Cognitive Technology for improving Ultra-Wideband (UWB) Coexistence

(Invited Paper)

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Abstract— **Cognitive radio technology enables the opportunistic operation of secondary devices in frequency bands allocated to primary users. In this paper we explore how this technology can enable Ultra-Wideband (UWB) systems to coexist with primary users. The distinguishing aspect of cognitive radio technology is the ability to detect and avoid primary users. We discuss two options for detecting the presence of primary devices - energy detection and preamble detection. The presence of multiple UWB devices can aid detection by enabling cooperative sensing of the primary. We analyze various techniques for cooperative sensing which differ in the amount of information they need to exchange between radios and the regime in which they are potentially advantageous. Furthermore, the wideband aspect of UWB offers many challenges to detection but also facilitates the detection process in several ways. These distinguishing aspects of wideband detection are also highlighted in this paper.**

I. INTRODUCTION

Cognitive radios have been advanced as a technology for the opportunistic use of under-utilized spectrum since they are able to sense the spectrum and use frequency bands only if no primary user is detected. This approach is motivated by the fact that while spectrum allocation seems to suggest a scarcity of spectrum, actual utilization of spectrum is very low [1]. Such opportunistic, primary aware reuse of spectrum espoused by the cognitive radio community contrasts with the underlay, primary unaware philosophy behind the development of Ultra-Wideband (UWB) technology. UWB devices seek to provide non-interference guarantees to primary users by spreading their transmit power over a very large bandwidth which ensures that the transmit power in any individual band is very low. Hence UWB devices appear as noise to most primary users.

Cognitive radios and UWB represent contrasting philosophies to address the spectrum sharing problem. However, gains can be had by merging these two technologies; by adding cognitive technology to UWB radios. Some of the gains from this merger are as follows:

- UWB spectrum in Europe and parts of Asia Pacific overlaps with WiMax spectrum [2]. Due to this overlap, an UWB transmitter in close proximity to a WiMax customer premise equipment (CPE) can impact the CPE's ability to receive transmissions from a WiMax base station [2]. Hence regulators in Europe and the Asia Pacific are considering requiring UWB radios to detect the presence of WiMax receivers and to abandon the band if a potential victim is detected. Furthermore, UWB radios that posses cognitive technology may also be allowed greater transmit power in bands where the primary can be identified and avoided.
- The wideband nature of UWB radios can enable simultaneous detection of multiple primary signals. Simultaneous detection of multiple primaries provides better detection characteristics than the isolated detection of the same primaries [3]. This techniques is especially useful for the detection of downlink transmission from co-located base-stations.
- When primary systems do not span the entire UWB band, the remaining UWB spectrum capacity can be used to provide a low bandwidth control channel between UWB devices in a Piconet. This control channel can aid the cooperative detection of primary signals.

Cognitive radio technology for opportunistic use consists of two elements: sensing/detection technology to identify the presence of a primary signal and avoidance technology to ensure that the UWB signal does not interfere with the primary. In this paper we focus on detection technology from the perspective of UWB radios. We shall use WiMax as an running example of a primary user to illustrate the various detection techniques. Avoidance techniques for UWB based on the WiMedia specification have been discussed in [2].

The rest of this paper is organized as follows. In Section II we look at various options for detecting WiMax and the requirements/issues with each option. In Section III we look at various detection techniques and compare these techniques with regards to detection of the WiMax downlink signal. Next, in Section IV we move from a single radio to cooperative sensing. We examine several cooperative detection techniques and compare their performance for various SNR regimes. Finally, Section V discusses the impact of the wideband nature of UWB radios on the detection process.

II. DETECTION REQUIREMENTS

The key parameters for evaluating a detection algorithm are the probability of detection P_{D} and the probability of false alarm P_{FA}. Probability of detection is the probability that the detector is able to detect the presence of a primary signal. Likewise, probability of false alarm is the probability that noise triggered the detection algorithm into falsely believing the presence of a primary signal. Choosing particular values of P_{FA}, P_{D} and the number of samples imposes a lower bound on the minimum detectable Signal-To-Noise ratio (SNR) of the primary signal [4].

UWB devices can either detect a WiMax transmission from the base station to the CPE (downlink) and/or from the CPE to the base station (uplink). Both these options present different challenges for detection in terms of sensitivity requirements and signal availability.

A. Downlink Detection

The downlink detection problem is similar to the digital TV detection problem being studied by the IEEE 802.22 group [5]. In the presence of a WiMax basestation, the downlink will be present with a very high activity factor which enables faster detection. Furthermore, the downlink incorporates a minimum number of repeatable transmissions in the forms of beacons. Unfortunately UWB devices are far from the base station, and hence requires high sensitivity to detect weak signals. For a target P_{D}, the detection sensitivity of the receiver can be calculated based on the distribution function of the loss (path loss, multipath, shadowing) [6]. An easier way to calculate the target downlink detection sensitivity, is to set the sensitivity equal to that of a typical WiMax receiver (∼-100dBm/MHz) and budget an additional 25-30dB of fading margin. This implies that WiMax signals must be detected at a sensitivity of -125dBm/MHz to -130dBm/MHz which translates to an equivalent SNR of -10dB to -15dB.

B. Uplink Detection

Detecting the uplink is relatively easier since the subscriber station is close to the UWB device. If the downlink and uplink transmissions are time-multiplexed (TDD mode), calculating the sensitivity is straightforward. In this case, channel reciprocity holds and the detection and interference ranges are tightly coupled. The thermal noise floor in a 1MHz band is -114dBm. Typical Interference-to-Noise Ratio (INR) requirements at a WiMax receiver are around -6dB. Assuming a receiver noise figure of 5dB, this gives us a maximum interference limit of -115dBm. Since the UWB transmission device has an FCC-imposed power limit of -41.3dBm/MHz, a 74dB ($-41-(-115)=74$) isolation is needed between the WiMax CPE and UWB devices. Typical WiMax CPE's transmit at 21dBm in a 20MHz band (∼8dBm per MHz). With a 74dB isolation, this translates into a detection sensitivity of -66dBm/MHz (SNR of 48dB). In the case where the uplink and the downlink are separated in frequency (FDD), the multipath characteristics of the two may be completely different. On the other hand, shadowing correlation between downlink and uplink frequencies is still fairly high (0.66-0.9) [7]. Together we can budget an additional 20dB for multipath and shadowing mismatch. Hence in this case we will need to detect a signal of ∼-86dBm/MHz (SNR of 28dB).

As opposed to downlink detection, uplink detection confirms the presence of an actual WiMax CPE. Unfortunately, a CPE may never transmit if it cannot hear the downlink in the first place [2]. Hence mechanisms are needed in the UWB device to ensure that the downlink signal can be heard by the CPE [2]. Table I summarizes the different approaches discussed above.

III. SINGLE RADIO DETECTION TECHNIQUES

A. Energy Detection

The energy detector makes minimal assumptions about the primary signal - it only assumes that the received power of the primary signal is known.

To derive the tradeoffs involved with an energy detector we proceed as follows. In any detection problem we wish to distinguish between the following hypothesis:

$$\begin{aligned} \mathcal{H}_0 : Y[n] &= \quad W[n] & n &= 1,\ldots,M \\ \mathcal{H}_1 : Y[n] &= X[n]+W[n] & n &= 1,\ldots,M \end{aligned}$$

For convenience we assume that all $W[n]$ are independent and distributed as $\mathcal{N}(0,\sigma_w^2)$. Furthermore all $X[n]$ are independent and distributed as $\mathcal{N}(0,\sigma_s^2)$.

Then, the detection rule for energy detection is:

$$\frac{1}{M}\sum_{n=1}^{M} Y[n]^2 \underset{H_0}{\overset{H_1}{\gtrless}} \lambda$$

If noise power (σ_w^2) is completely known, then for a fixed probability of false alarm P_{FA} and a fixed number of samples (M), the probability of detection can be completely specified.

$$P_D = Q\left(\frac{Q^{-1}(P_{FA}) - \sqrt{\frac{M}{2}}SNR}{SNR+1}\right) \tag{1}$$

Figure 1 shows the use of the energy detector to detect a 1.25MHz wide WiMax signal using QPSK modulation at an SNR of -10dB and -15dB[1]. The performance of the detector for WiMax matches the theoretical performance as predicted by (1).

B. Preamble/Coherent Detection

To achieve low sensitivity levels we need to exploit features of the WiMax packet. One such feature is the packet preamble. IEEE 802.16d specifies two kinds of preambles: the long and short preamble. The long preamble consists of two WiMax OFDM symbols. In the first symbol every 4th subcarrier is loaded with a PN sequence. In the time domain, this leads to replication which is easy to identify with cross correlation. On correlating the received sequence with the known preamble,

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[1] The WiMax signal was generated using Agilent's Signal Studio and sampled using Agilent's Infiniium Sampling Scope

	Downlink	Uplink (FDD)	Uplink (TDD)
Sensitivity (dBm/MHz)	-125 → -130	-86	-66
Detection Scheme	Preamble	Energy with Cooperation	Energy
Activity	high	low	low
Dynamic Range requirements (dB)	84-89	45	25

TABLE I
DETECTION OPTIONS FOR WIMAX.

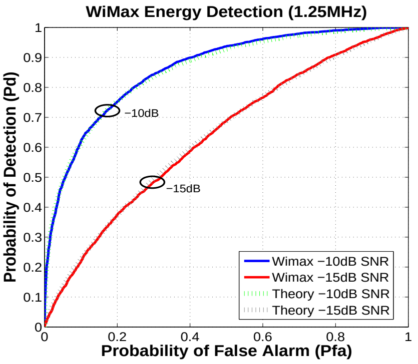


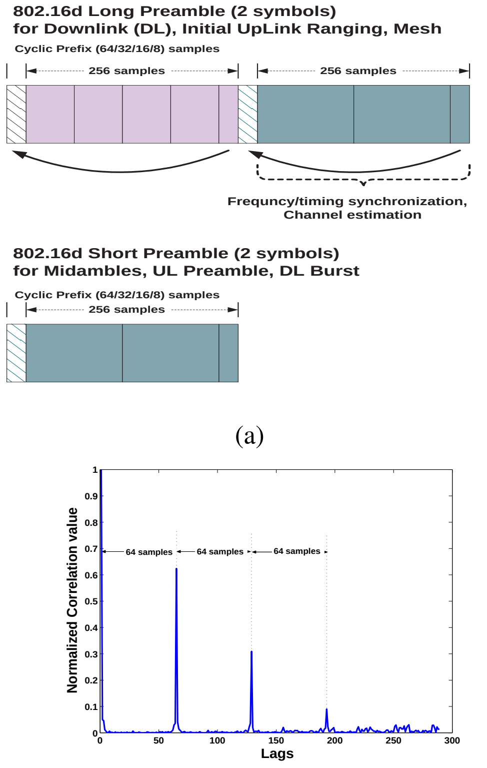
Fig. 1. Performance characteristics of WiMax detection using the energy detector. The WiMax signal is a 1.25MHz FDD signal using QPSK modulation (M=256).

4 peaks separated by 64 symbols are clearly identifiable. Figure 2(a) shows the structure of the long and short preambles while Figure 2(b) shows the 256 point auto-correlation of the long preamble with a cyclic prefix of 16 symbols.

Figure 3 shows the performance of the preamble detector for a 1.25MHz wide WiMAx signal at -15dB SNR. If the location of the main peak is known, the performance is significantly better than if the location is not known. When the location of the peak is unknown, we need to search for the maximum value at the output of the correlator. Hence the detection threshold has to be set using the maximum value of noise. This causes the probability of detection to degrade.

C. Discussion

Coherent detection gains over energy detection since the number of samples (M) to attain a similar level of performance scales as $O(\text{SNR}^{-2})$ for an energy detector and $O(\text{SNR}^{-1})$ for a coherent detector. However, in a packet environment the number of samples available for coherent detection is limited to the size of the preamble while energy detection can use all the samples in a packet. The effect of this can be seen with a simple calculation. The distribution of packets in the internet is bimodal with significant peaks at 40 bytes and 1500 bytes [8]. If we assume a simplified packet format for WiMax in FDD mode with the preamble followed by the MAC payload using QPSK modulation (i.e. we neglect the Frame Control Sequence, the DS-MAP and MAC headers), the average number of samples per packet available for energy detection is around 2500. Compare this to the 256 samples used for preamble correlation. For a P_D of .9 and a P_{FA} of .1,



(a)

(b)

Fig. 2. (a) WiMax (IEEE 802.16d) long and short preambles (b) 256 point autocorrelation of the long preamble (Cyclic prefix length = 16 symbols) which amounts to a processing gain of 24dB

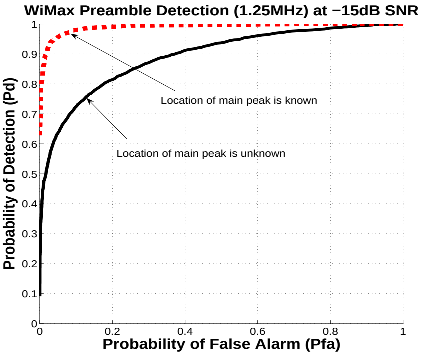


Fig. 3. Performance characteristics of WiMax detection using the preamble detector. The WiMax signal is a 1.25MHz FDD WiMax signal. The performance of the preamble detector is best when the location of the main peak is known.

this gives a minimum detectable SNR for an energy detector of -14dB and for a preamble detector of -16dB. Hence the energy detector and the preamble detector should show similar performance in practice.

IV. COOPERATIVE DETECTION

When specifying target sensitivity for a sensing radio in Section II we had to make worst case assumptions about shadowing and multipath. These worst case requirements can be eased by cooperative detection strategies in which sensing results from a number of radios are combined to make a collective decision. This occurs because the chance that multiple radios all see a bad fade is very low [6]. Since all communication schemes (expect broadcast) require at least two communicating radios, and all radios need to sense for the primary anyways, it is natural to exchange information and thus make a better decision. In the case of UWB radios used for wireless USB applications, the laptop and the communication device (eg. camera) need to agree on a set of channels where the primary is found. This requires low data rate signalling and can be performed on selected subcarriers where the primary is known not to exist. The same information can be used for cooperative detection. In this section we shall consider a few cooperative detection techniques. These techniques vary in the amount of information they need to exchange and gains they provide. We shall focus on the two user case.

A. OR detection rule

In the OR rule, we declare the primary to be present if any of the radios declares the primary to be present. If $P_{D_i}, 1 \leq i \leq 2$ and $P_{FA_i}, 1 \leq i \leq 2$ are the probability of detection and probability of false alarm of radio i respectively, then the system probability of detection and false alarm (assuming independence across the radios) are given by:

$$\begin{aligned} P_D^s &= 1-(1-P_{D_1})(1-P_{D_2}) \\ P_{FA}^s &= 1-(1-P_{FA_1})(1-P_{FA_2}) \end{aligned}$$

where P_D^s is the probability of detection of the system, and P_{FA}^s is the probability of false alarm of the system. The best performance of the OR rule is obtained when the two radios have the same probability of false alarm. This is the same phenomenon seen in [9] where the best performance is obtained when the radios estimate their own noise and set their own thresholds.

B. MAX detection rule

Another form of the OR rule is the max rule. Each radio computes its test statistic $T(Y_i)$ and the overall test statistic is the max of the individual test statistic ie.

$$T(Y) = max(T(Y_1) - \sigma_{w_1}^2, T(Y_2) - \sigma_{w_2}^2)$$

The performance of the MAX rule for the case of equal SNRs and unequal SNRs is shown in Figure 4 and Figure 5 respectively. In both cases, the best performing OR rule performs as good as the MAX rule. When the SNRs at the two radios is very different, both rules perform worse than a single radio at the higher SNR. Subtracting the noise power is useful when the two radios see different noise characteristics.

C. Calibrated Max detection rule

The basic problem with the MAX rule (or the OR rule) is that the chance of falsely triggering is much higher than a single radio when the primary is not present. Ideally we would like know the following: 'If the primary is present then the SNR at radio k will be the highest'. In this case we would use radio k's test statistic for the final decision i.e. $T(Y) = T(Y_k)$. Since this information is not available we can aim to learn/infer it in certain situations. This is true when there are multiple co-located primary transmitters. For example, twenty eight TV channels are broadcasted from a single TV transmitter located at Sutro tower in San Francisco [10]. Similarly many cellular base stations are mounted on the same tower to amortize tower costs. The same can be expected for WiMax base stations. The shadowing seen by co-located primary transmitters that are transmitting on nearby frequencies is very similar as was verified from UWB experiments in [3]. This means that the major variation in signal strength from such co-located primaries comes from differences in multipath. If the coherence bandwidth of the primary is small relative to the actual bandwidth of the signal, we can average over the multipath when performing energy detection. With multipath averaged out, there is very strong correlation between the signal strengths from co-located primary users.

If we knew that one of the primary users was always on (called the anchor primary), we could just compare the measurement of the anchor from various radios. The radio that would report the maximum signal strength of the anchor would then be declared the 'best' radio. Since there is a error associated with this calibration process, we need to budget for that. In the case of two users, if radio 1 is the better radio and Pe is the probability that we falsely identify the better radio then the new test statistic is:

$$T(Y) = Pe\, T(Y_2) + (1-Pe)\, T(Y_1)$$

The performance of the calibrated MAX rule for the case of equal SNRs and unequal SNRs is shown in Figure 4 and Figure 5 respectively. The real gains from this rule results when the SNRs at the two radios are very different. In this case the rule allows us to discount the radio with the worse SNR.

D. Optimal Rule

At this point we can ask the question: what is the optimal way to combine the results from two radios. To derive the optimal rule for combining the results from two energy detectors we first re-state the hypothesis:

$$\begin{aligned} \mathcal{H}_0 : Y_1[n] &= & W_1[n] & \quad n = 1, \ldots, M \\ : Y_2[n] &= & W_2[n] & \quad n = 1, \ldots, M \\ \mathcal{H}_1 : Y_1[n] &= & X_1[n] + W_1[n] & \quad n = 1, \ldots, M \\ : Y_2[n] &= & X_2[n] + W_2[n] & \quad n = 1, \ldots, M \end{aligned}$$

we assume that all $W_i[n]$ are independent and distributed as $\mathcal{N}(0, \sigma_{w_i}^2)$. Similarly we assume that all $X_i[n]$ are independent and distributed as $\mathcal{N}(0, \sigma_{s_i}^2)$. Furthermore we assume that two radios are not synchronized and hence $X_1[n]$ is independent of $X_2[m]$ for all $1 \leq n \leq M$ and $1 \leq m \leq M$.

Then the detection rule for uncorrelated radios becomes

$$\frac{\prod_{i=1}^{2} \prod_{m=1}^{M} \frac{1}{\sqrt{2\pi(\sigma_{s_i}^2+\sigma_{w_i}^2)}} \exp\left(\frac{-Y_i[m]^2}{2(\sigma_{s_i}^2+\sigma_{w_i}^2)}\right)}{\prod_{i=1}^{2} \prod_{m=1}^{M} \frac{1}{\sqrt{2\pi\sigma_{w_i}^2}} \exp\left(\frac{-Y_i[m]^2}{2\sigma_{w_i}^2}\right)} \underset{H_0}{\overset{H_1}{\gtrless}} \lambda$$

Taking log on both sides and renaming constants gives:

$$\sum_{i=1}^{2} \frac{\sigma_{s_i}^2}{\sigma_{w_i}^2(\sigma_{s_i}^2 + \sigma_{w_i}^2)} \sum_{m=1}^{M} \frac{1}{M} Y_i[m]^2 \underset{H_0}{\overset{H_1}{\gtrless}} \lambda'$$

We define the new test statistic as $T(Y) = \sum_{i=1}^{2} \frac{\sigma_{s_i}^2}{\sigma_{w_i}^2(\sigma_{s_i}^2+\sigma_{w_i}^2)} \sum_{m=1}^{M} \frac{1}{M} Y_i[m]^2$.

Under $\mathcal{H}_1$, $\sum_{m=1}^{M} \frac{1}{M} Y_i[m]^2$ is distributed as $\mathcal{N}\left(\sigma_{s_i}^2 + \sigma_{w_i}^2, \frac{2}{M}(\sigma_{w_i}^2 + \sigma_{w_i}^2)\right)$ for large M [4]. Hence,

$$T(Y|H_1) \sim \mathcal{N}(\left(\sum_{i=1}^{2} SNR_i, \frac{2}{M} \sum_{i=1}^{2} SNR_i^2\right)$$

Similarly under $\mathcal{H}_0$, $\sum_{m=1}^{M} \frac{1}{M} Y_i[m]$ is distributed as $\mathcal{N}\left(\sigma_{w_i}^2, \frac{2}{M}\sigma_{w_i}^2\right)$ for large M [4]. Hence,

$$T(Y|H_0) \sim \mathcal{N}\left(\sum_{i=1}^{2} \frac{SNR_i}{SNR_i + 1}, \frac{2}{M} \sum_{i=1}^{2} (\frac{SNR_i}{1 + SNR_i})^2\right)$$

If we define, $\mu_0 = \sum_{i=1}^{2} \frac{SNR_i}{SNR_i+1}$, $\sigma_0 = \sqrt{\frac{2}{M} \sum_{i=1}^{2} (\frac{SNR_i}{SNR_i+1})^2}$, $\mu_1 = \sum_{i=1}^{2} SNR_i$, $\sigma_1 = \sqrt{\frac{2}{M} \sum_{i=1}^{2} SNR_i^2}$, we can write,

$$P_{FA}^s = Q\left(\frac{\lambda' - \mu_0}{\sigma_0}\right) \text{ and } P_D^s = Q\left(\frac{\lambda' - \mu_1}{\sigma_1}\right) \quad (2)$$

The performance of the optimal rule for the case of equal SNRs and unequal SNRs is shown in Figure 4 and Figure 5 respectively. This rule results in the best performance since it weights the energy estimate with the actual signal strength. When the SNRs are equal, the optimal rule only serves to double the number of samples. This can be seen by eliminating λ' from (2). In doing this we get,

$$P_D^s = Q\left(\frac{Q^{-1}(P_{FA}^s) - \sqrt{M}SNR}{SNR + 1}\right)$$

Comparing this to (1), we see that the optimal detector doubles the number samples.

E. Optimal Rule with SNR estimates

The problem in implementing the optimal rule is in knowing the actual SNRs at each radio. The simplest solution to this problem is to estimate the signal power and use it in the test statistic. To do this we proceed as follows; we first calculate the empirical received power as: $\hat{P}_i = \frac{1}{M} \sum_{m=1}^{M} Y_i[m]^2$. With this estimate the new test statistic is:

$$T(Y) = \sum_{i=1}^{2} \frac{(\hat{P}_i - \sigma_{w_i}^2)}{\sigma_{w_i}^2}$$

Under $\mathcal{H}_1$, $\hat{P}_i$ is distributed as $\mathcal{N}\left(\sigma_{s_i}^2 + \sigma_{w_i}^2, \frac{2}{M}(\sigma_{w_i}^2 + \sigma_{w_i}^2)\right)$ for large M [4]. Using the distribution of $\hat{P}_i, 1 \leq i \leq 2$, the distribution of $T(Y)$ can be derived under the two hypothesis:

$$\begin{aligned} T(Y|H_1) &\sim \mathcal{N}\left(\sum_{i=1}^{2} SNR_i, \frac{2}{M} \sum_{i=1}^{2} (1 + SNR_i)^2\right) \\ T(Y|H_0) &\sim \mathcal{N}\left(0, \frac{4}{M}\right) \end{aligned}$$

The performance of this rule for the case of equal SNRs and unequal SNRs is shown in Figure 4 and Figure 5 respectively. For equal noise power, the SNR estimates rule compares the sum signal energy from the two radios to the threshold. Hence its performance is identical to the performance of the optimal detector when the SNRs are equal. However, in the case of unequal SNRs, the energy summing operation is not optimal and hence the performance of the rule suffers.

F. Discussion

A question arises at this stage - what is the optimal rule to use in practise? The performance of MAX and OR rules are similar and hence we can choose either one. Between the MAX and SNR estimates rules, the SNR estimates rule always outperforms the MAX rule. So the real choice is between the calibrated MAX rule and the SNR estimates rule. The calibrated MAX rule performs better than the SNR estimates rule when the SNRs at the two radios are very different. When the SNRs are similar, the SNR estimates rule provides better performance. However it must be noted that in the large sample regime (for a given SNR), the quantitative difference between the different rules disappears.

V. WIDEBAND NATURE OF UWB RADIOS

The wideband nature of UWB radios presents challenges not seen for narrowband detectors. Some of the challenges in detection using wideband radios are discussed in detail in [2]:

- Since the FFT/IFFT module is reused for energy detection, we are normally limited by the size of the FFT. This limits the resolution of the bins which in turn effect the detection sensitivity of narrowband primary signals.
- For wideband radios we attempt to perform detection across the entire band and hence we have to eliminate the case where a primary signal on a given frequency is

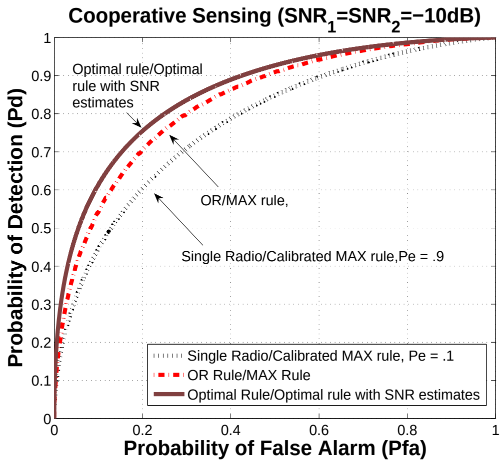


Fig. 4. Performance characteristics of various cooperative sensing schemes for two radios seeing the primary signal at the same SNR. In this case the detector using SNR estimates performs as well as the optimal detector. The best performing OR rule (equal P_{FA} for each radio) performs as well as the MAX rule. The calibrated MAX rule randomly chooses between the two radios and hence has the same performance as a single detector. The performance of the cooperative sensing for real signals (eg. WiMax) is qualitatively similar to the theoretical results.

not detected while a false alarm is triggered on another frequency.

- The shape of the baseband analog filter means that the gain for each FFT bin is different. Hence the baseband filter shape needs to be accounted for.

Wideband sensing also affords advantages over narrowband sensing. In particular,

- Multiple primary users can be detected simultaneously which reduces the latency between the time that a primary appears and the time at which it is detected by the system.
- A wideband receiver enables detection of multiple primaries. This can enable a radio to calibrate its shadowing environment using co-located primaries.
- Frequencies where the primary is known not to be present can be used for interference/noise measurement.

VI. CONCLUSIONS

The confluence of Ultra-Wideband (UWB) radio and cognitive technology presents us with some unique opportunities and challenges. Cognitive Technology enabled UWB devices are necessary to allow the use of UWB devices in the WiMax frequency bands in Europe and Asia Pacific. The energy and preamble detector provide good detection schemes for WiMax. In theory the preamble detector outperforms the energy detector but suffers from the low duty cycle of the preamble. The wideband aspect of UWB allows us to use some of the unoccupied frequency bands as a low bandwidth control channel for cooperative sensing. The cooperative sensing scheme enables us to improve upon the performance of the individual detector. The MAX and OR rule with equal P_{FA} perform the same under all SNR conditions. The optimal rule requires the knowledge of the primary signal and hence

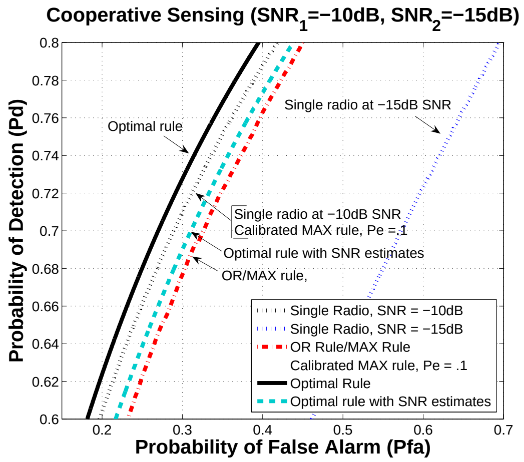


Fig. 5. Performance characteristics of various cooperative sensing schemes for two radios seeing the primary signal at different SNRs (SNR_1 = -10dB, SNR_2 = -15dB). The figure has been enlarged to illustrate the differences between the different schemes. In this case the MAX, OR and SNR estimates rule perform worse than a single radio at -15dBm. The calibrated MAX rule chooses the radio with SNR=-10dB 90% of the time and hence performs better than the other rules.

cannot be implemented in practise. The optimal rule using SNR estimates performs better than OR/MAX rules but loses out to the calibrated maximum rule when the SNRs are very different. The calibrated maximum rule however, requires co-located primaries to determine the 'best' radio, and hence may not be implementable if such primaries are not present.

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