Detect and Avoid: An Ultra-Wideband/WiMax Coexistence Mechanism

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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. Spectral cognition of this form can also be used by regulators to facilitate the dynamic coexistence of different service types. An example of this is the operation of ultra-wideband (UWB) devices in WiMax bands – UWB devices must detect and avoid (DAA) WiMax devices in certain regulatory domains. In this article, 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. Finally, we present measurement results for operation of a single 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 blocking the primary's 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 communications (∼10m) 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 (∼5 miles) [2]. The original 802.16 standard specifies operation between 10 and 66GHz. Subsequent additions to the standard specify operation in lower bands (2-11GHz). 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 Fig. 1(a).

The usage models of WiMax and UWB are both centered around laptop cards and hence a UWB device could potentially interfere with reception at the WiMax Customer Premise Equipment (CPE), as shown in Fig. 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 the effective transmitted power to minimize interference. This approach precludes dynamic spatial/temporal reuse of the spectrum. Furthermore,

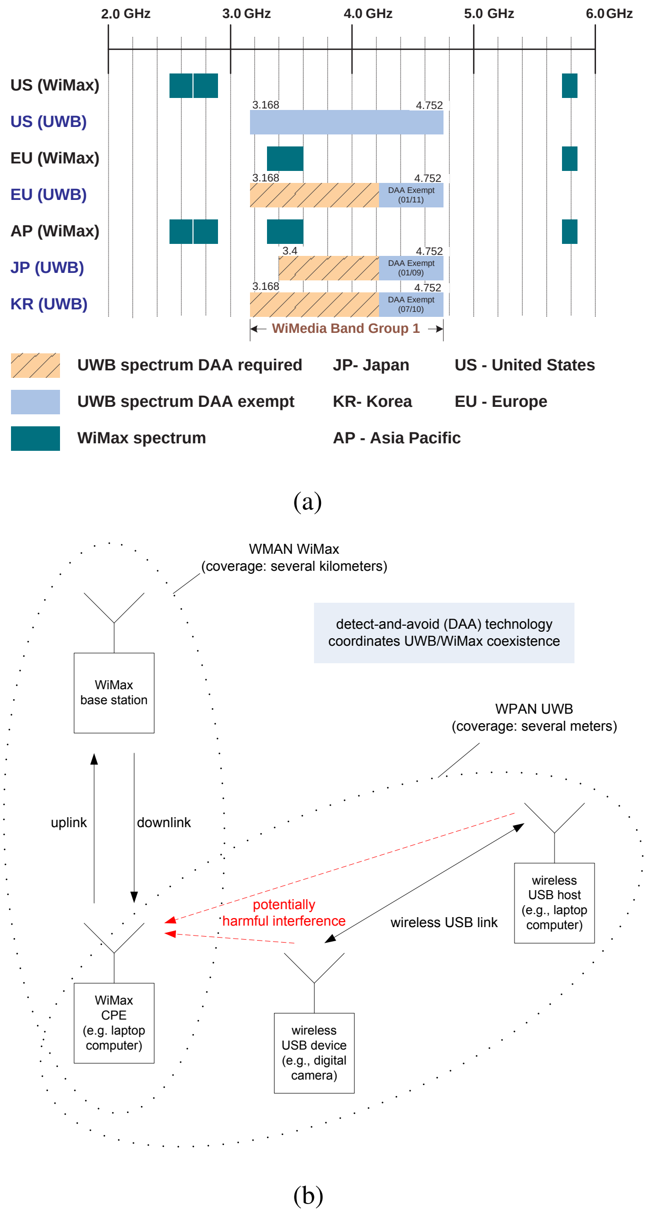

Fig. 1. (a) Overlapped frequency allocation for WiMax and ultra-wideband (UWB) in various countries and continents. (b) Potentially disruptive interference occurs when the WiMax equipped Customer Premise Equipment (CPE) is in close proximity of a UWB communication pair.

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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 Fig. 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 discuss different avoidance techniques. In Section IV we present an implementation example of an on-chip detection functionality and explain the various practical problems of robust detection. Finally, we provide coexistence results with an actual WiMax system.

II. DETECTION OF VICTIM SYSTEMS

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

$$\begin{aligned} \mathcal{H}_0 &\ :\ y[n] = w[n] \\ \mathcal{H}_1 &\ :\ y[n] = x[n] + w[n] \end{aligned}$$

given a sequence of observations $y[n]$ for $n = 1, 2, \ldots, N$. Hypothesis $\mathcal{H}_1$ assumes that the signal $x[n]$ to be detected is present with noise $w[n]$. Hypothesis $\mathcal{H}_0$ assumes that only noise is present. In our case the signal to be detected (the *victim system* to be protected) is a WiMax signal that could either be a downlink transmission from the basestation to the CPE, or an uplink transmission from the CPE to the base station, or could include both if WiMax employs time division duplexing (TDD) between uplink and downlink transmissions.

The key parameters for 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. Likewise, probability of false alarm is the probability that noise triggered the detection algorithm into falsely believing the presence of a primary signal. We would like to minimize both.

Algorithms for signal detection vary based on assumptions about the signal to be detected [4]. In the simplest case we can only make assumptions about the average power of the primary signal. In this case we end up with an energy detector. The implementation of the energy detector is simple but it may trigger on spurs and interference as described in detail in Section IV-B. We could also determine 'well known' features of the signal in question (in the case of WiMax this 'well known' feature could be the packet preamble). Gains from this approach depend on the relative energy in the 'well known' feature as compared to the rest of the signal. Such a pilot/coherent detector requires a library of features to detect different victim types and hence is more difficult to implement. In a third kind of detection we could replicate the victim receiver. This would greatly increase the cost of implementation but would enable protocol analysis.

In the first two approaches, integration time and overall performance depends on the average received power. In [3] the scaling of integration time with Signal-to-Noise Ratio (SNR) is examined for various detectors. This requires a 'detection' link budget analysis similar to the one performed for the Digital TVs in [5]. In the remaining part of this section we shall perform this analysis for the WiMax downlink and uplink detection.

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 [6], [7]. 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 which can only be achieved with large sensing times (sensing time $N \sim O(\mathrm{SNR}^{-2})$ for an energy detector and $O(\mathrm{SNR}^{-1})$ for a coherent detector) or by advanced detection techniques [3]. Note that detection sensitivity is defined as the minimum received power per unit bandwidth (dBm/MHz) that can be detected while achieving the target P_{MD}. 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) [8]. 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 [8].

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 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. 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 fairly high (0.66-0.9) [9]. 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.

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 (WiMax) in this case is different from the traditional additive interference; a secondary (UWB) 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.

III. AVOIDANCE OF VICTIM SYSTEMS

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:

Band dropping: A band-group is utilized for UWB communication by hopping between three subbands (one subband has a bandwidth of 528MHz). If WiMax is detected on any of the bands, the UWB devices could switch to a two-band hopping pattern. The switching is directed by the MAC layer at both the transmitter and receiver.

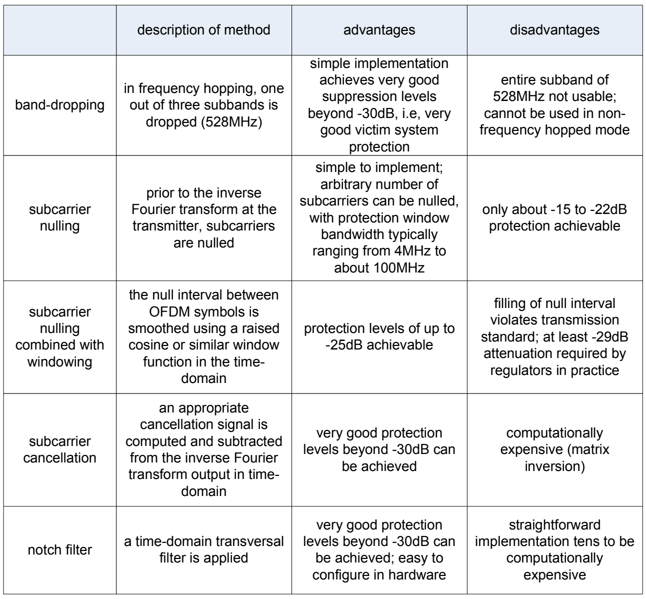
Subcarrier nulling: The transmitter does not send data on subcarriers that need to be avoided. The receiver may or may not know about the existence of the nulled subcarriers. Each subcarrier is modulated by a rectangular pulse drain, and thus, the frequency response is convolved with a sinc-impulse: Even with 48 subcarriers nulled, the maximum attenuation possible is just around 22dB, due to the spectral (sinc-)sidelobes of the neighboring subcarriers (those close to the nulled subcarriers), filling up the 'notch'.

Time-domain windowing: Smoothing of the time-domain waveform by using a raised cosine filter can improve the attenuation that can be achieved by subcarrier nulling. The receiver does not need to be aware of the windowing function being used. However, the combination of subcarrier nulling and a raised cosine window typically yields an attenuation of just about -25dB (this is true even with raised cosine roll-off factor (β) equal to 1), which is not sufficient. Moreover, smoothening the time-domain signal violates the WiMedia specifications which require that OFDM symbols are separated by a null interval.

Subcarrier cancellation: Another way to combat the problem is to 'tune' the modulation of a few subcarriers adjacent to the subcarriers being avoided such that they suppress the sidelobes of the transmitted spectrum [10]. This technique is sometimes referred to as 'active interference cancellation'. The information on the subcarriers that have been 'spoiled' can be recovered by channel coding. A system of linear equations has to be solved to compute the coefficients of the cancellation carriers, which requires an on-chip matrix inversion – an area intensive proposition. Cancellation carriers can achieve large attenuation levels.

Notch filter: A digital notch filter in the time-domain (after the inverse Fourier transform) can efficiently 'notch out' the corresponding subcarriers. 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 sufficiently high filter order. However, the actual notch depth at the RF output, as with any of the nulling/notching techniques described earlier, is limited by the resolution of the DAC and the non-linearities/phase noise characteristics of the analog transmitter RF chain.

The characteristics of the different avoidance techniques are summarized in Fig. 2.

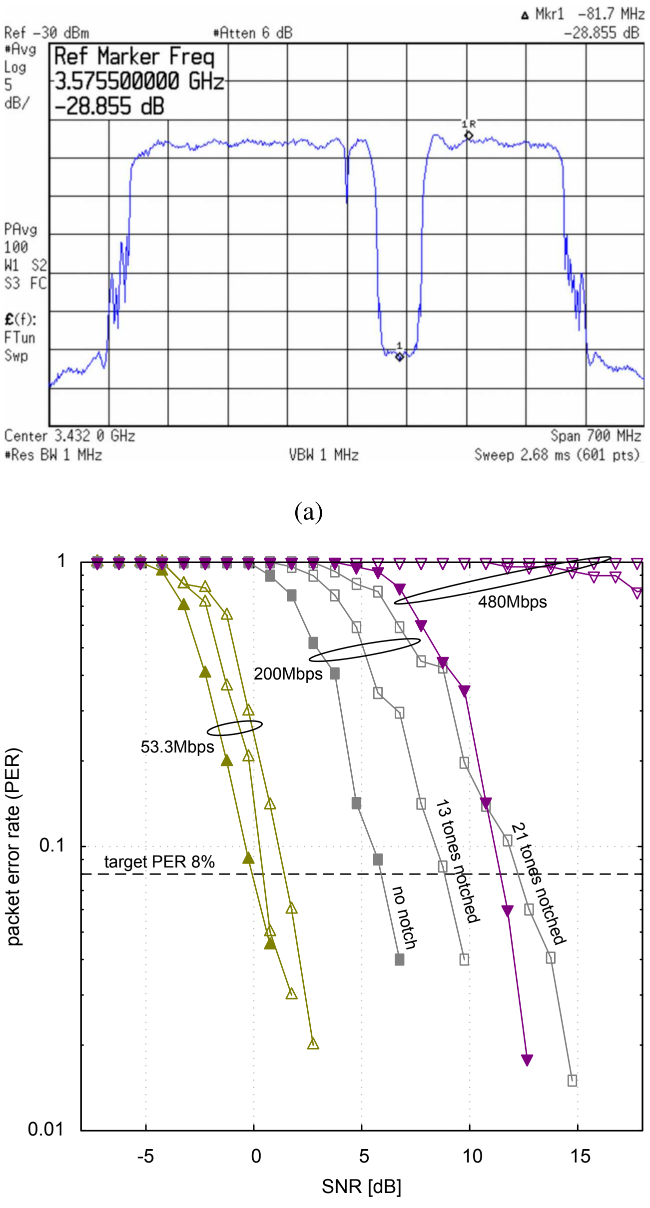


	description of method	advantages	disadvantages
band-dropping	in frequency hopping, one out of three subbands is dropped (528MHz)	simple implementation achieves very good suppression levels beyond -30dB, i.e, very good victim system protection	entire subband of 528MHz not usable; cannot be used in non-frequency hopped mode
subcarrier nulling	prior to the inverse Fourier transform at the transmitter, subcarriers are nulled	simple to implement; arbitrary number of subcarriers can be nulled, with protection window bandwidth typically ranging from 4MHz to about 100MHz	only about -15 to -22dB protection achievable
subcarrier nulling combined with windowing	the null interval between OFDM symbols is smoothed using a raised cosine or similar window function in the time-domain	protection levels of up to -25dB achievable	filling of null interval violates transmission standard; at least -29dB attenuation required by regulators in practice
subcarrier cancellation	an appropriate cancellation signal is computed and subtracted from the inverse Fourier transform output in time-domain	very good protection levels beyond -30dB can be achieved	computationally expensive (matrix inversion)
notch filter	a time-domain transversal filter is applied	very good protection levels beyond -30dB can be achieved; easy to configure in hardware	straightforward implementation tens to be computationally expensive

Fig. 2. Avoidance techniques for WiMedia UWB system based on multiband OFDM.

The implementation example in the next section uses notch filtering as the avoidance method, as it is fully compliant with the WiMedia standardization specification, achieves deep notches, and requires minimal change to the existing UWB transmit datapath. Fig. 3(a) shows the actual spectrum of the transmitted UWB signal with a notch-width of 13 subcarriers, corresponding to a bandwidth of about 55MHz. The attenuation achieved is greater than 28dB.

Fig. 3(b) 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 of 8% 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.



(a)

(b)

Fig. 3. (a) Actual measured UWB spectrum with digital notch-filter of width 13 subcarriers (55MHz) achieving an attenuation of greater 28dB. (b) Packet error rate (PER) performance versus SNR for various notch-widths. The simulations were performed in non-frequency hopped mode for a multipath channel of delay spread 20ns

IV. A Real-World Implementation Example

A. System Overview

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:

1) The silicon cost of implementing additional DAA functionality needs to be minimized. Many of the modules of the receiver already available on the chip (e.g., the FFT in the OFDM-based WiMedia UWB system of [1]) can be reused. 2) A separate sensing radio attempting to sense while UWB transmission is present in the same band needs a mechanism to subtract the transmitted waveform from the sensor results. This is a difficult task. Uncertainty about the noise and interence power can limit the detection sensitivity [3].

Fig. 4(a) shows the on-chip detection and avoidance engine based on a simple energy detector. The Analog-to-Digital converter (ADC) samples the analog input at 528MHz. The Fast Fourier Transform (FFT) transforms the complex output into frequency-domain, with 128 frequency bins, each 4.125MHz wide. For PSD estimation, the energy of the FFT output in each bin is integrated over a specified time-period. The maximum integration period is 20μs 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). This waveform is run through a notch filter which is intended to take out those frequency components where WiMax services have been detected. The resulting signal is converted into analog domain by the Digital-to-Analog converter (DAC). The chip is fabricated in TSMC 0.13μm process technology, contains 2 RF/ADC receiver chains, and measures 18mm^2 in silicon area. The DAA relevant area (FFT/notch filter) is around 1mm^2.

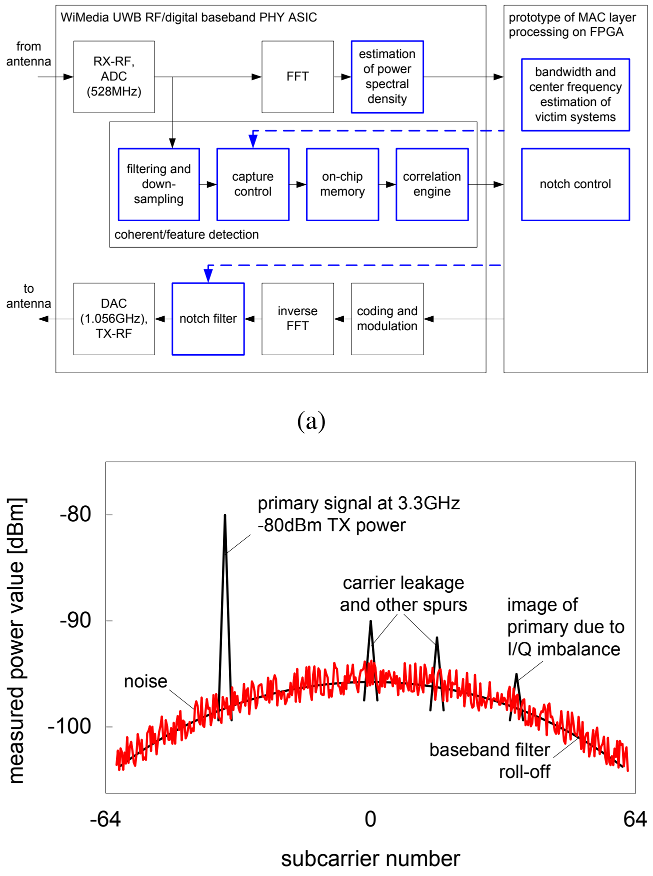
B. Energy Detection

In the case of the energy detector, we only make assumptions about the average power of the primary signal. To facilitate analysis, we assume that the signal is a white Gaussian process with a variance equal to the average power. The key guiding principles for the development of an energy detection algorithm are the following: 1) Ensure that the target values of P_{MD} and P_{FA} are met over the entire frequency range of 1.584GHz. 2) Engineer the detection parameters to eliminate the case where a WiMax signal on a given frequency is not detected while a false alarm is triggered on another frequency. 3) Minimize implementation complexity while ensuring that the target detection sensitivity of -86dBm/MHz (as calculated in Section II-B for uplink detection) is achieved.

Fig. 4(b) illustrates a spectrum capture for a -80dBm sinusoidal signal via the on-chip energy detector; it highlights some of the practical difficulties in implementing energy detection:

Noise and interference estimation: The biggest problem in energy detection is adequate noise and interference estimation (especially from other secondaries), to reliably set thresholds for identifying potential victim systems. 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 false alarm rate low.

Dealing with spurious tones: Spurious tones can affect the noise estimation process. 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 subcarri-



(a)

(b)

Fig. 4. (a) Detection engine implemented on a UWB RF/digital baseband chip. (b) Spectrum capture illustration of a -80dBm tone with possible measurement impairments.

ers housing spurious tones.

Dealing with the baseband filter: The spectrum at the output of the ADC is shaped by the baseband filter of the analog RF part in the receiver chain. This shape has to be accounted for in noise/interference estimation and threshold setting for victim system detection.

Bin size: Since the FFT size is fixed by the Wimedia standard, the noise bandwidth per bin is fixed to 4.125MHz. This means that large bandwidth signals are easier to detect than sinusoidal signals, unless separate FFT hardware dedicated to detection is implemented on chip.

Detecting narrowband signals: Some WiMax deployments can be at bandwidths as small as 1.25MHz. Such narrowband signals are hard to detect when they straddle the boundaries of two subcarriers. To allow the detection of such signals we need to average across adjacent bins. Again, this has a negative impact on the detection capability, but eliminates the case where narrowband signals are missed.

bandwidth [MHz]	frequency [GHz]	detection sensitivity [dBm/MHz]	
		simulation	experimental
28	3.3	-96.5	-92
20	3.96	-97	-93
10	3.5	-92	-89
1.5	3.3	-85.5	-82

TABLE I

Detection sensitivity for WiMax signals of various bandwidths and center frequencies. The integration time was set to 20μs.

C. *Cognitive Radio Prototype*

For fast prototyping, the detection algorithms were implemented on an FPGA, driving the PHY-chip. This way, the response time for enabling a notch – in case a WiMAX service has been detected – is below 100ms. Detection of each subcarrier occurs by using all other subcarriers for noise estimation, with a single mean as the final noise estimate. This sacrifices some detection sensitivity but leads to simpler code on the FPGA. A two-level detection scheme is applied: In the first level, candidate subcarriers are selected; adjacent subcarriers are grouped together and treated as candidate primary systems. At the second level, that candidate system with a ‘significantly’ larger power than the others was selected as the primary system (i.e., the victim). Based on the bandwidth of the selected primary, an appropriate notch-width 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 simulation and experimental results for detection of various WiMax bandwidths. For averaging the per-subcarrier energy over 64 OFDM symbols, and assuming a subcarrier bandwidth of 4.125MHz, a sensitivity limit of -110dBm can be computed [7]. The receiver has a noise figure of about 6dB which implies that there is an accumulated sensitivity loss of 14dB due to baseband filter compensation, conservative threshold setting, spurious tones and errors in noise/interference estimation, and an additional loss of 3-4dB from diverse other sources such as moving the detection algorithm from floating point to fixed point implementation etc. As can be seen from the table, signals with larger bandwidth showed better per-MHz sensitivities. We were able to achieve the desired sensitivity of -86dBm/MHz for all bandwidths except the 1.5MHz WiMax signal; however, a dedicated FFT-hardware for detection with 256 or more frequency bins can easily remedy this problem.

D. *Rolling Notches for Reliable Association*

As we have seen, the on-chip energy detection can reliably detect the presence of uplink transmissions. Unfortunately, as stated in Section II-B, the uplink transmission cannot get started if the downlink transmission is interfered with.

A first approach to deal with this problem is to introduce a *rolling notch* into the transmission, which continuously sweep through all the subcarriers. When the notch happens to be centered around a subcarrier that contains the downlink, it can be heard by the CPE, and the uplink transmission can start. The UWB device can then detect the uplink and place a permanent notch at the position of the downlink. If the WiMax system oper-

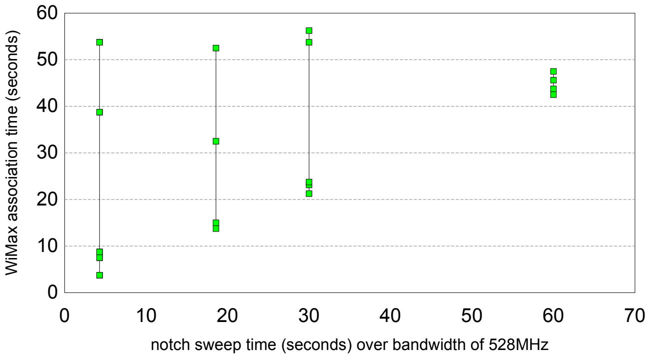


Fig. 5. Association time of WiMax as a function of the notch sweep time (time to sweep the entire 528MHz band). The notch-width used was 13 subcarriers ($\approx$ 55MHz wide).

ates 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 frequency 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 more than 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 Fig. 5 where the association time shows predictable responses for large sweep times and large variations for small sweep times. For this example, the notch always started at subcarrier -64, downlink frequency was 3.551GHz while the uplink frequency was 3.451GHz.

The *rolling notch* approach suffers from two problems that need to be addressed on the MAC layer: 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 exist, it is difficult for the UWB device to figure out which downlink triggered the uplink.

V. LOOKING FORWARD

DAA is just about to become a mature technology. Current research and development activities focus on solving the remaining challenges.

Coherent detection: As seen in Section IV-B, 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. Downlink packets use the long preamble which consists of two WiMax OFDM symbols. In the first symbol every 4th subcarrier is loaded with a pseudo-noise (PN) sequence. In the time-domain, this leads to replication which is easy to identify by cross-correlation. On correlating the received sequence with the known preamble, 4 peaks separated by 64 symbols can clearly be identified. Fig. 4(a) shows the possible architecture of a 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 – downsampling with respect to the relevant fragment of the spectrum reduces the number of samples that need to be stored. The downsampled signal is correlated with known patterns from a library with enables the reliable identification of the victim system. Our simulations show that for $P_{\rm MD} = 0.1$ and $P_{\rm FA} = 0.1$, respectively, correlation-based coherent detection can detect signals as low as -120.5dBm/MHz. Since the correlation window is $N = 256$ samples, the theoretical minimum sensitivity is -130dBm/MHz, as can be calculated using $-114\text{dBm} + 10\,\log_{10}\left(\left[Q^{-1}(P_{\rm FA}) - Q^{-1}(1-P_{\rm MD})\right]^2/N\right)$ [7].

Architectural considerations: Another area of research is concerned with optimal architectures for merging various detection techniques (energy detection, coherent detection and cyclostationary detection). In the current design, the energy detector is used to get an initial bandwidth and center frequency estimate. This estimate is used to ‘steer’ the downsampler to the relevant parts of the spectrum, and then run a coherent detection. There might be better ways to combine these techniques. The victim system detection has to be generic enough to be applicable to different systems, not just WiMax, yet sufficiently specific to achieve good detection sensitivity.

VI. CONCLUSIONS

This article has highlighted some challenges of implementing a basic cognitive radio on an ultra-wideband (UWB) RF/digital baseband chip. The *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. Preamble detection of WiMax can alleviate some of these problems, but requires more complex hardware support. As WiMax CPEs are *listen before talk* radios, they must listen to the WiMax downlink before they transmit. It is, therefore, a critical task to make the WiMax uplink associate with a base station, which can be accomplished by having a rolling notch that continuously sweeps through the entire 528MHz spectrum.

It is likely that UWB devices are the first commercial products to make widespread use of cognitive radio concepts. The results of the initial UWB/WiMax coexistence experiments are encouraging. Further improvements achievable with readily available hardware and simple algorithm development will be centered around reliable detection of downlink transmissions as well as, besides WiMax, identifying a broader class of potential victim systems.

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