interfering signal power at the Grade B contour must be less than approximately −100 dBm to avoid interfering with TV reception [25]. Lognormal shadowing introduces signal variability with a standard deviation of approximately 5 dB. If we include two standard deviations of shadow fade margin, the required mean interfering signal power must be less than −110 dBm. The minimum receive threshold of a typical 802.11 radio at an intermediate rate is approximately −90 dBm. Freespace pathloss will introduce 20 dB of attenuation for each factor of 10 increase in transmitter distance. In fact, long distant signals near the ground tend to suffer a greater rate of attenuation so that this is conservative. Thus using an interference distance, d, 10 times larger than the range of the BWA transmitter will conservatively produce interfering signals which are no more than −90 dBm (range of BWA transmitter) −20 dB (additional attenuation due to factor of 10 distance further away) = −110 dBm as required.

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