Cognitive Technology for Ultra-Wideband/WiMax Coexistence

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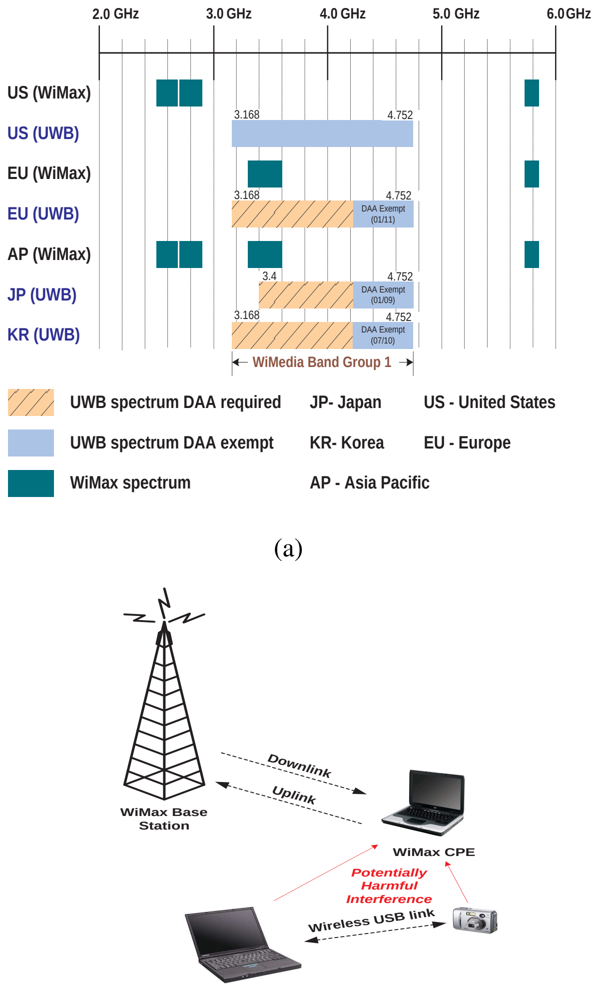
***Abstract*— Cognitive radios have been advanced as a technology for the opportunistic use of under-utilized spectrum wherein secondary devices sense the presence of the primary user and use the spectrum only if it is deemed empty. The distinguishing aspect of cognitive radios is the ability to sense the primary user and modify their transmission parameters to avoid interference to the primary. In this paper we explore the use of cognitive technology to enable the operation of ultra-wideband (UWB) devices in WiMax bands. In this particular example UWB devices must incorporate cognitive technology to detect and avoid (DAA) WiMax devices in certain regulatory domains. We start by discussing various options for detection and avoidance. We then describe the obstacles faced in achieving robust detection and avoidance with an on-chip implementation of basic DAA functionality. This implementation is based on the energy detector and can reliably detect WiMax uplink transmissions. Finally, we present empirical results for the operation of a single cognitive technology enabled UWB device with a WiMax system. This interaction also highlights the problem of dealing with *listen before speak* primaries where secondary transmission could interfere by denying the primary access to the medium.**

I. INTRODUCTION

Ultra-wideband (UWB) technology is termed as such since it occupies large swathes of spectrum and uses very low power to communicate. UWB's intended use is in the 3-10GHz bands for short range ($\sim$10m) communications for implementing Wireless Personal Area Networks (WPAN) [1]. WiMax (Worldwide interoperability for Microwave access), on the other hand, is the commercialization of the IEEE 802.16 standard and is meant to provide high speed wireless data services over a much wider area ($\sim$5 miles) [2]. The target bands for WiMax deployment are the 2.4GHz, 3.5GHz and 5.8GHz bands. The 3.5GHz band is free in most countries except the United States. Operation of WiMax in the 3.5GHz band is susceptible to interference from UWB devices operational in band group 1 (3.168GHz to 4.752GHz) as per the WiMedia specifications [1]. This is particularly true in Europe, Korea and Japan as illustrated in Figure 1(a).

The usage models of WiMax and UWB are both centered around laptop cards and hence an UWB device could potentially interfere with reception at the WiMax Customer Premise



(a)

(b)

Fig. 1. (a) Overlapped frequency allocation for WiMax and ultra-wideband (UWB) in various countries and continents. (b) Potentially disruptive interference between WiMax and UWB occurs when the WiMax equipped Customer Premise Equipment (CPE) is in close proximity of an UWB communication pair.

Equipment (CPE) (See Figure 1(b)). However since the two services occupy different spatial scales, if the transmissions of UWB are properly coordinated they could complement each other.

The traditional regulatory mechanism to handle interference is to separate contenders in space or in frequency. Thus regulators would impose artificial limits on transmissions to minimize interference. This approach precludes dynamic spatial/temporal reuse of the spectrum. Furthermore, with all frequency bands being allocated multiple times over, new spectrum is not readily available for such allocation. Thus by declaring that all new users of the spectrum are secondary users and requiring that they must detect and avoid (DAA) the primary user, the regulators are opening up spectrum for opportunistic use. In the absence of DAA functionality, UWB devices would have to forfeit the band designated as 'DAA required' in Figure 1(a) which would greatly reduce the spectrum available for communication.

In this article, we first describe the detection problem, profiling both downlink and uplink detection. We then explain various avoidance techniques and justify the adopted approach of using a 'notch filter'. In section IV we explain on-chip detection functionality as well as the various practical problems in implementing robust detection. Finally, we present coexistence results with an actual WiMax system.

II. THE DETECTION PROBLEM

The detection problem for UWB can be formulated as a binary hypothesis testing problem, where the aim is to distinguish between the following hypotheses [3]:

$$\mathcal{H}_0 \quad : \quad y[n] = w[n] \tag{1}$$

$$\mathcal{H}_1 \quad : \quad y[n] = x[n] + w[n] \tag{2}$$

given a sequence of observations $y[n]$ for $n = 1, 2, \dots, N$.

When $\mathcal{H}_1$ is true, the WiMax signal ($x[n]$) is present together with noise. The WiMax signal could be a downlink transmission from the basestation to the CPE or uplink transmission from CPE to the base station or could include both if WiMax employs time division duplexing between uplink and downlink transmissions.

The key parameters in evaluating a detection algorithm are the probability of missed detection (P_{MD}) and the probability of false alarm (P_{FA}). Probability of missed detection is the probability that the detection algorithm is unable to detect the presence of a primary signal. Probability of false alarm on the other hand, is the probability that noise triggered the detection algorithm into falsely believing the presence of a primary signal. We would like to minimize both.

A. Downlink Detection

The downlink detection problem is similar to the digital TV detection problem being studied by the IEEE 802.22 group and other research efforts [4][5]. In the presence of a WiMax basestation, the downlink will be present with a very high activity factor which enables faster detection. However, if the UWB device is far from the base station, detection of the downlink signal requires high detection sensitivity[1] which can be achieved only with large sensing times (sensing time N $\sim O(SNR^{-2})$ for an energy detector and $O(SNR^{-1})$ for a coherent detector) or by advanced detection techniques [3]. For a given target P_{MD}, 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 downlink detection sensitivity requirements, would be to set the sensitivity equal to that of a typical WiMax receiver (∼-100dBm/MHz) and budget an additional 10-20dB fading margin. Cooperative sensing can help reduce the fading margin to this level [6].

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, calculating the sensitivity is straight-forward. In this case, channel reciprocity holds and the detection and interference ranges are tightly coupled[2]. The thermal noise floor in a 1MHz band is -114dBm. Typical Interference-to-Noise Ratio (INR) requirements at a WiMax receiver is around -6dB. Assuming a receiver noise figure of 5dB, this gives us a maximum interference limit of -115dBm. Since the UWB transmission device has a FCC imposed power limit of -41dBm/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.

In the case where the uplink and the downlink are separated in frequency, the multipath characteristics of the two may be completely different. On the other hand, shadowing correlation between downlink and uplink frequencies is fairly high (0.66-0.9) [7]. Together we can budget an additional 20 dB for multipath and shadowing mismatch. Hence in this case we will need to detect a signal of ∼-86dBm/MHz.

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. Hence mechanisms are needed in the UWB device to ensure that the downlink signal can be heard by the CPE.

The problem that the CPE may never transmit if it does not hear the downlink, falls under the general problem of dealing with primary devices which follow the *listen before talk* protocol. Interference to the primary in this case is different from the traditional additive interference; a secondary does not interfere with a primary's transmission but with its *access* to the medium. Another case of the same would be cognitive radios operating in the ISM bands where WiFi radios are the de facto primary users. Since WiFi radios employ Carrier Sense Multiple Access (CSMA) protocol, they will not transmit if they hear another secondary device and hence may never access the medium.

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[1] Detection sensitivity is defined as the minimum received power per unit bandwidth (dBm/MHz) that can be detected while achieving the target P_{MD}.

[2] This assumes no spatial selectivity.

III. THE AVOIDANCE PROBLEM

The avoidance problem requires a UWB device to cease transmission and/or reduce transmit power in the bands where a WiMax link is detected. Avoidance techniques fall under one of the two classes - *Receiver Aware* or *Receiver Unaware*. In the first class of techniques, the receiver is aware of the changes in the transmission parameters (e.g. the receiver knows which subcarriers are not used) and may use the knowledge to improve its link performance. In the second class, the receiver is unaware of the modifications and tries to reconstruct information lost by exploiting the redundancy due to channel coding. The following is a list of possible avoidance techniques specific to the UWB implementation based on the WiMedia standard (WiMedia specifies OFDM modulation using a 128-point FFT):

1) *Band Dropping*: Each band group (a band group consists of three 528MHz wide frequency bands) is utilized for UWB communication by hopping between the three bands. If WiMax is detected on any one of the bands, the UWB devices could switch to a two-band hopping sequence. The switching is directed by the MAC layer at both the transmitter and receiver.
2) *Subcarrier Nulling*: In this approach, the transmitter does not send data on subcarriers that need to be avoided. The receiver may or may not know about the existence of the nulled subcarriers. The effect of subcarrier nulling on the UWB spectrum is shown in Figure 2. Even with 48 subcarriers nulled, the maximum attenuation possible is 22dB, due to the sidelobes of the neighboring subcarriers (those close to the nulled subcarriers) filling up the 'notch'.
3) *Windowing*: The problem with subcarrier nulling is that the sidelobes of the sinc impulse (due to the rectangular window, each subcarrier is convolved with a sinc impulse in the frequency domain) are not attenuated enough. One way around this problem is to smoothen the time domain waveform by using a raised cosine filter [8]. The receiver does not need to be aware of the windowing function being used. Our simulations reveal that a combination of subcarrier nulling and a raised cosine window, can yield a maximum attenuation of 25dB (this is true even with raised cosine roll-off factor (β) equal to 1). Unfortunately, using the raised cosine filter violates the WiMedia specifications which require a null postfix.
4) *Cancellation Carriers*: Another way to combat the problem is to use a few subcarriers adjacent to the subcarriers being avoided to suppress the sidelobes of the transmitted spectrum [9]. This technique is sometimes referred to as 'active interference cancelation'. The information on the subcarriers that have been 'spoiled' can be recovered by channel decoding. A system of linear equations has to be solved to compute the coefficients of the cancellation carriers which requires on-chip matrix inversion – an area intensive proposition. Cancellation carriers can achieve large attenuation levels.
5) *Notch Filter*: The transmitter implements a digital notch filter in the time domain (post IFFT) so as to notch out the corresponding subcarriers. Again, the location of the notch may or may not be available to the receiver. The digital notch filter overcomes the deficiency of subcarrier nulling by removing the sidelobes. Attenuation of around 40dB at the DAC input can be achieved by using a notch filter of sufficient order. However, the actual notch depth at the RF output, as with any of the nulling/notching techniques described earlier, is limited by the precision of the DAC and the non-linearities/phase noise of the RF. Figure 2(b) shows the actual spectrum of the UWB signal with a notch of width 13 subcarriers. The attenuation achieved is greater than 27dB.

For the purposes of DAA, notch filtering was the avoidance method of choice since it did not violate the WiMedia specifications and required minimal change to the hardware.

If the avoidance algorithm achieves a maximum of x dB reduction in transmitted power, then the UWB device can transmit with reduced power as long as the detected uplink signal is less then $-86 + x$ dBm/MHz. With a well calibrated sensing device, such an estimate of the power of the detected signal is reasonable to expect if the received signal is above the detection sensitivity.

Figure 3 shows the packet error rate (PER) for different notch widths. The PER curves were obtained by averaging over all notch positions. At 480MBits/s data rate and notch widths of 13 and 21 subcarriers, the target packet error rate cannot be reached for any transmit power. For all other rates and notch widths, the receiver can still operate at a reasonable PER albeit at lowered link margins.

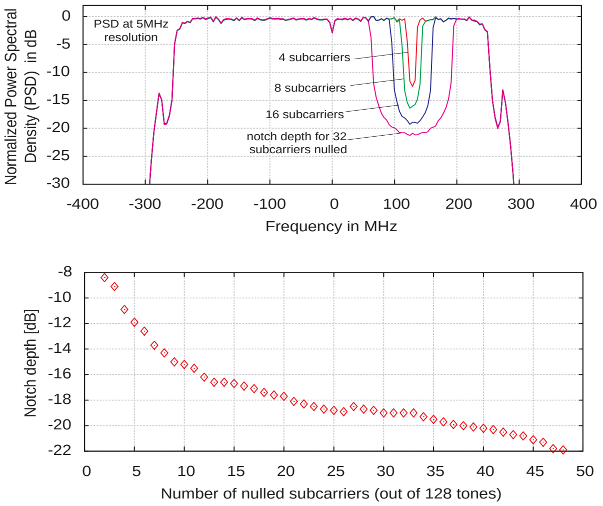
IV. WIMAX DETECTION: DESIGN AND IMPLEMENTATION

Traditionally, cognitive radios have been envisioned with separate sensing radios. UWB DAA functionality on the other hand, needs to be implemented on-chip and sensing has to be interleaved with transmission and reception. The reasons for this are the following:

- The silicon cost of implementing additional DAA functionality needs to be minimized. Many of the modules of the traditional receiver (for e.g. the FFT in the OFDM-based WiMedia UWB system of [1]) need to be reused.
- A separate sensing radio attempting to sense while UWB transmission is also on in the same band, needs a mechanism to subtract the transmitted waveform from the sensor results. This is a difficult task. Uncertainty about the power of noise and interference can limit the detection sensitivity [3].

A. Energy Detection

In the case of the Energy Detector, we only make assumptions about the average power of the primary signal. To



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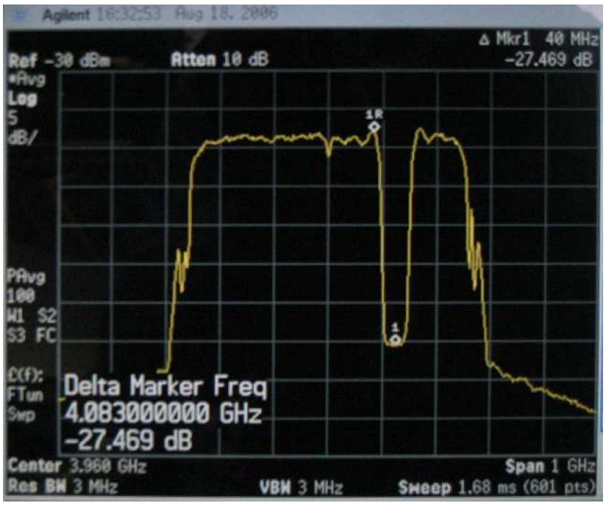


(b)

Fig. 2. (a) UWB spectrum with multiple subcarriers nulled. Attenuation from subcarrier nulling is limited to 20-22dB. (b) Actual UWB spectrum with a notch width of 13 subcarriers and a notch depth of 27dB. As opposed to subcarrier nulling, a notch filter can achieve a depth greater than 27dB for all notch widths (5/13/21 subcarriers).

facilitate analysis, we assume that the signal is a white Gaussian process with a variance equal to the average power. The Gaussian assumption allows us to derive the sufficient statistics for this detection problem which turns out to be the normalized power in the received signal ($T(y) = \frac{1}{N}\sum_{n=1}^{N}|y[n]|^2$) [10]. The decision rule then compares the energy estimate of the observed sequence with a threshold, i.e. we decide that a signal is present if $T(y) \geq \gamma$. We set the value of this threshold (γ) to meet the required probability of detection (P_D) and probability of false alarm (P_{FA}) i.e $P(T(y) \leq \gamma | H_1) \leq P_{MD}$ and $P(T(y) \geq \gamma | H_0) \leq P_{FA}$. Since the decision involves a comparison of the power of the signal with the power of noise, any uncertainty in the power of noise can

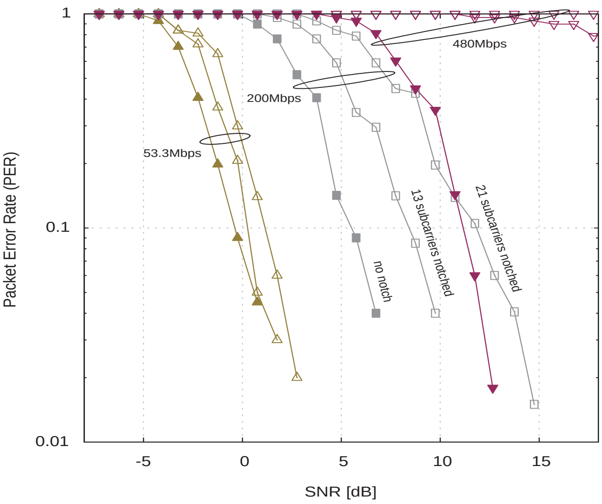


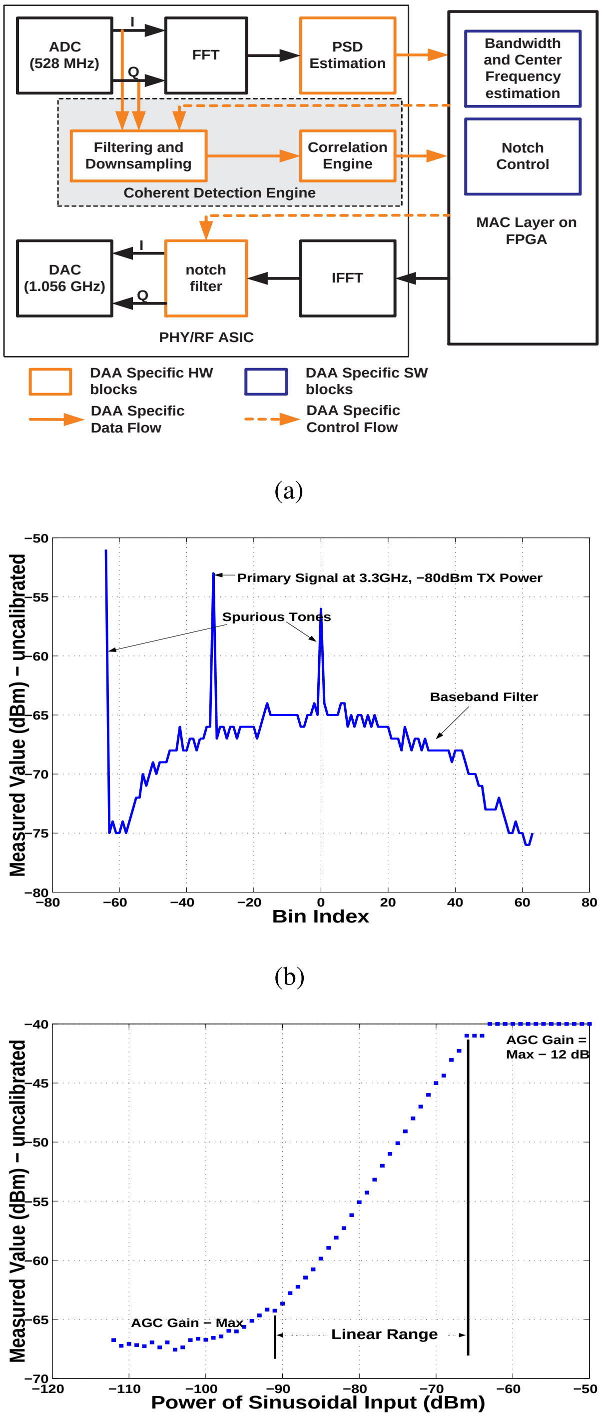
Fig. 3. Packet Error Rate (PER) performance with SNR for various notch widths. The simulations were performed in non-frequency hopped mode for a multipath channel of delay spread 20ns

limit detector performance since we will need to budget for worse case scenarios. This performance limitation due to noise uncertainty is discussed in [3] where the authors show that noise uncertainty can limit the minimum signal level that can be detected (for a given value of P_{MD} and P_{FA}). Hence noise estimation is key to ensuring that the target P_{MD} and P_{FA} are met.

The key guiding principles for the development of an energy detection algorithm were the following:

- Ensure that the target values of P_{MD} and P_{FA} are met over the entire 1.584 GHz spectrum range.
- Engineer the detection parameters to eliminate the case where a WiMax signal on a given frequency was not detected while a false alarm was triggered on another frequency.
- Minimize implementation complexity while ensuring that the target detection sensitivity of -86 dBm/MHz (as calculated in Section II-B for uplink detection) was achieved.

Figure 4(a) shows the on-chip detection engine. The Analog-to-Digital converter samples the incoming analog input at 528MHz. The Fast-Fourier-Transform (FFT) transforms the complex output into frequency-domain, with 128 frequency bins, each 4.125MHz wide. The PSD Estimate Engine integrates the energy in each bin over a specified integration period. The maximum integration period is $20\mu s$ which is much smaller than the length of a typical WiMax packet (2ms-20ms). In the transmit direction the data is converted into a time-domain waveform by the Inverse Fourier Transform (IFFT) module. This waveform is run through a notch filter which takes out those frequency components where WiMax services have been detected. The chip is fabricated in TSMC 0.13um process technology, contains 2 RF/ADC receiver chains, operating at 1.2V and measures $18mm^2$ in silicon area. The DAA relevant area (FFT/Notch filter) is around $1mm^2$.



(a)

(b)

(c)

Fig. 4. (a) Detection Engine implemented on-chip. The DAA functionality is implemented on a UWB RF/digital baseband chip fabricated in TSMC 0.13um process technology. The chip contains 2 RF/ADC receiver chains, operating at 1.2V and measures $18mm^2$ in silicon area. The DAA relevant area (FFT/Notch filter) is around $1mm^2$. (b) Spectrum capture of a -81dBm tone (c) Energy Detection transfer function at 3.3 GHz

Figure 4(b) shows the spectrum capture for a -80dBm sinusoidal signal via the on-chip energy detector. The capture highlights some of the practical technical difficulties in implementing energy detection. These issues are discussed in the following :

1) Noise and Interference Estimation: As stated earlier, the biggest problem in energy detection is adequate noise and interference estimation (especially from other secondaries). In [5], it has been suggested that guard bands around the primary be used for interference estimation. As long as guard bands are within a coherence bandwidth of the primary spectrum, interference estimation within the guard bands will be highly correlated to the interference in the primary band. [5] also requires that the interference estimation bands be more than a Doppler shift away from primary signal. In the case of WiMax, where primary is static, the Doppler shift should be zero. For our implementation, if we suspect that the primary signal is present on subcarriers $n, \ldots, n+i$, then we use the remaining subcarriers $1 \ldots n-1, n+i+1 \ldots n_{max}$ as an estimate of the noise and interference in the system. This causes the detection sensitivity to vary with time but keeps keeps false alarm rate low.
2) Dealing with Spurious Tones: Spurious tones as seen in Figure 4(b) on subcarriers 0 and 64 can affect the noise estimation process[3]. The location of the spurious tones can be determined by calibration on power-up. Hence we need to replace each bin suspected of spurious tones with an average of the bins surrounding it. As opposed to ignoring the bins, this averaging allows the detection of WiMax signals even within the subcarriers housing spurious tones.
3) Detecting narrowband signals - the need for averaging: Some WiMax deployments can be at bandwidths as small as 1.25MHz. Such narrowband signals are hard to detect when they straddle the boundary of two subcarriers. To allow the detection of such signals we need to average across adjacent bins. Again, this lowers the detection capability in average but eliminates the case with narrowband signals are missed.
4) Dealing with the Baseband filter: In Figure 4(b) we see the effect on the baseband filter in shaping the noise and the signal. The baseband filter shape has to be compensated for before the detection process can start.
5) Bin Size: Since the FFT size is fixed by the Wimedia standard, the noise bandwidth per bin is fixed at 4.125MHz. This means that large bandwidth signals are easier to detect than sinusoidal signals.
6) Automatic Gain Control (AGC): Figure 4(c) illustrates the transfer function for a tone at 3.3GHz. Due to the presence of the baseband filter this transfer function is frequency specific. On the lower left corner, the transfer

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[3] The spurious tone on subcarrier 0 is due to carrier leakage at the mixer stage in the RF.

function flattens since the gain is at a maximum. On the right top corner, the flattening of the transfer function occurs since the AGC algorithm would not reduce the gain beyond a certain value. So, for this implementation the linear range of operation (wherein we can estimate the WiMax power) is limited to 25dB. This implies that even if our avoidance algorithm could provide an attenuation beyond 25dB we would be unable to use the additional attenuation since our estimate of the WiMax power is not accurate beyond this point.

B. Practical Detection Algorithm and Results

The final detection algorithm took into account the factors listed above but had to compromise on detection capability to reduce memory and run-time costs.

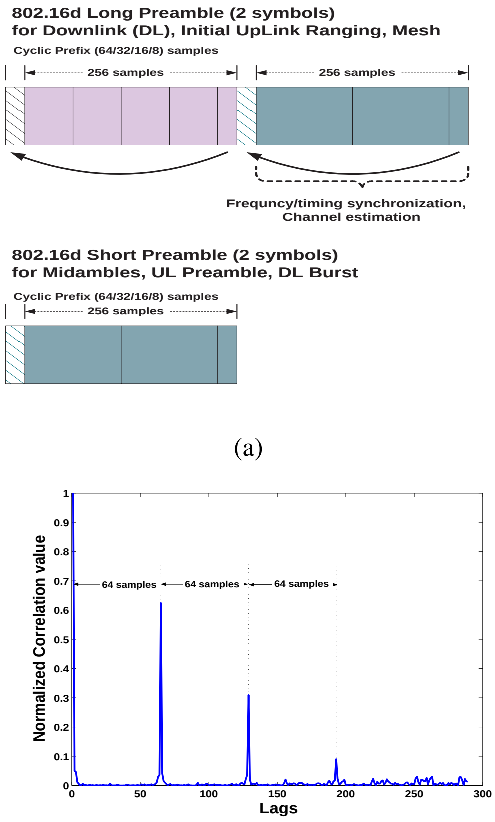
Here are some of the salient features of the algorithm implemented on the PowerPC of a Xilinx Virtex-II Pro FPGA:

- Detection of each subcarrier occurs by using all other subcarriers as an estimate of noise. For the actual implementation we used a single mean as a noise estimate for all tones. This sacrifices detection sensitivity but leads to simpler code for the FPGA.
- We employ a two level detection scheme. In the first level, candidate subcarriers are selected. Adjacent subcarriers are grouped together and these groups of subcarriers were treated as candidate primary systems. At the second level, the candidate system with 'significantly' larger power than the others was selected as the primary system. Based on the bandwidth of the selected primary, the appropriate notch width (5/13/21 subcarrier wide) was chosen.
- The threshold values for selecting candidate subcarriers and the final primary system were optimized to achieve a P_{MD} of 0.1.

Table I shows Matlab and experimental detection results for various WiMax bandwidths. The theoretically calculated sensitivity for 64 symbols over a bin bandwidth of 4.125MHz is -110dBm [5]. The device has a noise figure of 6dB which implies that there is a further 14dB sensitivity loss due to baseband filter compensation, conservative threshold setting, spurious tones and errors in noise/interference estimation. Furthermore, there is a further loss of 3-4dB from moving the detection algorithm from floating point implementation to fixed point implementation in C on the PowerPC.

C. Towards Coherent Detection

As seen in Section IV-A, energy detection suffers from noise uncertainty, spurious tones and filter compensation effects. To achieve lower detection levels (especially to sense the downlink), 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, 4 peaks separated by 64 symbols are clearly identifiable. Figure 5(a) shows the structure of the long and short preambles while Figure 5(b) shows the 256 point auto-correlation of the long preamble with a cyclic prefix of 16 symbols.



(a)

(b)

Fig. 5. (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

Figure 4(a) also shows the proposed architecture of the Coherent Detection Engine. The bandwidth and center frequency detection engine programs the downsampler and filter blocks to downsample the candidate primary signals and remove aliases. The on-chip memory is fast but limited. Down sampling the signal reduces the number of samples that need to be stored. The downsampled signals are correlated in the Correlation Engine with known patterns and the results are analyzed on the FPGA.

For now, we only use Matlab simulations to evaluate coherent detection sensitivity for given values of P_{MD} and P_{FA}. Our simulations show that for P_{MD} and P_{FA} of 0.1 and 0.1 respectively, coherent detection can detect signals as low as -120.5dBm/MHz.[4].

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[4] Since the correlation window (N) is 256 samples, the theoretical minimum sensitivity is -130dBm/MHz. The can be calculated using the formula $-114dBm + 10\,\log_{10}\left(\frac{(Q^{-1}(P_{fa})-Q^{-1}(1-P_{md}))^2}{N}\right)$ [5]

Bandwidth	Frequency	Detection Sensitivity (dBm/MHz) (Simulation)	Detection Sensitivity (dBm/MHz) (Experimental)
28 MHz	3.3 GHz	-96.5 dBm/MHz	-92 dBm/MHz
20 MHz	3.96 GHz	-97 dBm/MHz	-93 dBm/MHz
10 MHz	3.5 GHz	-92 dBm/MHz	-89 dBm/MHz
1.5 MHz	3.3 GHz	-85.5 dBm/MHz	-82 dBm/MHz

TABLE I

Detection Sensitivity for WiMax signals of various bandwidths and center frequencies. The integration time was set to 20μs. Large Bandwidth signals displayed better per MHz sensitivities. We were able to achieve the desired sensitivity for all bandwidths except the 1.5MHz WiMax signal.

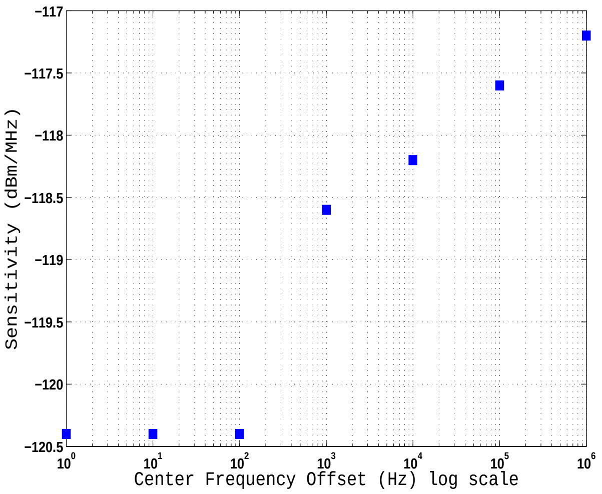

Fig. 6. Detection sensitivity for $P_D = 0.9$ and $P_{FA} = 0.1$ for various values of center frequency estimation error. The detection algorithm is robust to 1KHz of center frequency estimation error. The WiMax signal has a bandwidth of 1.25MHz.

Error in center frequency estimation can be as large as 4.125 MHz since that is the subcarrier resolution. Center frequency estimation error causes a loss in sensitivity. This loss is magnified due to the downsampling operation. Figure 6 shows the coherent detection sensitivity for a 1.25MHz WiMax as a function of center frequency estimation error ($P_D = 0.9$ and $P_{FA} = 0.1$). The sensitivity does not vary much until the center frequency estimation error is around 1KHz. This can be verified analytically. Center frequency estimation error introduces a $e^{\frac{j2\pi f_0 n}{f_s}}$ term in the preamble sequence (where f_0 is the center frequency estimation error (in Hz) and f_s is the sampling frequency). Due to downsampling, this term becomes $e^{\frac{j2\pi f_0 M n}{f_s}}$ (where M is the downsampling factor). To ensure minimal effect on correlation results, we would like $\frac{f_0 MN}{fs} \ll 1$ (where N is the length of the preamble sequence). For a sampling frequency of 528MHz and a over sampling factor (M) of ~ 400, we require $f_o \ll 5kHz$. This effect is captured in Figure 6.

V. System Issues

With the on-chip energy detection engine as presented in the paper we could reliably detect uplink transmissions. Unfortunately, as stated in Section II-B, the uplink transmission never starts if the downlink transmission is interfered with.

The first cut approach to deal with this problem was to introduce *rolling notches* in the transmission. In this approach, a notch would sweep through all the subcarriers. When the notch was centered over the subcarrier that contained the downlink, the downlink would be heard by the CPE and the uplink transmission would start. Once the uplink transmission started, the UWB device would detect the uplink and place a permanent notch at the position of the downlink. If the WiMax system operates in TDD mode, the downlink and uplink frequencies are the same and the problem of determining the downlink frequency is trivial. In FDD mode, knowledge of the separation between downlink and uplink frequencies is required.

The dwell time of the notch over the downlink frequency is a function of the notch width and the notch sweep time (time to sweep through all subcarriers). Our experiments have shown that in the absence of interference, the WiMax CPE (operating as per the IEEE 802.16d standard) needs an average of 3 seconds to associate (with a standard deviation of 2 seconds). If the notch persists for >7 seconds, the CPE should associate consistently. On the other hand if the dwell time is smaller, the behavior is unpredictable. This effect is captured in Figure 7 where the association time shows predictable response for large sweep times and large variation for small sweep times.

The *rolling notch* approach suffers from two problems: Firstly, with many UWB devices, all devices must have synchronized notch sweeps to ensure that the notch over the downlink occurs at the same time for all devices. Secondly, this approach assumes the presence of a single downlink. If multiple downlinks exists then it is diffcult for the UWB device to figure out which downlink triggered the uplink.

VI. Conclusions

In this article we have highlighted the issues in implementing a basic cognitive radio on an ultra-wideband (UWB) RF/digital baseband chip. This cognition is required to *detect and avoid* WiMax transmissions. Critical to the implementation of DAA functionality was dealing with noise estimation, baseband filter compensation and spurious tones. Together, these effects reduced the detection sensitivity by 14dB. Preamble detection of WiMax can alleviate some of these problems but requires a filter/downsampler and correlation engine on chip. Furthermore, preamble detection is sensitive to center

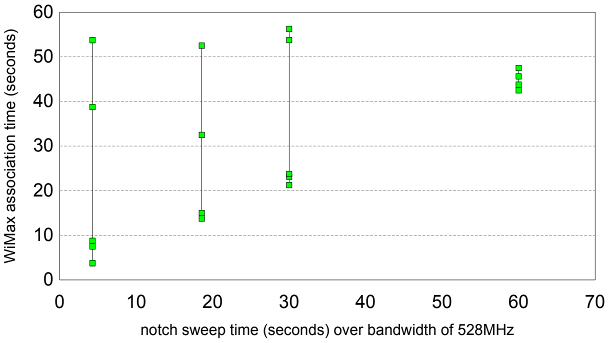

Fig. 7. Association time of WiMax as a function of the notch sweep time (time to sweep the entire 528MHz band). The notch width used was 13 subcarriers (≈ 54 MHz wide). For a 60 seconds sweep time, the notch persisted over the downlink frequency for a period of 6.56 seconds which was enough to ensure consistent association. When the sweep time was 16.7 seconds, the notch persisted over the downlink for 1.82 seconds which made the association time unpredictable. For this example, the notch always started at subcarrier -64, downlink frequency was 3.551GHz while the uplink frequency was 3.451GHz.

frequency estimation errors. Once a WiMax signal is detected and its bandwidth and center frequency has been estimated, a notch filter of appropriate width can be placed in the transmitted waveform. The notch filter attenuation demonstrated by the current chip was more than 27dB.

WiMax CPEs are *listen before talk* radios. They must listen to the WiMax downlink before they transmit; hence the critical task is to make the WiMax uplink associate with a Base Station which was accomplished by having a rolling notch that would sweep through the entire 528MHz spectrum. The association time shows predictable response for large sweep times and large variation for small sweep times.

It is likely that UWB devices are the first to make widespread use of cognitive radio concepts. The results of the initial UWB/WiMax coexistence experiments are encouraging. However, further studies are needed to reliably detect downlink transmissions and thus ensure fast association of WiMax CPEs.

REFERENCES

[1] Javier del Prado Pavn, Sai Shankar N, Vasanth Gaddam, Kiran Challapali, and Chun-Ting Chou. The MBOA-WiMedia specification for ultra wideband distributed networks. *IEEE Communications Magazine*, 44(6):128 – 134, June 2006.

[2] Z. Abichar, Yanlin Peng, and J.M. Chang. WiMax: The Emergence of Wireless Broadband. *IT Professional*, 8(4):44 – 48, July 2005.

[3] R. Tandra and A. Sahai. Fundamental limits on detection in low SNR under noise uncertainty. In *Proc. of the WirelessCom 05 Symposium on Signal Processing*, 2005.

[4] C. Cordeiro, K. Challapali, D. Birru, and Sai Shankar. IEEE 802.22: the first worldwide wireless standard based on cognitive radios. In *Proc. of the first IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, DySPAN*, 2005.

[5] A. Sahai, R. Tandra, S.M. Mishra, and N.K.Hoven. Fundamental Design Tradeoffs in Cognitive Radio Systems. In *Proc. of the First International Workshop on Technology and Policy for Accessing Spectrum, (TAPAS)*, 2006.

[6] S.M. Mishra, A. Sahai, and R.W. Brodersen. Cooperative Sensing Among Cognitive Radios. In *Proc. of the IEEE International Conference on Communications (ICC)*, 2006.

[7] E. Perahia and D.C. Cox. Shadow Fading Corelation Between Uplink and Downlink. In *Proc. of the IEEE Vehicular Technology Conference (VTC)*, volume 1, pages 592–596, 2001.

[8] T. Weiss, J. Hillenbrand, A. Krohn, and F.K. Jondral. Mutual Interference in OFDM-based Spectrum Pooling Systems. In *Proc. of the IEEE Vehicular Technology Conference (VTC)*, pages 1873–1877, 2004.

[9] S. Brandes, I. Cosovic, and M. Schnell. Reduction of Out-of-band Radiation in OFDM Based Overlay Systems. In *Proc. of the first IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, DySPAN*, pages 662–666, 2005.

[10] S.M. Kay. *Fundamentals of Statistical Signal Processing, Vol II - Detection Theory*. Prentice Hall, 1998.