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Cognitive UWB Radio:
A Smarter Radio for Smarter Products

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Abstract— **The area of cognitive radio has become an active research area; it promises a new paradigm in spectrum policy because it shifts the management of spectrum from being a political process at the national and world level to a set of algorithms that manage the airwaves around a more limited area. This is attractive because it allows much better spectrum reuse and spatial capacity.**

One of the primary requirements for cognitive spectral management is assessment of activity in a given frequency band; for maximal frequency reuse with minimal interference, the spectrum processor must assess the signal to interference ratio of a "preferred" signal with respect to a "shared" signal that interferes with it.

In this paper, we analyze the theoretical performance of the WiMedia multiband-OFDM UWB receiver as a cognitive spectral processor (radiometer) in the presence of interference, show actual measured data, and explore future research such as cyclostationary processing that could avoid some of the limitations of a radiometer based approach by exploiting the periodic properties of a desired signal.

***Index Terms*—Cognitive radio, ultrawideband, radiometer, frequency reuse, white space**

I. INTRODUCTION

The premise of using a cognitive radio for "white space" sensing [1] is that it will be able to detect the presence of a "preferred" service such as a television, radar, or WiMax signal at an arbitrary detection probability, then avoid interference with that service through the use of spectral sculpting, dynamic frequency selection, or other adaptation measure.

A practical implementation of a cognitive radio generally requires analysis of a given frequency band and assessment of whether there is spectral "white space" in that band. Obviously, if the preferred signal is continuously broadcasting, (e.g., a television signal) the time required to integrate to a desired detection probability will be much shorter than if attempting to detect a pulsed signal such as a WiMax beacon, which will have a much smaller duty cycle.

The key phrase in the discussion of detection of the preferred signal is "arbitrary detection probability." If the "shared" service can coexist with the "preferred" service on the channel, then we have increased the capacity of a scarce resource – spectrum. There is an inherent negotiation between the parties representing those services, and examples to date of dynamic spectrum access like this have been very contentious. This is not surprising, because "coexistence" and "arbitrary detection probability" are terms that have to be negotiated in much the same way that spectral allocations have historically been debated. The only difference here is that the debate is over "acceptable interference" as opposed to "frequency allocation."

So the most important concept to pin down is that of coexistence: what it means, how to measure interference, and at what level interference becomes "harmful." The IEEE 802.19 Coexistence Technical Advisory Group defines it as:

> *Coexistence: The ability of one system to perform a task in a given shared environment where other systems may or may not be using the same set of rules. [2]*

Implicit in this definition is assessing when the wireless system is no longer able to perform a task due to the interaction with another system. In practice, one of the most accepted criterion is the signal-to-interference ratio (SIR), or signal-to-interference-plus-noise (SINR). This is frequently computed for non-coherent detection using a radiometer test, which is constructed using a magnitude detector followed by an integrator, as shown in Figure 1. [3, p.27]

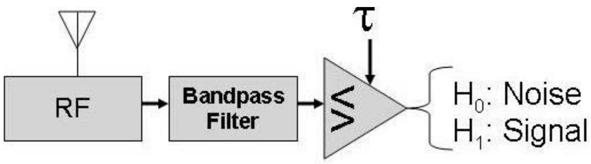

Fig.1: Classical radiometer detector

The radiometer test is based on classical detection theory [4] and is based on a hypothesis test that there is only noise energy in a frequency bin versus the alternative hypothesis that a signal plus noise is present. More formally:

H_0: $p(x|N)$ - probability distribution of noise alone
H_1: $p(x|S+N)$ – probability distribution of signal + noise

If p(x)> τ, choose H_1, else choose H_0

Where p(x|S+N) is the PDF of signal and noise being together at the energy detector output, p(x|N) is the PDF of noise alone, and the decision point τ is chosen according to a performance metric. Again, these are well known in detection theory, and can be expressed as:

$$p(S+N) = p(r) = \frac{r}{\beta^2}\exp\frac{-(r^2+A^2)}{2\beta^2}I_0\left(\frac{rA}{\beta^2}\right) \tag{1}$$

$$p(n) = \frac{n}{\beta^2}\exp\left(\frac{-n^2}{2\beta^2}\right) \tag{2}$$

Where equation (1) is a Rician distribution, and equation (2) is a Rayleigh distribution.

This leads to the graphical representation of the decision process shown in Figure 2, which clearly shows that the area under the p(S+N) curve to the right of τ is the probability of detection, P_D, and the area under the P(n) curve to the right of τ is the probability of false alarm, P_{FA} [3, p.42].

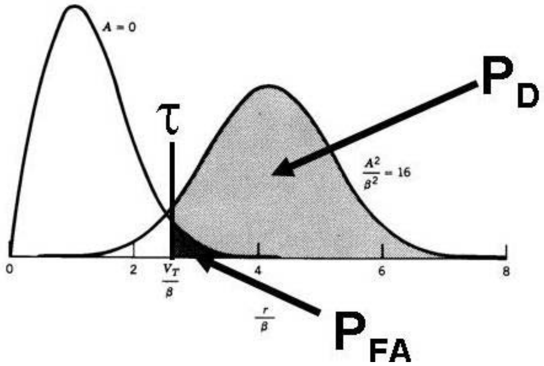

Fig 2: Graphical representation of radiometer hypothesis test showing P_D and P_{FA}

In theory, integration of the signal reduces its variance, so for a given received signal power the observed noise power decreases when integrated, causing an observed increase in signal to noise ratio, SNR. This increase in SNR allows an arbitrary increase in P_D and reduction in P_{FA}; in practice, while the improvement due to integration can be ~$O(1/SNR^2)$ [5], there are integration losses, especially for non-coherent averaging. Practically speaking, quantization noise can cause the integration gain to "floor," causing a limit on performance that makes the radiometer useless [5], so designers must insure there is adequate quantization in their spectral processor.

A key component in a cognitive radio platform is the spectrum processor that assesses whether the spectrum is occupied (using SIR or SINR) to a confidence level that equates to the desired detection probability. For a radiometer test, the regulatory requirement is that we detect a desired (or "preferred") signal with a specified probability. Often, this mandated P_D can be 0.99 or higher. Unfortunately, if the signal level is very low (implying a low SNR), the false alarm probability can be quite high, as Figure 2 clearly shows. This is of no concern to the regulatory authorities, but can render the channel unusable by the "shared" service, which must abandon the channel unless it has the required protection level for the "preferred" service, even if a false alarm indicates a channel is occupied. As an example, consider Figure 3, which shows the ambient noise levels around a typical desktop PC with a monitor and printer connected. This figure clearly shows the challenge of detecting preferred services using a radiometer as its signal level drops below -75dBm; as SNR becomes small, the P_{FA} becomes large, forcing the cognitive processor to abandon the channel even though it is not actually in use. While this would seem to call the whole concept of cognitive radio in to question, it actually points out the need for more sophisticated processing that uses a spectrum analyzer as its core. The WiMedia OFDM UWB radio enables such advanced signal processing technology.

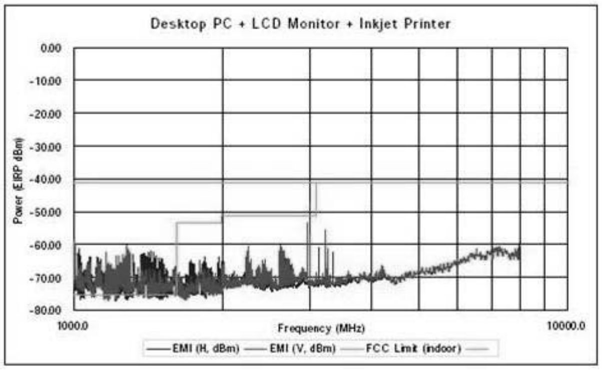

Fig. 3: Measured power spectrum around a desktop PC showing ambient noise levels of -60dBm to -75dBm (Courtesy TDK RF Systems, Inc.)

II. THE WIMEDIA MULTIBAND-OFDM RADIO

The WiMedia ultrawideband radio is a high performance OFDM system capable of data rates of up to 480Mb/s. [6]. Like any OFDM system, it uses an IFFT/FFT engine as the heart of the modem. In the case of the WiMedia PHY, each UWB channel covers 528MHz of bandwidth using 128 tones, each of which covers 4.125MHz of bandwidth. Since the receiver must implement an FFT, we have a natural spectrum analyzer, which could be the basis of a channelized radiometer. The WiMedia specification describes 14 of these 528MHz channels that span from 3.1-10.6GHz. Thus, a WiMedia radio could function as a spectrum analyzer that covers over 7GHz of bandwidth. While UWB systems can only radiate over this band, clearly it could be possible to extend the receiver to lower frequencies so that the WiMedia FFT processor could function in the ISM band at 2.4GHz and even lower[1]. This offers the exciting possibility of a single

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[1] Current UWB regulations do not allow signals to be transmitted below 3.1GHz, except over coaxial cable. Thus, the UWB PHY can only be used as a receiver below 3.1GHz.

UWB radio, which will be incorporated in many laptop and mobile platforms as Wireless USB or High Speed Bluetooth, acting as a spectrum analyzer that can cover 7GHz or more of spectrum, and allow a host processor to determine whether there is activity in a band of interest using radiometer techniques or more exotic algorithms. The host can then take whatever cognitive radio actions are required and allowed by regulations.

Perhaps the biggest issue, other than the fixed channelization of 4.125MHz, is dynamic range. The ADC resolution of these systems is only 5 or 6 bits, so dynamic range is limited to around 30dB or so, although a properly functioning AGC will maximize the utility of this span. In addition, since the FFT resolution is 4.125MHz, this equates to a thermal noise level of about -108dBm. We also have to add approximately 6dB for noise figure in the receiver, and there will be some inevitable implementation losses as well. Nevertheless, the sensitivity of the resulting practical system could approach -100dBm when measured over coaxial cable. [7] As noted in Section I, the ambient noise levels around a computer make it unlikely such levels could be detected in an over-the-air measurement.

III. THE WIMEDIA UWB RADIO AS A SPECTRUM PROCESSOR

Figure 4 shows a block diagram of a WiMedia OFDM UWB radio, where the FFT/IFFT engine is highlighted to indicate that the complex FFT samples can be sent over the standard MAC/PHY interface to a host at speeds of up to 500 megasamples/second. This capability is the heart of Alereon's CogniPHY™ technology [8] that is embodied in the radio. CogniPHY™ technology in the PHY can perform spectral averaging and hypothesis testing with no host system overhead, allowing the UWB system to operate as a spectral coprocessor.

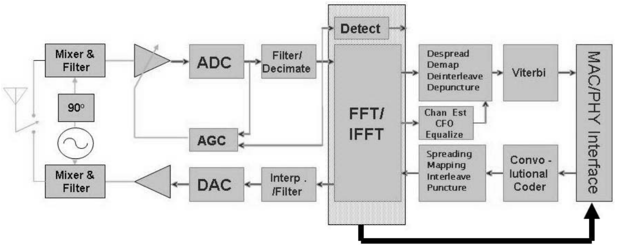


Fig. 4: Alereon's WiMedia-compliant UWB radio with CogniPHY™ technology

Since the WiMedia standard requires rapid band switching, the PHY can sweep through all 14 WiMedia bands in less than 10µS (assuming no spectral averaging). If radiometer processing is not sufficient, the CogniPHY™ processor can rapidly transfer complex FFT or time series data to a host for additional postprocessing.

IV. PERFORMANCE OF THE WIMEDIA SPECTRUM PROCESSOR

The CogniPHY™ processor has been extensively tested; in this section, we will present a summary of some of the observed performance.

Figure 5 shows the noise spectrum as measured in WiMedia's band 1, which is 528MHz wide centered at 3432MHz. This noise spectrum was measured with the RF and mixed signal amplifiers turned up to maximum gain, so it shows the ambient noise at the limit of sensitivity of the system. As expected, the dynamic range is on the order of 30dB, indicating the interaction between AGC and ADC's.

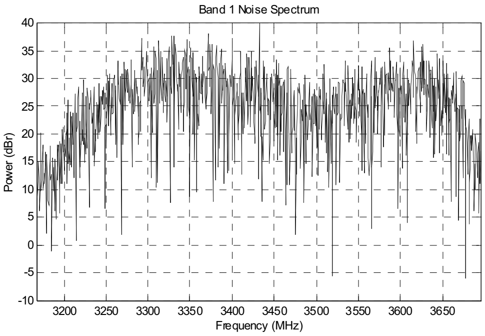


Fig. 5: Power spectrum of ambient noise in band 1, including external and internal noise

In Section I, it was stated that the distribution of noise should be Rayleigh; using the CogniPHY™ systems ability to extract time samples, the histogram of 1024 complex samples at 6 bit resolution is shown in Figure 6, where the magnitude (not magnitude squared!) function was applied before the histogram was calculated. While no explicit distribution test was performed, the histogram visually appears to be quite close to a Rayleigh distribution, as expected.

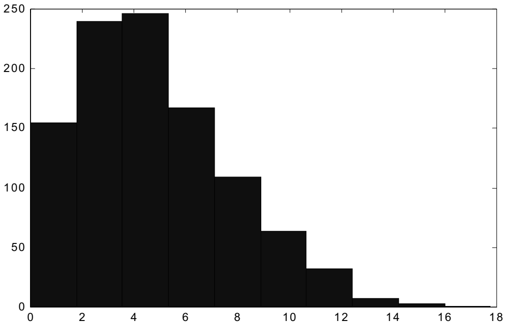


Fig. 6: Histogram of magnitude of complex samples from WiMedia band 1

Clearly, if frequency and time samples are available from the CogniPHY™ system, then more elaborate signal processing techniques are possible. For example, Figure 7 shows a two-dimensional time-frequency plot with a periodic signal occurring in a portion of the band, as indicated by the darker spots in the figure.

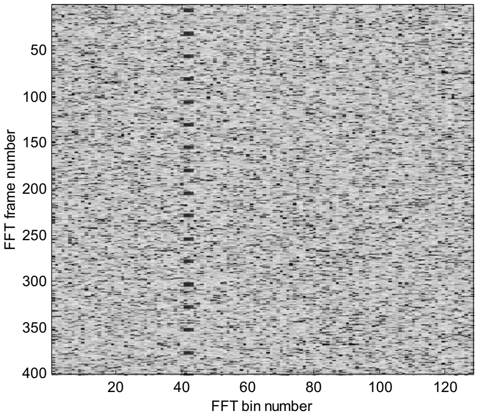
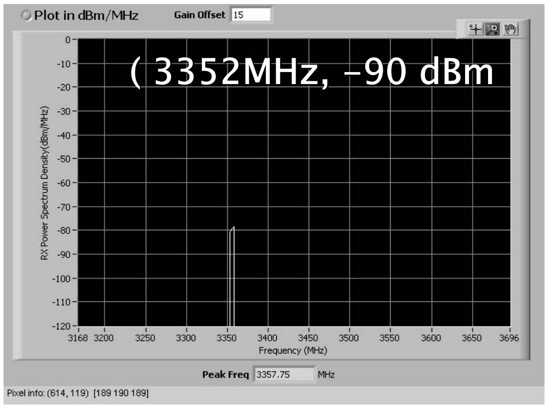


Fig. 7: Time-Frequency plot of UWB signal with a periodic signal in its passband

As mentioned previously, the CogniPHY™ processor can detect narrowband signals using radiometer techniques; as an example, Figure 8 shows the UWB receiver operating in band 1 (over coaxial cable) and the spectrum analysis indicates the presence of a sinusoid at 3352MHz with a signal level of -90dBm; the actual minimum sensitivity level is lower. While it is highly likely that ambient noise would make this level of signal almost impossible to detect with acceptable P_{FA} , it does indicate that in a “clean” environment, the CogniPHY™ processor delivers detection performance near the theoretical limits.



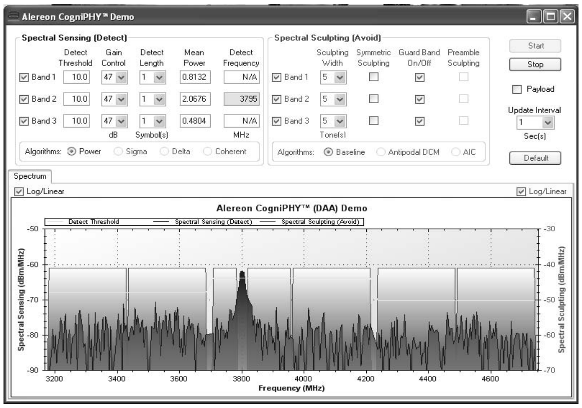
Gain Offset 15

Peak Freq 3357.75 MHz

Pixel info: (614, 119) [189 190 189]

Fig. 8: Detection of narrowband sinusoid in a WiMedia UWB OFDM channelized receiver

The final figure, Figure 9, shows a screen snapshot of the CogniPHY™ processor scanning three WiMedia bands for a toal coverage of 1584MHz of bandwidth. The PHY is capable of scanning these three bands in approximately 1μS, which is remarkable, in addition to the ability to observe the spectrum over 7GHz of bandwidth. This figure also shows the spectral shaping capability of the CogniPHY™ processor, which is import to implement Detect and Avoid (DAA), a necessary technology for regulatory certification outside of the United States. [8]



Spectral Sensing (Detect)

	Detect Threshold	Gain Control	Detect Length	Mean Power	Detect Frequency
☑ Band 1	10.0	47	1	0.8132	N/A
☑ Band 2	10.0	47	1	2.0676	3795
☑ Band 3	10.0	47	1	0.4804	N/A
		dB	Symbol(s)		MHz

Algorithms: ● Power ○ Sigma ○ Delta ○ Coherent

Spectral Sculpting (Avoid)

	Sculpting Width	Symmetric Sculpting	Guard Band On/Off	Preamble Sculpting
☑ Band 1	5	☐	☑	☐
☑ Band 2	5	☐	☑	☐
☑ Band 3	5	☐	☑	☐
	Tone(s)			

Algorithms: ● Baseline ○ Antipodal DCM ○ AIC

☐ Payload

Update Interval 1 Sec(s)

☑ Log/Linear

☑ Log/Linear

Fig. 9: CogniPHY™ technology used for spectrum analysis and spectral sculpting of UWB signals.

V. CONCLUSION

The WiMedia OFDM UWB radio is the core of Wireless USB and High Speed Bluetooth solutions, which will become pervasive in computers and mobile devices in the coming years. CogniPHY™ technology can be added to these systems for NO additional cost or power consumption (other than overhead for post-processing). A CogniPHY™ processor has unprecedented capability to analyze over 7GHz of bandwidth with very good dynamic range and spectral resolution. While much research remains to assess the viability of radiometer techniques for “white space” detection, CogniPHY™ technology can be either a channelized radiometer or the core of a more sophisticated signal analysis coprocessor that could use cyclostationary or other time-frequency analysis techniques.

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