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Feasibility Study of Sensing TV Whitespace with Local Quiet Zone

(Invited Paper)

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***Abstract*—Unused TV spectrum, namely TV whitespace, is nearly ready for utilization by unlicensed TV band device (TVBD) given they provide sufficient protection to licensed TV devices, also called incumbents. A combination of a geo-location database and sensing is required to determine channel availability information. Sensing only device is also potentially allowed. From sensing perspective, TVBD should be able to detect incumbent signal as low as –114 dBm. To detect such low level incumbent signal, it is expected that a TVBD will quiet neighboring TVBDs during incumbent detection. Several mechanisms have been discussed in the literature to coordinate sensing. Among others, message based common inband wireless signaling, called quiet signaling, has been proposed to establish local Quiet Zone within which every TVBD suspends transmission to enable incumbent detection. However, there is little study on sensing performance in the presence of interference and the minimum size of local quiet zone required for detecting the weakest incumbent signals. Moreover, the sensing performance in a heterogeneous environment is not clear. In this paper, we intend to answer these questions. We analyze the impact of the incumbent signal strength, the interference power level, the transmission power of quiet signaling, and the minimum SIR tolerable to detect incumbent. We present discussion of homogeneous networks as well as heterogeneous networks where low power personal/portable TVBDs and high power fixed TVBDs may coexist. Although we focus on the detection of ATSC signal only in this paper, the methodology developed in this paper could be also applied to the detection of other primary signals.**

***Index Terms*—Cognitive radio, spectrum sensing, TV whitespace, performance**

I. INTRODUCTION

The paradigm of spectrum usage has shifted from dominantly fixed allocation to more dynamic spectrum access, to increase the utilization efficiency of spectrum. New spectrum policies are being developed by some of the regulatory bodies [1][2] to allow the operation of unlicensed devices in the frequency bands designated for licensed operation on a non-interference basis.

We categorize licensed users as primary users or incumbents, and unlicensed devices as secondary users, in this paper. The secondary devices can operate in a particular channel when it is not being used by a primary and should vacate the channel when the primary appears. The secondary devices can use sensing as one of the mechanisms to determine channel availability. These secondary devices are also referred to as Spectrum Agile Radios (SARA) or Cognitive Radios (CR) due to their ability to sense the radio environment and adapt accordingly.

The Federal Communications Commission (FCC)[1] in US is planning to open up some parts of the spectrum in the UHF band for unlicensed secondary devices. The term whitespaces is usually used to refer to parts of this spectrum that is not being utilized in any particular geographical location. The allowed unlicensed TV Band Devices, referred as TVBD devices, are classified into two categories: 1) High power fixed devices, and 2) low power personal/portable devices. A combination of sensing and geo-location database should be used to determine channel availability information. Sensing only TVBD may also be allowed subject to rigorous testing. Further, all TVBDs have to use transmit power control (TPC) mechanisms to minimize interference to primary incumbents.

A TVBD is required to sense for ATSC signals in order to avoid interfering with the licensed DTV services in this band. It also has to protect wireless microphones (Part 74 devices) and other primary occupants of this band. The FCC's proposed rules [1] specify that the TVBD devices detect DTV (and other primary) signals above –114 dBm levels and that they check for the incumbent signals every 60 seconds.

To detect such low incumbent signals, it is expected that a TVBD will quiet neighboring TVBDs during incumbent sensing. The time period during which neighboring devices suspend transmission is called a quiet period (QP). As shown in Figure 1, TVBD A creates a Quiet Zone within which all surrounding TVBDs including TVBD B should suspend transmission during the sensing period, namely quiet period.

Several mechanisms have been discussed in the literature to coordinate sensing [3][4]. For example, Global Positioning System (GPS) may be used to synchronize Quiet Period such that a universal quiet zone could be possibly established. However, GPS information may not be available to every device, especially for in-building personal/portable devices. Another mechanism, which is the focus in this paper, is message based common inband wireless signaling. This protocol uses quiet signaling to establish a Quiet Zone. The message based quiet signaling has been adopted in 802.22 [3]. Since the size of Quiet Zone created by the message based quiet signaling is limited, a sensing TVBD is still subject to the interference of another TVBD outside Quiet Zone.

Thus it is important to understand the sensing performance given interference and the effectiveness of quiet signaling in

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minimizing interference, whereby the probabilities of misdetection and false alarm are acceptable. There is very little study so far in this field. Moreover, the sensing performance under heterogeneous environment is also not known. In this paper, we intend to answer whether the quiet signaling can reach far enough to create the minimum Quiet Zone required to detect the weakest incumbent signals. This feasibility study is carried under the context that TVBD may use different transmission powers given TPC is used and power limits varies according to TVBD types. In other words, we present discussion of homogeneous networks as well as heterogeneous networks where low power personal/portable devices and high power fixed devices could coexist. We analyze the impact of the incumbent signal strength, the interference power level, the transmission power of quiet signaling, and the minimum tolerable *SIR* to detect incumbent.

Although we use ATSC signal detection as an example in this paper, the methodology could also be applied to the detection of other primary signals.

The rest of paper is organized as follows. In Section II, we describe the system model, notations and some assumptions we made for the analysis. In Section III, we analyze the sensing performance in the presence of interference and derive the quiet zone requirements. In Section IV, we further discuss the implication of sensing requirement on protocol design. In Section V, we conclude the paper and summarize future work.

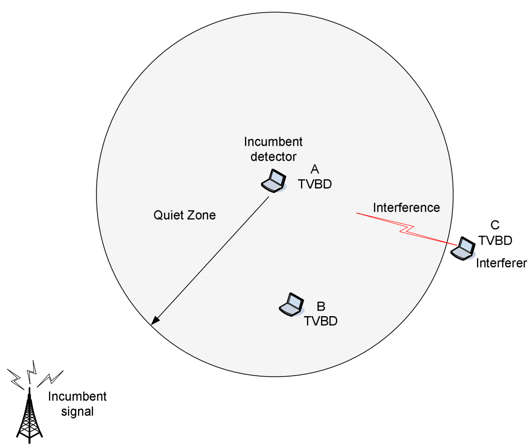

Figure 1 An illustration of quiet zone

II. System Model and Assumptions

The transmission power of TVBDs could vary significantly depending on device type and TPC range. For fixed TVBDs, the maximum conducted output power over the TV channel of operation shall not exceed one watt. For personal/portable TVBDs, the maximum conducted output power over the TV channel of operation shall not exceed 100 mW if both sensing and geo-location/database are employed to protect incumbents, and shall not exceed 50 mW if only sensing mechanism is employed. If personal/portable TVBDs do not meet the adjacent channel separation requirements, the maximum conducted output power shall not exceed 40 mW. According to FCC rules, all TVBDs have to use transmit power control (TPC) mechanisms to minimize interference to the primary incumbents.

A TVBD would have geo-location/database access and/or sensing capabilities together with its regular communication functions. In this paper, we assume that a TVBD determines channel occupancy based on sensing information alone.

The performance of a detector is usually evaluated under two scenarios of: 1) when a signal is present, and 2) when a signal is absent. If the detector indicates that a signal is absent when in fact it is present, then this error event is classified as misdetection. On the other hand, if the detector indicates that a signal is present when the channel is not occupied, then this error event is classified as false alarm. The probabilities of these two events are referred to as probability of misdetection (P_{MD}) and probability of false alarm (P_{FA}) respectively. The detector's performance is usually measured in terms of P_{MD} and P_{FA}. Another important factor to consider in evaluating a sensor's performance is the duration of sensing time (T_{sense}). It is defined as the amount of time required to reliably detect a signal. Shorter sensing time enables a TVBD to better protect incumbents and also to efficiently utilize the available bandwidth.

The notations used in this paper are described in Table 1. The *SNR* is defined as ATSC signal power to noise power in 6 MHz bandwidth (one TV channel). The *SIR* is defined as ATSC signal power to TVBD signal power in 6 MHz bandwidth. We assume that the total noise power is –100dBm. Unless we note, we also assume that: 1) the signal bandwidth of TVBD is limited to 5 MHz, and 2) the signal has very little energy at the location corresponding to the location of the DTV pilot. We use a filter to attenuate the signal by at least 30 dB at DTV pilot location. For comparative analysis, we also evaluate the performance of the DTV sensing algorithm in the presence of other TVBD signals using the full 6 MHz bandwidth.

Table 1 Notations

Notation	Description
SNR	DTV signal to noise ratio.
SIR	DTV signal to TVBD interference ratio
P_s	Received DTV signal strength
P_i	Transmission power of an interfering TVBD
P_t	Transmission power of TVBD quiet signaling
P_{rxth}	receiving threshold to decode quiet signaling
I_{max}	The maximum tolerable interference to detect DTV
SIR_{min}	Minimum SIR to detect DTV
$PL(d)$	Path loss at distance d
α	Path loss factor
P_{FA}	Probability of False Alarm
P_{MD}	Probability of Misdetection

In the presence of inband interference, the sensing performance is influenced by SIR in addition to SNR and the sensing time. In this study, we assume a fixed sensing period. As previous studies [7][8] suggest, the sensing of a weak primary signal will not be reliable when interference goes above certain level. According to FCC, TVBDs should be able to sense TV signals at levels as low as –114 dBm. Thus, we should limit the level of neighborhood interference to achieve reliable sensing.

III. Sensing Performance and Quiet Zone Requirement

We now evaluate the performance of the sensing scheme in the terms of probability of misdetection (P_{MD}) and the probability of false alarm (P_{FA}). Given the P_{MD} and P_{FA}, we derive the minimum quiet zone. We further transform the minimum quiet zone problem into the TPC problem. We also derive the feasible region of transmission power control.

A. P_{MD} and P_{FA} as a function of SNR and SIR

A number of sensing algorithms have been proposed in recent times for reliable detection of DTV (ATSC) signals [5][6]. The pilot detection algorithms described in [5] applies a narrow bandwidth (~50 kHz) filter around the expected pilot location and then performs a 256-point FFT on the filtered signal. It then verifies the peak energy and the consistency of the peak location of the averaged FFT output to make a decision on the presence of a DTV signal in that particular TV channel. It uses a sensing time of 40 ms which can be interspersed over a longer duration if necessary.

In the absence of TVBD signal (i.e. during QPs), the only impairment (assuming a multi-path free channel) that would have an impact on the detection is the white noise. In the majority of situations, the ambient noise is constant and therefore fixed threshold values can be used to identify the DTV incumbent. Using the pilot detection algorithm we can achieve a 100% detection rate for signal levels up to -118 dBm and also have a P_{FA} close to 0 at the same time. It is assumed that the medium is quiet (i.e. free of other TVBD transmissions) during the sensing period.

In this section, we evaluate the performance of DTV pilot sensing algorithm in the presence of other TVBD signal transmissions. This scenario will occur when a TVBD is not able to receive and decode the quiet signal. We assume that the TVBD signal is wideband with a flat power spectral density and therefore it can be modeled as filtered white noise. Further, we also impose the condition that the TVBD signal bandwidth is less than 5MHz. This restriction, combined with a good transmit filter, will ensure that the sensor's performance does not degrade significantly in the presence of a TVBD signal. We simulated the performance of the sensing algorithm for different levels of interference. For each interference level, the results are averaged over 1000 simulation runs.

Figure 2 shows the probability of misdetection (P_{MD}) vs. *SIR* plots for *SNRs* of -15 dB and -20 dB. We assume that the total noise power in the 6 MHz band is -100 dBm and therefore the corresponding DTV levels are equal to -115 dBm and -120 dBm respectively. It can be observed that the misdetections are very high for *SIRs* less than -55 dB. When the *SIR* is -50 dB or higher, then P_{MD} goes down to less than 5%.

Another observation from this exercise is that the detection performance is dependent on *SIR*, i.e. on the relative difference in the levels of the ATSC signal and the TVBD signal, and not on the absolute level of the TVBD signal. This implies that a sensor could detect, for example, a DTV signal at a level of -115 dBm in the presence of TVBD signal with levels -65 dBm and below, while it could detect DTV signal at a level of -70 dBm in the presence of TVBD signals with levels -20 dBm and below.

Figure 3 shows the false alarm rate for different levels of interference power. The false alarm rate is close to zero for TVBD signal levels of -80 dBm and below. The false alarm rate is less than 6% even when the interference levels are as high as -40 dBm.

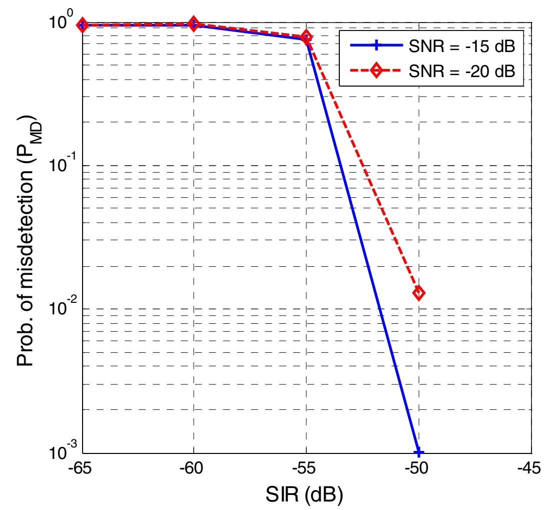

Figure 2 Probability of misdetection (P_{MD}) vs. SIR for SNR of -15 dB and -20 dB

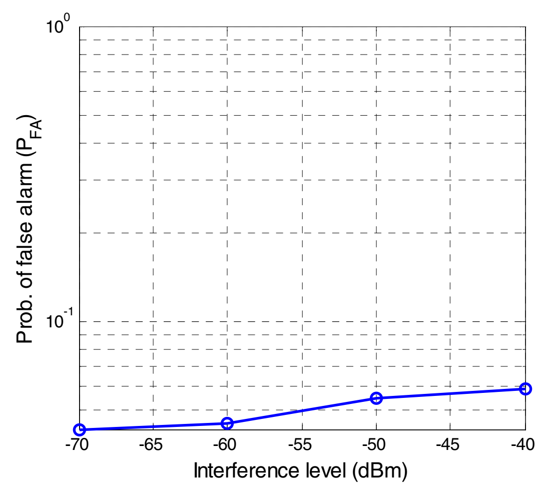

Figure 3 Probability of false alarm (P_{FA}) vs. interference level for a TVBD

B. Minimum Quiet Zone

We define the quiet zone as the separation distance, *d*, between a sensing device and an interferer. The minimum Quiet Zone is derived based on both the probability of false alarm and the probability of misdetection. As a benchmark study, we assume the sensing requirements as P_{MD} of 5 % and P_{FA} of 10%.

To meet the requirement of the probability of misdetection (≤ 5%) when incumbent signal is –114dBm or above, we have

$$P_s - (P_i - PL(d)) \geq SIR_{min} \quad (1)$$

where SIR_{min} is the minimum SIR to detect incumbent, P_s is the received incumbent signal power, and P_i is the transmission power of interference signal from other TVBDs.

To meet the requirement of the probability of false alarm (≤ 10%)when an incumbent signal is not present, we have

$$P_i - PL(d) \leq I_{max} \quad (2)$$

where $I_{\max}$ is the maximum tolerable interference.

Therefore, minimum separation distance, d_{min}, between sensing device and interferer is derived as follows:

$$PL(d_{min}) = \max\{(P_i + SIR_{min} - P_s), (P_i - I_{\max})\} \quad (3)$$

For a system that relies on inband signaling to quiet neighbors, Eq. (3) implies that the quiet signaling should reach a distance of at least d_{min}. Assume P_{rxth} is the receiving threshold of quiet signaling. We assume P_{rxth} at –85dBm.Typical values could be lower, -90 dBm and sometimes even -100 dBm, depends on the lowest data rate mode. Then the transmission power of quiet signaling should satisfy the below equation

$$P_t - PL(d_{min}) \geq P_{rxth} \quad (4)$$

where P_t is the transmission power of quiet signaling.

By combining Equations (3) and (4), we have

$$P_t - P_i \geq P_{rxth} + \max\{(SIR_{min} - P_s), (-I_{\max})\} \quad (5)$$

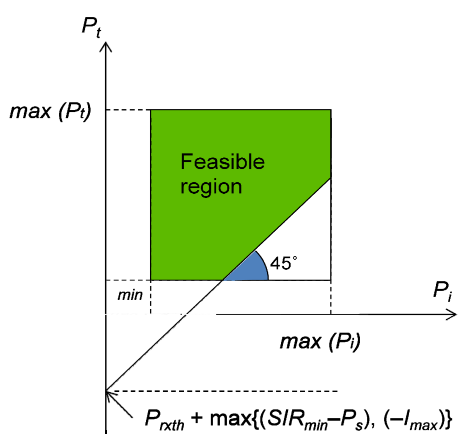

Figure 4 Feasible region

C. Feasible operation region of sensing

Now we examine whether message based inband signaling is feasible to create large enough quiet zone to have reliable sensing. From Eq. (5), we can derive the feasible region of transmission power of quiet signaling and the transmission power of an interferer, as described in Figure 4.

Assume the TV signal is at the lowest detection level, i.e., –114dBm, the receiving threshold to decode quiet signaling (P_{rxth}) is –85dBm, SIR_{min} is –50dB, and I_{max} is –50dBm. Under these conditions the transmission power of the quiet signaling should not be more than 21 dB lower than the transmission power of an interfering TVBD signal.

In homogeneous networks, if every TVBD uses the same level of transmission power, it is clear that the inband signaling is very effective for quieting neighbor TVBDs. However, if TPC is applied, the TPC range should not be larger than 21dB. In other words, the lowest transmission power of quiet signaling should not be more than 21dB lower than the highest transmission power.

In heterogeneous networks, TVBDs devices from different networks could use different transmission schemes with varying power levels. However, we assume the quiet signaling is common across heterogeneous networks. While it is not a problem for a high power fixed device to quiet personal/portable device, a personal/portable device, on the other hand, may not be able to effectively quiet a fixed device due to asymmetric link problem. Applying a similar analysis as used above, we can derive that the transmission power of a personal/portable device should not be more than 21dB lower than that of a high power fixed device. If the transmission power of fixed device is 1 W, i.e., 30 dBm, the transmission power of quiet signaling of personal/portable TVBD should be at least 9 dBm.

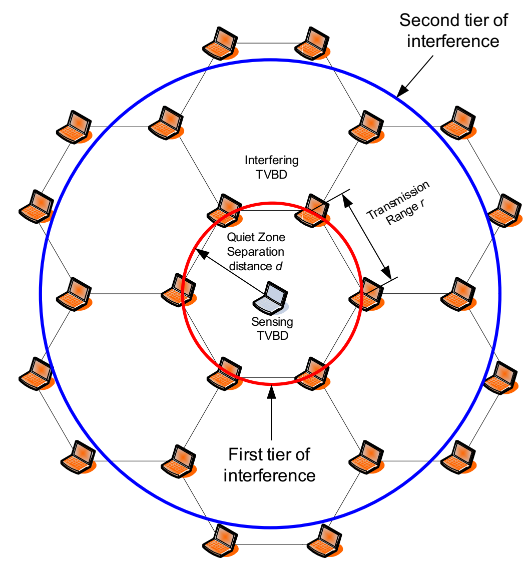

Figure 5 An illustration of multiple interference sources

D. Impact of multiple interferers

A device could also experience interference from multiple interference sources, i.e., interfering TVBDs, thereby impacting its sensing performance. As shown in Figure 5, we can divide interfering devices into multiple tiers according to their separation distance to the sensing device. It is obvious that the first tier of interference carries dominant weight. Therefore we only consider the first tier of interference, which is at the edge of quiet zone of the sensing TVBD.

Denote N as the number of interfering TVBDs at the edge of the quiet zone, i.e., the first tier interfering TVBDs. If the interfering TVBDs generate same level of interference then from Eq. (5), we have

$$P_t - P_i \geq$$

$$10\log \mathrm{N} + P_{rxth} + \max\{(SIR_{min} - P_s), (-I_{\max})\} \quad (6)$$

Assume r as the transmission range of interfering TVBDs and d as quiet range of a sensing TVBD. Then N is limited to $\max\left\{1, \left\lfloor \frac{2\pi d}{r} \right\rfloor\right\}$. Assume that the transmission range equals to quiet range, then $\frac{d}{r} = 10^{\frac{P_t - P_i}{10\alpha}}$, where α is the path loss factor. As a result, the number of interfering TVBDs depends on $P_t - P_i$. Then, from Eq. (6), we approximately have

$$P_t - P_i \geq \frac{\alpha}{\alpha-1}\left(10\log 2\pi + P_{rxth} + \max\{(SIR_{min} - P_s), (-I_{\max})\}\right) \quad (7)$$

IV. Further Discussions

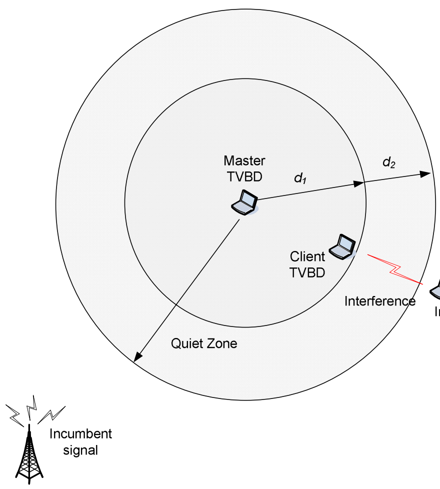

Figure 6 Quiet Zone for master-client network

A. *Whether client device should participate in quiet signal transmission*

According to current FCC rules, both master and client devices should participate in sensing. We know that globally synchronized quiet period is not needed. Under this scenario, a question arises whether it is sufficient only for the master to send quiet signaling or is it necessary for every device to participate in the transmission of quiet signaling.

To understand this problem, we consider Figure 6 as an example. Let's define d as the quiet zone range, d1 as the network size and d2 as the separation distance from network edge to quiet zone edge. It is apparent that d2 should not be shorter than the minimum separation distance defined in Eq. (3).

From Eqs. (3), we have

$$PL(d_2) \geq \max\{(P_i + SIR_{min} - P_s), (P_i - I_{\max})\} \quad (8)$$

From Eq (4), we also have

$$P_t - PL(d_1 + d_2) \geq P_{rxth} \quad (9)$$

Combining Eqs. (8) and (9), we have

$$P_t - P_i \geq PL\left(\frac{d_1+d_2}{d_2}\right) + P_{rxth} + \max\{(SIR_{min} - P_s), (-I_{\max})\} \quad (10)$$

Assume d_2 equals to d_{min}, then we have

$$P_t - P_i \geq PL\left(\frac{d_1+d_{min}}{d_{min}}\right) + P_{rxth} + \max\{(SIR_{min} - P_s), (-I_{\max})\} \quad (11)$$

Define $PL\left(\frac{d_1+d_{min}}{d_{min}}\right) \stackrel{\text{def}}{=} 10\alpha\log\left(\frac{d_1+d_{min}}{d_{min}}\right)$, where α (≥ 2) is the path loss factor. Then, we have

$$P_t - P_i \geq 10\alpha\log\left(\frac{d_1+d_{min}}{d_{min}}\right) + P_{rxth} + \max\{(SIR_{min} - P_s), (-I_{\max})\} \quad (12)$$

Again, assume P_t equals –114dBm, P_{rxth} equals –85dBm, SIR_{min} equals –50dB, I_{max} is at –50dBm, and α equals 3. Then we have

$$d_1 \leq d_{min}\left(10^{\frac{P_t - P_i + 21}{30}} - 1\right) \quad (13)$$

B. *Impact of TVBD signal bandwidth*

The simulation results presented in the previous section assume that TVBD signal bandwidth is limited to 5 MHz and also that a transmit filter is used to reduce the out of band emissions. However, in practical situations it would be difficult to enforce this requirement, especially so in the case of heterogeneous networks.

We evaluated the performance of the DTV sensing algorithm in the presence of other TVBD signals using the full 6 MHz bandwidth. This condition would represent the worst case scenario as in practice the bandwidth would be less than 6 MHz to satisfy the requirements for out-of-band emissions (OOBE). Figure 7 and Figure 8 show the probability of misdetection and the probability of false alarm, respectively, for different interference levels under this scenario. In this case, the misdetection rate is less than 5% for SIRs of -30 dB and above. This implies that for a DTV signal level of -115 dBm, the sensing algorithm can reliably detect this signal only if the interferer (TVBD) signal level is less than -85 dBm. This results in much larger interference range compared to the case when signal bandwidth is limited to 5 MHz.

In the case of single interference source, from Eq. (5), we have that P_t should not be more than 1 dB lower than P_i. In the case of multiple interference sources, from Eq. (7), P_t should be more than $\frac{\alpha}{\alpha-1}(10\log 2\pi - 1)$dB higher than P_i.

C. *Other coexistence mechanisms*

From the above analysis, we find the biggest challenge for self-coexistence is for personal/portable TVBD to coexist with high power fixed device due to asymmetric link problem. A personal/portable device may not reach far enough to quiet high power TVBDs and are therefore subject to either high false alarm rate and/or high misdetection rate. It is even more difficult to spatially reuse the same channel with high power TVBDs. One recommended practice is to allow low power TVBDs to detect and avoid high power TVBDs. Besides, high power TVBDs cannot operate in adjacent channels while personal/portable devices can. When operating in adjacent channels, personal/portable TVBDs do not need to be concerned about quieting high power devices anymore.

In additional to inband quiet signaling, other methods can be used for coordinating quiet period schedule and sharing spectrum if suitable. For example, if every TVBD network is connected to internet, the coordination quiet period synchronization and spectrum allocation can be done through a centralized coexistence manager using either IEEE 802.21-like concepts or IEEE 1900.4 concepts [4].

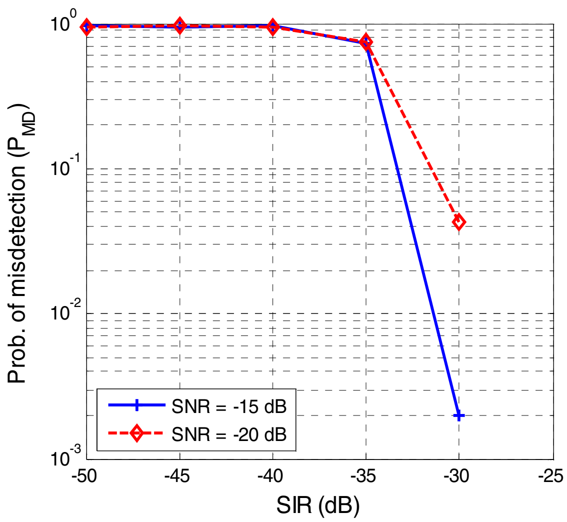

Figure 7 – Probability of misdetection vs. SIR in the presence of TVBD signals using the full 6 MHz bandwidth

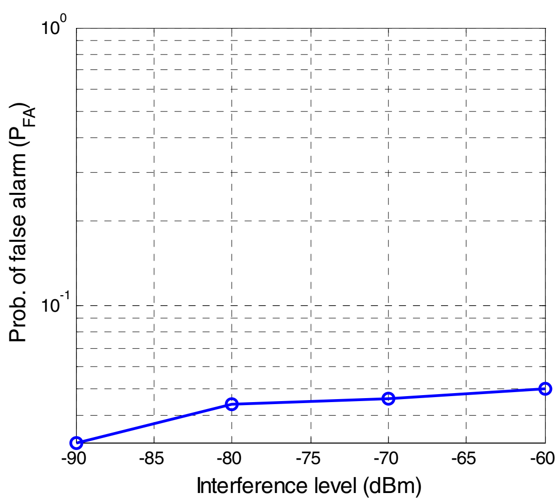

Figure 8 Probability of false alarm vs. interference in the presence of TVBD signals using the full 6 MHz bandwidth

V. Conclusions and Future Works

In this paper, we presented the study of sensing performance in the presence of interference and the minimum size of local quiet zone required for detecting the weakest incumbent signals. We studied the homogeneous networks and heterogeneous networks where low power personal/portable TVBDs and high power fixed TVBDs may coexist. We translated the problem of minimum quiet zone into the problem of the feasible operation region of TVBDs' transmission power according to sensing capability. We found that message based inband wireless signaling is effective to establish local quiet zone for reliable incumbent detection. It is relatively challenging for low power TVBDs to coexist with high power TVBDs. This suggests that some coexistence mechanisms for heterogeneous networks are desired to have in unlicensed TV bands.

Although we focus on the detection of ATSC signal only in this paper, the methodology developed in this paper could be applied to the detection of other primary signals, e.g., wireless microphone. In the future work, we would also like to take into the account other effects of the front-end such as the ADC precision, AGC, etc.

References

[1] Federal Communications Commission, "Second Report and Order and Memorandum Opinion and Order", Nov 14, 2008, FCC 08-260.

[2] Ofcom. http://www.ofcom.org.uk/consult/condocs/cognitive/

[3] 802.22 IEEE 802 LAN/MAN Standards Committee 802.22 WG on WRANs. http://www.ieee802.org/22.

[4] TV Whitespace Tutorial Intro. IEEE 802 Executive Committee Study Group on TV White Spaces. March 10 2009. Document number: sg-whitespace-09-0055-00-0000. http://grouper.ieee.org/groups/802/802_tutorials/09-March/2009-03-10%20TV%20Whitespace%20Tutorial%20r0.pdfMarch/2009-03-10%20TV%20Whitespace%20Tutorial%20r0.pdf

[5] Monisha Ghosh, et. al., "Spectrum Sensing Prototype for Sensing ATSC and Wireless Microphone Signals", CrownCom May 2008.

[6] Apurva Mody , August 2007, doc.: IEEE 802.22-07/0370r2

[7] A. Sahai, N. Hoven, and R. Tandra, "Some fundamental limits on cognitive radio," presented at Allerton Conference on Communication, Control, and Computing, October 2004.

[8] R. Tandra, and A. Sahai, "SNR walls for signal detection," in the IEEE Journal on Selected Topics in Signal Processing, pp. 4-17, Feb 2008.