Ultra-Wideband Interference Mitigation Using Cross-layer Cognitive Radio

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Abstract. Cognitive Radio (CR) is an emerging approach for a more efficient usage of the precious radio spectrum resources, which it considers an expanded view of the wireless channel by managing and adapting various dimensions of time, frequency, space, power, and coding. In this paper, we define the system requirements for cognitive radio, as well as the general architecture and basic physical and link layer functions. In order to self-adapt the UWB pulse shape parameters and maximize system capacity while co-exist with in-band legacy NB systems (WiFi and UMTS) in the surrounding environments.

1 Introduction

Ultra-Wideband (UWB) technology is one of the promising solutions for next-generation wireless communications in multimedia-rich environments. UWB systems spread the transmitted signal power over an extremely large frequency band, and the power spectral density (PSD) of the signal is very low. Due to the wide bandwidth of the transmitted signal, UWB signal energy will spread over the frequency bands allocated to other radio systems.
The idea behind Cognitive radio is that performance can be improved and interference reduced if wireless systems were aware of other RF signals in their environment. The improvements accrued from this technology could be dramatic, while communication engineers have historically though of channel capacity and Shannon's law simply in terms of bandwidth, a cognitive radio takes an expanded view of the channel by managing and adapting time, frequency, space, power, and coding parameters. Cognitive radios can ascertain their location and adapt to real time conditions of their operating wireless environment, including the ability to sense spectrum usage by neighboring devices, change operating frequency, adjust output power and even alter transmission parameters and characteristics [1], [2].

Recent studies have shown that UWB signals can significantly affect the operation of underlying narrowband systems [3], [4]. The coexistence of power-controlled ultra-wideband systems with UMTS, GPS, DCS1800, and fixed wireless systems was presented in [3]. In [4], the authors show that UWB devices operating at the peak allowable power can significantly impact the achievable signal to noise ratio of 802.11a WLAN and UMTS clients in modified Saleh-Valenzuela channel model. In [5] aggregate UWB interference to UMTS link is calculated as a function of distance between the communicating devices, also, the realistic channel model is taken into

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account. The calculation is that interference to noise ratio of less than -6dB to -10dB is achieved.
The term Cognitive Radio was first defined by Mitola [5]. General interference mitigation methods, which are not limited to UWB only, are presented in [6] and [7]. In [6], collaborative and non-collaborative coexistence mechanisms are proposed. A Cognitive Radio approach for usage of virtual unlicensed spectrum based on spectrum pooling idea is developed by Danijela [7]. In [8] a review of possible scenarios is addressed, where the UWB technology is proposed as the natural platform for CR. A briefly present for a possible Cognitive Radio network analysis tool based on a game-theoretic approaches been discussed in [9].
In this paper, we define a cognitive radio system model for UWB in-band interference (IBI based on new FCC waiver grant. For our well known no previous work discussed coexistence based on new FCC waiver rule. Also expressions for adaptive pulse shape to counteract IBI and at the same time to grantee low spectral emission over continuous background NB transmissions.

This paper is organized as follows. Section II describes FCC rules for UWB, section III describe our proposed system model for UWB cognitive radio, Numerical results in section IV, and conclusions are given in section V.

2 FCC Rules for UWB-Coexistence

In April 2002 the Federal Communications Commission (FCC) released UWB emission masks and introduces the concept of coexistence with traditional and protected radio services in the frequency spectrum, which allows the operation of UWB systems mainly in the 3.1 to 10.6 GHz band, limiting the power level emission to -41dBm/MHz.
In March 2005, the FCC granted the waiver request filed by the MBOA [10]. Which it is approved the change in measurement for the all UWB technologies (neutral approach). The FCC's waiver grants effectively removes the previous transmit power penalties for both frequency-hopping and gated UWB technologies (TH and DS), which it can transmit at higher power levels and then sit quiet, as long as they still meet the same limits for average power density. Table I shows the FCC waiver new rules.

Table I. Pre- and Post-FCC Waiver Ruling Effects.

	Power Requirement	Method of Measurement
Pre-Waiver Ruling	-41 dBm/MHz	Power measured in always-on mode
Post Waiver Ruling	-41 dBm/MHz	Only average power measured; systems now allowed to burst and then sit quiet
Effect	No change; spectrum holders still protected from interference	Both FH and gated UWB systems benefit

3 System Model

A cognitive radio (CR) is a radio that can change its transmitter parameters based on interaction with the environment in which it operates. This interaction may involve active negotiation or communications with other spectrum users (spectrum sensing), decision making (spectrum adaptation) within the radio, and share these information within the network members (Co-operation).

As shown in Figure 1, System starts with discovery the wireless channel so as to sense the available spectrum resources. Here we consider two types of interference to UWB receiver; co-existence systems interference (NBI) and UWB to UWB interference. There are two types of co-existence interference, background interference and burst interference. The signals from GSM base-stations and WLAN access points are considered as background noise since they are transmitting almost continuously, which can be mitigated by using a high-pass filter or antennas, whose frequency transfer functions show strong out-of-band attenuation and use new FCC waiver rules. The term burst interference is used for narrow band interferences (NBIs) that transmit their data burst-wise, as, e.g., WLAN and UMTS-FDD nodes (shown in Table II).

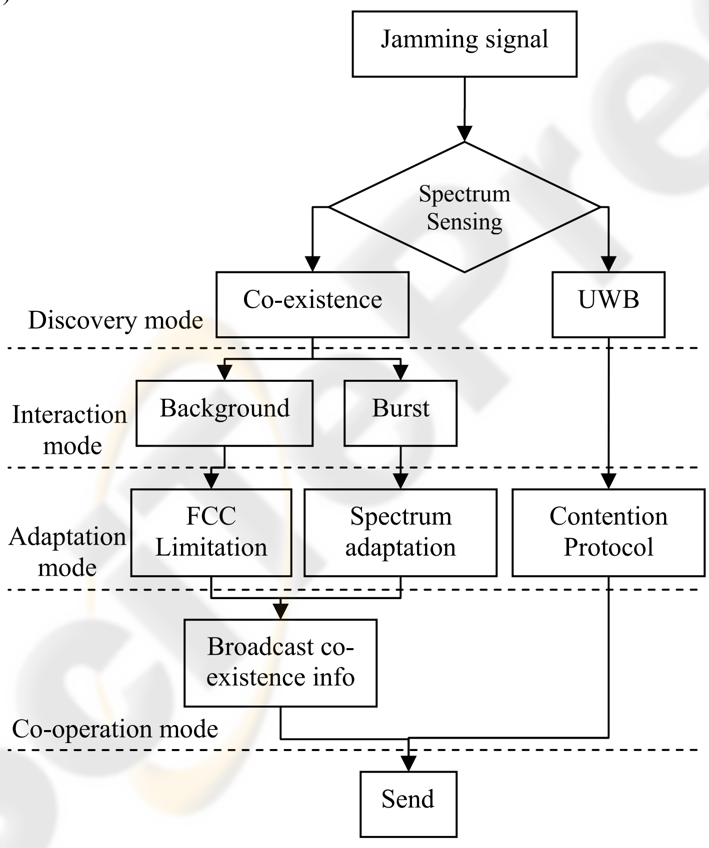

Fig. 1. Cognitive Radio system model.

Table II. In-band burst interference Narrowband Systems.

	IEEE 802.11n WLAN	UMTS-FDD Downlink
In-band NBI (GHz)	2412-2472	2.11 – 2.17
PHY Technique	OFDM and MC-CDMA	WCDMA
Modulation	16-QAM	QPSK
Maximum Power	20dBm	+33 dBm
Symbol Rate (f_s)	16.25Msps	3.84 Mcps
Data Rate	100Mbps	384 kbps
Channel Coding	convolutional code	convolutional code
Pulse filtering	Root raised cosine, roll-off = 0.23	Root raised cosine, roll-off = 0.22

3.1 Spectrum Sensing

Spectrum sensing is best addressed as a cross-layer design problem since sensitivity can be improved by enhancing radio RF front-end sensitivity, exploiting digital signal processing gain (matched filter) for specific NB signal, and network cooperation where users share their spectrum sensing measurements [9].
In next section we discuss the effect of NB receiver filters and their bit error rate

3.1.1 Effect of NB Receive Filter

In a typical NB radio, using digital modulation, the same symmetric baseband pulse-shape is used at both the transmitter and the receiver, namely the root-raised cosine filter (RRCF) with transfer function $H_{rrcf}(f)$ with nominal bandwidth W, roll-off factor or excess bandwidth parameter denoted by $\Omega\ (0 \le \Omega \le 1)$, and overall bandwidth $W(1+\Omega)$ [11].

Taking into account the fact that the front-end band-pass filter and the low-pass filter following the demodulator typically have larger bandwidth than the root-raised cosine filter (RRCF) transfer function $H_{rrcf}(f)$, we note the overall filter for the UWB impulse-train is given by,

$$\begin{aligned} G(f) &= 0.5\left[P(f-f_c)+P(f+f_c)\right]H_{rrcf}(f) \\ &= \overline{P}(f)H_{rrcf}(f) \end{aligned} \qquad (1)$$

where $P(f)$ is the FT of the Gaussian monocycle, and f_c is the carrier frequency for the NB system, where for UMTS RRC roll-off=0.22

3.1.2 BER Analysis

Let $r(t)$ denote the received signal, after down-conversion to baseband. Consider the usual matched filter (MF) plus threshold receiver for BPSK signaling, which is optimal for the AWGN channel. In the k-th symbol interval, $r(t)$ can be written as:

$$r(t) = \sqrt{E_b}\, b_k s(t) + n(t) + i(t) \qquad (2)$$

where $s(t)$ is the unit energy signal waveform with duration T (corresponding to $H_{rrcf}(f)$), E_b is the energy per bit, b_k {-1, 1} is the unknown bit, $n(t)$ is AWGN with two-sided PSD No/2, and $i(t)$ is the interference. Applying the MF, we have

$$z = \int_0^T \left[\sqrt{E_b}\, b_k s(t) + n(t) + i(t)\right] s(t)dt$$
$$= \sqrt{E_b}\, b_k + \tilde{n} + \upsilon(\varsigma) \qquad (3)$$

Here $\tilde{n}$ represents the 'noise' term and is zero-mean Gaussian, with variance No/2. The term $\upsilon(\varsigma)$ represents the interference. Assuming that the interfering pulse $i(t)$ is completely contained within the symbol period and has a relative delay of ς, we have

$$\upsilon(\varsigma) = \int_0^T i(t)s(t)dt = \sqrt{E_p}\int_{-\infty}^{\infty} \overline{P}(-f)S(f)e^{j2\pi f\varsigma}df \qquad (4)$$

E_b is the energy in the received UWB pulse. For an NB $S(F)$, $\overline{P}(f)$ is essentially constant over the bandwidth of $S(F)$, so that

$$\upsilon(\varsigma) \approx \sqrt{E_p}\, P(f_c)s(\varsigma) \qquad (5)$$

Define the SNR impairment factor,

$$\delta = \sqrt{\frac{E_p}{E_B}}\, P(f_c)s(\varsigma) \qquad (6)$$

Matched filter effectively requires priori knowledge of primary user signal at both PHY and MAC layers, e.g. modulation type and order, pulse shaping, packet format. However, since we work only in in-band interference for UWB (e.g., WLAN and UMTS). Such information might be pre-stored in UWB node memory. To achieve coherency with NB signal by performing timing and carrier synchronization, even channel equalization. This is still possible since most NB systems have pilots (e.g., UMTS), preambles synchronization words (e.g., WLAN) or spreading codes that can be used for coherent detection.

3.3 Spectrum Adaptation

There are some UWB pulse waveform candidates (i.e. Hermits, PSWF…etc). In our simulation we use Gaussian doublet with a pair of separated narrow monocycles, a positive pulse followed by a negative pulse. This offers two degrees of time-cognitive radio freedom, time separation between the two pulses in the doublet (T_n) and doublet pulse time length (T_p).

The Gaussian pulse waveform $p(t)$ can be expressed as:

$$p(t) = \frac{A}{\sqrt{2\pi}\sigma}\exp\left[-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2\right] \qquad (7)$$

Where μ is the mean and σ is the variance of the statistical distribution characterized by the function. Since infinite pulses cannot be used in practical implementation and leading to unavoidable overlap between pulses, and ISI. We can introduce the time length of the pulse T_p, related to σ through the linear transformation

$$T_p = 2\pi\sigma \tag{8}$$

Which pulse is nulled outside the interval $\{-T_p/2, T_p/2\}$ and the factor A is introduced so that the total energy of the monocycle is normalized to unity, i.e. $\int p^2(t)dt = 1$, in the simulations the transmitting and receiving antennas are modeled as differentiation (derivative) operations [12].

The null frequencies of Gaussian doublet can be controlled by regulating the position of the Gaussian pulse (the first pulse $p_0(t)$ begins at $t = 0$, the second one $p_1(t$ begins at $t = T_n$). With spectrum analysis, we have:

$$p(t) = p_0(t) - p_1(t) \tag{9}$$

$$p(t) = A\left\{\exp\left[-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2\right] - \exp\left[-\frac{1}{2}\left(\frac{t-\mu-T_n}{\sigma}\right)^2\right]\right\} \tag{10}$$

Which has a Fourier transform given by

$$p(f) = 2A'\sqrt{2\pi}\sigma\sin(\pi f T_n)\exp\left[-\frac{1}{2}(2\pi\sigma f)^2\right] \exp\{-j[2\pi f(\mu + 0.5T_n) - 0.5\pi]\} \tag{11}$$

For this simulation, the Monte Carlo simulation is considered, which an independent normal variable is generated for each sample, with variance (var_{smp}) given by

$$\mathrm{var}_{smp} = \frac{\sum_{i=0}^{N} A_i}{2E_b/N_0} \tag{12}$$

where N is the number of samples in a pulse, A_i is the amplitude of a sample of the pulse, and E_b/N_0 is the average SNR measured, which it meet the new FCC waiver rules. These samples are then processed, and the BER estimate is formed by taking the ratio of the number of errors in the received bits to the total number of transmitted bits.

Conceptually, a pulse-train (which may be dithered to reduce spectral lines, to accommodate user codes, to represent data via PPM, and so on) is convolved with the pulse-shape, so that the power spectrum of the transmitted UWB signal is essentially given by $|P(f)|^2$. The effect of dithering makes the modulation zero-mean and removes periodicities in the data, so that the PSD has no spectral lines. The monocycle pulse $p_0(t)$ with the pulse shape factor σ of 0.6 nsec and its doublet unmodulated pulse in the time domain with time separation of 0.7 nsec were shown in Figure 1, where Figure 3 shows the 'PSD' $|P(f)|^2$, which depicted that there are spectral lines in the doublet waveform which cause interference to other co-existence systems.

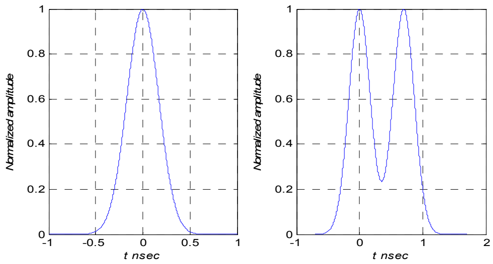

Fig. 2. Gaussian pulse in the time domain and its Gaussian doublets.

3.2 Cooperative Spectrum Sensing

Here we rely on the variability of signal strength at various locations, which the performance of matched filter technique is limited by received signal strength which may be severely degraded due to multipath fading and shadowing and due to hidden terminal problem and UWB nodes in quite-mode can receive sensing information, which can be used in on-mode. In large network of UWB nodes with sensing information exchanged between neighbors would have a better chance of detecting the NB bursts compared to only individual sensing.

4 Numerical Results

The design procedure detailed in the following sections optimizes the PSD expression of (9) to minimize UWB interference into a given narrowband systems. This approach is justified because the utilized pulse shape is only capable of changing this part of the PSD, which including a spectral notch in the transmitted PSD. The simulation was done using MATLAB®.

4.1 Waveform PSD Smoothing

In our simulation, we assume a monocycle pulse $p_0(t)$ with σ =318.31 ps, producing a 200 ps wide pulse. The methodology for choosing σ to produce a signal that is compliance with the FCC spectral mask is discussed in detail in [13] and thus, is omitted here.

The term $\sin(\pi f T_n)$ in equation (9) represent the discrete component (spectral lines) that shown in Figure 2, for deduce spectral lines power, one can adjust the time between the pulses (T_n) so as the term $\sin(\pi f T_n)=1$, as can be seen in Figure 4.

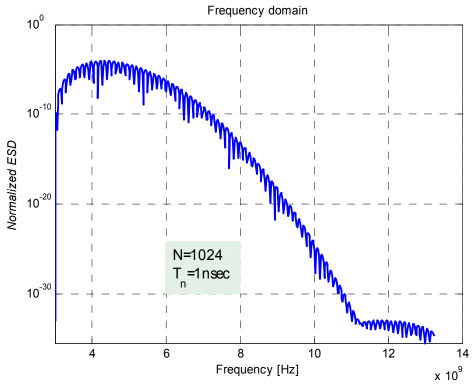

Fig. 3. Energy Spectral Density for Gaussian doublet pulse.

4.2 Effect of UWB Interference

This section introduces the effect of UWB spectrum interference to the narrowband systems performance degradation. Error probability (P_e) curves are presented for both victim systems (WLAN and UMTS-FDD) utilizing UWB Gaussian doublet waveform shown in Figure 2.

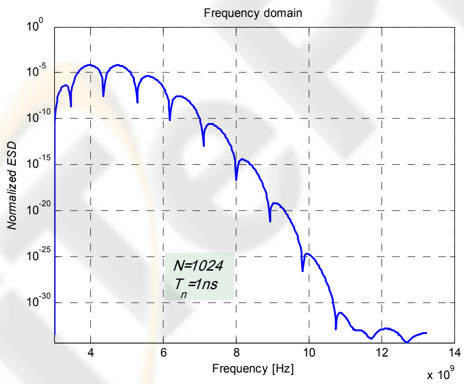

Fig. 4. The effect of adjust the time between pulses (T_n).

In Figure 5 the effect of different signal to interference ratio (SIR) are studied in presence of UWB in-band interference. The pulse length (T_p) are varied from 0-5nsec, the average signal to noise ratio is SNR=15dB. The UWB PSD is evenly distributed inside the considered WLAN/UMTS-FDD bands. From results one can notice that WLAN system degrades more than UMTS in presence of UWB spectrum, which error probability is higher for smaller SIR and higher pulse length (T_p). The difference in NB systems performance is based on the different spectrum location at the UWB signal related to these systems. In this case study, two UWB monocycles were produce doublet waveform with T_n =1.1nsec, which generates spectrum that overlaps the victim systems spectrums.

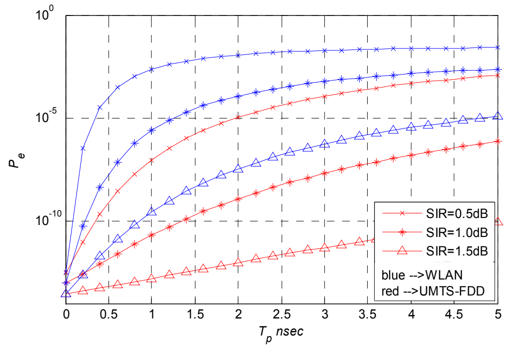

Fig. 5. probability of error (P_e) for UWB co-existence interference WLAN (IEEE802.11n) and UMTS-FDD uplink for different SIR values.

4.3 Spectrum Adaptation

As we want the ESD of UWB interference is as small as possible at the victim narrowband system's band, the null frequencies of Gaussian doublet pulse's ESD is preferred to be positioned in victim system's band. For deep interference as caused in IEEE802.11a and UMTS-FDD center frequencies the proposed cognitive radio system will respond with notch in the victim frequencies by adapt the number of samples (N) and pulse length (T_p) as can be seen in Figure 6.

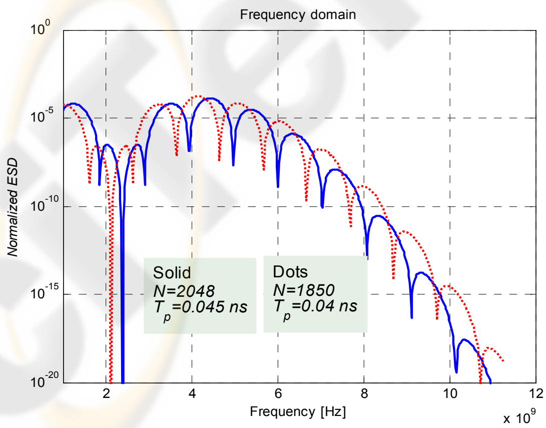

Fig. 6. Normalized ESD for two type of UWB doublet pulse waveform design to mitigate the U-NII center frequency for IEEE802.11n (solid line) and UMTS-FDD uplink center frequency (dots line).

5 Conclusions

The paper introduces the concept of cognitive radio for IBI UWB, which wireless systems based on UWB transmission able to self-adapt to the characteristics of the surrounding in-band systems (e.g., unlicensed WLAN 5.3GHz ISM (industrial, scientific, and medical) band and UMTS). Cognitive radio sensitivity can be improved by enhancing radio RF front-end sensitivity, exploiting UWB digital signal processing gain for specific narrowband signal, and network cooperation where users share their spectrum sensing measurements.
For future work the other factors such as code and space (distance) cognitive radio can be considered.

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