Towards the Realization of Cognitive Radio:
Coexistence of Ultrawideband and Narrowband Systems

by

Mustafa Emin Şahin

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Electrical Engineering
Department of Electrical Engineering
College of Engineering
University of South Florida

Major Professor: Hüseyin Arslan, Ph.D.
Vijay K. Jain, Ph.D.
Thomas Weller, Ph.D.

Date of Approval:
March 20, 2006

Keywords: Interference Avoidance, Narrowband Interference, Opportunistic Spectrum Usage, Spectrum Sensing, Spectrum Shaping

DEDICATION

To my wife *Müberra*

ACKNOWLEDGMENTS

First, I would like to sincerely thank my advisor, Dr. Hüseyin Arslan for his guidance, encouragement, and support throughout the course of this thesis. The enthusiasm he generates and passes on to his students leads to hard work and success. It has been a genuine privilege to have the opportunity to do research as a member of Dr. Arslan's research group. I am grateful to him because he has taught me not only numerous topics in wireless communications but also many different aspects of real life.

I wish to thank Dr. Vijay K. Jain and Dr. Thomas Weller for serving on my committee and for offering valuable suggestions. I hope to be able to benefit from their profound knowledge and experience in the coming years, too.

I owe much to Ismail Güvenç for his strong technical assistance, tolerance to countless questions, and, of course, his sincere friendship. Without his support, I might have given up pursuing a graduate degree at the very beginning of this long journey. I am also very proud on his behalf that I am going to be able to call him Dr. Güvenç from now on.

Special thanks go to my friends Hasari Çelebi, Tevfik Yücek, Sadia Ahmed, Hisham Mahmoud, Serhan Yarkan, Kemal Özdemir, Ramy Tannious, Tony S. Price, Nigel Brown, and Abdur-rub Abdur-rahman. They are the ones with whom I work together seven days a week. I have learned a lot of different things from them, both technical and non-technical. They enabled me to become familiar with different cultures. With these special people, we have not only been sharing the same working environment, and but the same life, as well.

I am also grateful to our friends in the Turkish community living in Tampa and Brandon, Florida, especially to Salih Erdem, for making life much more easier and enjoyable than it is in reality.

I also want to thank my parents in law for their kindness and continuous support, and my brother in law, Ahmet, for teaching me how to play soccer.

My deepest gratitude goes to my wife, Müberra, for her love, all the sacrifices she has made, her firm support, her vast patience, and her steady encouragement. If she did not have such a deep understanding and tolerance for the hardships of being the wife of a graduate student, I could not even try to obtain this degree. I want to thank her from my heart for everything she has done.

Last, but by no means least, my sincere appreciation goes to my parents and my elder sister for bringing me up, leading me to the right direction, and always encouraging me for pursuing higher degrees. It is not possible to thank them enough, but I want them to know that I will be grateful to them throughout my life.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ACRONYMS

AWGN Additive White Gaussian Noise

BER Bit Error Rate

BPSK Binary Phase Shift Keying

CDMA Code Division Multiple Accessing

CM Channel Model

DFE Decision Feedback Equalizer

DOF Degree of Freedom

DSSS Direct Sequence Spread Spectrum

DWT Discrete Wavelet Transform

FCC Federal Communications Commission

FEC Forward Error Correction

FFT Fast Fourier Transform

IEEE Institute of Electrical and Electronics Engineers

IR Impulse Radio

ISI Inter-symbol Interference

LOS Line Of Sight

MED Maximum Excess Delay

MMSE Minimum Mean-square Error

NBI Narrowband Interference

OFDM Orthogonal Frequency Division Multiplexing

OOK On-Off Keying

PAM Pulse Amplitude Modulation

PPM Pulse Position Modulation

PDP Power Delay Prole

PSWF Prolate Spheroidal Wavelet Functions

RF Radio Frequency

SDR Software Defined Radio

SNR Signal-to-noise Ratio

SPTF Spectrum Policy Task Force

TH Time-Hopping

TR Transmitted Reference

UWB Ultrawideband

WLAN Wireless Local Area Network

WPAN Wireless Personal Area Network

TOWARDS THE REALIZATION OF COGNITIVE RADIO: COEXISTENCE OF ULTRAWIDEBAND AND NARROWBAND SYSTEMS

Mustafa Emin Şahin

ABSTRACT

Ultrawideband and cognitive radio are two of the most important approaches that are shaping the future of wireless communication systems. At a first glance, the aims of UWB and cognitive radio do not seem to be overlapping significantly, however, there is a strong synergy between the capabilities of UWB and the goals of cognitive radio. One of the objectives of this thesis is to shed the first light on the marriage of these two important approaches.

Ultrawideband (UWB) is a promising technology for future short-range, high-data rate wireless communication networks. Along with its exciting features including achieving high data rates, low transmission power requirement, and immunity to multipath effects, UWB is unique in its coexistence capability with narrowband systems.

In this thesis, the details of practical UWB implementation are provided. Regarding the coexistence of UWB with licensed narrowband systems, narrowband interference (NBI) avoidance and cancelation techniques in the literature are investigated. It is aimed to emphasize that UWB is a strong candidate for cognitive radio, and this fact is proven by providing two different approaches in which ultrawideband is combined with cognitive radio to maximize the performance of unlicensed communications.

CHAPTER 1

INTRODUCTION

Wireless communication systems have been evolving substantially over the last two decades. The explosive growth of the wireless communication market is expected to continue in the future, as the demand for all types of wireless services is increasing. New generations of mobile radio systems aim at providing higher data rates and a wide variety of applications to the mobile users, while serving as many users as possible. However, this goal must be achieved under the constraint of limited available resources such as power and frequency spectrum. Given the high cost of power and scarcity of the spectrum, radio systems must provide higher capacity and performance through a more efficient use of the available resources. Hence, in order not to limit the economic and technological improvement of the wireless world, it is necessary to find immediate solutions regarding the usage of existing resources. A recent solution for this problem is cognitive radio [1].

Cognitive radio aims at a very efficient spectrum utilization employing *smart* wireless devices with awareness, sensing, learning, and adaptation capabilities [2]. As a solution for the spectrum scarcity problem, cognitive radio proposes an opportunistic spectrum usage approach [3], in which frequency bands that are not being used by their primary (licensed) users are utilized by cognitive radios.

Since cognitive radio is a very new concept, there is no consensus on how to implement it. However, if the targets of cognitive radio are taken into account, and the properties of various candidate systems are considered, it is seen that there is a strong match between what cognitive radio aims at and what ultrawideband (UWB) offers.

UWB is a promising technology for future short and medium range wireless communication networks with various throughput options including very high data rates. It has many tempting features such as low power consumption, significantly low complexity transceivers, and immunity to multipath effects. According to the modern definition, any wireless communication technology that has a bandwidth wider than 500 MHz or a fractional bandwidth [1] greater than 0.2 can be considered a UWB system. The features of UWB systems that make these systems very tempting for cognitive radio include that

- they do not require a license to utilize the spectrum.
- they can coexist with licensed communication systems by employing interference avoidance and cancelation methods.
- their transmission parameters such as power, pulse shape, and data rate are highly adaptive.
- their practical implementation does not have a high cost.

Because of these properties, UWB can be used either as a means of implementing cognitive radio, or it can be combined with a cognitive system to complement it in different ways.

This thesis investigates ultrawideband systems in detail, including practical implementation aspects. Coexistence of UWB with other systems is discussed thoroughly, and the appropriateness of UWB for fulfilling the requirements of cognitive radio is proven. The cognitive radio concept is introduced, and various properties of cognitive radio systems are studied. Two different approaches of supplementing cognitive radio with ultrawideband are provided, first of which is a cognitive UWB-OFDM system, and the second one, a cognitive network whose nodes share the spectrum sensing information with each other by means of UWB.

1.1 Organization of the Thesis

The main topics covered in this thesis can be listed as follows:

- Practical implementation of ultrawideband (covered in Chapter 2)

[1] Fractional bandwidth $= 2 \cdot \frac{F_H - F_L}{F_H + F_L}$, where F_H and F_L are the upper and lower edge frequencies, respectively.

- Coexistence of ultrawideband and narrowband communication systems (covered in Chapter 3)
- Fundamentals of the cognitive radio concept (covered in Chapter 4)
- Combining cognitive radio and ultrawideband (covered in Chapter 5)

The outline of each chapter is as follows.

In Chapter 2, the basics of UWB are provided, and different modulation and receiver options for UWB implementation are discussed. A low complexity energy detector with optimized integration interval and threshold selection properties is proposed[2]. The performance of the proposed detector is analyzed. For high data rate applications, the inter-symbol interference (ISI) problem is investigated. A modified version of the energy detector that employs decision feedback equalization to cancel the ISI effect is proposed[3]. Its efficiency in enabling high data rate UWB communications is demonstrated.

In Chapter 3, the coexistence of UWB and narrowband systems is addressed. The effect of narrowband interference (NBI) on UWB is analyzed. The techniques of suppressing NBI, which are classified as NBI avoidance and NBI cancelation methods, are investigated in detail[4].

In Chapter 4, the cognitive radio concept is introduced, and the objectives aimed with cognitive radio are addressed. Spectrum opportunity is defined, and it is investigated how to sense the spectral opportunities. Different spectrum shaping approaches in the literature are provided, and an alternative method based on the usage of raised cosine filters is proposed.

In Chapter 5, with the purpose of maximizing the efficiency of unlicensed systems, it is considered to combine UWB with the cognitive radio. Two different methods are proposed; the first one is cognitive UWB-OFDM[5], and the second one is a cognitive system that shares the spectrum sensing information between its nodes using UWB signaling.

---

[2]This work is published in [4]
[3]This work is published in [5]
[4]This work is published in [6]
[5]This work is to partly appear in [7]

In Chapter 6, the contributions of the thesis are summarized and possible future research topics related to the studies in the thesis are provided.

CHAPTER 2

ULTRAWIDEBAND

In this chapter, the basics of UWB are provided and different modulation and receiver options for UWB implementation are discussed. A low complexity energy detector with optimized integration interval and threshold selection properties is proposed. The performance of the proposed detector is analyzed. For high data rate applications, the inter-symbol interference (ISI) problem is investigated. A modified version of the energy detector that employs decision feedback equalization to cancel the ISI effect is proposed. Its efficiency in enabling high data rate UWB communications is demonstrated.

2.1 Introduction

Ultrawideband (UWB) is a promising technology for future short-range, high-data rate wireless communication networks. Compared to other communications systems, UWB is unique in that it has the exciting feature of combining many desired characteristics like the increased potential of achieving high data rates, low transmission power requirement, and immunity to multipath effects. Two basic techniques considered for implementing UWB are the impulse radio (IR) and Orthogonal Frequency Division Multiplexing (OFDM).

Impulse radio is based on transmitting extremely short (in the order of nanoseconds) and low power pulses that have a very wide spectrum. In Fig. 1, a time hopping ultrawideband (TH-UWB) system is demonstrated. In the illustrated scenario, each information carrying symbol is transmitted with four pulses. Pulses occupy a location in the time-frame based on the specific pseudo random (PN) code assigned for each user. Two different codes and the corresponding pulse locations are shown in the figure. Note that these two codes are orthogonal (i.e. they do not interfere with each other).

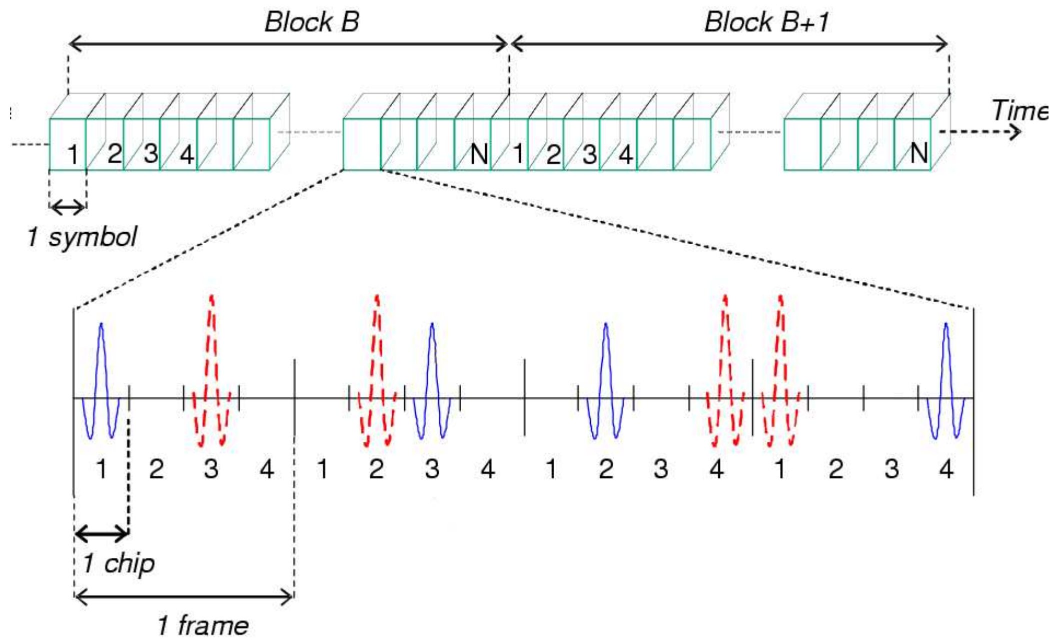

Figure 1. Impulse radio based time hopping UWB.

In UWB-OFDM, the data bearing symbol stream is split into several lower rate streams, and these streams are transmitted on different carriers. The carriers are sinusoids with different frequencies and they are limited in time. Since they are time limited, they correspond to *sinc* functions in the frequency domain as shown in Fig. 2. From this perspective, this system is not different from regular OFDM. The requirement specific to UWB-OFDM is that the minimum frequency band occupied should exceed 500 MHz (or fractional bandwidth should be larger than 0.2).

This chapter is organized as follows. In Section, 2.2, various modulation and receiver options for impulse radio UWB are discussed. In Section 2.3, optimum selection of integration interval start/stop times, and the threshold is addressed. Exact and Gaussian approximation methods for BER evaluation are analyzed. In Section 2.4, the ISI problem is discussed, a performance evaluation of the UWB system in the presence of ISI is provided, and an ISI cancelation algorithm is explained in detail.

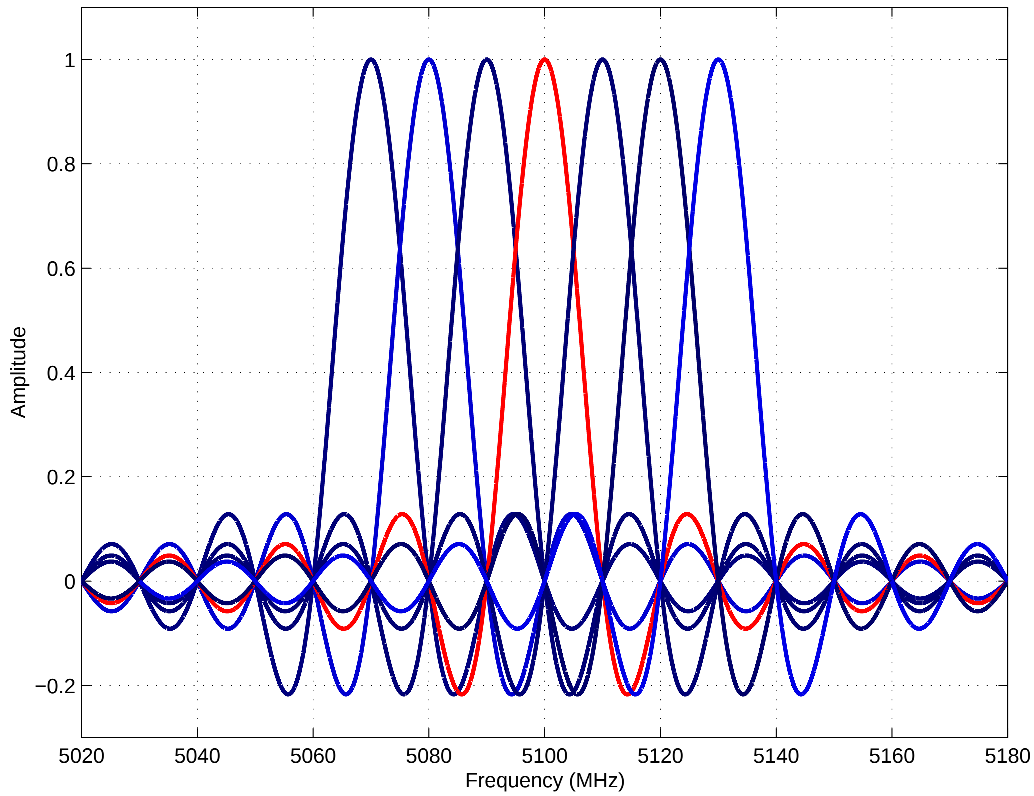

Figure 2. OFDM carriers in the frequency domain.

2.2 Modulation and Receiver Options for Impulse Radio UWB

Impulse radio is advantageous in that it eliminates the need for up and down-conversion, and allows to utilize low-complexity transceivers. It also enables employing various types of modulations, including on-off keying (OOK), pulse amplitude modulation (PAM), pulse position modulation (PPM), and binary phase shift keying (BPSK), as well as different receiver types such as energy detector, RAKE, and transmitted reference receivers.

Coherent receivers (such as RAKE and correlator receivers) are commonly used for impulse radio signal reception due to their high power efficiencies. However, implementation of such receivers requires estimation of *a priori* channel information regarding the timing, fading coefficient, and the pulse shape for each individual channel tap. Coherent signal reception also stipulates high sampling rates and accurate synchronization. On the other hand, non-coherent receivers have less stringent a priori information requirements and can be implemented with lower complexity. For example, in transmitted reference (TR) receivers, transmission of the reference pulse(s) (which includes the channel information) to correlate the information bearing pulse(s) eliminates the need for estimating the channel parameters. Therefore, throughout the rest of this chapter, the focus is going to be on non-coherent receivers, especially on the energy detector.

2.3 Energy Detector Receivers

Energy detector is a non-coherent approach for ultrawideband signal reception, where low complexity receivers can be achieved at the expense of some performance degradation [8]. As opposed to more complex RAKE receivers, estimation of individual pulse shapes, path amplitudes, and delays at each multipath component is not necessary for energy detectors. Moreover, energy detectors are less sensitive against synchronization errors [9], and are capable of collecting the energy from all the multipath components.

On-off keying is one of the most popular non-coherent modulation options that has been considered for energy detectors. OOK based implementation of energy detectors is achieved by passing the signal through a square law device (such as a Schottky diode operating in square-region) followed by an integrator and a decision mechanism, where the decisions are made by comparing the outputs of the integrator with a threshold. Two challenging issues for the enhancement of energy detector receivers are the estimation of the optimal threshold, and the determination of synchronization/dump points of the integrator.

The effect of integration interval on the system performance has been analyzed before for energy detectors [8,10]. However, optimal joint selection of the integration start and stop times, and the threshold is not covered in the literature. In this section, the contributions are as follows:

- The optimal joint parameter selection using the bit error rate (BER) expressions with exact analysis and Gaussian approximation is addressed, and it is shown that Gaussian approximation works well only at large bandwidths,

- A framework is defined for synchronization/dump hypotheses with different sampling options,

- When an exact analysis is considered, using the Gaussian approximation *for calculating the threshold* yields very small performance losses, and can be considered as a practical alternative for exact threshold evaluation,

- The parameter estimation requires explicit BER minimization (rather than SNR maximization) since the statistics corresponding to different bits are not identical,

- The number of training symbols required to converge to the ideal parameter estimates is shown to be less than one hundred for practical operating scenarios.

2.3.1 System Model

Let the impulse radio based UWB signal received for bit i in a multipath environment be represented as

$$r_i(t) = \sum_{l=1}^{L} \gamma_l b_i p_l\big(t - \tau_l - iT_s\big) + n(t) \ , \tag{1}$$

where L is the number of multipath components arriving at the receiver, l is tap index, b_i is the ith transmitted bit with OOK modulation, $p_l(t)$ is the received pulse shape for the lth path, γ_l and τ_l are the fading coefficient and the delay of the lth multipath component, respectively, and T_s is the symbol duration. The additive white Gaussian noise (AWGN) with double-sided noise spectral density $N_0/2$ is denoted by $n(t)$. The received signal is passed through a bandpass filter of bandwidth B to capture the significant portion of signal spectrum while removing out-of-band noise and interference, resulting in $\tilde{r}(t)$. For the sake of simplicity, we consider single pulse per symbol; however, the discussion in the sequel also (generally) applies to multiple pulses per symbol. The following decision statistic is used to make a symbol detection by sensing if there is energy or not within the symbol interval

$$h_i = \int_{T_i} |\tilde{r}(t)|^2 dt \underset{0}{\overset{1}{\gtrless}} \xi \ , \tag{2}$$

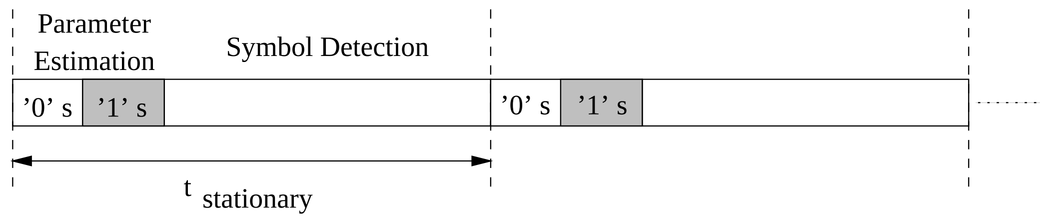

Figure 3. Parameter estimation and symbol detection in block-fading channel model.

where T_i is the integration window defined by synchronization and dump points (u, v), and the symbol decision is performed by comparing h_i with a threshold ξ. Observing (2), it is seen that optimal (joint) estimation of (u, v, ξ) tuple is of critical importance for the performance of energy detectors, as will be discussed throughout the rest of this section.

2.3.2 Optimum Joint Parameter Selection

Wireless communication systems typically require the estimation of channel-related parameters for optimal demodulation of received symbols. Since channel characteristics change in time, the parameter estimation has to be tracked and/or repeated every once in a while; how often the parameter estimation has to be repeated depends on the coherence time of the channel. A commonly used model for UWB channels is a block fading channel model [11], where the channel is assumed stationary within a specific block (e.g. for 200 microseconds [12]), and different channel realizations are considered for different blocks. Therefore, the radio channel characteristics vary in the long-term, and they may be assumed stationary in the short-term.

Since the optimal parameters for an energy detector will vary for different channel realizations, a receiver design that optimizes the performance for a particular channel realization is needed. As illustrated in Fig. 3, the parameters can be estimated at the beginning of each block, and then be used for demodulation of the symbols for the rest of the block. The proposed adaptive receiver, which takes into account the changes in the channel, is shown in Fig. 4. In this receiver, the received signal is first amplified, band pass filtered, and squared. Then, different hypotheses for (u, v) are considered, and the corresponding threshold is estimated for each hypothesis. Throughout the rest of this section, first, issues related to obtaining the integrator start/stop hypotheses will be discussed. Then, exact and Gaussian approaches for threshold estimation will be presented.

2.3.2.1 Obtaining the (u, v) Hypotheses with Different Sampling Approaches

When implementing an energy detector, specifying an integration interval that sacrifices the insignificant multipath components in order to decrease the collected noise energy will improve the performance. For a better performance it is also required that the receiver synchronizes with the starting point of the multipath energy. Therefore, the optimal interval, which minimizes the BER, can ideally be achieved by a joint and adaptive determination of the starting point and duration of integration.

Let $u(k)$ and $v(k)$ denote the starting and dump points of the kth hypothesis, respectively. Granularity of the $(u(k), v(k))$ pair depends on the sampling rate, and they may be obtained using different architectures. Below, three convenient ways of obtaining the start/stop points for multiple hypothesis are presented:

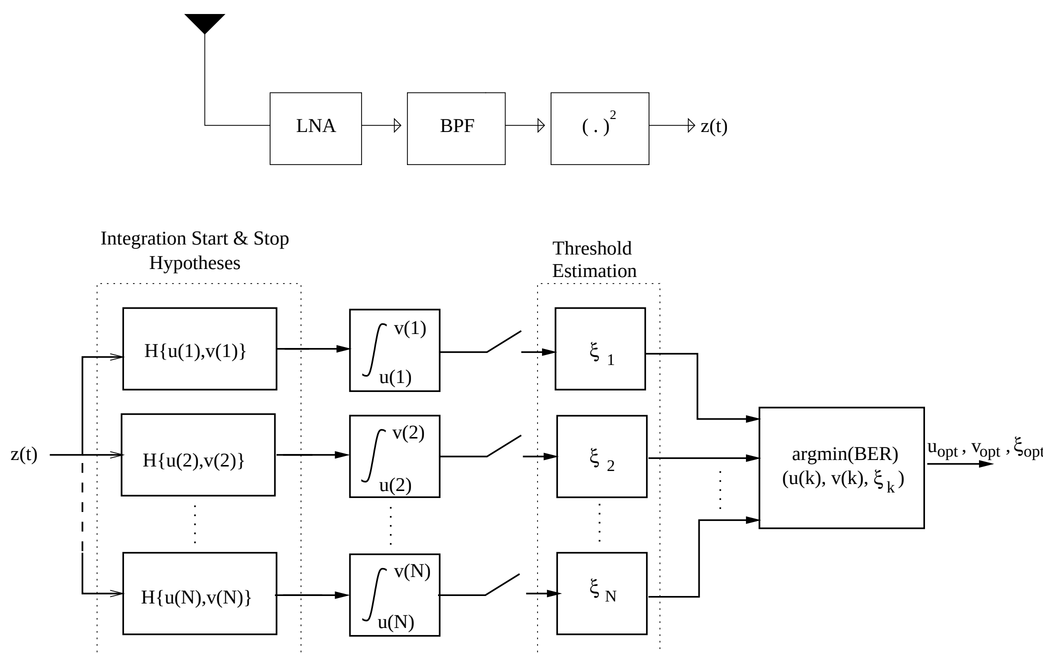

Figure 4. Block diagram for the proposed joint parameter estimation for energy detector receivers.

Multiple parallel integrator branches

Each branch has a different time constant and hence a different length of integration interval. Integration starting points are adjusted using delay elements. The integrator outputs are sampled at a symbol-spaced rate, and the effective granularity is T_s/N, where N is the number of integrators. The disadvantage of this approach is the large number of integrators that may be required.

Single integrator with high sampling rate

The high-rate sampling at a rate T_s/N enables determining the energy in finer resolution. The starting and stop points are selected by combining these sample energies in such a way to yield the optimum total energy. The drawback compared with other options is the requirement of a high speed analog to digital converter (ADC). Multiple parallel ADCs may also be considered to increase the sampling rate.

Single integrator employing training sequences

Training sequences longer than usual enable testing different integration intervals in a sequential manner. Symbol-rate sampling of the integrator is sufficient. However, since large number of training symbols are required to increase the sampling rate, the coherence time of the channel should be sufficiently long. On the other hand, since symbol-rate sampling will be used in the symbol demodulation anyway, this is the least complex implementation of the receiver.

Note that increasing the rate at which the output of the integrator is sampled, in effect, increases the 'integration time resolution' of the receiver and enhances the likelihood of obtaining a lower BER. However, this comes at the expense of additional hardware complexity. On the other hand, high sampling rates are required only when estimating the integration start/stop times, and symbol-spaced sampling is sufficient during symbol detection. Nevertheless, we assume in the sequel that using one of the above approaches, the integration start/stop hypothesis become available to the receiver.

A sub-optimal solution, where the initial point of the received signal is taken as the common starting point for all possible integration durations, yields very close performance to the optimal case, when the power delay profile (PDP) of the channel realization is exponentially decaying. For example, the channel model 1 (CM1) in [11] reflects such a minimum phase scenario where single synchronization point performs as well. For dispersive channels (such as CM4) however, there will be some performance degradation.

2.3.2.2 Threshold Selection Using Exact and Gaussian Analysis

The *exact* optimal threshold $\xi_k^{(E)}$ can be calculated using the centralized and non-centralized Chi-square distributions, corresponding to bits 0 and 1, respectively, and where k denotes the hypothesis number. However, this requires a search over possible threshold values in order to find the one that minimizes the BER, or, high signal to noise ratio (SNR) assumption in order to use asymptotic approximation of the Bessel function (which still yields a threshold estimate based on tabulated data) [13]. Relying on the fact that the normalized threshold for practical SNR values falls in between 0.25 and 0.5 [10], in order to decrease the computational complexity, here a serial search for $\xi_k^{(E)}$ in the range $(MN_0 + 0.5E_b, MN_0 + E_b)$ is considered, where M is the degree of freedom (DOF) defined by $2M = 2BT_i + 1$, and E_b is the average energy of bits 0 and 1, bit 1 having an energy of $2E_b$.

By approximating the Chi-square distributions with Gaussian distributions (which becomes more valid for large DOF), the threshold estimates $\xi_k^{(G)}$ can be obtained (as an approximation to $\xi_k^{(E)}$). Even though these estimates are suboptimal, they can be obtained easily, without requiring any search over possible threshold values. Let the means and variances of the Chi-square distributions for bits 0 and 1 be given by $\mu_{0,k}$, $\sigma_{0,k}^2$, $\mu_{1,k}$, and $\sigma_{1,k}^2$, respectively, where, according to [14],

$$\mu_{0,k} = MN_0 \quad (3)$$

$$\sigma_{0,k}^2 = MN_0^2 \quad (4)$$

$$\mu_{1,k} = MN_0 + 2E_b \quad (5)$$

$$\sigma_{1,k}^2 = MN_0^2 + 4E_bN_0 \ . \quad (6)$$

The threshold estimate using the Gaussian approximation is located at the intersection of the two Gaussian distributions, which can be evaluated from

$$\frac{\exp\left(-\frac{(\xi_k^{(G)}-\mu_{0,k})^2}{2\sigma_{0,k}^2}\right)}{\sqrt{2\pi\sigma_{0,k}^2}} = \frac{\exp\left(-\frac{(\mu_{1,k}-\xi_k^{(G)})^2}{2\sigma_{1,k}^2}\right)}{\sqrt{2\pi\sigma_{1,k}^2}} \ . \tag{7}$$

Taking the natural logarithm of both sides and rearranging the terms, one obtains

$$C_1(\xi_k^{(G)})^2 + C_2\xi_k^{(G)} + C_3 = 0 \ , \tag{8}$$

where the coefficients are given by

$$C_1 = \sigma_{1,k}^2 - \sigma_{0,k}^2 \ , \tag{9}$$

$$C_2 = -2\Big(\mu_{0,k}\sigma_{1,k}^2 - \mu_{1,k}\sigma_{0,k}^2\Big) \ , \tag{10}$$

$$C_3 = \sigma_{1,k}^2\mu_{0,k}^2 - \sigma_{0,k}^2\mu_{1,k}^2 - 2\sigma_{0,k}^2\sigma_{1,k}^2 \ln\left(\frac{\sigma_{1,k}}{\sigma_{0,k}}\right) \ , \tag{11}$$

with (8) being a second order polynomial equation that can be easily solved for $\xi_k^{(G)}$ (only one of the roots is appropriate) yielding

$$\xi_{opt} = \frac{-C_2 + \sqrt{C_2^2 - 4C_1C_3}}{2C_1} \ . \tag{12}$$

As an alternative to using frequent training symbols, the threshold can be updated (tracked) in a decision-directed manner once it is initially estimated in a similar way to a data-aided channel estimation [15].

2.3.3 BER Performance Evaluation

Three different approaches are considered for evaluating the BER of the energy detector receivers as summarized in Fig. 5. Due to the square-law device used in the receiver, the decision statistics in an energy detector have a Chi-square distribution. First, the exact statistics are considered, and the BER expressions as available in the literature are

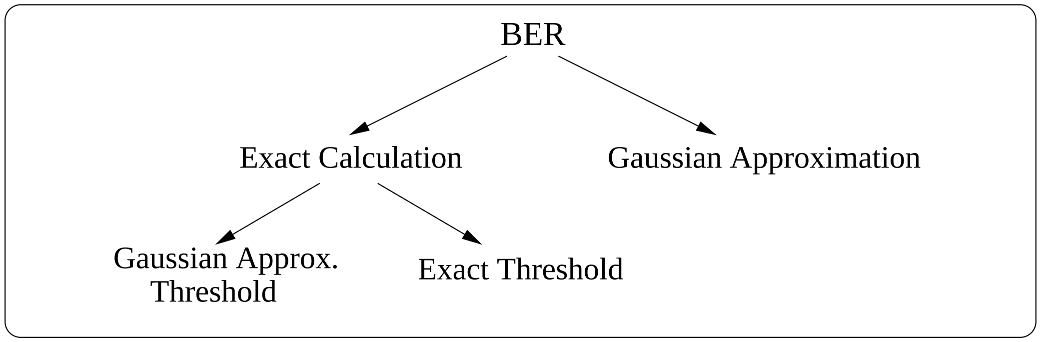

Figure 5. Three different approaches for performance evaluation.

evaluated. However, the threshold is considered using both the exact approach (using a search over possible threshold values) and the Gaussian approximation (using analytical expressions obtained in previous sections). Later, the BER evaluation using the Gaussian approximation of the Chi-square statistics is considered.

2.3.3.1 Exact BER Performances

When the exact Chi-square statistics of the received signal are considered, the BER observed for each hypothesis when using a serial search or a Gaussian approximation for threshold estimation are denoted by $P_b^{(E)}\big(k, \xi_k^{(E)}\big)$ and $P_b^{(E)}\big(k, \xi_k^{(G)}\big)$, respectively. Using the exact expressions, the BERs employing either threshold are given by

$$P_b^{(E)}\big(k, \xi_k\big) = P_{k,\xi_k}^{(E)}(0|1)\, p(1) + P_{k,\xi_k}^{(E)}(1|0)\, p(0)\ , \tag{13}$$

$$P_{k,\xi_k}^{(E)}(0|1) = 0.5 - 0.5\mathcal{Q}_M\left(\sqrt{\frac{4E_b}{N_0}}, \sqrt{\frac{2\xi_k}{N_0}}\right)\ , \tag{14}$$

$$P_{k,\xi_k}^{(E)}(1|0) = \frac{e^{-\frac{\xi_k}{N_0}}}{2} \sum_{u=1}^{\lfloor M \rfloor} \frac{(\xi_k/N_0)^{M-u}}{\Gamma(M-u+1)}, \tag{15}$$

where $p(0)$ and $p(1)$ are the probabilities for bit 0 and bit 1, respectively, $\mathcal{Q}_M$ is the generalized Marcum-$\mathcal{Q}$ function of order M, and

$$\Gamma(x) = \int_0^\infty t^{x-1} e^{-t} dt \ , \quad x > 0 \tag{16}$$

$$\Gamma(x) = (x-1)! \ , \quad x > 0 \ \textit{is an integer}$$

$$\Gamma(0.5) = \sqrt{\pi} \ , \quad \textit{and} \quad \Gamma(1.5) = \frac{\sqrt{\pi}}{2} \ .$$

The optimum integrator parameters are the ones that minimize the BER, i.e.

$$(u_{opt}, v_{opt}, \xi_{opt}) = \underset{u(k), v(k), \xi_k}{\operatorname{argmin}} \left(P_b^{(E)}(k, \xi_k) \right) \ . \tag{17}$$

As an alternative to minimizing the BER, one may consider to maximize the SNR (which has less complexity since no BER expressions are evaluated). However, the definition of

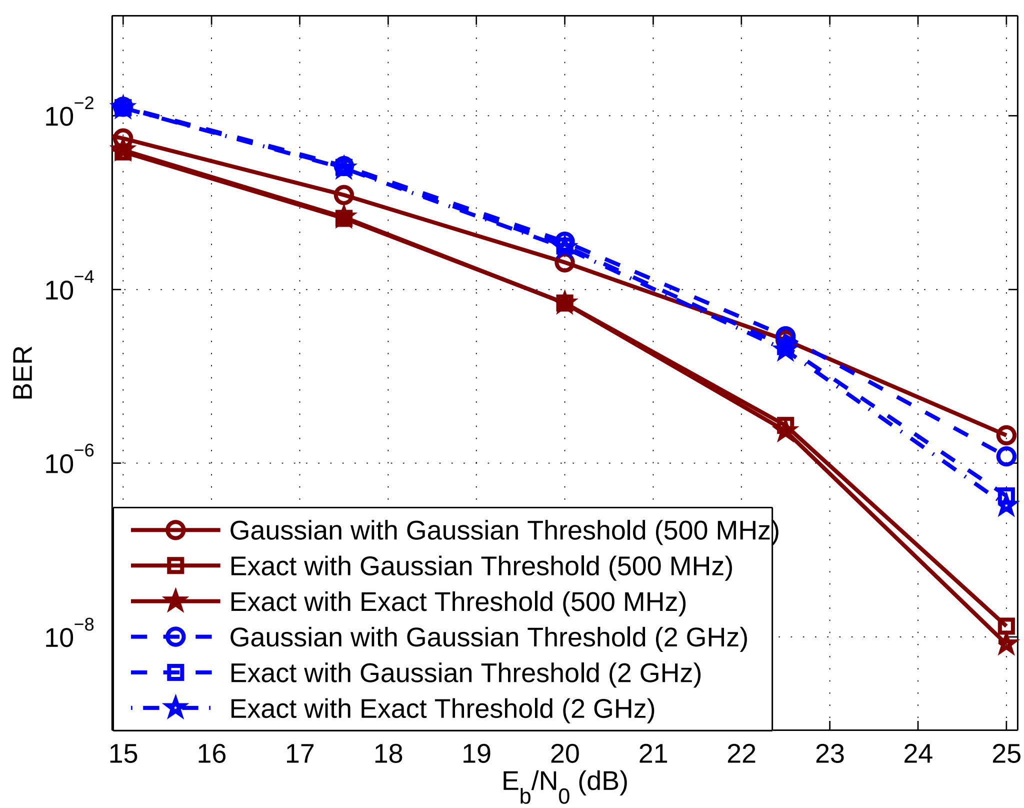

Figure 6. Bit error rate vs. E_b/N_0 for CM1 (BW = 500 MHz and 2 GHz cases) for both Gaussian approximated and exact threshold estimates.

SNR is critical in energy detectors. One may define the SNR to be the ratio of the square of the mean-shift due to the existence of signal to the output noise variance when signal is present [16], which is expressed as

$$\begin{aligned} \mathrm{SNR} &= \frac{(\mu_{1,k}-\mu_{0,k})^2}{\sigma^2_{1,k}} \ , \\ &= \frac{4E_b^2}{MN_0^2+4E_bN_0} \ , \end{aligned} \tag{18}$$

and the parameters that maximize (18) can be selected. However, note that (18) does not account for the noise statistics when signal is not present, and thus does not capture the whole picture. This is as opposed to a coherent system, where noise statistics corresponding to both bit-0 and bit-1 are identical, and maximization of the SNR implies the minimization of the BER.

2.3.3.2 BER Using the Gaussian Approximation

For theoretical purposes, an approximate BER formulation that gives a feasible estimate for $P_b(k,\xi_k)$ is given by

$$P_b^{(G)}(k,\xi_k^{(G)}) = \frac{1}{2}Q\left(\frac{\xi_k^{(G)}-\mu_{0,k}}{\sigma^2_{0,k}}\right) + \frac{1}{2}Q\left(\frac{\mu_{1,k}-\xi_k^{(G)}}{\sigma^2_{1,k}}\right) \ . \tag{19}$$

Since the Chi-square statistics can be approximated with a Gaussian for large degree of freedoms, the above expression is expected to approximate the BER at large bandwidths, or large integration intervals. It is also valid for systems that use large number of pulses per symbol[1].

2.3.4 Numerical Results

Computer simulations are done to analyze the performances of the proposed approaches using the channel models in [11]. To be more specific, in these simulations the energies

[1]Note that if more then one pulse is used per symbol, and the pulses are combined non-coherently, the number of pulses can be folded into the integration interval, implying that the decision statistics approach to a Gaussian distribution

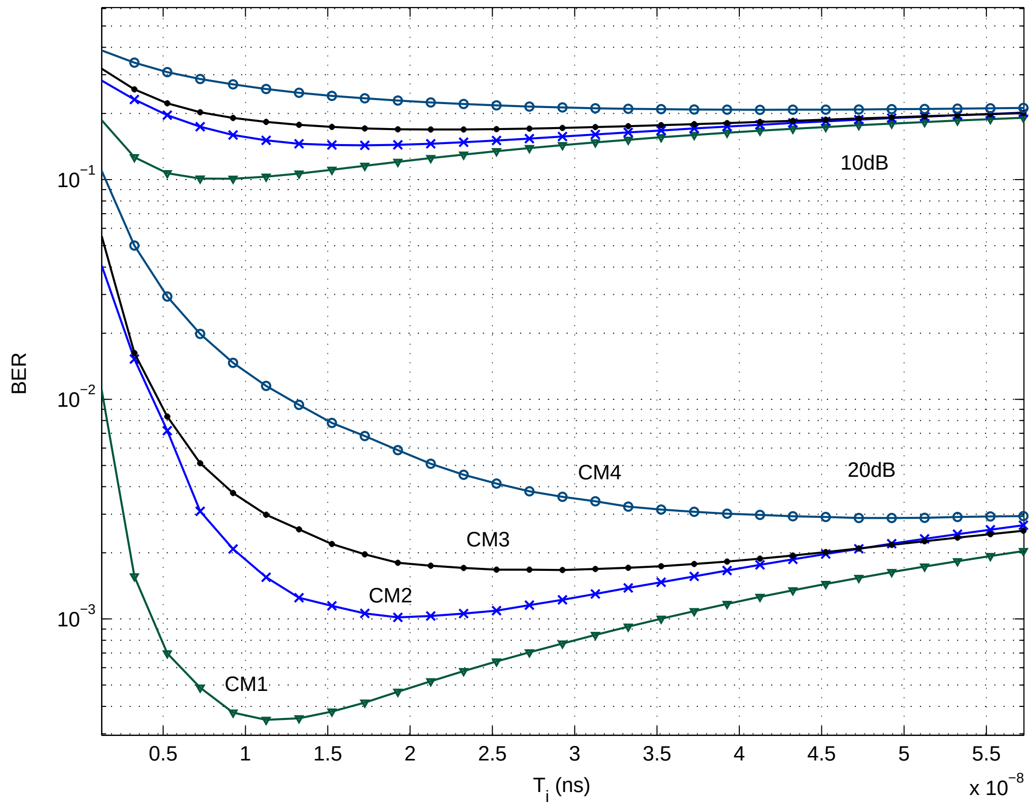

Figure 7. BER vs. integration interval for different channel models (at $E_b/N_0 = 10$ dB and 20 dB).

corresponding to the different channel realizations and parameter sets are evaluated, and used in the BER expressions.

In Fig. 6, the BERs obtained using the three different performance analysis approaches (shown in Fig. 5) are compared for $B = 0.5$ GHz and $B = 2$ GHz. While the Gaussian approximation fails to yield close results to the exact expressions for $B = 0.5$ GHz, it is seen that the approximation error decreases as the bandwidth increases. On the other hand, for both bandwidths practical estimation of the threshold using the Gaussian approximation yields very close results with the exact threshold (which has to be calculated after a serial search). Hence, the Gaussian approximated threshold can be employed to decrease the computational complexity.

Another observation is that the optimum integration interval changes substantially for different channel models, implying the fact that significant gains can be obtained for a mobile device when the integration interval is adaptively determined. Both the BER minimization and SNR maximization approaches are employed to find the optimum integration interval. The results are shown in Fig. 7 and in Fig. 8, respectively. Although the resulting curves have a similar behaviour, the optimum integration intervals determined by the SNR maximization approach turn out to yield higher BERs than the ones found with the BER minimization. Therefore, it is reasonable to conclude that minimizing the BER is favorable to maximizing SNR despite its computational complexity.

In Fig. 9, the variation of the optimal integration interval with respect to E_b/N_0 is plotted for different channel models. It is observed that the line-of-sight (LOS) component of CM1 yields a parallel variation with CM2. On the other hand, CM3 and CM4 also exhibit a parallel behavior and they have larger optimal integration values (and slopes) due to the more spread distribution of their multipath components over time.

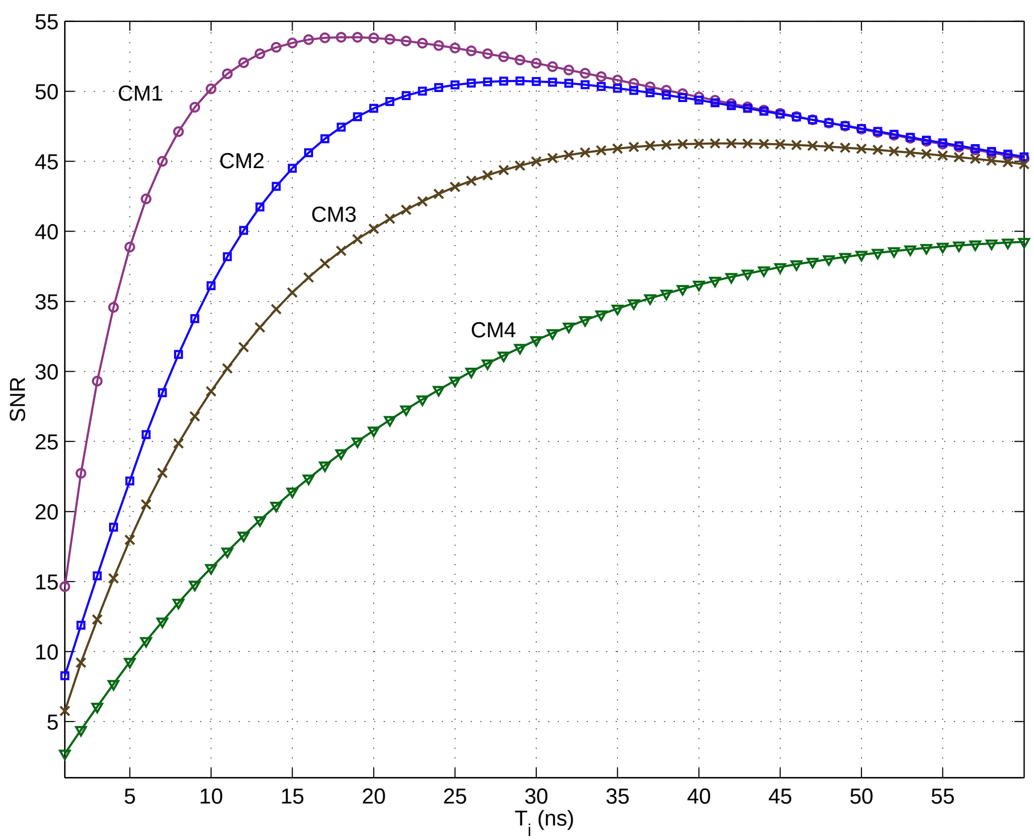

Figure 8. SNR vs. integration interval for different channel models (at $E_b/N_0 = 20$ dB).

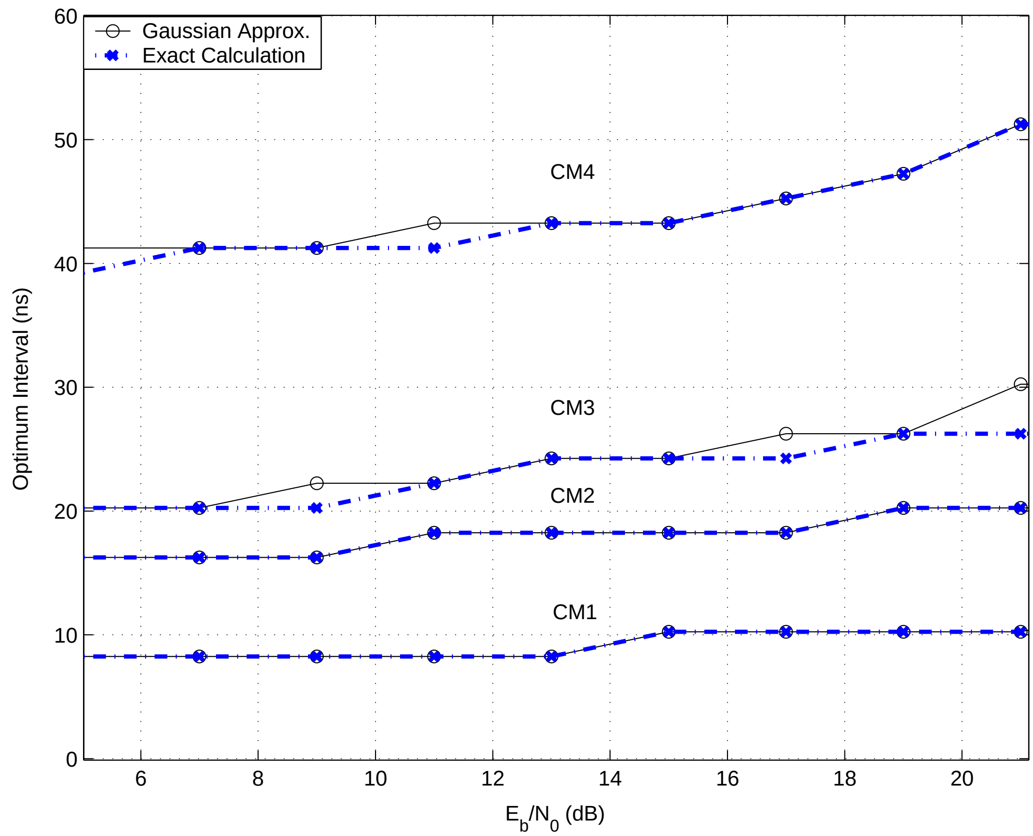

Figure 9. Optimum integration interval vs. E_b/N_0 for different channel models.

In Fig. 10, the BER performances of a non-adaptive receiver and the proposed receiver are compared. The non-adaptive receiver is assumed to have a *fixed* integration interval of 20ns, which is a reasonable duration considering the optimum values for different channel models given in Fig. 9. The resultant BER curves are presented for CM1 and CM4. The performance of the proposed receiver is better than the non-adaptive receiver with an appropriately selected fixed integration interval by approximately 1 dB. In the same figure, the synchronization effect is also illustrated. Synchronization is achieved by having the receiver synchronize itself with the starting point of the optimum integration interval rather than the initial multipath component. It is seen that the effect of synchronization is negligible for CM1 and very slight for CM4.

In the previous simulations, perfect parameter estimates for (3)-(6) were considered. Another analysis investigates how the number of training symbols affects the parameter

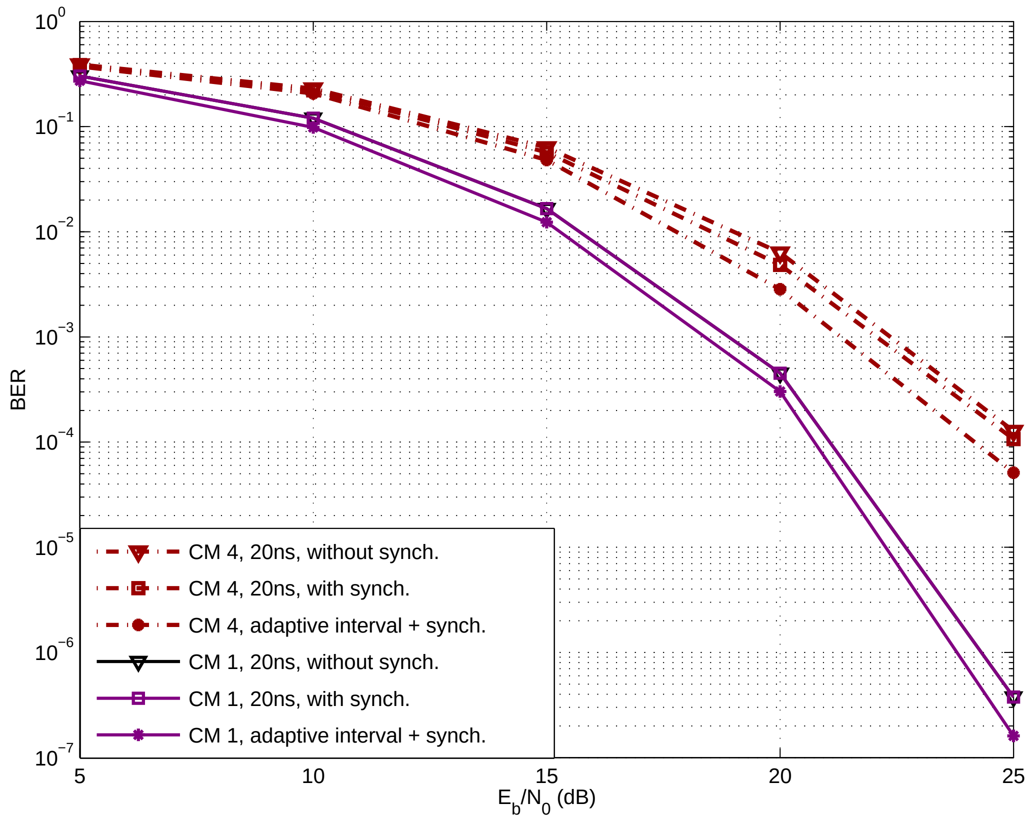

Figure 10. BER vs. E_b/N_0 for fixed integration intervals, adaptive integration interval, and adaptive synchronization point.

estimation and, as a result, the BER. This is an analytical examination rather than a simulation, and therefore, practical channel realizations are not considered. In Fig. 11, the BER vs. number of training symbols curves are plotted at different E_b/N_0 values. These results are obtained by taking samples from the centralized and non-centralized Chi-square distributions of bit-0 and bit-1, respectively. Each sample corresponds to a training symbol transmitted. Obviously, taking more samples yields a better estimate for the symbol energy. A significant conclusion that can be drawn from this figure is that as E_b/N_0 increases, the number of training symbols required to converge to the optimum BER increases as well. The reason for this fact is that as the signal energy rises, the probability density function for bit-1 becomes broader, and hence, more samples are required for a more accurate estimation. The theoretical optimum BERs are also indicated on the figure. Note that these BERs are

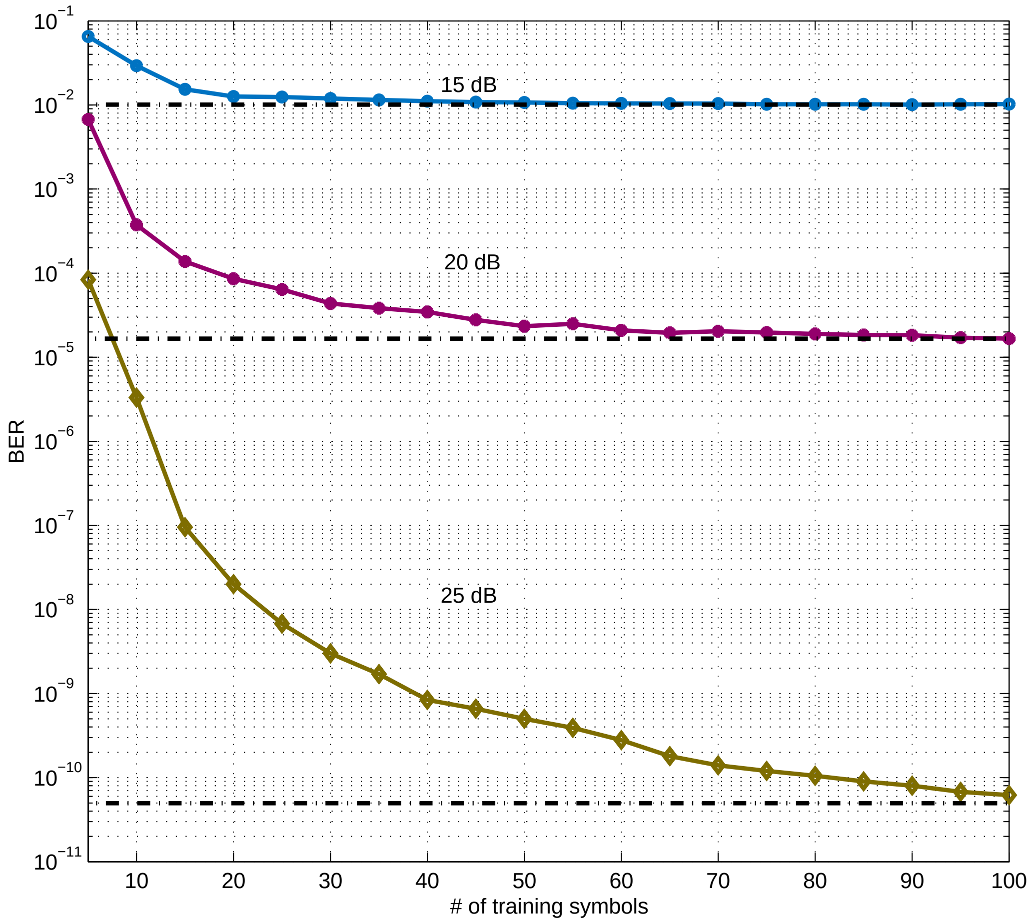

Figure 11. Analytical results regarding BER vs. number of training symbols (at $E_b/N_0 =$ 15 dB, 20 dB, and 25 dB).

different from the ones shown in Fig. 7. This is because in this analysis, the entire symbol energy is considered rather than only the energy confined to the integration interval.

2.4 High Data Rate UWB Using Energy Detector Receivers

In this section, the inter-symbol interference (ISI) issue in impulse radio UWB systems is addressed. An energy detector based receiver that has high data rate capability through ISI cancelation is proposed. The ISI suppression algorithm of the receiver depends on the usage of a simplified decision feedback equalizer (DFE), which does not employ feed-forward filters, but only feedback filters. In spite of the fact that decision feedback equalizers are known to cause error propagation, an important feature of the proposed DFE equalizer is that it does not have error propagation. The DFE equalizer requires some parameters to be measured. The parameter estimation in energy detector receivers will be addressed, and a simple algorithm will be developed to estimate the signal energy leaking from one symbol into the following symbol.

2.4.1 ISI Problem

Because of its tempting features such as aiming at extremely high data rates with considerably low cost circuitry, UWB is considered a candidate for wireless personal area networks (WPAN), whose range is up to 10 meters. For the channel models CM1 and CM2 in [11], which are appropriate for this range, the maximum excess delays (MED) are around 80 ns and 115 ns, respectively. Hence, at high data rates, some portion of the transmitted symbol energy unavoidably leaks into the following symbols, leading to inter-symbol interference. ISI is one of the primary factors degrading the detection performance of UWB systems and it has to be suppressed for successful implementation of high data rate UWB communications.

In order to meet the high data rate requirement, UWB system has to employ a receiver that is also capable of handling ISI. Although RAKE receivers can provide a satisfying solution to this problem [17]- [19], their high complexity increases the system cost dramatically. Hence, alternative transceiver designs are needed that have low computational and hardware complexity, while providing high data rates. Possible candidates are the non-coherent receivers such as the energy detector or the transmitted reference receiver.

2.4.2 System Model

The impulse radio based UWB signal received for bit i in a multipath environment can be represented as

$$r_i(t) = \sum_{l=1}^{L} \gamma_l p_l(t) + n(t) \ , \tag{20}$$

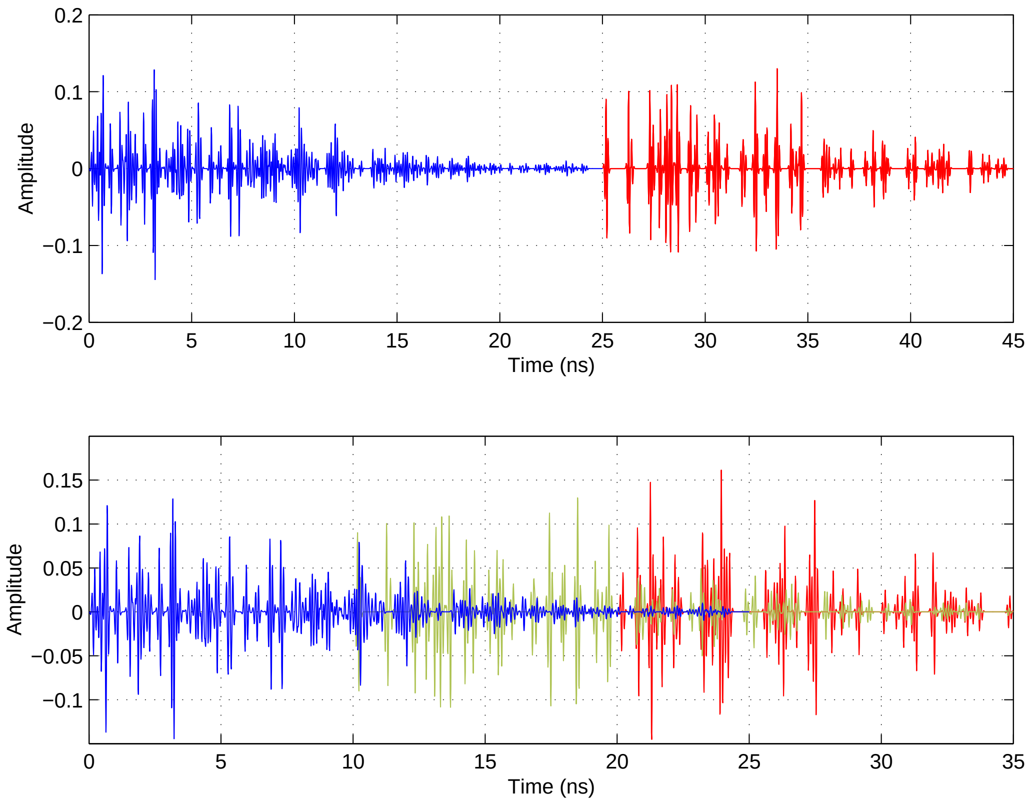

Figure 12. (a) The pulse repetition period (κ) greater than the maximum excess delay (D). (b) $D > \kappa$, energy leaks from one symbol to the subsequent symbol.

where

$$p_l(t) = \begin{cases} b_i v_l\big(t - \tau_l - T_d\big) + r_i v_l\big(t - \tau_l\big), & \text{for } PAM \\ v_l\big(t - \tau_l - T_d - b_i\delta\big) + r_i v_l\big(t - \tau_l\big), & \text{for } PPM \end{cases}$$

L is the number of multipath components arriving at the receiver, l is the tap index, b_i is the ith transmitted bit, γ_l, $v_l(t)$ and τ_l are the fading coefficient, the received pulse shape, and the delay of the lth multipath component, respectively, δ is the duration between the two possible positions in pulse position modulation, r_i has a binary value determining the existence of a reference pulse, and T_d is the delay between the reference and data in TR systems. In the case of an energy detector, both r_i and T_d become zero. The additive white Gaussian noise with double-sided noise spectral density $N_0/2$ is denoted by $n(t)$.

2.4.3 Effect of ISI

In the impulse radio based ultrawideband communications, the transmitted UWB pulses go through a highly frequency selective channel, and become dispersed in time. Let the maximum excess delay of the channel be denoted by D, and the pulse repetition period by κ. In many works dealing with UWB, κ is assumed to be longer than D (illustrated in Fig. 12-a). However, in practical high data rate communications, the pulse repetition period is much shorter than the maximum excess delay (Fig. 12-b), i.e. $\kappa \ll D$.

The temporal dispersiveness of the UWB pulse causes a considerable portion of the symbol energy to appear as a part of the following symbol, leading to inter-symbol interference. This problem is valid for all kind of transmission schemes, however, here on-off keying is considered, which is a specific case of PAM.

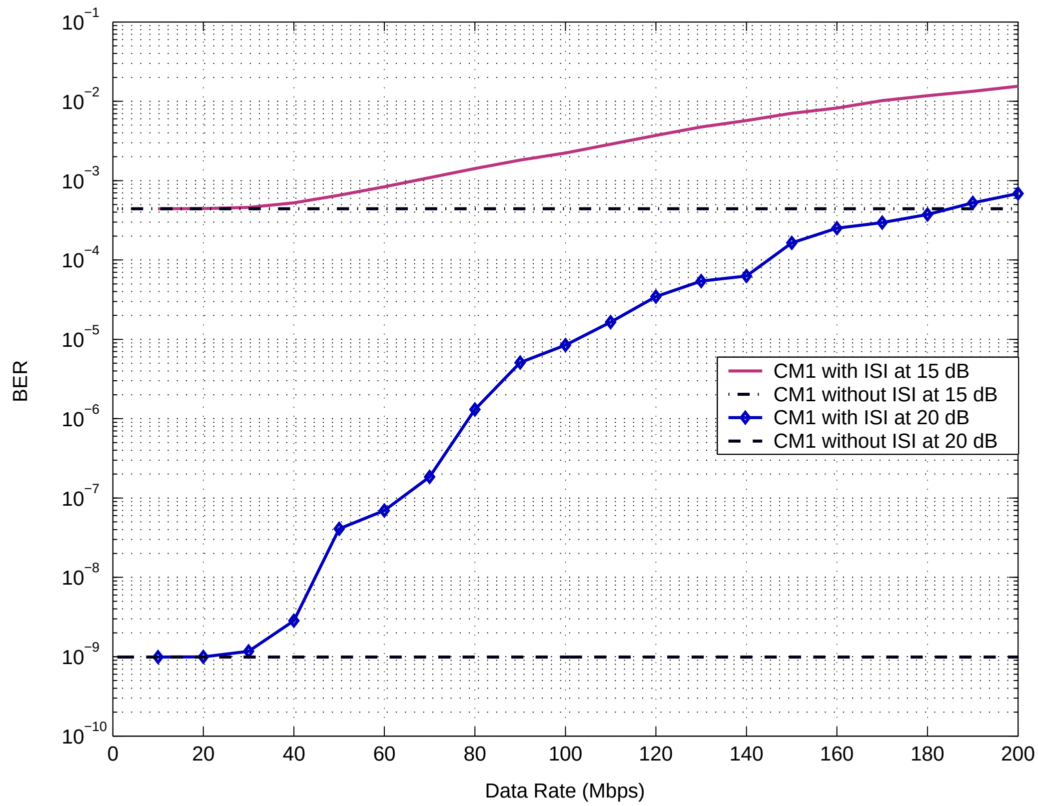

Figure 13. BER vs. data rate for channel model CM1 at E_b/N_0 values of 15 dB and 20 dB.

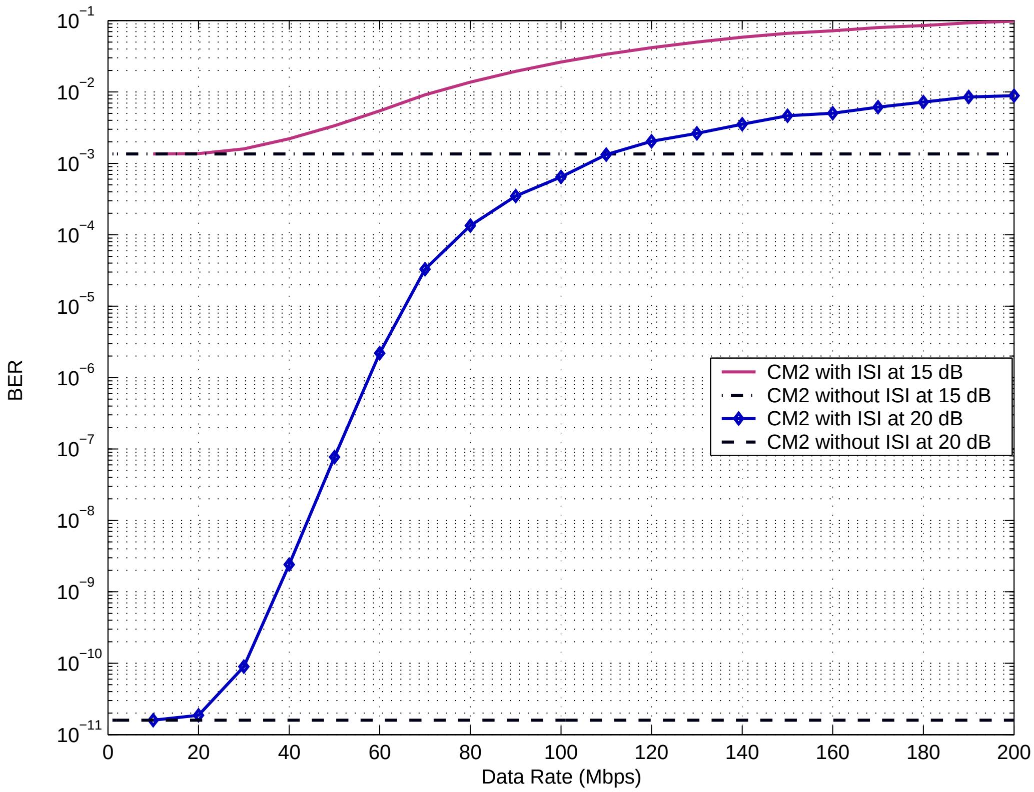

Figure 14. BER vs. data rate for channel model CM2 at E_b/N_0 values of 15 dB and 20 dB.

To visualize the ISI effect, simulations are performed considering the different channel models in [11]. In the simulations, a fifth order derivative of the Gaussian pulse, which satisfies the FCC limitations regarding the transmission bandwidth, is used. The results obtained reveal that at a data rate of 100 Mbps, the average ratio of ISI to the symbol energy is 11.8% for CM1, and as high as 25.89% for CM2. In Fig. 13 and Fig. 14, the effect of ISI in CM1 and CM2 for data rates up to 200 Mbps is demonstrated. The E_b/N_0 values used are 15 dB and 20 dB, respectively. At relatively low data rates such as 10 Mbps, the ISI effect is almost unnoticeable. However, as the data rate increases, ISI grows considerably. Towards 200 Mbps, the curves for 15 dB and 20 dB converge to the same level. The reason for this fact is that at high data rates, the effect of ISI almost totally dominates the noise effect.

2.4.4 ISI Canceling Receiver

The proposed energy detector (shown in Fig. 15) is implemented by taking the square of the received signal, integrating it, and passing it to a decision mechanism, where the symbol is determined. To make a symbol decision by sensing if there is energy or not within the symbol interval, the following decision statistic could be used if ISI did not exist

$$\epsilon(i) = \int_{T_i} \big(s_i(t) + n(t)\big)^2 dt \ . \tag{21}$$

In the existence of ISI, however, the valid decision statistic is

$$\begin{aligned}\widehat{\epsilon}(i) = \int_{T_i} \Bigg(\sum_{j=0}^{n} \Big[s^2_{(i-j)}(t) + 2 \sum_{x=0}^{j-1} s_{(i-j)}(t) s_{(i-x)}(t) \Big] \\ + n^2(t) \Bigg) \ dt \ , \qquad\qquad x \geq 0\end{aligned} \tag{22}$$

where

$$s_{(i-j)}(t) = \sum_{l=1}^{\kappa} b_{(i-j)} \gamma v_l \big(t - \tau_l\big) \ , \tag{23}$$

l is the tap index, b_{i-j} is the j^{th} previous symbol value, and κ is the number of taps inside the integration interval of i^{th} symbol. The decision statistic can be denoted as follows

$$\widehat{\epsilon}(i) = \epsilon(i) + \sum_{j=1}^{n} b_{i-j} \epsilon_{\lambda}(i,j) \ , \tag{24}$$

where $\epsilon_{\lambda}(i,j)$ is the amount of leaking energy from the j^{th} previous symbol to the i^{th} symbol. The symbol decision is performed by comparing $\widehat{\epsilon}(i)$ with a threshold ξ, $\widehat{\epsilon}(i) \underset{0}{\overset{1}{\gtrless}} \xi$. A detailed analysis about setting the optimum ξ is given in [4].

In order to improve the detection performance of the UWB system, the effect of ISI has to be canceled before a bit decision is made. In communication systems, decision feedback equalizers are commonly used for this purpose [20]. The decision mechanism of the proposed receiver makes use of a simplified DFE algorithm, which employs only feedback filters but no feed-forward filters. From (24), it is obvious that for determining b_i correctly, the DFE

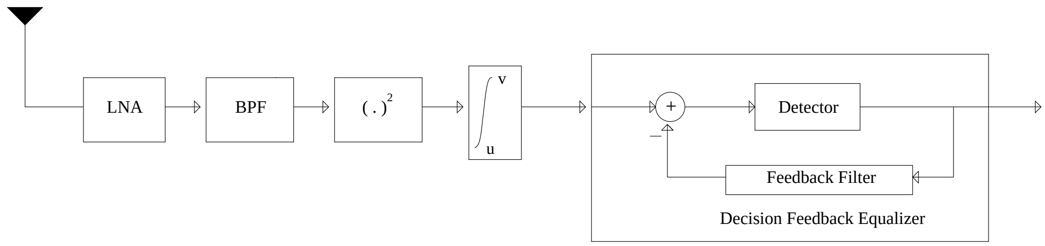

Figure 15. Decision feedback equalization based ISI canceling energy detector.

requires the estimation of $\epsilon_\lambda(i,j)$, which are the equalizer coefficients with positive real values. In this section, only the energy leaking from the immediately previous symbol $\big(\epsilon_\lambda(i,1)\big)$ is considered, because this has the strongest effect on the current symbol. In order to estimate $\epsilon_\lambda(i,1)$, transmitting sequences of training symbols between the packets of data symbols is proposed. During the training sequences, the channel is assumed to be non-varying, hence the filter coefficients are considered constant. First, transmitting

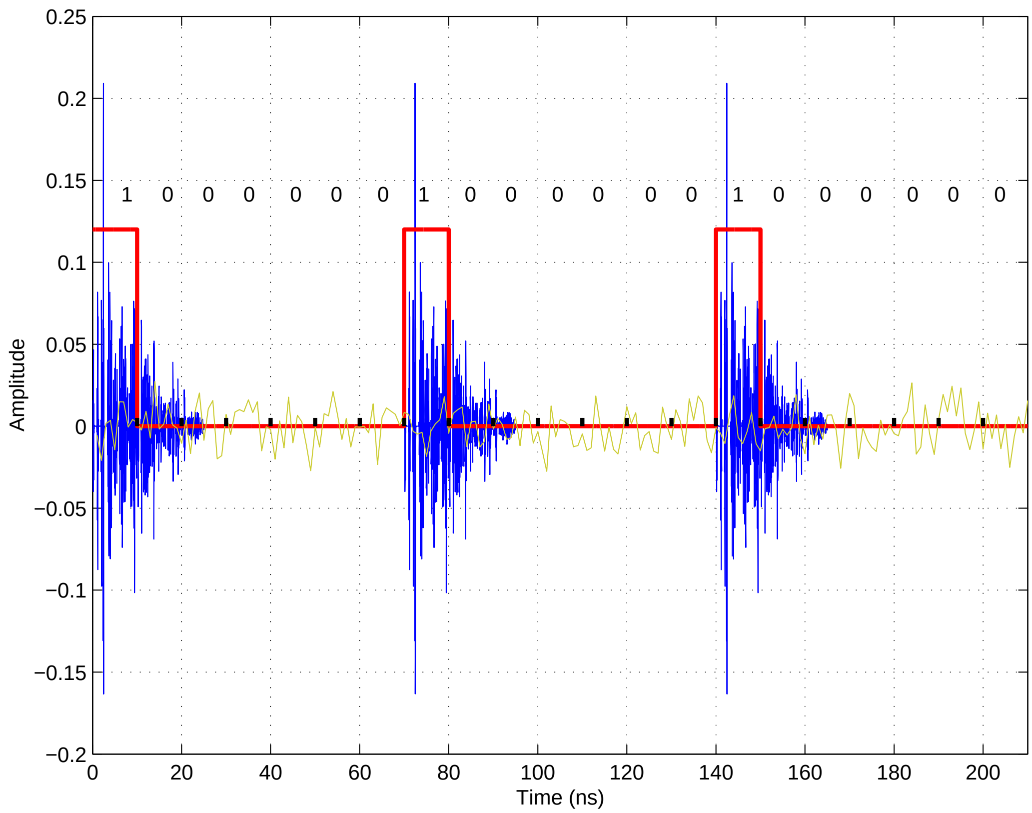

Figure 16. Successive training sequences used for estimating the feedback filter coefficients.

a set of '0's, the noise energy $\left(\int_{T_i} n(t)^2 dt\right)$ is estimated. Then, a reasonable approach is transmitting sequences in the form of $\left[\ 1\ 0\ 0\ ...\ 0\ \right]$ (shown in Fig. 16). The energy obtained during the first '0' following the '1', which can be shown as

$$b_{i-1}\epsilon_\lambda(i,1) + \int_{T_i} n(t)^2 dt \ , \tag{25}$$

is measured. The DFE coefficient $\epsilon_\lambda(i,1)$ is found by subtracting the estimated noise energy from this composite energy. The '0's following the first '0' are transmitted as a guard band considering that at high data rates ISI may be severe, and further symbols may be affected. Using multiple training sequences successively, an average value for $\epsilon_\lambda(i,1)$ can be found. Then, during the data processing, every time when a '1' is detected, the DFE mechanism subtracts this DFE coefficient from the immediately following symbol energy, and thus cancels the ISI effect. If the channel is highly dispersive, the number of feedback filter taps can be increased such that the effect on further symbols is suppressed. The required coefficients can be found the way $\epsilon_\lambda(i,1)$ is determined.

The decision feedback equalizers are known to cause error propagation when processing the received data. In the case of OOK modulated UWB signals, however, this problem does not occur. Keeping in mind that after each '1' the leaking energy has to be removed from the next symbol, if b_i is '0', and it is mistakenly detected as '1', then the DFE coefficient is unnecessarily subtracted from b_{i+1}. If b_{i+1} is '1', this subtraction may cause it to be detected as '0'. So, the error is propagated by one symbol in this case. If b_{i+1} is already '0', the error in b_i does not cause it to change. If, on the other hand, b_i is '1', and it is mistakenly detected as '0', no subtraction is done on b_{i+1}, therefore, no error related to DFE occurs. Obviously, the proposed algorithm has the advantage that an error arisen due to any reason is not forwarded by more than one subsequent symbol, hence there is no error propagation.

2.4.5 Performance Results

Simulations are done to test the performance of the proposed energy detector receiver. A pulse bandwidth of 2 GHz is assumed, and the channel models in [11] are used. For each channel model, the optimum integration duration given in [4] is used (as long as it does not exceed the symbol period). In Fig. 17, the bit error rates obtained at a data rate of 100 Mbps, with and without implementing the proposed ISI cancelation algorithm are compared for channel models CM1-CM4. It is revealed that an important gain can be achieved using the ISI canceling energy detector.

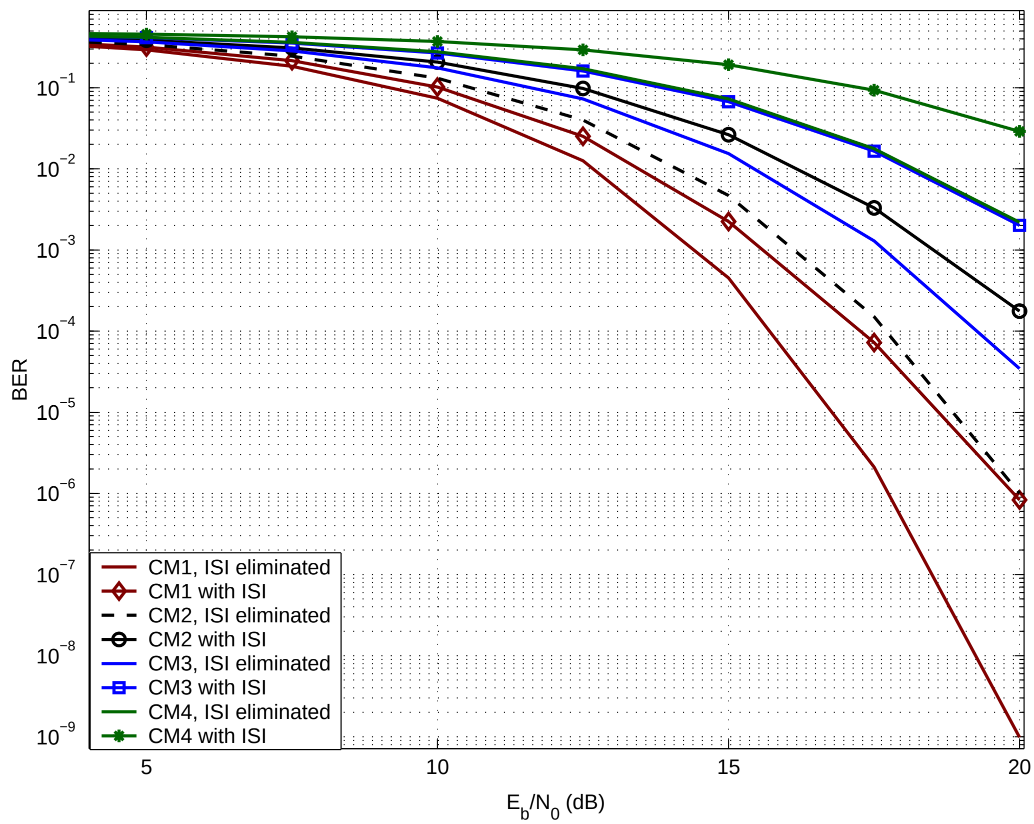

Figure 17. Bit error rate vs. E_b/N_0 for different channel models before and after the ISI suppression.

2.5 Conclusion

In this chapter, after introducing UWB and discussing various possible modulation and receiver type options, optimization of adaptive energy detector receivers for UWB systems is discussed. The need for the joint adaptation of the integration interval, optimal threshold, and the synchronization point (for certain channels) is clearly demonstrated, which can be extended to other non-coherent approaches. Threshold estimation can benefit from the computational easiness brought by the Gaussian approximation of received signal statistics, which yields reasonable results for certain bandwidths.

In the second part of the chapter, the inter-symbol interference problem in high data rate UWB systems employing OOK based energy detectors is investigated. The increasing negative effect of ISI on the system performance with increasing data rate is demonstrated. In order to overcome the ISI problem, a modified energy detector that has a built-in symbol decision mechanism based on decision feedback equalization is proposed. A simple but clever way of using training symbols with the purpose of estimating the decision feedback filter coefficients is introduced. It has been proven that the error propagation problem, which is generally observed in decision feedback equalizers, does not exist in the proposed approach. In the final section, the gains achievable with the proposed energy detector are exhibited. These gains turned out to be considerably high, verifying the necessity of ISI cancelation and showing the effectiveness of the proposed detector.

CHAPTER 3

UWB AND NARROWBAND SYSTEMS

In this chapter, the coexistence of UWB and narrowband systems is addressed. The effect of narrowband interference (NBI) on UWB is analyzed. The techniques of suppressing NBI, which are classified as NBI avoidance and NBI cancelation methods, are investigated in detail.

3.1 Introduction

Ultrawideband is becoming an attractive solution for wireless communications, particularly for short and medium range applications. UWB systems operate over extremely wide frequency bands, where various narrowband technologies also operate with much higher power levels (illustrated in Fig. 18). The unlicensed usage of a very wide spectrum that overlaps with the spectra of narrowband technologies brings about some concerns. Therefore, significant amount of research has been carried out lately to quantify the effect of UWB signals on narrowband systems [21].

The transmitted power of UWB devices is controlled by the regulatory agencies (such as the FCC in the United States), so that narrowband systems are affected from UWB signals only at a negligible level. This way, UWB systems are enabled to co-exist with narrowband technologies. However, looking at the fact from the other side, the influence of narrowband signals on the UWB system can still be significant, and in the extreme case, these signals may jam the UWB receiver completely. Even though narrowband signals interfere with only a small fraction of the UWB spectrum, due to their relatively high power with respect to the UWB signal, the performance and capacity of UWB systems can be affected considerably [22]. The recent studies show that the bit-error-rate (BER)

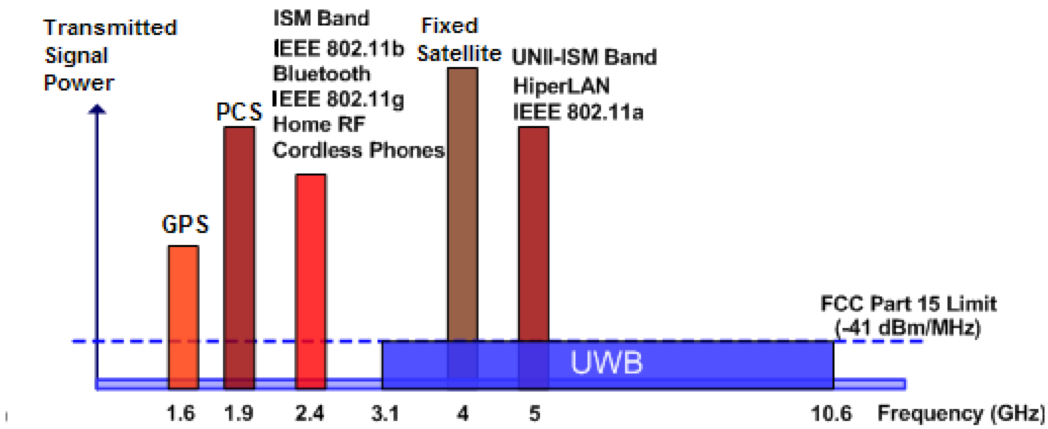

Figure 18. Spectrum crossover of the narrowband interferers in UWB systems.

performance of the UWB receivers is greatly degraded due to the impact of narrowband interference [23] - [28]. The high processing gain of the UWB signal can cope with the narrowband interferers to some extent. However, in many cases, even the large processing gain alone is not sufficient to suppress the effect of the high power interferers. Therefore, either the UWB system design needs to consider avoiding the transmission of the UWB signal over the frequencies of strong narrowband interferers, or the UWB receivers require to employ NBI suppression techniques to improve the performance, the capacity, and the range of the UWB communications.

NBI is not a new problem. It has been studied extensively for wideband systems like direct sequence spread spectrum - code division multiple accessing (DSSS-CDMA) based wireless communications [29], and for the operation of broadband OFDM systems in unlicensed frequency bands [30]. In DSSS-CDMA systems, NBI is partially handled with the processing gain as well as by employing interference cancelation techniques. Approaches including notch filtering [31], linear and non-linear predictive techniques [32]- [37], adaptive methods [38]- [41], minimum mean square error (MMSE) detectors [42, 43], and transform domain techniques [44]- [50] have been investigated extensively for interference suppression. Similarly, in OFDM systems, interference cancellation as well as interference avoidance techniques have been studied [30], [51] - [54]. Compared to these wideband systems, NBI suppression in UWB is a more challenging problem because of the restricted power transmission and the higher number of narrowband interferers due to the extremely wide band occupied. More significantly, in carrier modulated wideband systems, before demodulating the received signal both the desired wideband and the narrowband interfering signals are down-converted to the baseband, and the baseband signal is sampled at least with the Nyquist rate. Sampling at the Nyquist rate allows to employ numerous efficient narrowband interference cancelation algorithms based on advanced digital signal processing techniques. However, in UWB, the desired signal is already in the baseband, while the narrowband interferer is in radio frequency (RF). Sampling the received signal at the Nyquist rate before the pulse correlator requires an extremely high sampling frequency, which is not realizable with the existing technology. In addition to the high sampling rate, the analog-to-digital-converter (ADC) must support a very large dynamic range to resolve the signal from the strong narrowband interferers. Currently, such ADCs are far from being practical. As an alternative, applying analog (notch) filtering before the pulse correlation is considered. However, this method requires a number of narrowband analog filter banks, since the frequency and power of the narrowband interferers can be various. Therefore, employing analog filtering adds complexity, cost, and size to the UWB receivers. Also, adaptive implementation of the analog filters is not straightforward. As a result, many of the NBI suppression techniques applied to other wideband systems are either not applicable for UWB, or the complexities of these methods are too high for the UWB receiver requirements.

Given the low complexity requirements in both hardware and computation, and considering the other limitations such as low power and low cost transceiver design in many UWB applications, the NBI problem needs to be handled more carefully, and effective techniques that are able to cope with NBI need to be developed. One approach to deal with NBI is to avoid the transmission of the UWB signal over the frequencies of possible strong narrowband interferers. Attempts toward this goal include approaches like multiband-UWB (both using impulse based and OFDM based techniques) [55, 56]. Another approach to handle NBI is to design interference canceling receivers. However, as mentioned previously, the interference cancellation approach in UWB has more limitations compared to the conventional NBI cancellation approaches employed for other wideband systems. Very recently, some NBI cancellation techniques, most of which are based on the previous methods implemented in CDMA systems, have been considered for UWB. Analog bandpass filtering has been applied before the correlation receiver in [57]. As discussed above, fixed analog filtering is not an efficient solution, unless the interferer is fixed (i.e. the frequency, bandwidth, power, and channel of the interferer is constant), and always exists. In [46], notch filtering (or peak clipping) is applied doing a high-speed sampling before the correlation. The frequency domain signal is obtained from these digital samples through front-end fast-Fourier-transform (FFT). Then, the narrowband interferers in the frequency domain, which are the collection of large peaks in the frequency, are clipped or notch-filtering is applied on these locations. However, as discussed above, high sampling rate before correlation makes the practical and cost-effective implementation of this technique difficult. Modifying and estimating the optimal receiver template for the correlation of the received signal is another solution that is proposed for partial suppression of NBI [57, 58]. By far the most popularly considered approach is the use of Rake (multiple correlators) receiver along with MMSE combining [59]- [62]. MMSE combining is known to perform well when the noise is not white (i.e. noise on different Rake fingers are correlated). The performance of MMSE depends on the number of fingers. Note also that Rake receivers are much more complex compared to the correlation receivers, and their complexity increases with the number of Rake fingers.

In this chapter, NBI in UWB systems will be studied. In Section 3.2, the effect of NBI on the performance of UWB transmission will be discussed. Appropriate models for NBI sources will be investigated. In Section 3.3, techniques for avoiding NBI in UWB system design will be reviewed. Approaches including multi-band/multi-carrier transmission and pulse shaping for avoiding NBI will be discussed briefly. In Section 3.4, NBI handling approaches based on interference cancelation will also be investigated for relaxing the system and transmission requirements. Finally, section 3.5 will conclude the chapter with the discussion of some future research areas.

3.2 Effect of NBI in UWB Systems

According to the modern definition, UWB transmission is not limited to the impulse radio. Any technology that has a bandwidth greater than 500 MHz or a fractional bandwidth greater than 0.2 can be considered a UWB system. Therefore, depending on the access technology, the signal and interference models might vary. In general, the UWB signal bandwidth is extremely large and the transmitted signal power is very low. On the contrary, the narrowband signal occupies a much smaller bandwidth, where its power spectrum is very high. Another distinction is that the narrowband signal is modulated with a carrier, and it is a continuous time signal, whereas the UWB signal can be a baseband signal composed of discrete short-time pulses as well as a carrier modulated signal.

Impulse radio based UWB transmission has some similarities to the widely used spread spectrum (SS) systems. In the SS systems such as direct sequencing (DS), the bandwidth occupied is larger than the bandwidth required for transmitting the data bits for a single user. Each user is assigned a pseudo-random (PN) sequence of N chips (where the chip durations are much shorter than the actual symbol duration) to transmit a symbol. Without the spreading, the same transmission bandwidth can be used to transmit N information symbols. But, the spreading operation allows simultaneous transmission of information from multiple users on the same bandwidth without interfering with each other, leading to the CDMA type of multiplexing. Therefore, even though the peak data rate is reduced for a single user, the capacity of the system is preserved to a great extent by allowing multiple users in the system. In addition to these, spreading provides immunity to interference sources like NBI, reduces the power of the transmitted signal (so that it causes less interference to other systems sharing the same band), allows path diversity in the presence of multipath signals that are longer than a chip period, and last but not least, provides covert communications.

The NBI jamming resistance of DSSS systems has been studied extensively [26]. The jamming resistance in these systems is provided by the processing gain, which is obtained by spreading. The larger the spreading ratio (the ratio of bandwidths of the spread signal and the original information), the higher the processing gain, and hence, the better jamming resistance is obtained. At the receiver, the transmitted spread spectrum signal and the narrowband interferer go through a despreading operation, where the receiver takes the wideband spread spectrum signal and collapses it back to the original data bandwidth, while spreading the interferer to a wide spectrum. As a result, within the data bandwidth, the effect of interferer is mitigated, a fact, which is referred as the jamming resistance or the natural interference immunity of the spread spectrum signals.

Similar to the DSSS systems, impulse radio based UWB also has inherent immunity to NBI. Time-hopping UWB (TH-UWB) systems can be considered as an example. The processing gain of TH-UWB signal is mainly obtained by transmitting very narrow pulses with a very low duty cycle. Fig. 19-a demonstrates a simple scenario that shows the UWB pulses and the continuous time narrowband interferer. During the reception of TH-UWB signals, using a matched filter that basically operates as a time gate (i.e. lets the UWB signal along with interference pass over the duration of the expected pulses, and blocks the rest of the received signal), the power of the interfering signal is reduced significantly (shown in Fig. 19-b). As a result, jamming resistance against NBI is obtained. Note that there will be still partial interference at the output of the matched filter depending on the processing gain, the power of the interferer, and other factors.

It is necessary to investigate the models of the UWB signal and narrowband interferers for a thorough understanding of NBI effects on UWB systems. Considering a binary pulse position modulated (BPPM) time-hopping UWB signal, the transmitted waveform can be modeled as [63]

$$s_{tr}(t) = \sum_{i=-\infty}^{+\infty} p_{tr}(t - iT_f - c_iT_c - \delta d) \tag{26}$$

where p_{tr} denotes the UWB pulse, T_f is the pulse repetition duration, c_i is the time-hopping code in the ith frame, T_c is the chip time, δ is the pulse position offset regarding BPPM, and d represents the data, which is a binary number.

Depending on its type, the narrowband interference can be modeled in various ways. For example, it can be considered to consist of a single tone interferer, which can be modeled

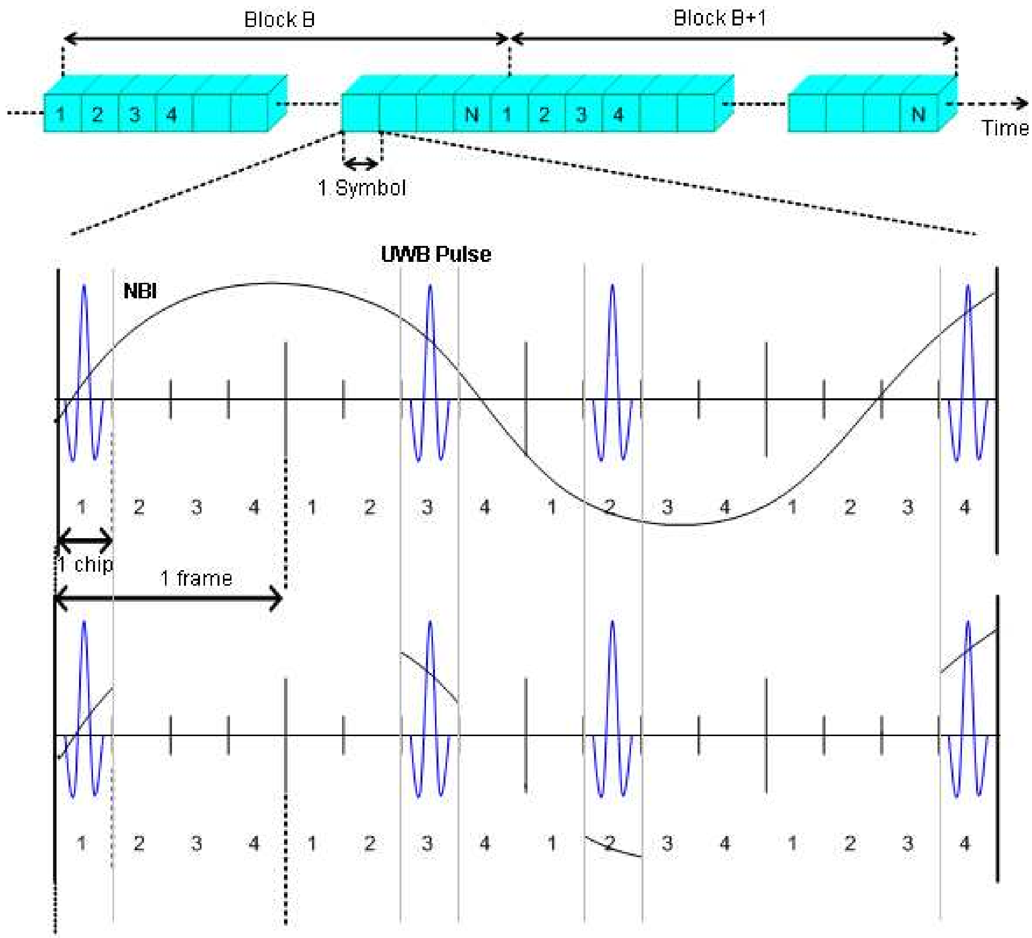

Figure 19. (a) TH-UWB pulses along with a narrowband interferer. (b) Reduced interference power by means of time gating.

as

$$i(t) = \gamma\sqrt{2P_i}cos(2\pi f_c t + \phi_i) \ , \tag{27}$$

where γ is the channel gain, P_i is the average power, f_c is the frequency of the sinusoid, and ϕ_i is the phase.

NBI can also be thought as the effect of a band limited interferer, then the corresponding model is a zero-mean Gaussian random process and its power spectral density is as follows

$$S_i(f) = \begin{cases} P_{int}, & f_c - \frac{B}{2} \leq |f| \leq f_c + \frac{B}{2} \\ 0, & otherwise \end{cases} , \tag{28}$$

where B and f_c are the bandwidth and the center frequency of the interferer, respectively, and P_{int} is the power spectral density.

Since the narrowband signal has a bandwidth much smaller than the coherence bandwidth of the channel, the time domain samples of the NBI are highly correlated with each other. Therefore, for the investigation of the narrowband interferers, the correlation functions are of primary interest, rather than the time- or frequency-domain representations. The correlation functions corresponding to the single tone and band limited cases can be written as

$$R_i(\tau) = P_i\,|\gamma|^2 \cos(2\pi f_c \tau) , \tag{29}$$

$$R_i(\tau) = 2 \cdot P_{int}\, B \cos(2\pi f_c \tau)\, sinc(B\tau) , \tag{30}$$

respectively. The resulting correlation matrices for the kth and lth interference samples are [64]

$$[\mathbf{R_i}]_{k,l} = 4\, N_s P_i\, |\gamma|^2\, |W_r(f_c)|^2 \left[\sin(\pi f_c \delta)\right]^2 \cos\left(2\pi f_c(\tau_k - \tau_l)\right) \tag{31}$$

for the single tone interferer, and

$$\begin{aligned} [\mathbf{R_i}]_{k,l} &= 2\, N_s\, P_{int}\, B\, |W_r(f_c)|^2 \\ &\cdot \Big[\; 2\cos\left(2\pi f_c(\tau_k - \tau_l)\right) sinc\Big(B(\tau_k - \tau_l)\Big) \\ &- \cos\left(2\pi f_c(\tau_k - \tau_l - \delta)\right) sinc\Big(B(\tau_k - \tau_l - \delta)\Big) \\ &- \cos\left(2\pi f_c(\tau_k - \tau_l + \delta)\right) sinc\Big(B(\tau_k - \tau_l + \delta)\Big) \;\Big] \end{aligned} \tag{32}$$

for the case of band limited interference, where $|W_r(f_c)|^2$ is the power spectral density of the received signal at the frequency f_c.

The other strong candidate for UWB communications beside the impulse radio is the multi-carrier approach, which can be implemented using OFDM. OFDM has become a very popular technology due to its special features such as robustness against multipath interference, ability to allow frequency diversity with the use of efficient forward error correction (FEC) coding, capability of capturing the multipath energy, and ability to provide high bandwidth efficiency through the use of sub-band adaptive modulation and coding techniques. OFDM can overcome many problems that arise with high bit rate communications, the most significant of which is the time dispersion. In OFDM, the data bearing symbol stream is split into several lower rate streams, and these streams are transmitted on different carriers. Since this increases the symbol period by the number of non-overlapping carriers, multipath echoes affect only a small portion of the neighboring symbols. The remaining inter-symbol interference (ISI) can be removed by cyclically extending the OFDM symbol. In terms of adapting the transmission parameters, OFDM offers many possibilities. Adapting the transmit power, cyclic prefix size, modulation and coding, and the number of sub-carriers are some of these transmission parameters. In addition to adaptation over each packet (as in the case of single carrier systems), OFDM also offers adaptation of parameters for each carrier or over a small group of carriers. In other words, adaptation can be done independently over narrower bands rather than the entire transmission band.

A strong motivation for employing OFDM in UWB applications is its resistance to narrowband interference, and its ability to turn the transmission *on* and *off* on separate carriers depending on the level of interference. The NBI models that can be considered for OFDM include one or more tone interferers, as well as a zero-mean Gaussian random process that occupies certain carriers along with white noise as

$$S_n(k) = \begin{cases} \frac{N_i+N_w}{2}, & \text{if } k_1 < k < k_2 \\ \frac{N_w}{2}, & \text{otherwise} \end{cases}, \tag{33}$$

where k is the carrier index, K is the total number of carriers, and $\frac{N_i}{2}$ and $\frac{N_w}{2}$ are the spectral densities of the narrowband interferer and white noise, respectively.

3.3 Avoiding NBI

NBI can be avoided at the receiver by properly designing the transmitted UWB waveform. If the statistics regarding the NBI are known, the transmitter can adjust the transmission parameters appropriately. NBI avoidance can be achieved in various ways, and it depends on the type of access technology.

3.3.1 Multi-carrier Approach

Multi-carrier approach can be one way of avoiding NBI. OFDM, which was mentioned in the previous section, is a well known example for multi-carrier techniques. In OFDM based UWB, NBI can be avoided easily by an adaptive OFDM system design. As the simple interference scenario illustrated in Fig. 20 shows, NBI will corrupt only some carriers in OFDM spectrum. Therefore, only the information that is transmitted over these frequencies will be affected from the interference. If the interfered carriers can be identified, transmission over these carriers can be avoided. In addition, by sufficient FEC and frequency interleaving, jamming resistance against NBI can be obtained easily. Avoiding or adapting the transmission over the strongly interfered carriers can provide more spectrum and power efficiency, as they increase the immunity against NBI, and hence relax the FEC coding power requirement.

At the OFDM receiver, the signal is received along with noise and interference. After synchronization and removal of the cyclic prefix, FFT is applied to convert the time-domain received samples to the frequency-domain signal. The received signal at the kth sub-carrier of the nth OFDM symbol can then be written as

$$Y_{n,k} = S_{n,k}H_{n,k} + \underbrace{I_{n,k} + W_{n,k}}_{NBI+AWGN}, \tag{34}$$

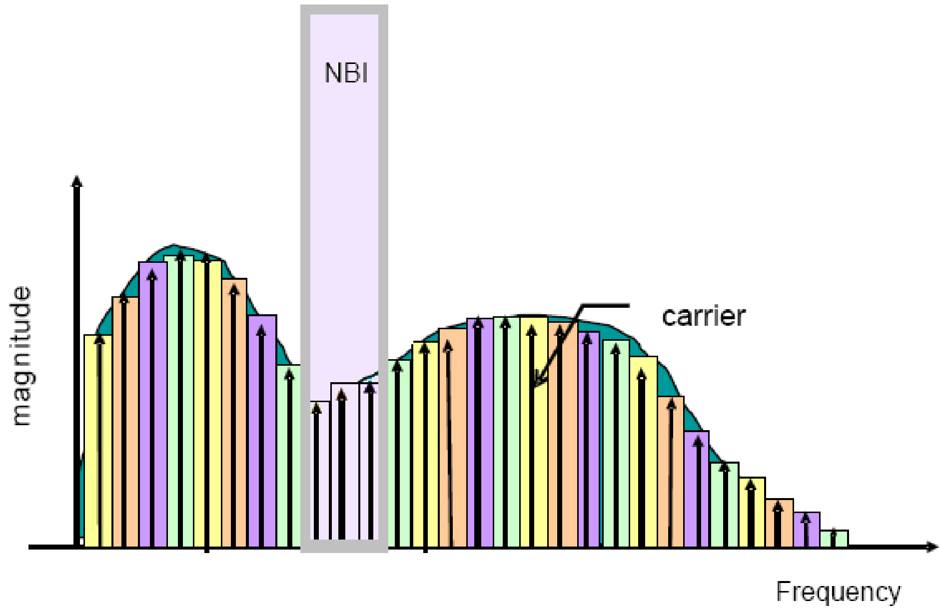

Figure 20. A simple NBI scenario for multi-carrier modulation systems.

where $S_{n,k}$ is the transmitted symbol which is obtained from a finite set (*e.g.* QPSK or QAM), $H_{n,k}$ is the value of the channel frequency response, $I_{n,k}$ is the NBI, and $W_{n,k}$ denotes the uncorrelated Gaussian noise samples. The impairments due to imperfect synchronization, transceiver non-linearities, etc. can be folded into the noise term $W_{n,k}$.

In OFDM, in order to identify the interfered carriers, the transmitter requires a feedback from the receiver. The receiver should have the ability to identify these interfered carriers. Once the receiver estimates these carriers, the relevant information will be sent back to the transmitter. The transmitter will then adjust the transmission accordingly. Note that in such a scenario, the interference statistics need to be constant for a certain period of time. If the interference statistics change very fast, by the time the transmitter receives feedback, and adjusts the transmission parameters, the receiver might observe different interference characteristics.

The feedback information can be various, including the interfered carrier index, in some cases the amount of interference on these carriers, the center frequency of NBI, the bandwidth of NBI, etc. The identification of the interfered carriers can also be various. One

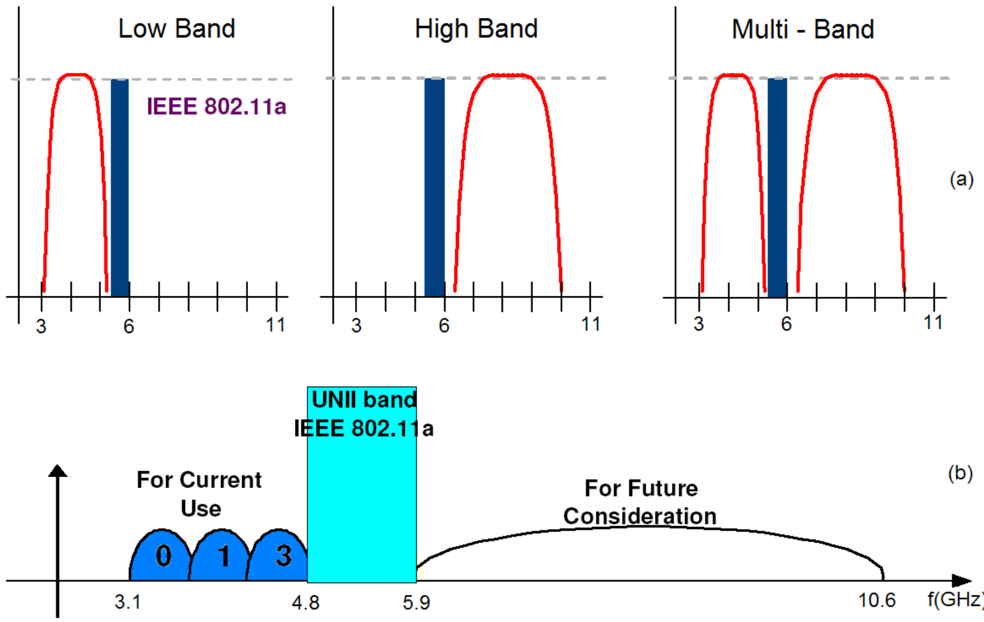

Figure 21. Some proposed multi-band approaches for WPAN: (a) The Xtreme Spectrum-Motorola proposal of a dual-band approach. (b) Multi-band OFDM.

simple technique is to look at the average signal power in each carrier, and compare it with a threshold. If the average received signal power of a subcarrier is greater than the threshold, that channel can be regarded as severely interfered by NBI. Instead of making a hard decision on whether a carrier is interfered or not, soft estimation of NBI power can also be done [65].

3.3.2 Multi-band Schemes

Similar to the multi-carrier approach, multi-band schemes are also considered for avoiding NBI. Rather than employing a UWB radio that uses the entire 7.5 GHz band to transmit information, by exploiting the flexibility of the FCC definition of the minimum bandwidth of 500 MHz, the spectrum can be divided into smaller sub-bands. The combination of these sub-bands can be used freely for optimizing the system performance. By partitioning the spectrum into smaller chunks (which are still larger than 500 MHz), a better coexistence with other current and future wireless technologies can be achieved. This approach will also enable worldwide inter-operability of the UWB devices, as the spectral allocation for UWB could possibly be different in various parts of the world. In multiband systems, information on each of the sub-bands can be transmitted using either single-carrier (pulse-based) or multi-carrier (OFDM) techniques. Fig. 21 shows some representative multiband schemes. The pulse-based approach (as shown in Fig. 21-a) uses dual-band with bandwidths in each band exceeding 1 GHz [66]. The lower band occupies the spectrum from 3.1 GHz to 4.85 GHz, and the upper band occupies the spectrum from 6.2 GHz to 9.7 GHz. The spectrum in between upper and lower bands is not used for UWB transmission, since potential interference sources like IEEE 802.11a operate in this unlicensed band. The OFDM-based multi-band approach (shown in Fig. 21-b) uses 528 MHz channels in each band, where the three lower band channels are for initial deployments and mandatory, and the upper bands are optional and for future use [67]. As the radio frequency technology improves, the upper bands are expected to be included into the system gradually.

3.3.3 Pulse Shaping

Another technique for avoiding narrowband interference is pulse shaping. As can be seen in (31) and (32), the effect of interference is directly related to the spectral characteristics of the receiver template pulse waveform. That means, if the transmission at the frequencies where NBI is present can be avoided, the influence of interference on the received signal can be mitigated significantly. Therefore, designing the transmitted pulse shape properly, such that the transmission at some specific frequencies is omitted, NBI avoidance can be realized. An excellent example for the implementation of this approach is the Gaussian doublet [68]. A Gaussian doublet, representing one bit, consists of a pair of narrow Gaussian pulses with opposite polarities. Considering the time delay T_d between the pulses, the doublet can be represented as

$$s_d(t) = \frac{1}{\sqrt{2}}\Big(s(t) - s(t - T_d)\Big). \tag{35}$$

The corresponding spectral amplitude of the doublet is then

$$|S_d(f)|^2 = 2|S(f)|^2 sin^2(\pi f T_d) \ , \tag{36}$$

where $|S(f)|^2$ is the power spectrum of a single pulse. Notice that due to the sinusoidal term in (36), the power spectrum will have nulls at $f = \frac{n}{T_d}$, where n can be any integer (shown in Fig. 22). The basic idea for avoiding NBI is adjusting the location of these nulls in such a way that they overlap with the peaks created by narrowband interferers. By modifying the time delay T_d, a null can be obtained at the specific frequency where NBI exists, and this way the strong effect of the interferer can be avoided. If T_d is adjusted to 2 ns, for example, the interferences located at the integer multiples of 500 MHz can be suppressed.

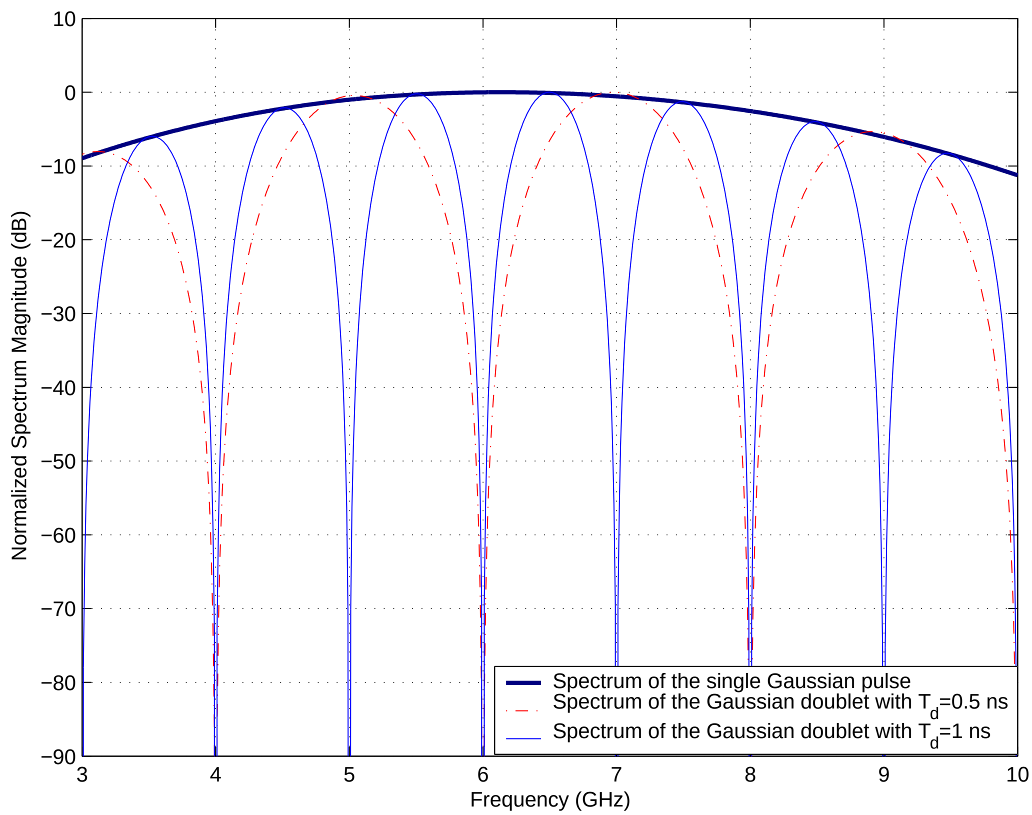

Figure 22. Normalized spectra for the single Gaussian pulse and two different Gaussian doublets.

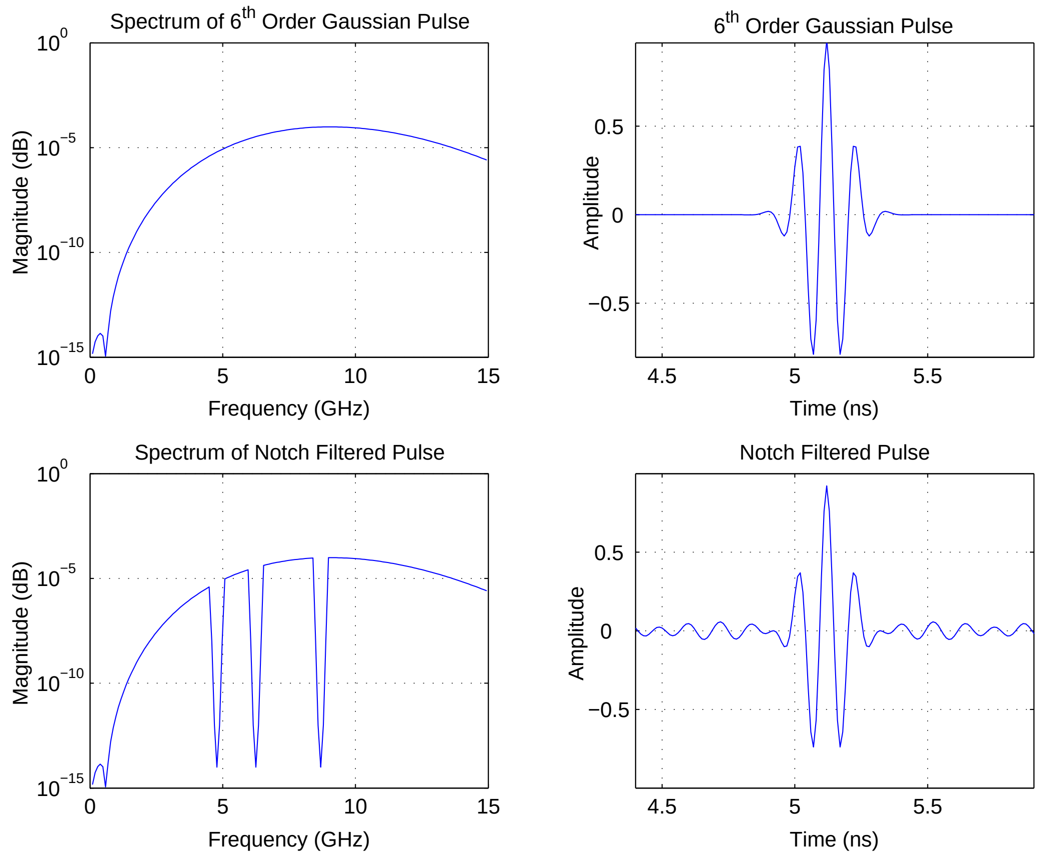

Figure 23. The effect of notch filtering on the transmitted pulse shape.

The purpose of avoiding NBI through abstaining transmission at frequencies of interference can also be carried out by making use of notch filters in the transmitter. To accomplish this, the parameters of the filters have to be adjusted such that the notches they create overlap with the frequencies of strong NBI. When notch filters are employed in the transmitter, the transmitted pulse is shaped in such a way (see Fig. 23) that the correlation of NBI with the pulse template in the receiver is minimized.

Pulse shaping techniques are not limited to the Gaussian doublet and notch filtering. Another feasible method is the adjustment of the PPM modulation parameter δ. Revisiting the correlation matrix for a single tone interferer given in (31), it is seen that $[\mathbf{R_i}]_{k,l} = 0$ for $\delta = n/f_c$, where $n = 1, 2, ..., M$, M being the number of possible pulse positions. Therefore, an effective interference avoidance can be attained by setting δ to n/f_c. Similarly, considering the correlation matrix corresponding to the band limited interference (32), it is seen that $\cos\Big(2\pi f_c(\tau_k-\tau_l\pm\delta)\Big)=\cos\Big(2\pi f_c(\tau_k-\tau_l)\Big)$, when $\delta=n/f_c$. Also, in the light of the knowledge that the bandwidth of the interference (B) is much smaller than its center frequency (f_c), the assumption $sinc\Big(B(\tau_k-\tau_l\pm\delta)\Big)\simeq sinc(B(\tau_k-\tau_l))$ can be made for $\delta=n/f_c$. These two facts lead to the conclusion that $[\mathbf{R_i}]_{k,l}$ in (32) becomes zero for the band limited interference case, too, when δ is set to n/f_c.

Although the adjustment of the PPM modulation parameter δ is a straightforward way of avoiding NBI, it has an important drawback. The correlation output is also dependent on δ, and for a certain value of it a maximum signal correlation can be obtained. However, this value of δ does not necessarily have to be equal to $1/f_c$. For the AWGN case (without considering the NBI), the bit-error-rate function from which the optimum δ can be determined is [69]

$$Q\left(\sqrt{\frac{N_sAE_p}{N_0}R_{opt}}\right)\ , \tag{37}$$

where $R_{opt}=R(0)-R(\delta_{opt})$, N_s is the number of pulses per symbol, A is the pulse amplitude, E_p is the pulse energy, $N_0/2$ is the double sided power spectral density of AWGN, and $R(\Delta t)$ is the autocorrelation function of the received pulse. Therefore, there is an obvious trade-off between maximizing R_{opt} and avoiding NBI, when determining the δ parameter. Depending on the level of NBI and AWGN, this parameter can be adjusted to provide an optimal performance.

3.3.4 Other NBI Avoidance Methods

For the time-hopping UWB systems, it is possible to avoid NBI by placing notches in the spectrum by adjusting the time-hopping code [70]. In [71], a pulse amplitude modulated (PAM) UWB signal is considered. Each symbol has a duration of T_s and is composed of N_s pulses, giving rise to N_s frames, which last for $T_f=T_s/N_s$ and are divided into chips with a duration of T_c. The pseudo-random TH code determines the position of the pulse inside the frame by selecting the chip where to place the pulse. In short, a PAM UWB signal over a symbol duration can be written as

$$u(t) = A \sum_{n=0}^{N_s-1} p(t - c_n T_c - nT_f - T_s) \ , \tag{38}$$

where $A \ \epsilon \ \{-1, 1\}$ denotes the amplitude of the pulse, and c_n is the TH code. In [70], the spectrum shape for the multi-symbol case is given by

$$P_u(f) = |W(f)|^2 \sum_{k=0}^{N_b-1} |T_k(f)|^2 \ , \tag{39}$$

where $W(f)$ is the Fourier Transform of the transmitted pulse, N_b is the total number of different TH codes used, k is the symbol index, and

$$T_k(f) = \sum_{n=0}^{N_s-1} exp(-j2\pi f(c_{n,k}T_c + nT_f + kT_s)) \ . \tag{40}$$

From (40), it is seen that changing the time-hopping code causes the spectrum of the transmitted signal to vary. This means that by employing various methods, the TH code can be adjusted in such a way that spectral notches are created at frequencies of strong NBI, allowing the system to avoid interference.

In addition to the methods mentioned, physical solutions can also be considered for avoiding NBI. In [72], an NBI avoidance technique depending on antenna design is proposed. The main idea is creating frequency notches by intentionally adding a narrowband resonant structure to the antenna, and thus, making it insensitive to some particular frequencies. This technique is more economical than the explicit notch filtering method since it does not require additional notch filters. In [72], a frequency notched UWB antenna suitable to avoid NBI is realized and explained in detail. This special-purpose antenna is obtained by employing planar elliptical dipole antennas and incorporating a half wave resonant structure, which is obtained by implementing triangular and elliptical notches. It is necessary to note that the performance of the antenna is reduced with increasing number of notches. This fact leads to the idea that the frequency notched antenna may not be successful enough in avoiding numerous simultaneously existing narrowband interferers.

3.4 Canceling NBI

Although most of the avoidance methods mentioned seem to have a high feasibility, they may not be implemented under all circumstances. The main limitation on these methods is their dependency on the exact knowledge about narrowband interferers. Without having the accurate information about the center frequency of the interference, suppressing NBI is not possible by means of any of the avoidance techniques explained. Even if the complete knowledge about the NBI is available, if there is an abundant number of interferers, methods like employing notch filters or changing the parameters of the transmitted pulse may lose their practicality. If it is not possible to avoid NBI at the transmission stage because of any reason, one should make effort at the receiver side for extracting and eliminating it from the received signal.

Throughout the previous section, methods of avoiding NBI have been discussed and limitations on their realization have been mentioned. In practice, UWB systems that employ only avoidance techniques are not totally successful in eliminating NBI. In this section, an overview of different types of NBI cancellation methods will be provided.

3.4.1 MMSE Combining

One of the popular receivers considered for UWB is the Rake receiver. Rake receivers are designed to collect the energy of strong multipath components, and with this purpose they employ *fingers*. In each Rake-finger, there is a correlation receiver synchronized with one of the multipath components. The correlation receiver is followed by a linear combiner whose weight is determined depending on the combination algorithm used. The output of the receiver for the i^{th} pulse can be denoted as [59]

$$y_i = \sum_{k=0}^{M-1} d_i c_k \psi \beta_k + c_k n_k \ , \tag{41}$$

where M is the number of Rake-fingers, d_i is the data bit transmitted on the i^{th} pulse, c_k, β_k and n_k are the weight used by the combiner, the channel gain, and the noise for the k^{th} multipath component, respectively, and

$$\psi = \int_{t=-\infty}^{\infty} p_{rx}(t)v(t)dt \ , \tag{42}$$

where $p_{rx}(t)$ denotes the received waveform, and $v(t)$ is the correlating function.

In the traditional Rake receiver, which employs maximal ratio combining (MRC), the weight of the combiner is the conjugate of the gain of the particular multipath component ($c = \beta^*$). Such a selection maximizes the SNR in the absence of NBI. However, when NBI exists, since interference samples are correlated, MRC is no longer the optimum method. Minimum mean square error (MMSE) combining, which is an alternative approach, depends on varying these weights in such a way that the mean square error between the required and actual outputs is minimized. In the existence of interference, the SNR is maximized when MMSE weight vector is used [73]:

$$\mathbf{c} = \alpha \mathbf{R_n}^{-1} \boldsymbol{\beta} \ , \tag{43}$$

where $\mathbf{c} = [c_1 c_2 \ ... \ c_M]^T$, α is the scaling constant, $\mathbf{R_n}^{-1}$ is the inverse of the correlation matrix of noise plus interference, and $\boldsymbol{\beta} = [\beta_1 \ \beta_2 \ ... \ \beta_M]^T$ is the channel gain vector.

The NBI cancellation methods other than MMSE combining can be grouped in three categories as frequency domain, time-frequency domain, and time domain approaches.

3.4.2 Frequency Domain Techniques

Cancellation techniques in the frequency domain can be exemplified by notch filtering in the receiver side. Having an estimation about the frequencies of powerful narrowband interferers, notch filters can be used to suppress NBI. The pleasant fact about this method is that it can be utilized in almost all kind of receivers, so that the UWB system is not forced to employ a correlation based receiver. The main weakness of frequency domain methods, on the other hand, is that they are useful only when the received signal, which is a superposition of the UWB signal and NBI from various sources, exhibits stationary behavior. If the received signal has a time-varying nature, methods that analyze the frequency content taking the temporal changes into account are required. These methods are called the time-frequency approaches.

3.4.3 Time-Frequency Domain Techniques

The most commonly employed time-frequency domain method for interference suppression is the wavelet transform. Similar to the well-known Fourier transform, the wavelet transform also employs basis functions, and expresses any time domain signal as a combination of them. However, these basis functions, which are called wavelets, are different from the complex exponentials used by the Fourier transform in the sense that they are not time unlimited. Hence, the wavelet transform is able to represent the time local characteristics of signals, and is not limited to stationary signals like the Fourier transform. A wavelet is defined as

$$\psi_{ab}(t) = \frac{1}{|\sqrt{a}|}\psi(\frac{t-b}{a}) \ , \tag{44}$$

where a and b are the scaling and shifting parameters, respectively. If these parameters are set as $a = 1$ and $b = 0$, the mother wavelet is obtained. By dilating and shifting the mother wavelet, a family of daughter wavelets are formed. The continuous wavelet transform can be expressed as

$$W(a, b) = \int_{-\infty}^{+\infty} f(t)\psi_{ab}(t)dt \ . \tag{45}$$

The version of the wavelet transform that is appropriate for computer implementation is the discrete wavelet transform (DWT), which is defined as [45]

$$d_{m,n} = \frac{1}{\sqrt{a_0^m}} \int f(t)\psi(\frac{t}{a_0^m} - nb_0)dt \ , \tag{46}$$

where m and n are integers.

Computers realize the DWT not by using wavelets, but employing filters. An effective algorithm for performing DWT based on using filters was proposed by Mallat [74]. The Mallat algorithm results in a detailed analysis, in which the lowest frequency component is expressed with the smallest number of samples, whereas the largest number of samples express the highest frequency component.

One possible way of suppressing the narrowband interference using the wavelet transform is to have the transmitter part of the UWB system estimate the electromagnetic spectrum, and set a proper threshold for interference detection [75]. The interference level at each frequency component is then determined with the wavelet transform, and compared to this threshold in order to distinguish between the interfered and not interfered frequency components. According to the results of this comparison step, the transmitter does not transmit at frequencies where strong NBI exists. Obviously, this method is quite similar to the multi-carrier approach in NBI avoidance techniques.

Methods employing the wavelet transform in the receiver side of the system also exist [76,77]. In these methods, wavelet transform is applied to the received signal, and frequency components with a considerably high energy are considered to be affected by narrowband interference. These components are then suppressed by using conventional methods like notch filtering.

Although the discrete wavelet transform is a very useful tool for eliminating NBI, the inability of current ADCs to sample the UWB signals at the Nyquist rate sets a practical limit to the feasibility of this method. Therefore, the effectiveness of DWT at the frame-rate and symbol-rate sampling has to be investigated thoroughly to be able to decide about the usefulness of this approach with the existing technology.

3.4.4 Time Domain Techniques

The third group of NBI cancellation methods is the time domain approaches, which can also be called predictive methods. Predictive methods are based on the assumption that the predictability of narrowband signals is much higher than the predictability of wideband signals, because wideband signals have a nearly flat spectrum [29]. Hence, in a UWB system, a prediction of the received signal is expected to primarily reflect the narrowband interference rather than the UWB signal. This fact leads to the consequence that NBI can be cancelled by subtracting the predicted signal from the received signal.

Predictive methods can be classified as linear and non-linear techniques. Linear techniques employ transversal filters in order to get an estimate of the received signal depending on the previous samples and model assumptions [36]. If one-sided taps are used, the filter employed is a linear prediction filter, whereas it is a linear interpolation filter if the taps are double-sided. It is worth to note that interpolation filters proved to be more effective in cancelling NBI.

Common examples for linear predictive methods are the Kalman-Bucy prediction, which is based on the Kalman-Bucy filter with infinite impulse response (IIR), and Least-Mean-Squares (LMS) algorithm based on a finite impulse response (FIR) structure.

Non-linear methods are found to provide a better solution than linear ones for direct-sequence (DS) systems because they are able to make use of the highly non-Gaussian structure of the DS signals [29]. However, for UWB systems, this is not the case because such a non-Gaussianity does not exist in UWB signals.

Adaptive prediction filters are considered as a powerful tool against NBI. When an interferer is detected in the system, the adaptation algorithm creates a notch to suppress the interference caused by this source. However, if the interferer vanishes suddenly, since there is no mechanism to respond immediately to remove the notch created, the receiver continues to suppress the portion of the wanted signal around the notch. If narrowband interferers enter and exit the system in a random manner, this shortcoming reduces the performance of the adaptive system dramatically. A more useful algorithm is proposed in [36], where a hidden-Markov model (HMM) is employed to keep track of the interferers entering and exiting the system. In this algorithm, the frequency locations where an interferer is present are detected by an HMM filter, and a suppression filter is put there. When the system detects that the interferer has vanished, the filter is removed automatically.

3.5 Conclusion

In this chapter, an overview of narrowband interference in UWB systems is given. The significance of the NBI problem for UWB systems has been discussed, different models for NBI have been analyzed, and the effects of NBI on UWB communications have been addressed. Methods of dealing with NBI have been examined under two separate categories as NBI avoidance and NBI cancellation algorithms. NBI avoidance methods including multi-carrier approaches and multi-band schemes, as well as alternative solutions based on pulse shaping, time-hopping code adjustment, and antenna design have been investigated. Among the cancellation techniques, details of MMSE combining algorithm are presented. Frequency domain techniques such as notch filtering, time-frequency methods like wavelet transform and time domain approaches, particularly linear techniques, have been discussed in separate sections.

As of now, none of the avoidance or cancellation methods has proved to be the optimum solution to the NBI problem. It seems that the most inexpensive and successful way of suppressing NBI can be achieved by employing an adaptive method combining the avoidance and cancellation approaches. The UWB communications can be initially started by applying the proper avoidance methods in the transmitter side, then in the light of the feedback provided by the receiver, the effectiveness of interference excision can be determined, and if it is found that the interferers can not be suppressed satisfactorily, NBI cancellation methods can be run in the receiver side of the system. Considering that the computational burden related to the cancellation methods is generally much higher than avoidance methods, such an adaptive approach can be very useful in terms of wise usage of resources.

CHAPTER 4

COGNITIVE RADIO

In this chapter, the cognitive radio concept is introduced, and the objectives aimed with cognitive radio are addressed. Spectrum opportunity is defined, and it is investigated how to sense the spectral opportunities. Different spectrum shaping approaches in the literature are provided, and an alternative method based on the usage of raised cosine filters is proposed.

4.1 Introduction

Traditional communication system design is based on allocating fixed amounts of resources to the user. Adaptive design methodologies, on the other hand, typically identify the requirements of the user, and then allocate just enough resources, thus enabling more efficient utilization of system resources and consequently increasing capacity. Pushing the adaptive system design further by introducing advanced attributes such as multi-dimensional awareness, sensing, as well as learning from its experiences to reason, plan, and decide future actions to meet user needs leads to the *cognitive radio* concept. Ignited by the earlier work of Mitola [1], cognitive radio is a novel concept for future wireless communications, and it has been gaining significant interest among the academia, industry, and regulatory bodies [78].

Even though there is no consensus on the formal definition of cognitive radio, the concept has evolved recently to include various meanings in several contexts. One of its main aspects is related to autonomously exploiting locally unused spectrum to provide new paths to the spectrum access. Other aspects include

- inter-operability across several networks,
- roaming across borders, while being able to stay in compliance with local regulations,

- adapting the system, transmission, and reception parameters without user intervention,
- having the ability to understand and follow actions and choices of the users,
- and learning over time to become more responsive and to anticipate the user needs.

Cognitive radio concept proposes to furnish the radio systems with the abilities to measure and be aware of parameters related to the radio channel characteristics, availability of spectrum and power, interference and noise temperature, available networks, nodes, and infrastructures, as well as local policies and other operating restrictions. The primary advantage targeted with these features is to enable the cognitive systems to utilize the available spectrum in the most efficient way.

The organization of the chapter is as follows. In Section 4.2, opportunity is defined, and opportunistic spectrum usage is investigated. In Section 5.2, a cognitive UWB-OFDM system is proposed, and the details regarding its implementation are explained. Finally, in Section 4.5, conclusions and possible future research topics are given.

4.2 Opportunistic Spectrum Usage

Conventionally, frequency spectrum allocation for radio systems has been done in the form of licensing different frequency bands to separate applications. In this procedure, a licensed user possesses the absolute ownership of the spectrum it is allocated, and the spectrum can not be offered to the usage of other potential users, even if the licensed user is temporarily not making use of it. Therefore, the static frequency allocation leads to a highly poor utilization of the spectrum. It has been shown by the Spectrum Policy Task Force (SPTF) of the FCC that many licensed frequency bands are not being used for long durations [79]. Also, a recent experiment conducted in New York, United States in September 2004 revealed that the average duty cycle of the spectrum between 30 MHz and 3 GHz was only 13% [80].

Cognitive radio initiates a revolution regarding the spectrum allocation considerations by putting forward a new concept called opportunistic spectrum usage, which involves the soft usage of the current licensed and unlicensed available spectrum. This concept proposes that licensed bands can be utilized by secondary users at times when they are not being used by their owners, leading to the most efficient exploitation of the entire spectrum. In this opportunistic way of spectrum usage, it has to be guaranteed by the unlicensed systems that their operation does not affect the primary users. Although this approach is similar to the UWB from the point that both are unlicensed, there are two main differences between the opportunistic usage and UWB. First, UWB systems are forced to occupy a band of at least 500 MHz width, which is not the case for the opportunistic usage; and second, for UWB communications there is a strict transmit power limitation, whereas in opportunistic usage the transmitted power can be comparable to the power of licensed systems.

A solid understanding of the opportunistic spectrum usage concept requires that *opportunity* is defined clearly. Cognitive radios periodically scan the spectrum and detect the spectra that are temporarily not being used by their licensed users, which can be called *white bands*. In many works, white bands are directly taken as the spectrum opportunities. However, there are spectral, temporal and spatial requirements that a white band has to satisfy in order to be useful and to be considered an opportunity [81,82]. These requirements can be listed as follows.

- Opportunity is not an instantaneous white space in spectrum. It is necessary to monitor a white space continuously over a time frame (in the order of seconds) and ensure that it does not display an erratic behavior, i.e. for a reasonably long time the noise temperature in that band resides below a certain threshold, and the band remains as a white space.

- It may not be reliable to consider a white band an opportunity if it is detected by only one single cognitive radio device. The reasons include that the device has a limited sensing range, as well as that it may be experiencing shadowing. Optimally, the spectrum has to be sensed by a number of cognitive nodes over a region that goes well beyond the range of a single cognitive device. A band can be considered a candidate for being a spectrum opportunity only if it is detected as white by many cognitive nodes at different locations that exchange the spectrum sensing information with each other.

- If a frequency band to be utilized is too narrow, it may be hard for the cognitive radio to generate a temporally limited pulse shape that fits into that band. Therefore, a white band has to be wider than a certain bandwidth for being targeted for opportunistic spectrum usage.

Apparently, these rules are required to minimize the risk of causing interference to licensed systems. Beside this, such an opportunity definition is optimum from the point of minimizing the computational burden, as well, because it saves a cognitive radio from doing computations and changing its parameters without ensuring the dependability of a white band.

4.3 Sensing the Spectrum Opportunities

As it has been made clear in the previous section, an unavoidable requirement for using the spectrum in an opportunistic way is that the cognitive radio periodically scans the frequency spectrum. An important concern about spectrum sensing is about how to set the boundaries of the spectrum targeted by cognitive radio. Considering the extreme abundance of frequency spectra that may contain white bands, it is obvious that even in the case of cognitive radio communications, which is conceptualized to remove the borders around open spectrum access, the targeted spectrum should be limited. Among the numerous reasons, the primary ones are that this way

- It can be possible to sample the received signal (after the down-conversion) at or above the Nyquist rate even with the current technology, which enables digital processing of the signal.

- The computational burden associated with spectrum sensing can be restricted to a reasonable level, leading to limited hardware complexity.

- The analog front-end required for a very wide spectrum scan (including a wideband antenna, wideband amplifiers and mixers), which have a rather high cost, can be avoided.

- It can be prevented that a single type of cognitive radio occupies the majority of the bands that are open to opportunistic usage.

The spectrum allocation for different types of cognitive radios (like mobile phones, WLAN modems, and palm devices) can be done by regulatory agencies such as the FCC depending on the intended range and the throughput requirement of the specific application. From this point of view, high data rate cognitive radios aiming at wide range applications such as TV broadcast systems should be assigned wider target spectra at lower frequency bands, whereas relatively low date, short range communication devices like cordless phones may be allocated narrower bands at higher frequencies.

In the literature, there is a limited number of methods proposed regarding the implementation of spectral sensing for cognitive radio [2, 83, 84]. At the system level, spectral sensing can be implemented in an individual or distributed manner [85]. In the individual sensing, the cognitive UWB device senses the spectrum by its own means, and depends on this knowledge when making decisions. However, because of the definition of opportunity, it is not the preferred method for sensing. In the distributed sensing, which can be non-centralized or centralized, multiple devices scan the spectrum, and share the gathered information with each other. In non-centralized spectrum sensing, it is considered to have an allocated control channel to transmit this information [86]. In centralized sensing, on the other hand, it is contemplated to have a central controller that gathers this information, decides for spectrum availability, and allocates distinct bands to different cognitive users [85, 87].

4.4 Spectrum Shaping

A challenging requirement of opportunistic usage is that the cognitive transceiver has to be able to dynamically adapt its transmission parameters to operate over a wide range

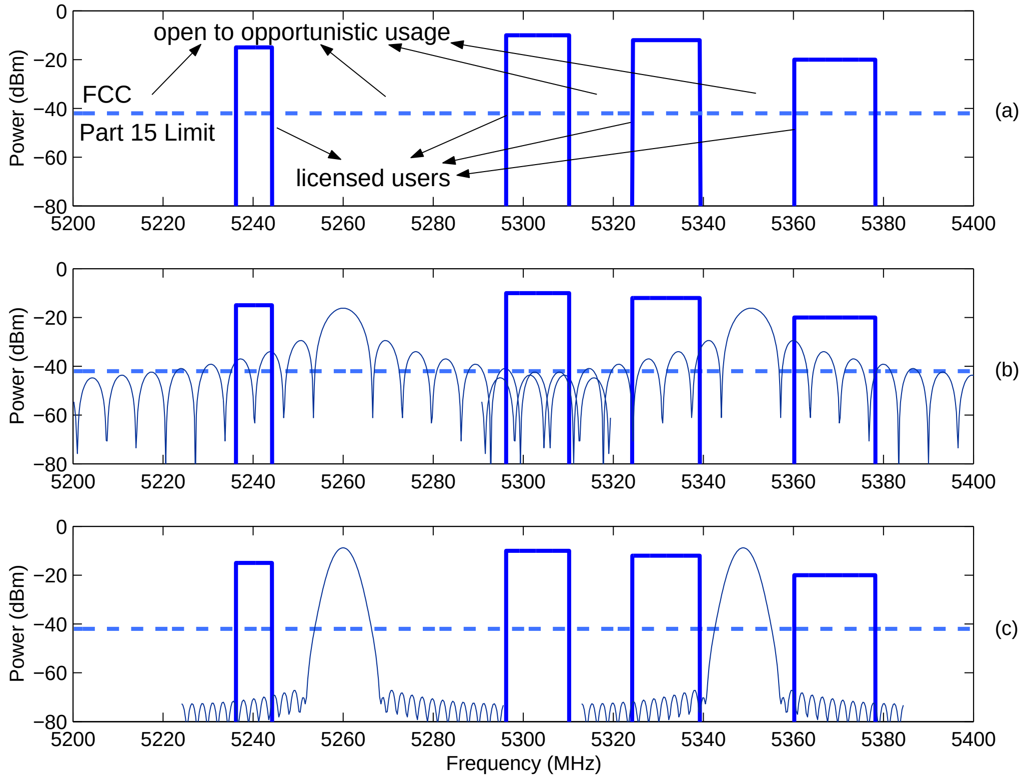

Figure 24. (a) A snap-shot of the spectrum in time. (b) Opportunistic spectrum utilization employing time limited sinusoids. (c) Opportunistic spectrum usage employing special pulses.

of spectrum with different bandwidths, which can be called *spectrum shaping* capability. Spectrum shaping is accomplished by modifying the transmitted power level and the pulse shape in such a way that the spectrum of the pulse fills the detected spectrum opportunities as efficiently as possible. Various methods to implement pulse shaping for cognitive radio are given in [88]- [92].

A possible option for filling the white spaces is to employ OFDM carriers as in the case of UWB-OFDM. OFDM based implementation of spectrum shaping can be found in [88] and [89]. However, when shaping the spectrum of the transmitted pulse, it has to be strictly ensured that the leakage from the opportunity bands to the licensed systems in the adjacent bands remains at a negligible level (illustrated in Fig. 24). If the transmitted pulses are time limited sinusoids (as in the case of OFDM) and no windowing is used, the resulting side lobes may be unacceptably high (see Fig. 25-a). Therefore, it is very important to employ special pulses that

- have sharp fall-offs and suppressed side lobes in the frequency domain
- are limited both in time and bandwidth,
- have a pulse width and bandwidth that can be controlled simultaneously.

Prolate Spheroidal Wavelet Functions (PSWF) satisfy these requirements to a large extent (shown in Fig. 25-d). Spectrum shaping methods employing the PSWF are provided in [90] and [91].

An alternative method for shaping the spectrum of the transmitted pulse is an impulse radio technique. This technique is based on the usage of raised cosine (or root raised cosine) filters, which can be exemplified as in Fig. 25-b (and c). In this method, first, the center frequencies f_{c_i} and bandwidths B_i of each opportunity O_i for $i = 1, 2, ..., N$, are determined, where N is the total number of opportunities. In the next step, making use of its awareness property, the cognitive radio selects the raised cosine filters $r_i(t)$ that are the most suitable for each O_i. Filling a higher percentage of a white space requires a higher roll-off filter, which corresponds to a longer symbol in time, leading to inter-symbol interference or a lower throughput. Hence, the cognitive radio determines the filter to be used according to the amount of available bandwidth and the data rate required. The selected filters are multiplied with digitally generated cosine signals yielding

$$\phi_i(t) = cos(2\pi f_{c_i} t) \cdot r_i(t) \ . \tag{47}$$

$\phi_i(t)$ can be exemplified as in Fig. 26-a,b, and c, which are generated using $r_i(t)$ with roll-off coefficients 0.9, 0.3 and 0.5, respectively. Each of these pulses is filling one of the opportunities in Fig. 26-e. The final pulse shape (demonstrated in Fig. 26-d) is obtained by taking the sum of all these separate pulses

$$p(t) = \sum_{i=1}^{N} \phi_i(t) \ , \tag{48}$$

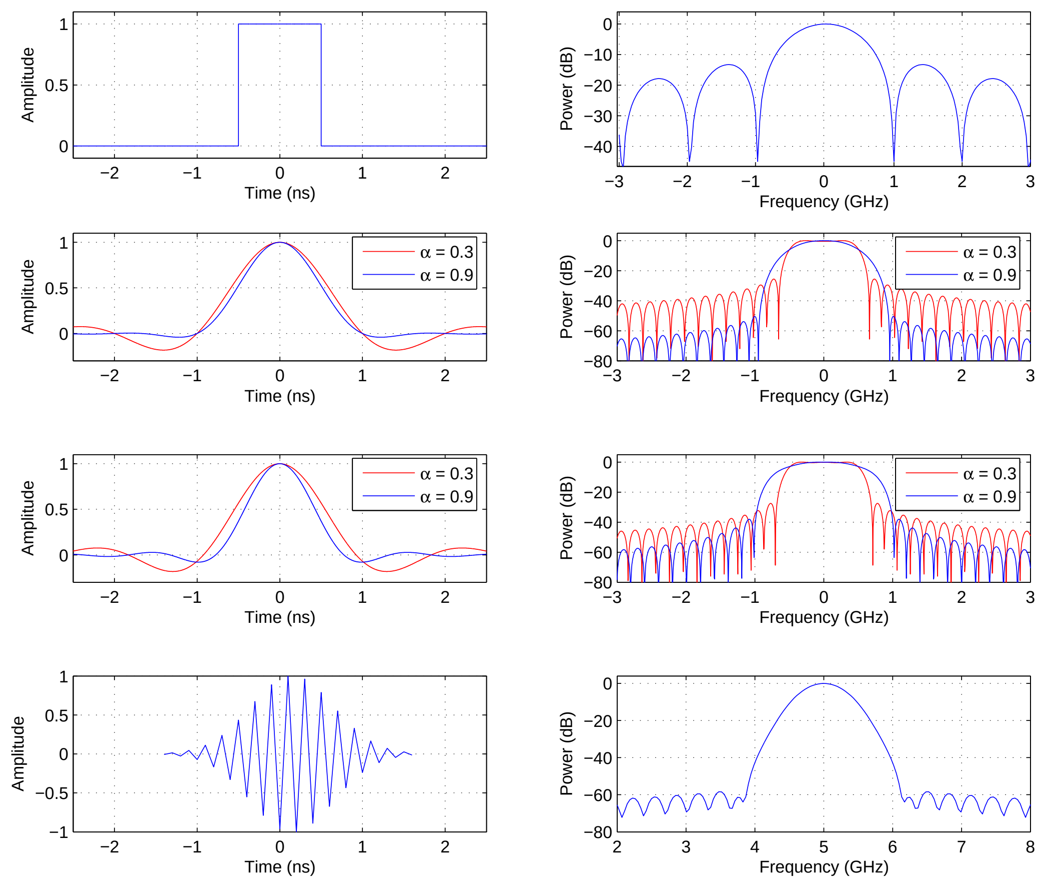

Figure 25. Different pulse shapes and their spectra (a) Rectangular window. (b) Raised cosine windows with roll-off factors $\alpha = 0.3$ and $\alpha = 0.9$. (c) Root raised cosine windows with roll-off factors $\alpha = 0.3$ and $\alpha = 0.9$. (d) A high order prolate spheroidal wavelet function.

and it fills the opportunities as shown in Fig. 26-f.

The current transceivers include an analog front-end, which is mostly fixed for a specific function to operate over a small range of frequencies. Such an analog front-end is not flexible and not programmable. This gives rise to a new concept called software defined radio (SDR), where this fixed analog circuitry needs to be replaced with software programmable hardware [78]. The ideal SDR concept digitizes the received signal as soon as possible so that a flexible radio functionality can be obtained. As can be seen, this is a challenge with the current analog-to-digital-converter (ADC) capabilities and with the processing power

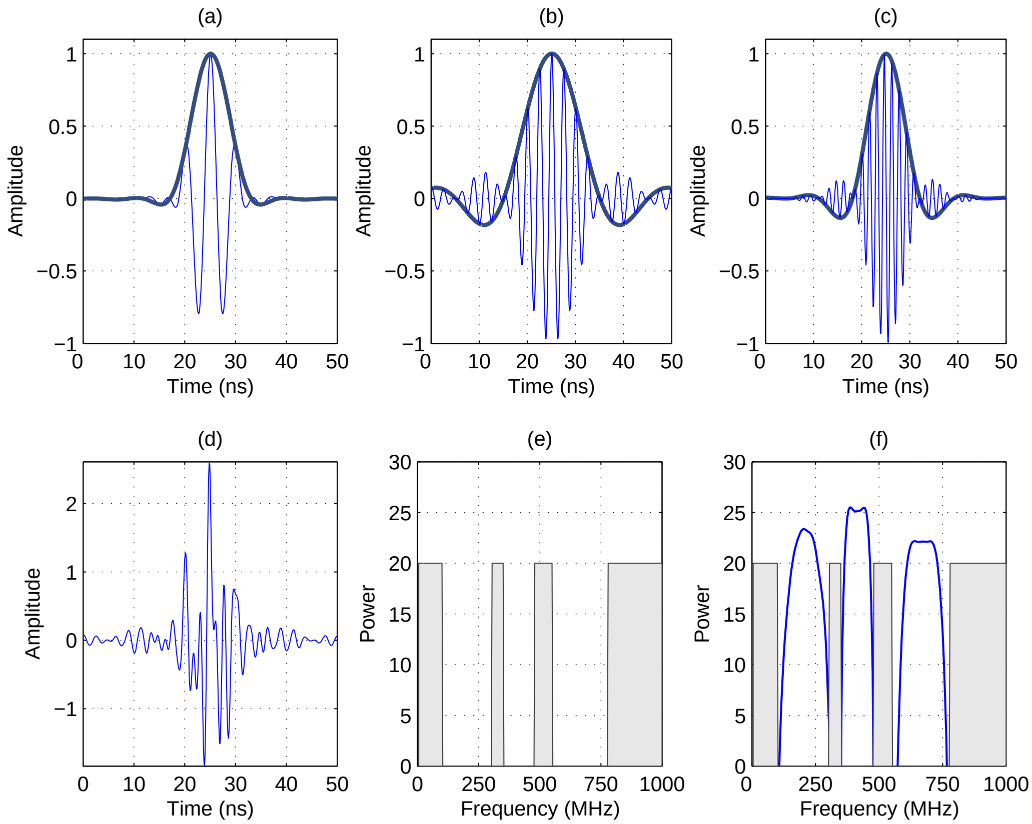

Figure 26. (a), (b), (c) Separate pulses obtained via raised cosine filtering that fit into different opportunities. (d) Sum of the separate pulses. (e) Binary classification of frequency bands as 'occupied' or 'opportunity'. (f) Spectrum of the designed pulse filling the opportunities.

available. Therefore, currently, the new generation wireless systems are slowly integrating a version of this concept.

4.5 Conclusion

In this chapter, the cognitive radio concept is introduced. It is emphasized the concept of opportunity, which is of crucial importance for cognitive radio systems, should have a solid definition, and a detailed definition, that investigates the opportunity from spectral, temporal and spatial perspectives is provided. The opportunity sensing and spectrum shaping features of cognitive radios are discussed and different approaches are addressed. An alternative method for shaping the spectrum of the transmitted pulse is also provided.

CHAPTER 5

COGNITIVE UWB

In this chapter, with the purpose of maximizing the efficiency of unlicensed systems, it is considered to combine UWB with the cognitive radio. Two different methods are proposed; the first one is cognitive UWB-OFDM, and the second one is a cognitive system that shares the spectrum sensing information between its nodes using UWB signaling.

5.1 Introduction

Systems with a spectral allocation similar to UWB are often referred as *underlay* systems. Under the current FCC regulation, underlay systems are allowed to have a very limited transmit power. This severe power limitation on underlay systems restricts their usage to only very short range applications. Hence, all current underlay wireless communication studies both from industry and academy are in the direction of making UWB systems work in an underlay scenario, and aim at wireless personal area networks (WPAN), only.

The main contribution of this chapter is that two different methods of combining underlay UWB with cognitive radio are proposed. The first method is a cognitive UWB-OFDM approach, which supplements the underlay UWB with overlay opportunistic spectrum usage. The potential behavior of the proposed system under many different scenarios is analyzed, in which either UWB-OFDM or opportunistic spectrum usage may be more preferable. In the second method, a cognitive system that shares the spectrum sensing information within its network via ultrawideband is proposed. The range of cognitive communications in this scenario is investigated. Both of these methods aim at increasing the capacity, performance, range, and variety of cognitive communications making use of ultrawideband.

The organization of the chapter is as follows. In Section 5.2, the cognitive UWB-OFDM is introduced. In Section 5.3, a cognitive system that shares the spectrum sensing information via ultrawideband is provided. The practical implementation of this system is explained in detail. The possible range of cognitive communications is investigated. In Section 5.4, a summary of the chapter along with conclusions is provided.

5.2 Cognitive UWB-OFDM

In this section, a cognitive UWB-OFDM system that is capable of switching between UWB and opportunistic spectrum usage, whichever is more advantageous, is considered. In the UWB-OFDM communications that will be investigated in this section, for UWB devices without cognitive capabilities, the power limitations specified with the published spectral masks will remain as they are. For the cognitive UWB radios, however, it is expected that the regulatory agencies provide additional freedom for the transmitted power. A motivating example is the fact that the SPTF has already been considering alternative ways of allocating the spectrum [79]. By raising the power level, it is aimed to free the UWB devices from being restricted to short range applications.

Being able to implement both, cognitive UWB-OFDM systems decide between UWB-OFDM and opportunistic usage according to the conditions. One of the main decision criteria is that UWB-OFDM can make instant changes in the spectrum it occupies by turning on and off some carriers depending on the spectrum usage of licensed systems. Opportunistic usage, on the other hand, requires that a band is scanned by a number of cognitive radios, remains available for a certain time, and satisfies some spectral quality conditions, and therefore, it is not suitable for speedy changes.

Opportunistic usage may be especially attractive for applications that require a high quality-of-service (QoS) because of its high transmit power and wide band usage (relative to narrowband systems). Also, if the available bands, which may be targeted for either UWB-OFDM or opportunistic usage, are at high frequencies, the latter can be a better option because of the higher path loss at these frequencies.

Although, in general, opportunistic usage seems to be more advantageous and desirable than UWB-OFDM, in certain scenarios, such as the ones listed below, cognitive UWB radios may have to select UWB-OFDM.

- If some primary users have a frequency hopping signal, and hence, the spectral conditions are changing very fast, the cognitive radio may not able to keep track of the spectrum opportunities and it can switch to UWB-OFDM.
- If the primary user is time hopping, cognitive radio might need to monitor the spectrum for an extra long time frame and may still not determine the timing sequence, or may be unable to adapt itself to continuously changing spectrum.
- If the primary user is mobile (or steadily moving in a certain area), it may be risky to use the spectrum opportunistically because the communication of the primary system can be easily disturbed. Hence, UWB-OFDM can be employed.
- The bands open to opportunistic usage may be too much divided by narrowband systems (into a number of separated narrow bands), leading to extra long pulses in time. Again, in this case UWB-OFDM can be preferable.
- If numerous licensed users join and leave the spectrum in a frequent manner (like in a GSM band), opportunistic usage may not be feasible.
- Opportunistic usage requires setting a threshold in order to determine whether a certain band is occupied. If the noise floor in a band is changing continuously, it may not be possible to determine a reliable threshold, and UWB-OFDM may be preferred.
- Gray bands (the bands in which the noise temperature is not as low as in the white bands) can be a potential target for UWB-OFDM.
- If the spectrum sensing results from different nodes in a cognitive network do not match to a large extent, this may indicate that either some of the nodes are being shadowed (and can not detect primary users), or the spectrum sensing information

of some nodes can not be transmitted (or detected) correctly. In both cases, as a precaution, switching to UWB-OFDM can be reasonable.

- Even if there is an adequate amount of spectrum open to opportunistic usage, the number of cognitive users that target at this spectrum might be too high, forcing some of these users to switch to UWB-OFDM.

5.3 A Cognitive System Supported by UWB

In this section, a cognitive communications system is considered that utilizes UWB signaling for sharing the spectrum sensing information. As it will be shown, the cognitive system benefits from the processing gain property of UWB in order to increase its range.

The first thing about the cognitive system that will be proposed in this section is that both the transmitter and the receiver have transmission and reception capabilities. In order to match the results of spectrum sensing operation done by both parties, each of them will transmit the information regarding the white spaces they have detected. We propose that the transmission of spectrum sensing results is done via low power UWB signaling that complies with the FCC regulations. Since this transmission will be accomplished in an underlay manner, it can be done simultaneously with the real data communication without affecting each other.

Considering the relatively low throughput needed to transmit the sensing information as well as the low cost transceiver requirement, it turns out to be a proper option to use an uncomplicated non-coherent receiver such as an energy detector, and to employ on-off keying (OOK) modulation. The implementation issues regarding the OOK based energy detector receivers such as estimating the optimal threshold and determining the optimum integration interval, which can be found in [4], were discussed in Chapter 2.

Once both parties of communication receive the spectrum sensing information obtained by the other party, they logically 'AND' the white spaces each of them has detected separately. The reason behind this operation is that frequency bands can be considered available for opportunistic usage only if both parties classify them as white space. Depending on the knowledge about the common white spaces, each party designs a new pulse shape. Since the new pulses designed by both parties will be the same, this method has the very advantageous feature that it enables highly efficient matched filtering during the real data traffic. To be more clear, what the receiving party uses as the template to match the received pulse will be (almost) the same as the transmitted pulse by the other party, leading to a high correlation between them, and hence, to a successful matched filtering.

5.3.1 Steps of Practical Implementation

Steps of practical implementation of opportunistic spectrum usage can be summarized as follows.

- Capturing any signal in the target spectrum (e.g. 2.1-2.3 GHz) by using an appropriate antenna and analog band pass filter
- Analyzing the spectral content of the received signal either by analog means:
  - Sweeping the target spectrum via a mixer and passing the down-converted signal through an IF filter with a narrow pass-band (to obtain an acceptable frequency resolution)
  - Determining the existence of signals inside the target spectrum by using an energy detector that consists of a square law device, an integrator, and a comparator
  - Labeling the binary output of the energy detector as *occupied* or *white space* (see Fig. 26-e)
- or by digital means:
  - Down-converting the signal to an IF frequency
  - Sampling the signal at a rate above the Nyquist rate and digitizing it (applying analog-to-digital conversion)
  - Computing the power spectral density either by taking the Fast Fourier Transform (FFT) and squaring, or by applying more advanced power estimation methods such as Welch's method or Thomson's multitaper method

  - Comparing the obtained power spectral density with a pre-determined power threshold. This way, determining the occupied spectra and the white spaces

- Comparing the bandwidths of the white spaces with a pre-determined minimum bandwidth in order to find out if they are wide enough to be utilized

- Transmitting the information regarding the usable white spaces to the other party via UWB signaling

- Receiving the white space data from the other party

- Finding the common white spaces

- Designing a pulse shape that utilizes as much usable white space as possible

- Initiating the cognitive communication and repeating the entire sensing process at a regular period

5.3.2 Range of Cognitive Communications and Cognitive Networks

In cognitive radio communications, in order to make sure that the intended frequency spectrum is not in use, both parties of communication have to scan the spectrum and inform each other about the spectral conditions. Therefore, there should not be a gap between the sensing ranges of them. If the sensing ranges are not at least partially overlapping, there is always a risk that a licensed user located inside the gap between the sensing ranges is not detected. Therefore, the receiving sensitivity of both parties has an integral role in determining the range of communication. Assuming a rather high sensitivity around $-120dBm$ to $-130dBm$ and free space propagation, in which the transmitted power (P_{tx}) and received power (P_{rx}) are related to each other by the Friis equation (ignoring the system loss and antenna gains)

$$P_{rx} = \frac{P_{tx}\,\lambda^2}{(4\pi)^2\,d^2}\ , \qquad (49)$$

where λ is the wavelength, and d is the distance. With these assumptions, it is seen that the scope of cognitive radio is limited to $50m$ to $150m$, which is comparable to the range of

WLANs. If the targeted range of communications is wider than this level, or if the cognitive devices are experiencing shadowing and are hardly able to detect the existence of licensed users, a network of collaborating cognitive nodes may be an effective solution.

In this part of this section, we focus on a cognitive network (see Fig. 27) whose nodes communicate with each other using UWB to exchange spectrum information. The fact that UWB signaling is proposed may seem to be contradicting with the aim of increasing the range of cognitive radio because of the limited range of UWB. However, looking at the bit error rate (BER) expression for OOK modulated UWB signals

$$Q\left(\sqrt{\frac{N_s A E_p}{2N_0}}\right), \tag{50}$$

where N_s is the number of pulses per symbol, A is the pulse amplitude, E_p is the received pulse energy, and the additive white Gaussian noise (AWGN) has a double sided spectrum of $\frac{N_0}{2}$, it is seen that increasing N_s, which can be accomplished by repeated transmission of data, results in lower BER. This fact leads to a very advantageous feature of UWB called the *processing gain*. By applying the necessary amount of processing gain, it can be made possible that the farthest nodes in a cognitive network can share the spectrum sensing information. Although this comes at the expense of lowered throughput, it is not a limiting factor in this case because a quite low data rate is enough to transmit the spectrum sensing information. By enabling all the nodes in a cognitive network to talk to each other via UWB, there is no need

- either to allocate a separate channel for sharing the sensing information,
- or to employ a centralized controller that collects such information, processes it, and transfers it to other cognitive users.

The sensing information received from all the other nodes in the network can be combined in each node, and pulse design can be done according to the common white spaces.

Increasing the network size results in an increased probability of overlapping with licensed systems. This fact sets a practical limit to the size of the cognitive network, because

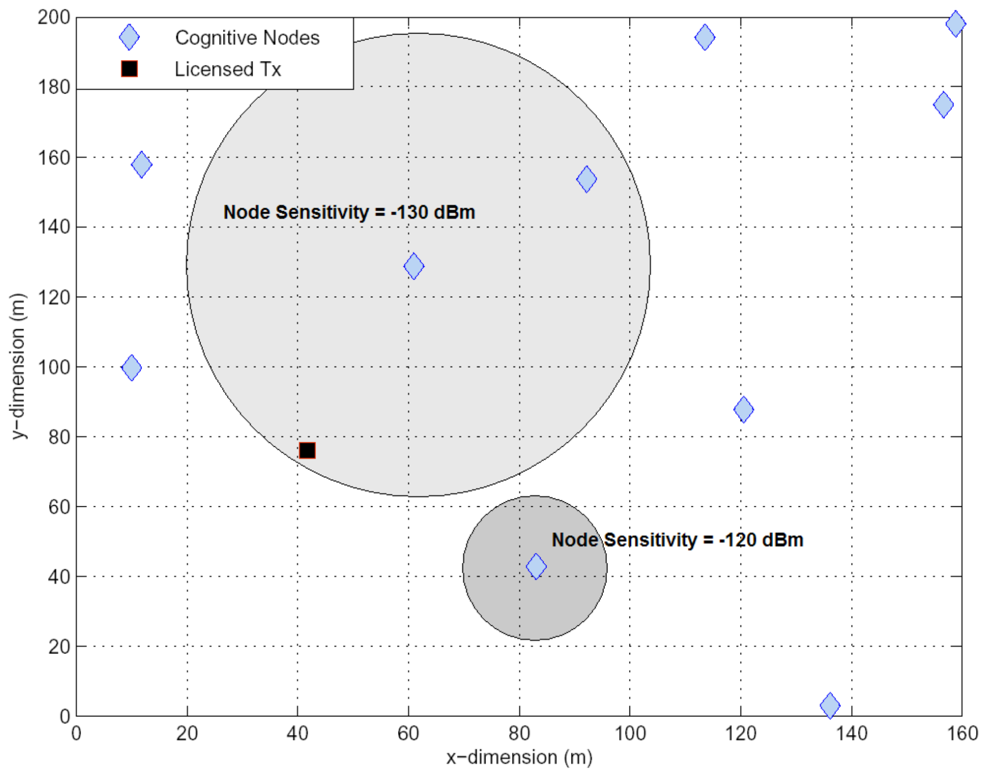

Figure 27. Network of cognitive transceivers (sensitivity ranges are not drawn to scale).

continuing to enlarge the network the common white bands become less and less, and after some point their amount becomes insufficient to ensure the minimum quality-of-service. For the details of how the common white bands are going to be shared by the cognitive nodes in the network, the reader can be referred to [93] and [94].

5.3.3 Numerical Results

Computer analysis and simulations are performed regarding the practical implementation of cognitive radio communications. These are related to the transmission of spectrum sensing results via UWB, the range of cognitive communications, and the capability of a cognitive network to detect a licensed system. In the simulations regarding the UWB signaling, the channel model $CM3$ in [95], which corresponds to an office environment with line-of-sight (LOS), is utilized. The frequency range is 3.1-3.6 GHz, the reference path loss 35.4 dB, the path loss exponent is 1.63, the receiver antenna noise figure is 17 dB, the implementation loss is 3 dB, the throughput is 20 Mbps, and the integration interval is 30ns.

A theoretical analysis was performed to investigate the performance of OOK modulated UWB data transmission depending on the distance between a cognitive transmitter-receiver pair. According to [95], the path loss assumed can be shown as

$$L(d) = L_0 + 10n\, log_{10}(\frac{d}{d_0}), \tag{51}$$

where the reference distance (d_0) is set as $1m$, L_0 is the path loss at d_0, and n is the path loss exponent. The average noise power per bit is

$$N = -174 + 10\, log_{10}(R_b)\ , \tag{52}$$

where R_b is the throughput. In Fig. 28, the effect of distance on the probability of error is demonstrated. The results show that the BERs obtained for up to $40m$ are still acceptable. For further distances, however, some processing gain is definitely needed. The processing gain is obtained by repeated transmission of the same information. A simulation was done that investigates the number of repetitions required in order not to exceed the BER obtained at $40m$, which corresponds to $10^{-3.2}$. The number of repetitions needed vs. the distance is shown in Fig. 29.

A simulation is done to investigate the effect of the number of nodes on the probability of a licensed system being detected by the cognitive network. Fig. 27 demonstrates a network composed of cognitive radio devices. The nodes in the network are randomly distributed in a $200m$x$200m$ area inside a building. It is assumed that there is a licensed transmitter, which is a $GSM900$ cell phone transmitting at $-60dBm$, whose location is random, as well. Depending on the level of the node sensitivity, the number of nodes required to make a reliable detection might vary. The results of this simulation are demonstrated in Fig. 30.

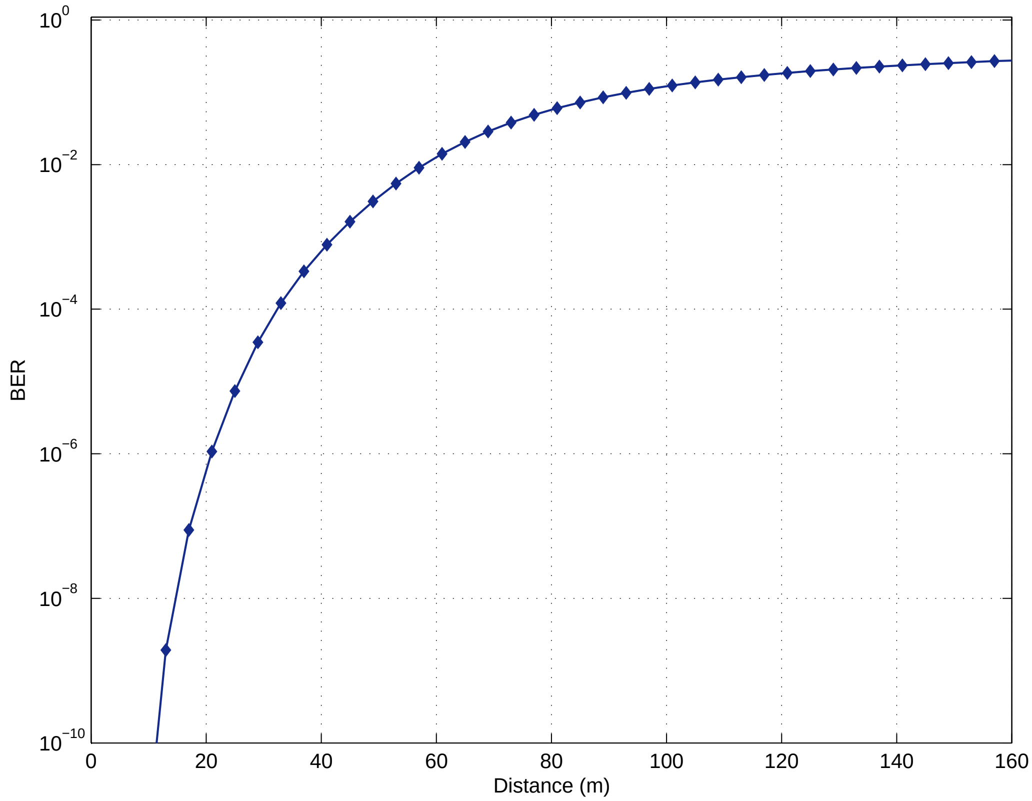

Figure 28. BER vs. distance between the nodes for UWB signaling.

5.4 Conclusion

The continuously increasing need for frequency spectrum requires to increase the efficiency of spectrum usage. Therefore, it is necessary to develop flexible and adaptable radio access technologies that can take advantage of the available spectrum in an opportunistic way.

In this chapter, two different methods for combining UWB with cognitive radio are provided. First, it is shown that the marriage of OFDM based UWB with opportunistic spectrum usage will open the doors for further improvements in spectral efficiency, and bring about concepts that will allow the joint underlay and overlay usage of the spectrum. Although this comes at the expense of increased hardware complexity relative to pure UWB, it is made clear that the advantages of cognitive UWB-OFDM would pay off for this increase. Second, a cognitive system is proposed that benefits from UWB in distributing the spectrum

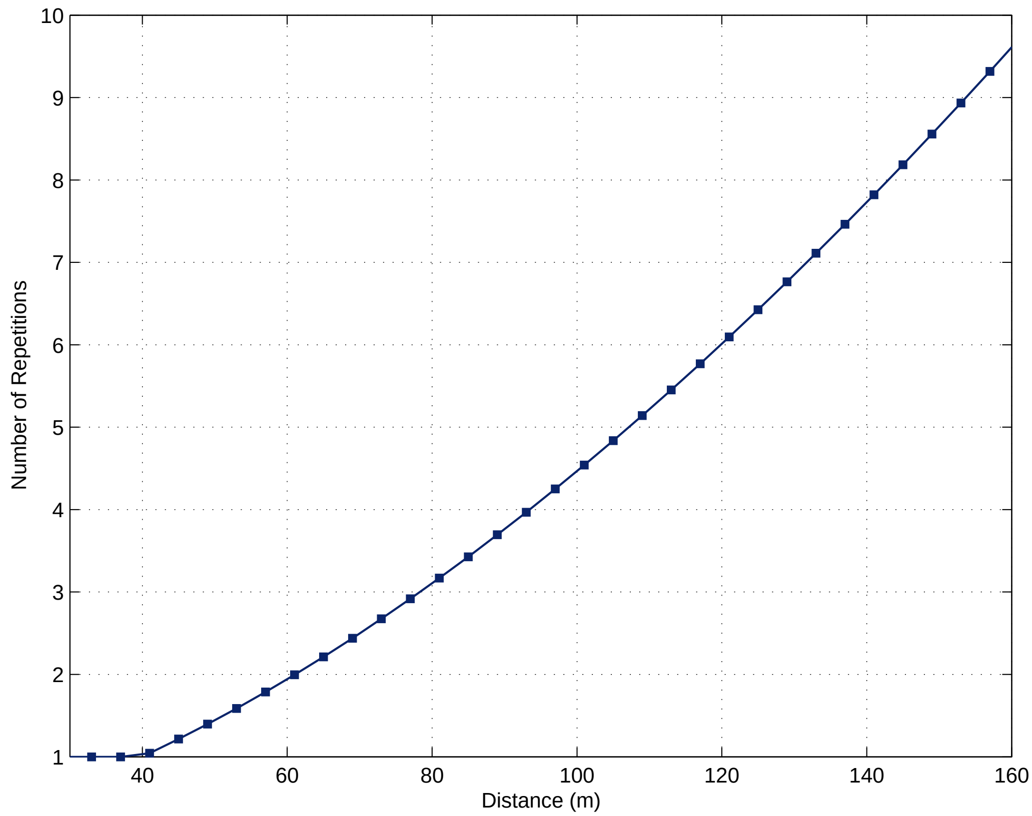

Figure 29. Repetition rate required for reliable UWB signaling vs. distance.

sensing information. It is shown that such a system can make use of the processing gain property of ultrawideband to increase the targeted range of cognitive communications.

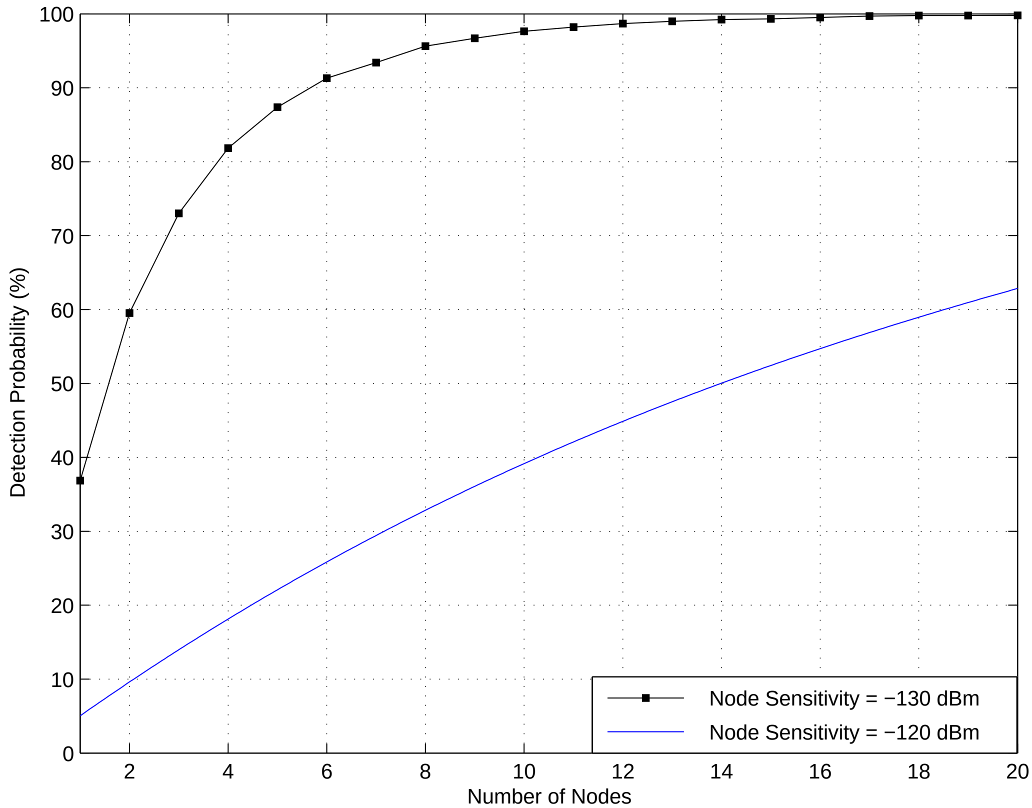

Figure 30. Probability of a licensed transmitter being detected by the cognitive network.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 Summary of Contributions

The thesis focuses on the implementation of ultrawideband and its coexistence with narrowband systems in order to lead towards the realization of the cognitive radio concept. The novel contributions of the thesis can be summarized as follows.

Practical implementation of impulse radio UWB using energy detector receivers:

- The need for the joint adaptation of the integration interval, optimal threshold, and the synchronization point is clearly demonstrated.
- It is shown that threshold estimation can benefit from the computational easiness brought by the Gaussian approximation of received signal statistics, which yields reasonable results for certain bandwidths.
- The inter-symbol interference problem in high data rate UWB systems employing OOK based energy detectors is investigated.
- The increasing negative effect of ISI on the system performance with increasing data rate is demonstrated.
- In order to overcome the ISI problem, a modified energy detector that has a built-in symbol decision mechanism based on decision feedback equalization is proposed.
- A simple but clever way of using training symbols with the purpose of estimating the decision feedback filter coefficients is introduced. It has been proven that the error propagation problem does not exist in the proposed approach.

Coexistence of ultrawideband and narrowband systems; suppressing narrowband interference:

- NBI avoidance methods including multi-carrier approaches and multi-band schemes, as well as alternative solutions based on pulse shaping, time-hopping code adjustment, and antenna design have been investigated.

- Among the cancellation techniques, details of MMSE combining algorithm are presented.

- Frequency domain techniques such as notch filtering, time-frequency methods like wavelet transform and time domain approaches, particularly linear techniques, have been discussed in separate sections.

Opportunistic spectrum usage:

- The concept of opportunity, which is of crucial importance for cognitive radio systems, is defined from spectral, temporal and spatial perspectives.

- The opportunity sensing and spectrum shaping features of cognitive radios are discussed and different approaches are addressed. An alternative method for shaping the spectrum of the transmitted pulse is provided.

Cognitive UWB:

- Combining OFDM based UWB with opportunistic spectrum usage is proposed to improve the spectral efficiency and to bring about concepts that will allow the joint underlay and overlay usage of the spectrum.

- A cognitive system is proposed that benefits from UWB in distributing the spectrum sensing information. It is shown that such a system can make use of the processing gain property of ultrawideband to increase the targeted range of cognitive communications.

6.2 Conclusions

UWB, OFDM, and cognitive radio are terms that the wireless community has already been heavily exposed to over the recent years. It is anticipated that in the near future, the wireless community will be encountering that these terms are mentioned jointly in the context of the spectrum efficiency and opportunistic spectrum usage. In the light of this expectation, in this thesis, details of practical UWB implementation are given. The cognitive radio concept is introduced, and its requirements and objectives are explained in detail. It is shown that UWB can coexist with narrowband systems by utilizing NBI avoidance and cancelation methods, and hence, it is proven that UWB is a very appropriate candidate both for implementing or supporting cognitive radio. Two separate applications as case studies in which cognitive radio is combined with ultrawideband are provided. The first case study is an example of how UWB can be employed as a means of implementing cognitive radio, whereas the second one demonstrates how UWB can supplement a cognitive radio system. By providing these applications, it is aimed to open the doors for the marriage of UWB with cognitive radio and to motivate wireless communications researchers to involve UWB in their cognitive radio studies.

REFERENCES

[1] J. Mitola, "Cognitive radio for flexible mobile multimedia communications," in *Proc. Mobile Multimedia Commun. (MoMuC '99)*, Nov. 1999, pp. 3–10.

[2] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE J. Select. Areas Commun.*, vol. 23, no. 2, pp. 201–220, Feb. 2005.

[3] S. Mangold, Z. Zhong, K. Challapali, and C.-T. Chou, "Spectrum agile radio: radio resource measurements for opportunistic spectrum usage," in *Proc. IEEE Global Telecomm. Conf. (GLOBECOM)*, vol. 6, Dallas, TX, Dec. 2004, pp. 3467 – 3471.

[4] M. E. Sahin, I. Guvenc, and H. Arslan, "Optimization of energy detector receivers for UWB systems," in *Proc. IEEE Vehic. Technol. Conf.*, vol. 2, Stockholm, Sweden, May 2005, pp. 1386–1390.

[5] M. E. Sahin and H. Arslan, "Inter-symbol interference in high data rate UWB communications using energy detector receivers," in *Proc. IEEE Int. Conf. on Ultra-Wideband*, Zurich, Switzerland, Sep. 2005, pp. 176–179.

[6] H. Arslan and M. E. Sahin, *Ultra Wideband Wireless Communications*. Hoboken, NJ: John Wiley & Sons, Inc., 2006, chapter Narrowband Interference Issues in Ultrawideband Systems, to be published.

[7] ——, "Cognitive UWB-OFDM: Pushing ultrawideband beyond its limit via opportunistic spectrum usage," *Journal on Commun. Networks (JCN)*, June 2006, to appear.

[8] M. Weisenhorn and W. Hirt, "Robust noncoherent receiver exploiting UWB channel properties," in *Proc. IEEE Ultrawideband Syst. Technol. (UWBST)*, Kyoto, Japan, May 2004, pp. 156–160.

[9] A. Rabbachin and I. Oppermann, "Synchronization analysis for UWB systems with a low-complexity energy collection receiver," in *Proc. IEEE Ultrawideband Syst. Technol. (UWBST)*, Kyoto, Japan, May 2004, pp. 288–292.

[10] P. A. Humblet and M. Azizoglu, "On the bit error rate of lightwave systems with optical amplifiers," *J. of Lightwave Technology*, vol. 9, no. 11, pp. 1576–1582, Nov. 1991.

[11] J. Foerster, "IEEE P802.15 working group for wireless personal area networks (WPANs), channel modeling sub-committee report - final," Mar. 2003. [Online]. Available: http://www.ieee802.org/15/pub/2003/Mar03/.

[12] B. Mielczarek, M. Wessman, and A. Svensson, "Performance of coherent uwb rake receivers with channel estimators," in *Proc. IEEE Vehic. Technol. Conf.*, vol. 3, Orlando, FL, Oct. 2003, pp. 1880–1884.

[13] S. Paquelet, L. M. Aubert, and B. Uguen, "An impulse radio asynchronous transceiver for high data rates," in *Proc. IEEE Ultrawideband Syst. Technol. (UWBST)*, Kyoto, Japan, May 2004, pp. 1–5.

[14] J. Proakis, *Digital Communications*, 4th ed. New York: McGraw-Hill, 2000.

[15] V. Lottici, A. D'Andrea, and U. Mengali, "Channel estimation for ultra-wideband communications," *IEEE J. Select. Areas Commun.*, vol. 20, no. 9, pp. 1638–1645, Dec. 2002.

[16] N. F. Krasner, "Efficient search methods using energy detectors–maximum probability of detection," *IEEE J. Select. Areas Commun.*, vol. 4, no. 2, pp. 273–279, March 1986.

[17] A. Rajeswaran, V. Somayazulu, and J. Foerster, "RAKE performance for a pulse based UWB system in a realistic UWB indoor channel," in *IEEE Int. Conf. Commun. (ICC)*, vol. 4, Anchorage, AK, May 2003, pp. 2879 – 2883.

[18] A. Klein, I. Brown, D.R., D. Goeckel, and J. Johnson, C.R., "RAKE reception for UWB communication systems with intersymbol interference," in *IEEE Workshop on Signal Proc. Advances Wireless Commun. (SPAWC 2003)*, Rome, Italy, June 2003, pp. 244 – 248.

[19] X. Peng, F. Chin, and A. Madhukumar, "Performance studies of an over-sampling multi-channel equalizer for a multi-band UWB system," in *Proc. IEEE Ultra Wideband Syst. Technol. (UWBST)*, Reston, VA, Nov. 2003, pp. 413 – 417.

[20] A. Duel-Hallen and C. Heegard, "Delayed decision-feedback sequence estimation," *IEEE Trans. Commun.*, vol. 37, no. 5, pp. 428 – 436, May 1989.

[21] R. Johnk, D. Novotny, C. Grosvenor, N. Canales, and J. Veneman, "Time-domain measurements of radiated and conducted UWB emissions," *IEEE Aerospace and Electron. Syst. Mag.*, vol. 19, no. 8, pp. 18–22, Aug 2004.

[22] J. Foerster, "Ultra-wideband technology enabling low-power, high-rate connectivity (invited paper)," in *Proc. IEEE Workshop Wireless Commun. Networking*, Pasadena, CA, Sep. 2002.

[23] J. R. Foerster, "The performance of a direct-sequence spread ultra-wideband system in the presence of multipath, narrowband interference, and multiuser interference," in *Proc. IEEE Vehic. Technol. Conf.*, vol. 4, Birmingham, AL, May 2002, pp. 1931–1935.

[24] J. Choi and W. Stark, "Performance of autocorrelation receivers for ultra-wideband communications with PPM in multipath channels," in *Proc. IEEE Ultrawideband Syst. and Technol. (UWBST)*, Baltimore, MD, May 2002, pp. 213 –217.

[25] W. Tao, W. Yong, and C. Kangsheng, "Analyzing the interference power of narrowband jamming signal on UWB system," in *Proc. IEEE Personal, Indoor, Mobile Radio Commun. (PIMRC)*, Singapore, Sep. 2003, pp. 612–615.

[26] L. Zhao and A. Haimovich, "Performance of ultra-wideband communications in the presence of interference," *IEEE J. Select. Areas Commun.*, vol. 20, pp. 1684–1691, Dec. 2002.

[27] G. Durisi and S. Benedetto, "Performance evaluation of TH-PPM UWB systems in the presence of multiuser interference," *IEEE Commun. Lett.*, vol. 7, no. 5, pp. 224–226, May 2003.

[28] R. Tesi, M. Hamalainen, J. Iinatti, and V. Hovinen, "On the influence of pulsed jamming and coloured noise in UWB transmission," in *Proc. Finnish Wireless Commun. Workshop (FWCW)*, Espoo, Finland, May 2002.

[29] X. Wang and H. V. Poor, *Wireless Communication Systems: Advanced Techniques for Signal Reception.* 1st ed., Prentice Hall, 2004.

[30] D. Zhang, P. Fan, and Z. Cao, "Interference cancellation for OFDM systems in presence of overlapped narrow band transmission system," *IEEE Consum. Electron.*, 2004.

[31] J. Choi and N. Cho, "Narrow-band interference suppression in direct sequence spread spectrum systems using a lattice IIR notch filter," in *Proc. IEEE Int. Conf. Acoustics, Speech, Signal Processing (ICASSP)*, vol. 3, Munich, Germany, April 1997, pp. 1881–1884.

[32] L. Rusch and H. Poor, "Narrowband interference suppression in CDMA spread spectrum communications," *IEEE Personal Commun. Mag.*, vol. 42, pp. 1969–1979, Apr. 1994.

[33] ——, "Multiuser detection techniques for narrowband interference suppression in spread spectrum communications," *IEEE Trans. Commun.*, vol. 42, pp. 1727–1737, Apr. 1995.

[34] J. Proakis, "Interference suppression in spread spectrum systems," in *Proc. IEEE Int. Symp. on Spread Spectrum Techniques and Applications*, vol. 1, Sep. 1996, pp. 259–266.

[35] L. Milstein, "Interference rejection techniques in spread spectrum communications," in *Proc. IEEE*, vol. 76, June 1988, pp. 657–671.

[36] C. Carlemalm, H. V. Poor, and A. Logothetis, "Suppression of multiple narrowband interferers in a spread-spectrum communication system," *IEEE J. Select. Areas Commun.*, vol. 18, no. 8, pp. 1365–1374, August 2000.

[37] P. Azmi and M. Nasiri-Kenari, "Narrow-band interference suppression in CDMA spread-spectrum communication systems based on sub-optimum unitary transforms," *IEICE Trans. Commun.*, vol. E85-B No.1, pp. 239–246, Jan. 2002.

[38] T. J. Lim and L. K. Rasmussen, "Adaptive cancellation of narrowband signals in overlaid cdma systems," in *Proc. IEEE Int. Workshop Intel. Signal Processing and Commun. Syst.*, Singapore, Nov. 1996, pp. 1648–1652.

[39] H. Fathallah and L. Rusch, "Enhanced blind adaptive narrowband interference suppression in dsss," in *Proc. IEEE Global Telecommun. Conf. (GLOBECOM)*, vol. 1, London,UK, Nov. 1996, pp. 545–549.

[40] W.-S. Hou, L.-M. Chen, and B.-S. Chen, "Adaptive narrowband interference rejection in DS-CDMA systems: a scheme of parallel interference cancellers," *IEEE J. Select. Areas Commun.*, vol. 20, pp. 1103–1114, June 2001.

[41] P.-R. Chang, "Narrowband interference suppression in spread spectrum CDMA communications using pipelined recurrent neural networks," in *Proc. IEEE Int. Conf. Universal Personal Commun. (ICUPC)*, vol. 2, Oct. 1998, pp. 1299–1303.

[42] H. V. Poor and X. Wang, "Code-aided interference suppression in DS/CDMA spread spectrum communications," *IEEE Trans. Commun.*, vol. 45, no. 9, pp. 1101–1111, Sept. 1997.

[43] S. Buzzi, M. Lops, and A. Tulino, "Time-varying mmse interference suppression in asynchronous ds/cdma systems over multipath fading channels," in *Proc. IEEE Int. Symp. on Personal, Indoor and Mobile Radio Commun.*, Sep. 1998, pp. 518–522.

[44] M. Medley, "Narrow-band interference excision in spread spectrum systems using lapped transforms," *IEEE Trans. Commun.*, vol. 45, pp. 1444–1455, Nov. 1997.

[45] A. Akansu, M. Tazebay, M. Medley, and P. Das, "Wavelet and subband transforms: fundamentals and communication applications," *IEEE Commun. Mag.*, vol. 35, pp. 104–115, Dec. 1997.

[46] R. D. Weaver, "Spread spectrum interference suppression using adaptive time-frequency tilings," in *Proc. IEEE Asilomar Conf. Signals Syst. Comput. Pacific Grove*, CA, Nov 2003, pp. 1881–18 840.

[47] B. Krongold, M. Kramer, K. Ramchandran, and D. Jones, "Spread spectrum interference suppression using adaptive time-frequency tilings," in *Proc. IEEE Int. Conf. Acoustics, Speech, Signal Processing (ICASSP)*, vol. 3, Munich, Germany, April 1997, pp. 1881–18 840.

[48] Y. Zhang and J. Dill, "An anti-jamming algorithm using wavelet packet modulated spread spectrum," in *Proc. IEEE Military Commun. Conf.*, vol. 2, Nov 1999, pp. 846–850.

[49] E. Pardo, J. Perez, and M. Rodriguez, "Interference excision in DSSS based on undecimated wavelet packet transform," *IEEE Electron. Lett.*, vol. 39, no. 21, pp. 1543–1544, Oct. 2003.

[50] T. Kasparis, "Frequency independent sinusoidal suppression using median filters," in *Proc. IEEE Int. Conf. Acoustics, Speech, Signal Processing (ICASSP)*, vol. 3, Toronto,Canada, April 1991, pp. 612–615.

[51] R. Lowdermilk and F. Harris, "Interference mitigation in orthogonal frequency division multiplexing (ofdm)," in *Proc. IEEE Int. Conf. Universal Personal Commun. (ICUPC)*, vol. 2, Cambridge, MA, Sep 1996, pp. 623–627.

[52] R. Nilsson, F. Sjoberg, and J. LeBlanc, "A rank-reduced lmmse canceller for narrowband interference suppression in ofdm-based systems," *IEEE Trans. Commun.*, vol. 51, no. 12, pp. 2126–2140, Dec 2003.

[53] S. Vogeler, L. Broetje, K.-D. Kammeyer, R. Rueckriem, and S. Fechtel, "Blind bluetooth interference detection and suppression for ofdm transmission in the ism band," in *Proc. IEEE Asilomar Conf. on Signals, Syst., Computers*, vol. 1, Pacific Grove, CA, Nov 2003, pp. 703–707.

[54] M. Ghosh and V. Gadam, "Bluetooth interference cancellation for 802.11g wlan receivers," in *Proc. IEEE Int. Conf. Commun. (ICC)*, vol. 2, Anchorage, AK, May 2003, pp. 1169–1173.

[55] S. Roy, J. Foerster, V. Somayazulu, and D. Leeper, "Ultrawideband radio design: the promise of high-speed, short-range wireless connectivity," *IEEE Proceedings*, vol. 92, no. 2, pp. 295–311, Feb 2004.

[56] A. Batra, J. Balakrishnan, G. Aiello, J. Foerster, and A. Dabak, "Design of a multiband OFDM system for realistic UWB channel environments," *IEEE Trans. Microw. Theory Techniq.*, vol. 52, no. 9, pp. 2123–2138, Sep 2004.

[57] T. Ikegami and K. Ohno, "Interference mitigation study for uwb impulse radio," in *Proc. IEEE Personal, Indoor, Mobile Radio Commun. (PIMRC)*, vol. 1, Sep 2003, pp. 583–587.

[58] R. Wilson and R. Scholtz, "Template estimation in ultra-wideband radio," in *Proc. IEEE Asilomar Conf. on Signals, Syst., Computers*, Pacific Grove, CA, 2004.

[59] I. Bergel, E. Fishler, and H. Messer, "Narrowband interference suppression in impulse radio systems," in *IEEE Conf. on UWB Syst. Technol.*, Baltimore, MD, May 2002, pp. 303–307.

[60] H. Sheng, A. Haimovich, A. Molisch, , and J. Zhang, "Optimum combining for time hopping impulse radio UWB rake receivers," in *Proc. IEEE Ultrawideband Syst. Technol. (UWBST)*, Nov 2003.

[61] N. Boubaker and K. Letaief, "A low complexity MMSE-RAKE receiver in a realistic UWB channel and in the presence of NBI," in *Proc. IEEE Wireless Commun. Networking Conf. (WCNC)*, vol. 1, New Orleans,LU, March 2003, pp. 233–237.

[62] D. Cassioli, M. Z. Win, F. Vatalaro, and A. F. Molisch, "Performance of low-complexity RAKE reception in a realistic UWB channel," in *Proc. IEEE Int. Conf. Commun. (ICC)*, vol. 2, New York, Apr. 2002, pp. 763–767.

[63] M. Z. Win and R. A. Scholtz, "Impulse radio: How it works," *IEEE Commun. Lett.*, vol. 2, no. 2, pp. 36–38, Feb. 1998.

[64] X. Chu and R. Murch, "The effect of nbi on uwb time-hopping systems," *IEEE Trans. on Wireless Commun.*, vol. 3, no. 5, pp. 1431–1436, Sep 2004.

[65] T. Yücek and H. Arslan, "Noise plus interference power estimation in adaptive OFDM systems," in *Proc. IEEE Vehic. Technol. Conf.*, Stockholm, Sweden, May 2005, accepted for publication.

[66] R. Fisher, R. Kohno, H. Ogawa, H. Zhang, and K. Takizawa, “IEEE P802.15 working group for wireless personal area networks (WPANs), DS-UWB proposal update,” May 2004. [Online]. Available: www.uwbforum.org/documents/15-04-0140-04-003a-merger2-proposal-ds-uwb-p%resentation.ppt.

[67] “Ultrawideband: High-speed, short-range technology with far-reaching effects, multiband OFDM alliance,” Sep 2004. [Online]. Available: www.multibandofdm.org/papers/MBOA“˙UWB“˙White“˙Paper.pdf.

[68] A. Taha and K. Chugg, “A theoretical study on the effects of interference uwb multiple access impulse radio,” in *Proc. IEEE Asilomar Conf. on Signals, Syst., Computers*, vol. 1, Pacific Grove, CA, Nov. 2002, pp. 728–732.

[69] I. Guvenc and H. Arslan, “Performance evaluation of UWB systems in the presence of timing jitter,” in *Proc. IEEE Ultra Wideband Syst. Technol. Conf.*, Reston, VA, Nov 2003, pp. 136–141.

[70] L. Piazzo and J. Romme, “Spectrum control by means of the TH code in UWB systems,” in *Vehic. Technol. Conf.*, vol. 3, Apr. 2003, pp. 1649 – 1653.

[71] ——, “On the power spectral density of time-hopping impulse radio,” in *IEEE Conf. Ultrawideband Syst. Technol. (UWBST)*, May. 2002, pp. 241–244.

[72] H. Schantz, G. Wolenec, and E. Myszka, “Frequency notched UWB antennas,” in *IEEE Conf. Ultrawideband Syst. Technol. (UWBST)*, vol. 3, Nov. 2003, pp. 214–218.

[73] S. Verdu, *Multiuser Detection.* 1st ed. Cambridge, UK: Cambridge University Press, 1998.

[74] S. Mallat, “A theory for multiresolution signal decomposition: the wavelet representation,” *IEEE Pattern Anal. and Machine Intell.*, vol. 11, no. 7, pp. 674–693, 1989.

[75] R. Klein, M. Temple, R. Raines, and R. Claypoole, “Interference avoidance communications using wavelet domain transformation techniques,” *Electron. Lett.*, vol. 37, no. 15, pp. 987–989, July 2001.

[76] M. Medley, G. Saulnier, and P. Das, “Radiometric detection of direct-sequence spread spectrum signals with interference excision using the wavelet transform,” in *IEEE Int. Conf. on Commun. (ICC 94)*, vol. 3, May 1994, pp. 1648–1652.

[77] J. Patti, S. Roberts, and M. Amin, “Adaptive and block excisions in spread spectrum communication systems using the wavelet transform,” in *Asilomar Conf. on Signals, Syst., Computers*, vol. 1, Nov. 1994, pp. 293–297.

[78] W. D. Horne, “Adaptive spectrum access: Using the full spectrum space,” in *Proc. 31st Annual Telecommunications Policy Research Conference (TPRC 03)*, Oct. 2003.

[79] Federal Communications Commission, “Spectrum Policy Task Force Report ET Docket no. 02- 135,” Nov. 2002.

[80] "Spectrum Occupancy Report for New York City during the Republican Convention August 30 - September 1, 2004," Jan. 2005. [Online]. Available: http://www.sharedspectrum.com/?section=measurements.

[81] M. P. Olivieri, G. Barnett, A. Lackpour, A. Davis, and P. Ngo, "A scalable dynamic spectrum allocation system with interference mitigation for teams of spectrally agile software defined radios," in *Proc. IEEE Int. Symp. Dynamic Spectrum Access Networks (DySPAN) 2005*, Baltimore, MD, Nov. 2005, pp. 170–179.

[82] H. Zheng and L. Cao, "Device-centric spectrum management," in *Proc. IEEE Int. Symp. Dynamic Spectrum Access Networks (DySPAN) 2005*, Baltimore, MD, Nov. 2005, pp. 56–65.

[83] T. A. Weiss, J. Hillenbrand, and F. K. Jondral, "A diversity approach for the detection of idle spectral resources in spectrum pooling systems," in *Proc. 48th Int. Sci. Colloq.*, Illmenau, Germany, Sep. 2003.

[84] D. Cabric, S. M. Mishra, and R. W. Brodersen, "Implementation issues in spectrum sensing for cognitive radios," in *Proc. IEEE Asilomar Conf. on Signals, Syst., Computers*, vol. 1, Pacific Grove, CA, Nov. 2004, pp. 772–776.

[85] J. Hillenbrand, T. Weiss, and F. Jondral, "Calculation of detection and false alarm probabilities in spectrum pooling systems," *IEEE Comm. Letters*, vol. 9, no. 4, pp. 349–351, April 2005.

[86] X. Jing and D. Raychaudhuri, "Spectrum co-existence of IEEE 802.11b and 802.16a networks using the CSCC etiquette protocol," in *Proc. IEEE Int. Symp. Dynamic Spectrum Access Networks (DySPAN) 2005*, Baltimore, MD, Nov. 2005, pp. 243 – 250.

[87] G. Ganesan and Y. Li, "Cooperative spectrum sensing in cognitive radio networks," in *Proc. IEEE Int. Symp. Dynamic Spectrum Access Networks (DySPAN) 2005*, Baltimore, MD, Nov. 2005, pp. 137 – 143.

[88] T. A. Weiss and F. K. Jondral, "Spectrum pooling: an innovative strategy for the enhancement of spectrum efficiency," *IEEE Commun. Mag.*, vol. 42, no. 3, pp. 8–14, Mar. 2004.

[89] J. Poston and W. Horne, "Discontiguous OFDM considerations for dynamic spectrum access in idle TV channels," in *Proc. IEEE Int. Symp. Dynamic Spectrum Access Networks (DySPAN) 2005*, Baltimore, MD, Nov. 2005, pp. 607 – 610.

[90] R. Dilmaghani, M. Ghavami, B. Allen, and H. Aghvami, "Novel UWB pulse shaping using prolate spheroidal wave functions," in *Proc. IEEE Int. Symp. on Personal, Indoor and Mobile Radio Commun. PIMRC 2003*, vol. 1, Beijing, China, Sept. 2003, pp. 602 – 606.

[91] K. Wallace, B. Parr, B. Cho, and Z. Ding, "Performance analysis of a spectrally compliant ultra-wideband pulse design," *IEEE Trans. on Wireless Commun.*, vol. 4, no. 5, pp. 2172–2181, Sept. 2005.

[92] M. G. Di Benedetto and L. De Nardis, "Tuning UWB signals by pulse shaping," *Special Issue on Signal Proc. in UWB Commun., Eurasip Journal on Signal Proc., Elsevier Publishers*, 2005, to appear.

[93] H. Zheng and L. Cao, "Device-centric spectrum management," in *Proc. IEEE Int. Symp. Dynamic Spectrum Access Networks (DySPAN) 2005*, Baltimore, MD, Nov. 2005, pp. 56 – 65.

[94] R. Thomas, L. DaSilva, and A. MacKenzie, "Cognitive networks," in *Proc. IEEE Int. Symp. Dynamic Spectrum Access Networks (DySPAN) 2005*, Baltimore, MD, Nov. 2005, pp. 352 – 360.

[95] A. Molisch, K. Balakrishnan, C. C. Chong, S. Emami, A. Fort, J. Karedal, J. Kunisch, H. Schantz, U. Schuster, and K. Siwiak, "IEEE 802.15.4a channel model - final report," Sep. 2004. [Online]. Available: http://www.ieee802.org/15/pub/TG4a.html.