Energy capture selection for interference reduction in high-data-rate impulse radio ultra wideband

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**Energy Capture Selection for Interference
Reduction in High-Data-Rate Impulse Radio Ultra
Wideband**

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Summary

Impulse Radio Ultra Wideband (IR-UWB) promises a wireless communication system that is simple, yet capable of achieving a high data rate transmission. The wide bandwidth of the system implies that it has a large channel capacity. However achieving full utilization of this large channel capacity, while keeping the complexity of the system low, remains a practical challenge. This is mainly caused by the presence of Inter-Symbol Interference (ISI) in the high data rate transmission.

Despite this, in many system analyses of IR-UWB system, the effect of ISI is often neglected. Most of the time, it is generally assumed that the symbol period is longer than the channel excess delay. This assumption is not valid in situations where data rate is high. The efforts to mitigate the ISI are mainly in the form of the classical equalization techniques. Another variant of UWB system, the WiMedia, avoids the ISI through the use of Multiband Orthogonal Frequency Division Multiplexing (OFDM). These two approaches increase the overall complexity of the system.

The objectives of this research are to investigate the performance of high data rate IR-UWB and to develop good ISI reduction techniques, while keeping the simplicity of the system.

In this thesis, the mathematical derivation of the IR-UWB receiver's test statistic under high data rate system is presented. From the mathematical derivation, a complete separation between the desired energy and the undesired energy that make up the test

statistic of the detection system can be clearly observed.

Based on this observation, two novel techniques based on selective energy capture are developed. The first technique reduces the interference from other symbols through the implementation of pulse shape hopping in the transmitter. By modifying the pulse shapes transmitted at every transmission instant, the pulse shape hopping technique reduces the cross-correlation value between pulses from different symbols. The improvement of the error rate performance is shown to be good and scalable, especially when orthogonal pulse shapes are used.

The second technique introduces a correlation window selection, which is performed at the receiver. Through the use of the proposed selective transmitted reference technique, the receiver focuses the energy capture on the time period where the desired energy is stronger. The proposed selective transmitted reference technique outperforms other similar techniques presented in the literatures.

Since the two techniques deal with the interference from two different perspectives, the performance gain achieved by the two techniques are independent. Thus, combining the two techniques in a system produces a significant ISI reduction. The improvement of the error rates in a high data rate system with a non-line-of-sight channel is shown to be significant.

The combined techniques are also shown to be performing well in a high data rate Wireless Sensor Network (WSN) with a cooperative communication. In a high data rate cooperative communication, the ISI is significantly increased due to the additional interferences from other relay nodes. A system model utilizing the combined two techniques is presented and is shown to achieve a good error rate performance and a good spatial gain.

One of the main advantages of UWB is the spreading of the energy at the receiver. In high data rate system, however, this energy contains both the desired energy and the

unwanted interferences. By performing a selective energy capture, an IR-UWB system can significantly reduce the impact of ISI, and achieve good error rate performance in high data rate system.

Contents

Acknowledgements	i
Summary	ii
List of Abbreviations	xii
1 Introduction	1
1.1 Brief History of UWB	2
1.2 Potentials of UWB	4
1.3 Challenges of UWB	4
1.4 Thesis' Objectives	5
1.5 Organization	7
2 Literature Review	8
2.1 Transmitter System	8
2.1.1 Multiple Access Techniques in IR-UWB	10
2.1.2 Modulation Techniques for IR-UWB	12
2.1.3 Spectral Mask Consideration	13
2.2 Channel	13
2.2.1 Standards for UWB Channel Model	16

2.3	Receiver Structure	23
2.3.1	RAKE	24
2.3.2	Transmitted Reference	26
2.4	Combatting Interference in IR-UWB	29
2.5	Multiple Access in IR-UWB	34
2.6	Cooperative Communication	35
2.6.1	MIMO and Cooperative Communication	36
2.6.2	Cooperative Communication in UWB	38
2.7	Summary	40
3	Sources of Interference	41
3.1	Mathematical Derivation	42
3.2	Analysis and Discussion	49
3.3	Summary	57
4	Reducing Interfering Energy through Pulse Shape Hopping	59
4.1	Pulse Shapes in UWB	60
4.1.1	Pulse Shapes to Achieve Spectral Utilization Efficiency	62
4.1.2	Pulse Shapes to Carry Information	64
4.2	Pulse Shape Hopping (PSH)	64
4.3	Spectral Utilization Efficiency of the Pulse Shapes Used	72
4.4	Performance of Pulse Shape Hopping	78
4.5	Summary	91
5	Reducing Interfering Energy through Selective Transmitted Reference	92
5.1	Partial RAKE Receiver	93

5.2	Selective Transmitted Reference	94
5.2.1	Shift Window (SW) Approach	98
5.2.2	Generalization of Shift Window	101
5.2.3	Selective TR vs RAKE Receiver	104
5.3	Performance Results	105
5.4	Pulse Shape Hopping and Selective Transmitted Reference	109
5.5	Summary	112
6	High Data Rate Wireless Sensor Network Utilizing Cooperative Com-	
	munication UWB	113
6.1	Cooperative Communication in Wireless Sensor Network	115
6.2	Mathematical Derivation of Test Statistic	116
6.3	Proposed Approaches	123
6.4	Spatial gain of the proposed approach	125
6.5	Orthogonal pulse shape to mitigate inter pulse interference	127
6.6	Performance under Timing Jitter	131
6.7	Impact and Potentials	132
6.8	Summary	134
7	Conclusions and Future Works	136
7.1	Conclusions	136
7.2	Future Works	137
	Author's Publication List	156
	List of Publications	157

List of Figures

2.1	An example of one symbol transmission in TH-PPM IR UWB	9
2.2	Frequency Spectra without Modulation and Coding	13
2.3	Frequency Spectra Mask with Modulation and Coding	14
2.4	Realizations of the IEEE 802.15.3a Channel Model	17
2.5	Realizations of the IEEE802.15.4a Residential Channel Model	19
2.6	Realizations of the IEEE802.15.4a Office Channel Model	20
2.7	Realizations of the IEEE802.15.4a Outdoor Channel Model	21
2.8	Realizations of the IEEE802.15.4a Industrial Channel Model. (Please note on the different x-axis.)	22
2.9	RAKE Receiver	25
3.1	Bit error rate against symbol period for CM1 of 802.15.3a	51
3.2	Bit error rate against symbol period for CM3 of 802.15.3a	52
3.3	Bit Error Rate for Different Numbers of RAKE fingers for CM1	54
3.4	Bit Error Rate for Different Numbers of RAKE fingers for CM3	55
4.1	Spectral Mask for Indoor Channel defined by the FCC	61
4.2	Four Shift-Orthogonal Pulse Shapes	70
4.3	EIRP of the Four Shift-Orthogonal Pulse Shapes Against the Regulatory Spectral Mask	71

4.4	Autocorrelation (in solid line) and Cross-correlation (in dotted line) of Hermite Pulse	73
4.5	Autocorrelation (in solid line) and Cross-correlation (in dotted line) of Parr's Pulse	74
4.6	Spectral Utilization Efficiency of Different Pulse Shapes	75
4.7	Probabilty of Error Against AWGN	77
4.8	Error Rates vs Symbol Period from Different Sources of Interference for CM1	79
4.9	Error Rates vs Symbol Period from Different Sources of Interference for CM3	80
4.10	Error Rates for Different Numbers of RAKE Fingers at 500 Mbps for CM1	81
4.11	Error Rates for Different Numbers of RAKE Fingers at 500 Mbps for CM3	82
4.12	Performance of Hermite and Parr's Pulses Using PSH for CM1 of 802.15.3a	83
4.13	Performance of Hermite and Parr's Pulses Using PSH for CM3 of 802.15.3a	84
4.14	Performance of M-ary PSM in CM1 of 802.15.3a channel	86
4.15	Performance of M-ary PSM in CM3 of 802.15.3a channel	87
4.16	Performance of Parks-McClellan Pulse Using PSH for CM1	88
4.17	Performance of Parks-McClellan Pulse Using PSH for CM3	88
4.18	Performance under AWGN and CM1 of 802.15.3a	90
5.1	Performance of Partial RAKE Against Selective RAKE	95
5.2	Separation of Energy Capture	97
5.3	Severe Inter-Symbol Interference	100
5.4	Generalized View of ISI Reduction	101
5.5	Separation of Energy Capture in TR Receiver	103
5.6	Error Rate Performance of Selective TR	105

5.7	Performance of STR against the original Shift-Window (SW) approach . .	107
5.8	Performance of STR against other interference reduction approaches . .	108
5.9	Performance of Combined Selective TR and Pulse Shape Hopping	111
6.1	An Illustration of Wireless Sensor Network Transmission	116
6.2	Cooperative Communication. The dashed lines indicate cooperative communication through relay nodes, which are indicated by the filled circle. .	117
6.3	A simple relay system with 1 source (S), 1 destination (D), and 3 relay nodes (R1, R2, and R3).	118
6.4	Bit error rate against SNR (in dB) for CM1	127
6.5	Bit error rate against SNR (in dB) for CM3	128
6.6	Bit error rate against number of relays for CM1	129
6.7	Bit error rate against number of relays for CM3	130
6.8	Performance under timing jitter with $\sigma = 0.01$	132
6.9	Performance under timing jitter with $\sigma = 0.1$	133

List of Tables

3.1	Simulation parameters for investigating interferences	50
4.1	Parameter for Pulse Shapes Used	76
4.2	Simulation Parameter for Pulse Shape Hopping	78
5.1	Differences between S-RAKE and S-TR	104
5.2	Simulation Parameter for Selective Transmitted Reference	106

List of Abbreviations

AAF	Amplify-And-Forward
ALRT	Average Likelihood Ratio Test
AWGN	Additive White Gaussian Noise
BOK	Bi-Orthogonal Keying
BPSK	Binary Phase Shift Keying
CDMA	Code Division Multiple Access
CPI	Current Pulse Interference
DAF	Decode-And-Forward
DFE	Decision Feedback Equalizer
DS-BPSK	Direct Sequence - Binary Phase Shift Keying
DS-SS	Direct Sequence - Spread Spectrum
DS-UWB	Direct Sequence - Ultra Wideband
DSTBC	Distributed Space Time Block Code
DTR	Differential Transmitted Reference
ECMA	European Computer Manufacturers Association
EIRP	Equivalent Isotropically Radiated Power
FCC	Federal Communications Commission
FS-RAKE	Fractionally Spaced - RAKE

IEEE	Institute of Electrical and Electronics Engineers
IPI	Inter-Pulse Interference
IR-UWB	Impulse Radio Ultra Wideband
IRI	Inter-Relay Interference
ISI	Inter-Symbol Interference
ISI-C	Inter-Symbol Interference - Cancellation
LOS	Line-Of-Sight
MAC	Media Access Control
MAI	Multiple Access Interference
MB-OFDM	Multi Band - Orthogonal Frequency Division Multiplexing
MIMO	Multiple Input Multiple Output
MLSD	Maximum Likelihood Sequence Detector
MMSE	Minimum Mean Squared Error
MRC	Maximal Ratio Combining
MUD	Multi-User Detector
MUI	Multi-User Interference
NBI	Narrow Band Interference
NLOS	Non-Line-Of-Sight
OFDM	Orthogonal Frequency Division Multiplexing
OOK	On-Off-Keying
OSTBC	Orthogonal Space Time Block Code
P-RAKE	Partial RAKE
PHY	Physical
PIR	Previous symbols Interference from other Relay
PPI	Previous Pulses Interference

PPM	Pulse Position Modulation
PPM-PSM	Pulse Position Modulation - Pulse Shape Modulation
PSH	Pulse Shape Hopping
PSM	Pulse Shape Modulation
RI	Relay Interference
RR	Received Response
S-RAKE	Selective RAKE
SIG	Special Interest Group
SINR	Signal to Noise and Interference Ratio
SIR	Subsequent symbols Interface from other Relay
SNR	Signal to Noise Ratio
SPI	Subsequent Pulses Interference
SR-TR	Single Reference - Transmitted Reference
STBC	Space Time Block Code
STR	Selective Transmitted Reference
STTC	Space Time Trellis Code
SUE	Spectral Utilization Efficiency
SV	Saleh-Valenzuela
SW	Shift Window
TDMA	Time Division Multiple Access
TH	Time Hopping
TH-PPM	Time Hopping - Pulse Position Modulation
TPI	Total Previous symbols Interference
TR	Transmitted Reference
TSI	Total Subsequent symbols Interference

UWB	Ultra Wideband
UWEN	Ultra Wideband Wireless Embedded Network
WBAN	Wireless Body Area Network
WCDMA	Wideband Code Division Multiple Access
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network
ZF	Zero Forcing
ZI	Zero Interference

Chapter 1

Introduction

The classical Shannon's capacity theorem states that the channel capacity is logarithmically proportional to the Signal to Noise Ratio (SNR) and is directly proportional to the channel bandwidth. There are at least two implications of this statement with regards to the channel bandwidth. Firstly, the channel bandwidth has more impact on the channel capacity than the robustness of the transceiver system against noise. Secondly, given the same channel capacity and the same noise level, a system with a larger bandwidth requires less signal energy.

These two implications serve as the basis potential for the Ultra Wideband (UWB) communication. The very wide bandwidth of a UWB system can potentially produce a very high data rate transmission or have very low energy consumption (long battery life) for a low data rate transmission. A UWB communication is defined by the FCC as having an instantaneous bandwidth of at least 500 MHz or a fractional bandwidth of at least 20% [1]. The bandwidth of UWB is much wider than other systems currently considered as wideband. For example, WCDMA uses 20 MHz bandwidth and IEEE802.11n uses 22 MHz [2].

1.1 Brief History of UWB

The very basic notion of UWB communication is not new. In fact, when Marconi transmitted the first spark gap transmission, it was in a form of UWB communication [3]. However such a transmission occupying a large frequency bandwidth was deemed inefficient, because it practically blocks other users from using the spectrum. What followed was the development of narrow band radio where different systems occupy different portions of the shared spectrum. Examples include the AM/FM radio, the analog TV signal, etc. UWB was mainly used by the military, and most of the time, only for radar. However with improvements of transceiver techniques, it is now possible to do a UWB transmission with very low power, to the point that it is only viewed as noise by other radio system.

In 1993, Scholtz introduced impulse radio UWB (IR-UWB) with pulse position modulation and a time hopping scheme to enable multiple access [4]. The paper explains the simplicity of the transceiver's structure (with multiple access) and the potential of achieving the advantages of a wideband system, making it a landmark paper, which sparked a new interest in UWB communication. Many researchers were aware that the spectrum of IR-UWB resides in the frequency spectrum shared with other users (most notably the 802.11.a/g and the global Industrial, Scientific, and Medical band). However, the general sentiment was that IR-UWB transmit power can be kept very low so that it would appear only as noise to other spectrum users. Still, without proper regulation, IR-UWB remained just an academic research.

This changed in February 14, 2002 when the FCC (Federal Communications Commissions) approved the usage of UWB with a spectral mask limiting the equivalent isotropically radiated power (EIRP) to be at most -41.6 dbm/MHz within 3.1 GHz to 10.6 GHz. This means that the UWB transmission overlays other transmission system

within the 7.5 GHz range specified by the FCC. One important aspect about the FCC ruling is that it does not restrict the methodology of transmission.

Therefore, aside from the IR-UWB technique, the freedom provided by the FCC ruling liberates researchers to using other forms of transmission techniques to achieve UWB. In the standardization process for short-range high data rate Wireless Personal Area Network (WPAN), the IEEE 802.15.3a, there were two main proposals. One is the Direct Sequence UWB (DS-UWB), which is based on the IR-UWB. The other proposal is based on the usage of multiband system. The multiband system divides the wide spectrum allocated for UWB into smaller bandwidth and performs an enhancement of narrowband technology on each smaller bandwidth. The standardization process was not able to reach a consensus and thus it was disbanded [5].

Currently, the multi band system, especially the Multiband Orthogonal Frequency Division Multiplexing (MB-OFDM) is the most prevalent UWB technology for high data rate, short range radio system [6]. The WiMedia organization has come up with a MAC and PHY layer specification utilizing the MB-OFDM as the technology of choice for UWB-based Wireless Personal Area Network (WPAN), which was accepted by the European Standard Body as the ECMA-368. Although in 2006 it was initially chosen by the Bluetooth Special Interest Group (SIG) as the high data rate version of Bluetooth 3.0, in the end Bluetooth chose WiFi as the technology of choice mainly due to the availability of WiFi technology[7].

On the other hand, impulse radio has found its niches in the Wireless Sensor Network (WSN) system. The 802.15.4a standardization body included IR-UWB as the technology for high data rate (250 kbps) sensor network. Other non standardized IR-UWB usage for wireless sensor network also existed, e.g. Project UWEN [8] and the seismic acquisition system [9]. Aside from WSN, there are other varieties of application ranging from low data rate, e.g. Wireless Body Area Network (WBAN) [10], to extreme

high data rate, e.g. intra chip wireless communication [11].

In this thesis, our focus is mostly on the impulse radio-based UWB system. IR-UWB is a technique which has several important challenges that needs to be solved to reach it's full potential.

1.2 Potentials of UWB

Regardless of the technology of choice (MB-OFDM or Impulse Radio), they both share the same advantages. As implied by Shannon's capacity theorem, UWB is potentially capable of transmitting very high data rates (Gbps range) [12]. The wide channel bandwidth indicates that UWB transmission propagates through a frequency selective fading channel. This means that the multipath replicas at the receiver are separable, which enables time diversity exploitation. It also means that the ranging accuracy is very high (in the range of centimeter). This is very advantageous for WSN where location-based routing is used [13]. In the UWB regulation provided by the FCC, the low frequency spectrum (from 0 - 0.96 GHz) can also be used for transmission. The low frequency spectrum is very useful since it provides the best object penetration for wireless transmission. In the case of IR-UWB, all these potentials are available with the promise of simplicity of the transceiver system.

1.3 Challenges of UWB

Achieving all these potentials is however not easy. First of all, the regulation limits the EIRP of UWB transmission to be very low. The maximum EIRP is -41.6 dBm/Mhz, which essentially is the same as the noise induced by a lamp switch. This creates a challenge in trying to develop a system that fully utilizes the allowed spectrum.

The second challenge is related to the synchronization and channel estimation required for coherent detection. Since IR-UWB uses a very narrow pulse and the channel consists of large number of replicas, the synchronization and channel estimation are difficult.

Thirdly, frequency selective fading produces a large amount of multipath replicas at the receiver. Although this is beneficial for diversity, capturing all the replicas proved to be a practical challenge. The work in [14] shows that to obtain good performance, a large number of replicas have to be captured.

In many scenarios, the replicas can also act as interference to the receiver system. In high data rate systems, the replicas from the previous symbol transmission may arrive in the current symbol's detection and cause Inter-Symbol Interference (ISI). Similarly replicas from other users' transmission, replicas from other antennas in a MIMO system, or replicas from other relay nodes in a cooperative communication system will produce Multiple Access Interference (MAI) or MIMO interference. These different types of interference prohibit IR-UWB from achieving the very potentials it is supposed to fulfill. As shown in [15] the impact of interference is more than the impact of noise in the system, and it can be catastrophic if not mitigated properly.

1.4 Thesis' Objectives

There are two main objectives of this thesis. The first is to provide a study on the effect of high data rate interference to IR-UWB for single user system and for cooperative communication system. One of the characteristics of UWB channel is the presence of a large number of multipath replicas over a long channel excess delay (40 ns - 150 ns in IEE802.15.3a channel model). A channel excess delay is the time period between the arrival of the first multipath replica and the arrival of the last multipath replica

(or the replica with energy less than a certain specified threshold). Although the large number of replicas enables the use of time diversity receiver, in high data rate system the long channel excess delay means that many multipath replicas from the current symbol would arrive even after the current symbol period. This would cause inter-symbol interference (ISI). In addition to causing ISI, the long channel excess delay also causes a catastrophic collision in Time Hopping multiple access system, and thus increases the Multiple Access Interference (MAI). In a cooperative communication system, the ISI is increased due to the interfering multipath replicas coming from other relay nodes.

Implementing a high data rate IR-UWB remains a practical challenge. In fact, one of the reason why MB-OFDM is more prevalent in high data rate WPAN, is because it can minimize the inter-symbol interference through the use of frequency hopping.

Most of the available ISI mitigation techniques for IR-UWB are in the implementation of classical approaches, especially the use of equalizers. Equalizer is an effective way to combat ISI. However, the use of equalizer increases the complexity of the system due to the increase in circuitry and also in additional requirement of trainings.

In order to keep the complexity of the system low, and since IR-UWB receiver receives a large amount of energy (from the large number of multipath replicas), we propose that by selectively choosing which energy to be used for detection, we can reduce the interference caused by high data rate transmission.

The second objective of this thesis is to investigate on this claim and to develop a coherent-based transceiver systems based on the energy capture selection concept.

To do this, we derive the mathematical expression of the receivers test statistic with the purpose of studying the interference present in high data rate. From this analysis, we develop two energy capture selection methods, a Pulse Shape Hopping transmitter and a Selective Transmitted Reference receiver, which are able to reduce the high data rate interference both in a single user system and in a cooperative communication system.

Our analysis and investigation is focused for high data rate (100 Mbps and above) single user system and high data rate in cooperative communication where the presence of ISI aggravates the existing inter-relay interference (IRI).

There are four main contributions of this thesis. The first is the mathematical derivation of the receiver's test statistic, with the aim of separating the interferences from different sources. The test statistic shows that the interference causes unwanted energy contribution, which affects the detection process. The second contribution is the introduction of a Pulse Shape Hopping transmitter. The third contribution is the introduction of Selective Transmitted Reference, which is a novel energy capture selection technique for Transmitted Reference receiver. The fourth contribution is built on top of the second and third contribution, where the two approaches are used to produce a simple and practical solution for a high data rate cooperative communication.

1.5 Organization

The rest of this thesis is organized as follows. Chapter 2 provides a literature review on the current state of IR-UWB transceiver. In addition the general approaches on interference mitigation are also presented in this chapter. In chapter 3, we derive the test statistic of high data rate IR-UWB receiver. The derivation in this chapter is limited to the single user system. In chapter 4, the utilization of UWB pulse shapes for energy capture selection is explained. Chapter 5 explains our third contribution, a novel energy capture selection for Transmitted Reference (TR) receiver. Chapter 6 provides the final contribution where we build on the utilization of pulse shapes and the novel energy capture selection for TR receiver to mitigate interference in a high data rate cooperative communication. Chapter 7 concludes this thesis.

Chapter 2

Literature Review

The main goal of this chapter is to provide a review on the available high data rate interference mitigation techniques in IR-UWB. In order to provide a complete background study, this literature review starts by covering the transceiver system of the IR-UWB and also the channel on which the UWB signal propagates. This is followed by a review on the high data rate interference mitigation techniques available for UWB.

Since this thesis expands the discussion on the high data rate interference for cooperative communication UWB, this chapter ends with a review on the state of cooperative communication for UWB.

2.1 Transmitter System

An impulse radio transmission is characterized by a transmission of narrow pulse with a very low duty cycle. In the original paper [4], and its successor with more detailed explanation of impulse radio [16], the modulation used is Pulse Position Modulation (PPM) with Time Hopping (TH) for multiple access technique. A mathematical representation

of the n^{th} transmitted symbol of the u^{th} user is given as (2.1)

$$S_{u,n}(t) = \sum_{i=0}^{N_{pps}-1} p(t - iT_f - c_{u,i}T_c - \delta d_{u,n}) \quad (2.1)$$

The N_{pps} denotes the number of pulse per symbol and i denotes the frame index. One symbol period is divided into N_{pps} frames, each with frame period T_f . Within one frame period, there is only one pulse $p(t)$ transmitted. Each frame is further divided into N_c chips, each with chip period T_c . The position of the pulse in one frame is determined by the time hopping code $c_{u,i}$ and the symbol information $d_{u,n}$. The time hopping code is any real value between 0 and N_c , and each user u transmits using different time hopping code sequence $c_{u,i}$. The TH code is designed to enable sharing of the medium with other users. Finally $d_{u,n}$, the delay based on the symbol information of the u^{th} user, determines the delay within one chip period.

Figure 2.1 shows an example of one symbol with $N_{pps} = 2$ and $N_c = 4$. The chip code for the first frame and the second frame is 1 and 2 respectively. The symbol information transmitted is 1, and thus there is a δ delay after the start of the chip.

Figure 2.1: An example of one symbol transmission in TH-PPM IR UWB

This form of IR-UWB (using TH and PPM) is one of the simplest forms of UWB system. Both the detection and the multiple access are achieved purely based on the

position of the pulse in the frame.

As IR-UWB research matures, different multiple access and modulation techniques have been introduced. Notable multiple access implementations include the multiband UWB, the use of orthogonal pulse shapes, and the Direct Sequence (DS)-UWB.

2.1.1 Multiple Access Techniques in IR-UWB

In multiband UWB [17], [18], the large available bandwidth for UWB is divided into several smaller bands and each transmitter transmits using different band. The disadvantage of this approach is that a single link would not be able to reap the benefit of using the whole large bandwidth. In addition, there is an extra complexity involved in dividing the bandwidth, which needs to be done through the use of a modulator [19] or a linear filter [18]. A transmission of one symbol in multiband UWB using a modulator is given in (2.2).

$$S_{u,n}(t) = \sum_{i=0}^{N_{pps}-1} p(t - iT_f - \delta d_{u,n}) \cos(2\pi f_u t) \quad (2.2)$$

The equation is very similar to (2.1), but without the time hopping. The transmitted pulse is modulated with center frequency $= f_u$. The center frequency differs for different user.

The use of orthogonal pulse shape for multiple access implementation is similar to the multiband UWB. However, instead of transmitting at different frequency band, each transmitter transmits using a different pulse shape from a set of mutually orthogonal pulse shapes. Since the pulse shapes are mutually orthogonal, the cross-correlation between different pulse shapes always produce zero energy. Thus a correlation-based receiver can use the pulse shape of the wanted user as the correlation template. Orthogonal pulse shape technique for IR-UWB was first introduced in [20], where the author

presented a derivation of a Hermite-based pulse shape. Since then, other orthogonal pulse shapes have since been introduced (for example Prolate Spheroidal pulse [21] and [22]). Equation 2.3 shows a transmission of one symbol using orthogonal pulse shapes for multiple access.

$$S_{u,n}(t) = \sum_{i=0}^{N_{pps}-1} p_u(t - iT_f - \delta d_{u,n}) \quad (2.3)$$

The DS-UWB [23], [24], [25], [26], which originates from the Code Division Multiple Access (CDMA) system, divides the transmitted symbol into multiple chips and multiplies them with a set of quasi-orthogonal code. The process of dividing a symbol period into multiple smaller chip periods is called spreading. Unlike in narrowband CDMA system, in DS-UWB the spreading is not used to increase the bandwidth of the system. Instead, it is used only to differentiate the transmission from different transmitters. One of the main motivations in using DS-UWB is to achieve data rate higher than that of TH-PPM. The higher data rate is achievable because the symbol period is only divided into multiple chips. This is as opposed to the TH-PPM where one symbol is divided into multiple time frames, which is further divided into multiple chips, which is again further divided to provide position modulation. Equation 2.4 shows a DS-UWB symbol transmission.

$$S_{u,n}(t) = \sum_{i=0}^{N_{pps}-1} a_{u,n} c_{u,i} p(t - iT_c) \quad (2.4)$$

In DS-UWB, the information is modulated either by the amplitude or the phase of the pulse (denoted by $a_{u,n}$). In a binary system, when either amplitude modulation or phase modulation is used, the $a_{u,n}$ is either a $-1/+1$. The number of pulse per symbol, N_{pps} , is the same as the length of the DS code used. Any narrowband CDMA code [27] (such as Gold code or M-sequence code) can be used for DS-UWB. The CDMA code sequence is a sequence of $-1/+1$, and this sequence is denoted as $c_{u,i}$.

2.1.2 Modulation Techniques for IR-UWB

Aside from the original PPM, other modulation techniques have been proposed for UWB including the use of phase, amplitude, On-Off-Keying (OOK), pulse shape, and any combination of them [28, 29, 30, 31]. Equation 2.5 shows a generic form of a transmitted symbol for DS-UWB.

$$S_{u,n}(t) = \sum_{i=0}^{N_{pps}-1} a_{u,n} c_{u,i} p_{u,n}(t - iT_f - \delta d_{u,n}) \quad (2.5)$$

For phase modulation, the term $a_{u,n}$ denotes the phase, which represents the transmitted information. For a Binary Phase Shift Keying (BPSK) the value is either $-1/+1$. The term $a_{u,n}$ can also be represents the amplitude in amplitude modulation or to indicate an on or off keying in OOK. The main difference for OOK is that it can only represents a binary information (in OOK case, $a_{u,n}$ is either a 0 or a 1), whereas both the amplitude and phase modulation can be used for any M -ary modulation, where $M \geq 2$. For these three modulations, the pulse shape used $p_{u,n}(t)$ remains the same regardless of the user and the symbol (i.e. $p_{u,n}(t) = p(t)$), and the value of $d_{u,n}$, which indicates the delay of the pulse position within a frame period is always 0. The value of $d_{u,n}$ is only non-zero when pulse position modulation is used.

For pulse shape modulation (PSM), the transmitted pulse $p_{u,n}(t)$ changes for different information symbol. Once again, the use of orthogonal pulse is necessary in this case to ensure that the receiver can differentiate the information being transmitted. For pulse shape modulation, the value of $a_{u,n}$ and $c_{u,i}$ are always 1 and the value of $d_{u,n}$ is always 0.

Equation 2.5 also covers modulation which combine different sources of differentiation. One example is the use of combined pulse shape and position modulation (PPM-PSM) [30]. In this case, the value of both $p_{u,n}(t)$ and $d_{u,n}$ change depending on

the transmitted information.

2.1.3 Spectral Mask Consideration

One important design parameter for the transmitter is the regulatory spectral mask. In IR-UWB, the shape of the pulse defines the spectrum of the system. However, even if the spectrum of the pulse shape fulfills the spectral mask, the periodic transmission of the pulse generates periodic spikes, which increases the EIRP of the transmission. This is where modulation and coding prove to be beneficial. Coding and modulation introduce randomness to the transmission and thus reduces the spikes in the spectrum [32]. Figure 2.2 shows the spectral mask when there is no modulation and coding, whereas figure 2.3 show the spectral mask when modulation and coding is used.

Figure 2.2: Frequency Spectra without Modulation and Coding

2.2 Channel

One main characteristic of a UWB system is that the channel is a frequency selective fading channel. In frequency selective fading, the multipath replicas arriving at the receiver are separable from one another. This condition has a large impact on the

Figure 2.3: Frequency Spectra Mask with Modulation and Coding

design of receivers for UWB system. Thus before delving into UWB receiver, we would first present the literature study on UWB channel.

In order to come up with a proper channel model, extensive channel sounding and measurement experiments need to be performed. Several notable experiment methods and their results have been presented in [33], [34], and [35]. A complete channel model consists of modeling for the large-scale path-loss model, and the small scale fading [34].

The large-scale path-loss model provides the average power loss ratio between the transmitter and the receiver. In general, the ratio is given as.

$$L(d, f_c) = \left(\frac{4\pi f_c d}{c}\right)^\gamma \quad (2.6)$$

The ratio depends on three parameters and one constant. The constant used is the speed of light, which is denoted as c . The three parameters are d , which is the distance between the transmitter and the receiver, f_c , which is the center frequency of the transmitted signal, and γ , which is the path-loss exponent. The path-loss exponent is a value which is obtained through experiment. For a free-space path-loss, γ value is 2. In a more practical scenario, the reflection, diffraction, and scattering will affect the value of the

path-loss exponent.

The equation clearly shows that as the distance between the transmitter and the receiver directly affects the path-loss. Since UWB systems are mostly used for short range communication system, the large scale path loss has little impact to the system's performance and as such, there have not been many research on this issue.

The small scale fading model provides the modeling of the multipath. This includes the statistic of the channel gain and the modeling of the replicas arrival time. A multipath channel can be modeled as a tapped delay line model.

$$h(t) = \sum_{l=0}^{L-1} a_l \delta(t - \tau_l) \quad (2.7)$$

In this model, there are L number of replicas. a_l denotes the channel gain of the l^{th} replica and τ_l denotes the arrival time of the l^{th} replica. The term $\delta(t)$ is the Dirac-delta function. In narrow band system, the channel gain fading is normally modeled as Rayleigh fading for a Non-Line-Of-Sight (NLOS) channel or as Ricean fading for a Line-Of-Sight (LOS) channel. For UWB, there are two main fading model used, the Nakagami fading [33] and the log-normal fading [35].

For UWB channel, it has been observed that there is a clustering phenomenon in the multipath. Thus a Saleh-Valenzuela (SV) channel model [36], as shown in equation 2.8, is a more suitable.

$$h(t) = \sum_{k=0}^{K-1} \sum_{l=0}^{L-1} a_{k,l} \delta(t - T_k - \tau_{k,l}) \quad (2.8)$$

The multipath consists of K clusters and within each cluster, there are L rays. The k^{th} cluster arrival time is denoted as T_k . The channel gain of the l^{th} ray of the k^{th} cluster is denoted as $a_{k,l}$, and the arrival time is denoted as $\tau_{k,l}$. The arrival time between the

clusters, and between the rays within one cluster is modeled as a Poisson processes [35].

2.2.1 Standards for UWB Channel Model

There are two main standards for UWB channel model. The standardization body made use of the available researches to produce a standard which enable researchers to investigate UWB transceiver design based on a standardized channel model. The two standards are the IEEE 802.15.3a, which is defined for high data rate WPAN and the IEEE 802.15.4a, which is defined for low data rate WSN. Although the IEEE 802.15.3a group was disbanded in 2006 due to the inability to reach consensus on the transceiver system, it produced important investigation and analysis results including the high data rate channel model for UWB.

Channel Model Based on IEEE 802.15.3a

The 802.15.3a channel model is a multipath channel based on a modified Saleh-Valenzuela (SV) channel model.

The i^{th} realization of the channel impulse response is expressed as [37].

$$h_i(t) = X_i \sum_{l=0}^L \sum_{k=0}^K \alpha_{k,l}^i \delta(t - T_l^i - \tau_{k,l}^i) \quad (2.9)$$

The channel impulse response consists of L clusters, and each cluster consists of K rays. Independent fading is assumed for each cluster, as well as each ray within the cluster. $\alpha_{k,l}$ denotes the combined channel gain for the k^{th} ray of the l^{th} cluster. T_l denotes the arrival time of the l^{th} cluster and $\tau_{k,l}$ denotes the arrival time of k^{th} ray of the l^{th} cluster, with respect to the arrival time of the l^{th} cluster. The multipath gain magnitude is denoted by X_i , and it follows log normal distribution, instead of the usual Rayleigh distribution. The decision on using log normal fading was made based on the

results of practical indoor channel measurements, which were submitted to the IEEE 802.15.3a standardization committee. The $\delta(t)$ is the Dirac-delta function.

The 802.15.3a channel model provides four different instances (CM1-CM4), representing different scenarios of the WPAN. CM1 is a Line of Sight (LOS) channel for a distance of 1 - 4 meters. CM2 and CM3 are Non Line of Sight (NLOS) channel for distances of 1 - 4 meters and 4 - 10 meters respectively. CM4 represents an extreme NLOS multipath channel.

An example for each channel models' realization is shown in figure 2.4.

Figure 2.4: Realizations of the IEEE 802.15.3a Channel Model

Channel Model Based on IEEE 802.15.4a

The 802.15.4a channel model covers both UWB and non UWB based channels. This is because the 802.15.4a standard uses UWB only as a physical (PHY) layer alternative for short range WSN, especially to achieve higher data rates and better ranging precision.

The UWB based channel model covers frequency ranges of 100 - 1000 MHz and 2 - 10 GHz. Similar to the 802.15.3a channel model, it is also based on a modified Saleh-Valenzuela (SV) channel. The discrete channel response is represented in Eq. (2.10) [38].

$$h(t) = \sum_{l=0}^L \sum_{k=0}^K \alpha_{k,l} e^{j\phi_{k,l}} \delta(t - T_l - \tau_{k,l}) \quad (2.10)$$

Similar to the 802.15.3a, the channel impulse response consists of L clusters and K rays per clusters. There is one additional term $e^{j\phi_{k,l}}$ which provides the phase gain of the channel impulse response.

It is generally assumed that the energy of arriving replicas will continually decline, however the authors in [38] emphasized that there are situations where the energy of replicas arriving within a cluster increases to a certain peak value before eventually decreasing. This is especially so in NLOS scenario in indoor office and industrial area.

The 802.15.4a channel model provides four different instances, representing different scenarios of the WSN, namely residential, office, industrial environment, and outdoor. An example for each channel models' realization is shown in figures 2.5 - 2.8.

Summarizing the two standards

The two channel models from the two different standards target two different applications. However, they share several similar characteristics:

1. Both channel impulse responses exhibit cluster-based phenomenon

Figure 2.5: Realizations of the IEEE802.15.4a Residential Channel Model

Figure 2.6: Realizations of the IEEE802.15.4a Office Channel Model

Figure 2.7: Realizations of the IEEE802.15.4a Outdoor Channel Model

Figure 2.8: Realizations of the IEEE802.15.4a Industrial Channel Model. (Please note on the different x-axis.)

2. They both have long channel excess delay
3. The channel model can be represented by a tapped delay line channel

These characteristics are important for subsequent analysis of the source of interference in the next chapter.

2.3 Receiver Structure

The channel impulse response can be generalized in the form of tapped delay line $h(t) = \sum_{l=0}^{L-1} a_l \delta(t - \tau_l)$, where $\delta()$ is the Dirac-delta function. There are L number of paths, arriving at τ_l each with gain a_l . Assuming that the antenna gains at both the transmitter and receiver are unity, the received signal is the convolution of the channel impulse response and the transmitted pulse, which can be expressed as follows.

$$\begin{aligned} r(t) &= h(t) * s(t) \\ r(t) &= \sum_{l=0}^{L-1} a_l s(t - \tau_l) \end{aligned} \tag{2.11}$$

Eq. (2.11) shows that for each transmitted pulse, there are multiple replicas received at the receiver. Based on the channel model shown in figures 2.4 – 2.8, the number of replicas can be very large. This means that the energy of the transmitted pulse is spread over the channel excess delay. Since the bandwidth of the channel is very wide, the transmitted energy undergoes a frequency selective fading, and consequently, the channel excess delay is much larger than the pulse period. The frequency selective fading also means that the replicas are separable. The two characteristics are highly desirable because such a system can potentially benefit from the use of time diversity-

based receiver, such as a RAKE receiver [14].

Due to the emission regulation, the energy of the transmitted pulse is very low. Achieving a high signal to noise ratio at the receiver is very important and challenging. Some of earlier publications on IR-UWB have studied the energy capture behavior of the time diversity-based receiver. One notable paper [14] shows that in order to obtain a good enough energy to combat the AWGN, a large number of replicas must be captured (at least around 40-50). This implies that the use of time diversity-based receiver is no longer an option, but a necessity.

There are two main techniques used for coherent UWB receiver, which will be explained in the following two sub sections. They are the RAKE and Transmitted Reference (TR) receiver. Another technique which is sometimes discussed is the energy detector or OOK (On/Off Key) receiver [39]. For the energy detector, only binary symbol is supported, where one symbol is represented by a transmission of a pulse and another symbol is represented by the absence of a transmission. It is the simplest detection technique which can be used for a system with low-complexity requirement.

2.3.1 RAKE

RAKE receiver was first introduced for a direct sequence spread spectrum (DS-SS) system (or widely known as CDMA system) [27]. The DS-SS system widens the spectrum usage of the transmitted system by spreading the symbol period with multiple chips, which are coded with the objectives of both achieving security and enabling multiple access (hence the name CDMA). Similar to the UWB system, the DS-SS system propagates through a frequency selective fading channel, which means a large amount of the energy is not covered within the chip period. In order to capture the energy outside the chip period, time diversity technique is required, and RAKE receiver was introduced

for this.

RAKE receiver is fundamentally a correlation-based receiver. However, instead of having a correlator template to capture the symbol energy, a RAKE receiver has several parallel correlation templates which capture multiple sources of the received energy [40]. Figure 2.9 shows a diagram explaining the concept of a RAKE receiver.

Figure 2.9: RAKE Receiver

For a CDMA based system, the RAKE templates (generally referred to as Fingers) are spaced at regular intervals. This interval is usually the chip period. This suffices because each template will capture the energy of the whole chip period.

In the case of IR-UWB system, the RAKE template is usually the pulse shape. This means that each finger captures only the energy of one pulse period only (which is usually much smaller compared to the chip period). This means using a chip period interval between the templates is not sufficient for an IR-UWB system. A research paper [41] shows that a fractionally spaced RAKE (FS-RAKE) produces a better performance for IR-UWB. However, this comes at an expense of more complex synchronization and channel estimation.

Main research of RAKE receiver for IR-UWB generally covers approaches on ways to obtain sufficient energy capture without increasing the complexity of the system. It is shown in [16] that in order to obtain sufficient energy against noise, a UWB system requires at least 40 templates. Many existing works try to address this issue by introducing different approaches to select the energy and also different approaches to combine the captured energy from different replicas. Recently a simple partial RAKE receiver [42] is shown to achieve a good enough performance.

2.3.2 Transmitted Reference

In order to alleviate the necessity of complex synchronization and channel estimation, a Transmitted Reference (TR) receiver was introduced for UWB system [43]. In a TR receiver, the transmitter sends a pilot symbol prior to sending the data symbol. The pilot symbol is then used by the receiver as a template for the correlation operation. Using the pilot symbol as the correlation template means that it contains both noise and interference. This leads to the doubling of noise in the receiver. In addition, the overall throughput of the system is reduced due to the necessity to transmit the pilot. Despite these limitations, the TR receiver has one major advantage over RAKE receivers. The TR receiver does not require channel estimation. This is especially important because of the narrow pulses used in UWB.

Researches on TR receiver mainly focus on how to minimize the doubling of the noise in the system and on how to alleviate the lower throughput problem.

Lower Throughput

In the original presentation of TR receiver [43], [44], for every transmitted symbol, the transmitter must transmit a pilot symbol. This means that TR system has one

half of the throughput compared to RAKE receiver. This is true for the original TR structure. However several other TR structures have since been introduced to alleviate this problem. The survey provided in [45] explained all the different TR structures.

One notable improvement of the TR structure is the differential transmitted reference (DTR) [46]. In binary symbol DTR transmitters, when the current information symbol is the same as the last transmitted symbol, the transmitter will transmit a +1 symbol. If the current information symbol is different than the last transmitted symbol, the transmitter will transmit a -1 symbol. This way, the receiver will be able to decode the right information by correlating the current received symbol with the last received symbol. And in doing so, the receiver is basically using the last received symbol as a pilot for the correlation. There is no throughput reduction in this case. The problem with DTR is the possibility of error propagation. In addition, in high data rate transmissions, both the pilot symbol and the information symbol would experience severe interference, and correlating them would increase the interference level.

Another TR structure which has been introduced is the single reference TR (SR-TR) [45]. In SR-TR, one pilot symbol is used as a template for multiple information symbols. It is generally assumed that the channel impulse response remains invariant throughout several symbol periods and thus using one pilot symbol as a template is acceptable. In SR-TR, the throughput of the system is the same as that of a RAKE receiver, because channel estimation is required in RAKE receiver. Transmissions of training symbols are usually used to estimate the channel impulse response. In a similar way, the transmission of the pilot symbol is required to provide a template for the demodulation of subsequent information symbols. Thus, with regards to the RAKE receiver, the use of SR-TR basically alleviates the problem of throughput reduction of the TR receiver.

Noise Enhancement

Another important problem of the TR receiver is the enhancement of noise. Unlike the RAKE receiver where the fingers used is the result of channel estimation, the TR receiver uses a raw pilot symbol as the correlation template. Since every transmission in a communication system is always affected by noise, the template used for correlating the incoming information symbol is also affected by noise. Correlating a noisy template with a noisy information symbol would result in noise enhancement in the test statistic used for detection.

One of the simplest ways to reduce the noise enhancement is done through averaging of the pilot symbols. Instead of using the raw pilot symbol, several pilot symbols are averaged to reduce the noise. In [47], the authors investigate the performance of the system under different ways of averaging the pilot symbols. Generally, the noise level can be reduced significantly through the use of pilot averaging.

Another simpler approach is presented in [48]. In this approach, the receiver measures the signal to noise ratio of different portions of the pilot symbols. Any portion of the symbol that is below a certain threshold will not be used as a template. The goal is to only use portions of the pilot which have less noise.

More complex approaches are presented in [49] and [50]. After receiving the pilot symbol, the receiver will perform an optimization logic and produce a weighing factor. The weighing factor is then multiplied with the template prior to the correlation operation. These approaches increase the complexity of the system because in order to produce a more accurate weighing factor, it requires a higher resolution in processing the pilot symbol. The work in [49] uses a average likelihood ratio test (ALRT) to come up with a weighing factor whereas minimum mean squared error (MMSE) is used in [50].

Summarizing the two types of receiver

For both types of receiver, the main challenge is on how to obtain a good energy capture, given the limitation of the receiver techniques. Due to the strict emission rule for UWB, early researches mainly dwelled on the performance of IR-UWB against the presence of noise. However, in a more practical scenario, interference plays a large role in causing detection errors, and it comes from many different sources. High data rate transmissions potentially produce inter-symbol interference. Communication systems involving many transmission nodes, such as wireless sensor networks, would have to handle multiple access interference. In addition, a MIMO receiver would have to handle multiple antenna interference. Unlike AWGN, the strength of interference is always related to the strength of the transmitted pulses.

2.4 Combatting Interference in IR-UWB

The main objective of the receiver systems discussed thus far is to capture as much energy as possible in a multipath channel and to combat AWGN. They are not designed to handle interference. In the targeted applications of UWB (WPAN and WSN), there are interferences in the system due to both the high data rate and the large number of nodes. Additional techniques to mitigate the interference are required in order to achieve an acceptable signal to interference and noise ratio (SINR).

Equalization is one of the most widely accepted techniques for mitigating ISI. As such, a large number of publications have focused in on the usage of equalization on IR-UWB system. The optimal equalization solution to mitigate ISI is the Maximal Likelihood Sequence Detector (MLSD) and its more practical variation (Viterbi decoder). This is covered in [43], [44], and [45]. In [51] the author shows the interference mitigation using the basic Zero Forcing (ZF) equalizer, whereas in [52], the classical Minimum

Mean Squared Error (MMSE) equalizer is used together with a RAKE receiver. The RAKE receiver ensures the energy capture is sufficient for detection and the equalizer combats the interference by equalizing the impact of preceding and subsequent symbols.

Since the method of equalization is a classical technique, most of the available publications dwell on the more practical implementation aspect of the equalizer. In a two-part paper in [53], [54], the author presents how a MMSE equalizer can be used for both BPSK modulation and an 4-ary BOK (Bi-orthogonal keying). A dual decision feedback equalizer (DFE) system using RAKE receiver is shown in [55]. Almost all of the available publications on equalizer use DS-BPSK for their transmission modulation. In [56], the author shows the implementation and performance of equalizer for TH-PPM UWB. TH-PPM presents additional challenge because the strengths of the interfering symbols are fluctuating depending on the data being transmitted. This is due to the variation of the pulse position within the symbol period.

A variation of equalizer, pre-equalization, where the transmitter performs the equalization prior to transmitting the pulse are presented in [57] and [58]. In [57], ZF pre-equalization is combined with a pre-RAKE combining. This approach significantly reduces the complexity of the receiver since both the energy combining and interference mitigation is performed at the transmitter. In [58], the TR receiver is used with both ZF and MMSE receiver. Several other interesting discussion on MMSE equalization for TR receiver can be found in [59], [60], [61]. In this work, the pilot symbol is divided into smaller fractions, which would then be weighed prior to the correlation. The weights of the smaller fractions are derived using a MMSE algorithm.

One major challenge in the implementation of equalizer for UWB is to reduce the complexity of the receiver. The large number of multipath replicas and the narrowness of each replica imply that a large number of equalization tap with a good timing synchronization is required to achieve good performance improvement. As such there are

many publications which present interesting approaches to reduce the complexity of the equalizer.

In [62], the author presents a tap selection technique to reduce the number of taps used by the equalizer. In [63] and [64], the use of equalizer is combined with the use of other interference mitigation techniques with the goal of reducing the complexity of the equalizers. In [63], the ISI is reduced by using multiband UWB approach where subsequent symbols are transmitted on different bands. In [64], a novel self pilot approach is used to assist the receiver in performing a channel deconvolution. Equalization is performed only when the deconvolution does not produce enough performance improvement. Another complexity reduction technique used is the reduced rank interference cancellation which are presented in both [65] and [66].

Aside from the use of equalizer, there is another popular form of interference mitigation technique, the multi-user detector (MUD), which was originally introduced for mitigating multi-user interference (MUI) [67]. In order to mitigate the interference, the receiver iteratively subtracts the unwanted signal from the received signal. For MUI, this means the receiver will iteratively subtract signals received from other unwanted transmitter. Since the MUD was introduced for CDMA system, this means the receiver can reproduce the unwanted signal by using the code of other users.

In the case of ISI mitigation, the iterative cancellation subtracts the unwanted portion of the preceding and subsequent symbols arriving in the current symbol period. The MUD receiver requires iteration and training to obtain a good performance. The implementation and performance of ISI mitigation using MUD are presented in [68], [69], [70], and [71].

Another approach to reduce the bit error rate due to interference is through the use of coding. Different types of coding have been used for UWB and some of them are capable to reduce the error due to ISI. In [72], the use of superorthogonal convolutional

coding with chip interleaver is shown to successfully mitigate ISI (especially when the interleaver is random). A novel use of multiple long codes presented in [73] is shown to be capable of mitigating ISI for a system with data rate 500 Mbps.

The use of code in combination with other approaches have also been covered in [74] where a pre-RAKE system is used with a turbo codes, and in [69] where turbo code is used together with a MUD. Both are shown to perform well in high data rate.

In the approaches discussed thus far (equalization, MUD, and coding), the received signal contains both the wanted signal and the unwanted interference. The proposed approaches then try to suppress this interference. Another way to combat interference is by avoiding the interference at the first place.

High data rate interference avoidance is generally achieved by lengthening the symbol period or transmitting subsequent data in different orthogonal channels or combination of both. The most prominent example of the use of this combination is in WiMedia system [2]. The interference avoidance is achieved through the use of zero postfix (lengthening the symbol period) and by performing OFDM (transmitting subsequent data in different orthogonal frequency channel). Full interference avoidance comes with a price, usually in a form of slower data rate or a more complex system.

Both the classical approaches (equalization, MUD, and coding) and the avoidance approaches aim to completely eliminate interference. Due the complexity introduced by these techniques, several simpler techniques have been proposed. The objective of these approaches is not to completely eliminate the interference, but to reduce it.

A simple technique using energy detector is shown in [39]. The transmitter first transmits a pilot symbol. The receiver stores the portion of the pilot symbol which is greater than the symbol period. Prior to performing a detection of the current symbol, the receiver checks if the previously detected symbol is a 1 (indicating that there was a presence of a pulse). If it is, the receiver would have to subtract the received signal

with the stored portion of the pilot, prior to performing a detection. If the previous detected symbol is a 0 (indicating that there was an absence of a pulse), the receiver can perform the detection straight away. This is a simple technique, which was shown to have a reasonably good performance, however it is limited to only using energy detector, which does not perform as well as a coherent receiver.

In [75], the authors presented a shift window approach for mitigating high data rate interference in inter chip wireless communication (wireless communication among the different chips inside a personal computer). The receiver shifts its correlation window period based on the training sequence and an optimization process. This solution assumes that the energy of the multipath replicas continuously declines.

The third ISI reduction technique, Received Response Code Sequence, is presented in [76]. The transceiver system first tries to find several strongest replicas in the channel impulse response. A code sequence is then designed based on these strongest replicas, such that a pulse is transmitted at the time instance where this strongest replicas lies. The objective is to strengthen the desired energy, which in this case is the energy of the current symbol.

Another interesting technique is presented in [77], where the authors proposed to reverse the usual transmission of a pilot followed by an information symbol. This, combined with a delayed correlation window was shown to reduce the impact of high data rate interference.

The last four approaches try to either increase the energy captured from the desired energy, or to reduce the energy captured from the undesired energy. One of the unique features of UWB is the frequency selective fading. The energy of the received signal spreads across a very long channel excess delay. These four techniques exploit this feature in order to achieve interference reduction.

2.5 Multiple Access in IR-UWB

During the early development of IR-UWB system, many of the research focus on the multiple access performance of the system. In the original paper by Scholtz [4], the author presented a time hopping method to enable multiple access of the system. Other approaches have since been introduced to handle different objectives. The direct sequence technique was used as one of the proposal in 802.15.3a standardization. The advantage of the DS approach is to achieve high data rate transmission. More complex approach such as the multi user detector has also been proposed for UWB [78]. This is to handle more severe multiple access interference in the system. A recent survey paper [79] provides a good summary of techniques to combat the multi access interference available in the literatures.

In practical systems however, multi access interference mitigation is not employed. Instead, the system is designed to avoid the interference. In a recent MAC layer survey presented in [80] and [81], proposed protocols with scheduled transmissions outnumbers the proposed protocols without scheduled transmissions. The standards 802.15.3, 802.15.4a, and the WiMedia standards use either a time division multiple access (TDMA) or a contention-based approach. TDMA is used for guaranteed data rate communication. In this case, all the communicating nodes have to announce when they are going to transmit their information and to whom they are going to transmit. For bursty transmissions, the contention-based approach is used where the node will have to back out whenever there is collision. In both of these approaches, multi access interference is virtually not present.

Thus, instead of focusing on multiple access interference, in this thesis we focus on the inter-relay interference (IRI), which occurs on a cooperative communication.

2.6 Cooperative Communication

Cooperative communication is one of the hottest topics in wireless communication. Recently there have been many published papers covering different areas of cooperative communication, ranging from the discussion on the basic premises [82],[83], relay selections [84], coding in physical layer [85], channel models [86], MAC layer [87], network layer [88], and even application layer [89]. Cooperative communication takes advantage of the broadcast nature of wireless communication by allowing overhearing nodes to relay the information to the intended recipient. The cooperation among these relay nodes with the sender and the other relay nodes makes possible an enhancement in achievable range, data rates, and error performance.

Such improvements are generally achieved through the spatial diversity obtained due to the transmission from different relays. In wireless communication, spatial diversity has been extensively researched in MIMO (Multiple Input Multiple Output) system where the diversity is obtained through the transmission using multiple antennas [85]. Correspondingly, many techniques in MIMO system have been successfully translated to cooperative communication. The disadvantage of a MIMO system is that it increases the complexity of the system. This is generally acceptable in a cellular-based communication system where the base station can have a multi antenna setup.

But for other system where complexity is not acceptable (such as wireless sensor network), the use of MIMO is not practical. Instead the low complexity requirement of the nodes and the huge number of nodes deployed in the WSN, make it a good system which can benefit from cooperative communication. Cooperative communication involves cooperation between a transmitter and multiple relay nodes in transmitting information to the recipient. The large number of nodes provides a large pool of nodes, which can be selected as relay nodes. Utilizing cooperative communication in WSN

allows the nodes to transmit using less power, or reach further nodes [87].

2.6.1 MIMO and Cooperative Communication

As mentioned earlier, the application of multiple parallel transmission techniques have been extensively researched in MIMO communication. These applications can be categorized into 3 basic categories [90]: spatial multiplexing, spatial diversity, and smart antenna.

In spatial multiplexing, different transmitters transmit different information to the recipient. The objective of spatial multiplexing is to increase the amount of data which can be transmitted in the same bandwidth and time period.

In spatial diversity, different transmitters transmit the same information to the recipient. The objective is to increase the robustness of the transmission process. In MIMO, Space Time Block Coding (STBC) [91] is used to combat the interference introduced from transmission from multiple antennas. Orthogonal Space Time Block Code (OSTBC) attempts to achieve the optimum maximal ratio combining for all the signals received from different transmitting antenna [92]. The OSTBC achieves optimality when the number of transmitting antennas is 2, and the OSTBC used in this scenario is widely known as the Alamouti code [90]. The STTC (Space Time Trellis Code) improves on the OSTBC approach by adding additional coding gain on top of the combining gain [93].

In smart antenna or beamforming, the dynamic antenna array is physically moved such that the phases of signals from different antennas arrive constructively. In a perfect scenario, the arriving signal from different antenna arrays can be fully separated.

In cooperative communication, only spatial diversity and beamforming are used. Achieving spatial multiplexing would require transmitting different information through

different relays. Transmitting different information through different antenna makes sense in MIMO systems because the antenna resides in the same node, and the transmission is done in parallel. However transmitting different information through different relays does not benefit the system, since without multiple antennas, the transmission cannot be done in parallel.

To obtain spatial diversity, the same information is transmitted through multiple relays to the same recipient. A special variant of STBC, Distributed STBC (DSTBC) [85] has been vastly researched. The DSTBC is basically an extension of STBC, and thus most of the research deals with how the code is distributed among the relays and with synchronization issues. The objective of introducing DSTBC is exactly the same as that of STBC, which is to reduce the interference introduced due to the parallel transmission of the signal. There are additional parameters which would influence the error performance of the DSTBC such as the propagation error during the relay, synchronization problem, etc. However, the main target remains the same as in STBC, which is to achieve MRC (maximal ratio combination) of all the transmitted signals. Assuming that the whole energy of the transmitted signal can be captured in the receiver (and it is normalized), and the signals from different relays can be fully separated (through the use of STBC), the maximum achievable energy captured in the receiver is M^2 , where M is the number of relays used.

Similar to STBC in cooperative communication, the beamforming in cooperative communication is an extension of beamforming in MIMO. Thus, the main researches have been concentrated in the distribution of the channel state information among the relays. The objective of the cooperative beamforming is to ensure that the signals arriving at the receivers are added up constructively. Assuming that all the energy from the different relays are captured, and they are added up constructively, and assuming that the signal is normalized, the maximum achievable energy captured in the receiver

is M^2 , where M is the number of relays used.

Although spatial diversity and beamforming are two different methods, they are basically trying to achieve the same thing.

2.6.2 Cooperative Communication in UWB

Cooperative communication is an extension of MIMO and thus will need to achieve the same performance of MIMO, which is the Maximal Ratio Combining (MRC).

In MIMO, the spatial diversity is achieved through the use of multiple antennas. In cooperative communication, however, it is achieved through the use of relay nodes. This adds additional dimension in the field of research because the overall performance does not only rely on the combining effect at the receiver, but also in the network layer design of the system. Correspondingly, researches on cooperative communication on UWB can be categorized into two main areas, the network layer and the physical layer.

The objective of the network layer research is on how to manage the relays and the routing in order to fully utilize the spatial diversity gain of the system. One of the main research topics is on the relay selection algorithm. There are varying degrees of techniques proposed to optimize the relay selection. In [94], the authors present a study on the optimal number and the arrangement of the relays to achieve total orthogonality in the cooperative network. A relay selection based on game theory is presented in [95]. A different approach in performing relay selection is proposed in [96]. In this approach the algorithm starts from a single route from the source to the destination. It then decides whether the neighboring nodes should cooperatively help in routing the information.

Aside from the relay selection protocol, there are several other network layer advances in cooperative communication UWB. A unique MAC layer proposal which is

shown to outperform the usual ALOHA protocol used for IR-UWB is shown in [84] and [97]. And finally in an interesting research on the usage of cooperative communication UWB for Wireless Body Area Network (WBAN) [98], the authors show that the positioning of the nodes (source, relays, and destination) significantly affects the achievable diversity gain.

The objective of the physical layer research is mainly on techniques to improve the spatial diversity combining at both the transmitter and the receiver. The most obvious technique is the use of DSTBC technique available for the narrowband cooperative communication. This is covered in [99], where the authors show the bit error rate performance of the system using Alamouti code. In [100], the authors show an adaptive scaling technique, in which the relays apply the inverse channel gain scaling to the transmitted signal. The objective of this is to mitigate the impact of the multipath in the system. It is shown that such approach performs better than a non-scaled approach. In [101] and [102] the authors propose a time-hopping-based technique to ensure orthogonality of the signal arriving from different relays. Essentially, the number of time hopping slots is increased to accommodate additional slots for different relays. The performance improvement is shown for different relay protocols: decode-and-forward (DAF) in [101] and amplify-and-forward (AAF) in [102]. A space frequency coded cooperative communication is proposed in [103]. In this approach different relays transmit in different frequency bands. As expected this approach produce orthogonal separation, which mitigates the relay interference. However the authors did not explain how to achieve the frequency separation.

The performance of cooperative communication in other forms of UWB system (Multiband OFDM) have also been presented in [104] and [105].

Of all the available researches on the physical layers, to the best of our knowledge, there is no paper covering the high data rate cooperative communication. In fact, some

of the available techniques such as [102] would not be possible in high data rate due to the presence of ISI.

2.7 Summary

In this chapter, we have presented a general survey of the transmitter, receiver, and channel model of UWB system. This is followed by the review on the current available techniques to combat high data rate interference in UWB. In addition, we covered a brief history of cooperative communication and the current state of cooperative communication in IR-UWB.

In subsequent chapters, we present our own techniques, which will make use of the uniqueness of UWB system, to combat interference especially in high data rate system. We will start by first deriving the mathematical expression of the contribution of the interferences in the detection process. The objective of the derivation is to fully separate the desired energy from the undesired energy. Since there are different sources of interferences, the mathematical derivation also separates the different source of interference in the undesired energy. From the total separation, we would then be able to propose our techniques to mitigate them.

Chapter 3

Sources of Interference

Aside from the ever-present Additive White Gaussian Noise (AWGN), in practical wireless communication system, interference also plays a big role in determining the error rate performance of the receiver. Interference comes from different sources, including interference from other radio systems which UWB overlays, interference from other antenna in MIMO system, interference from other users in multi user system, and inter-symbol interference in a high data rate system.

The main objective of this chapter is to dissect the impact of different sources of interference in the detection process. The main focus is on the high data rate interference in a single user system.

Although there have been many available papers covering the mathematical analysis for UWB performance against interference, most of these papers do not try to dissect the different sources of interference, and they do not analyze their individual impact to the receiver's performance. Instead, the aim of these papers is usually to obtain the combined impact from all the different interference in the form of a single Signal to Interference and Noise Ratio (SINR). In [106], the authors provide a Signal to Noise Ratio (SNR) for RAKE receiver propagating through the IEEE802.15.3a channel. The

analysis, however, is only for low data rate system and thus does not contain ISI. In [107], SINR analysis for both RAKE and TR receivers are presented. Although the analysis covers the multiple user interference (MUI), it is limited to a low data rate system. In [108, 109], SINR analyses for a system with both MUI and ISI are presented. Unlike in these available papers, instead of combining all the affecting interference and present a single SINR formulation, in this chapter the impact of different sources of interference to the detection process is studied individually.

We start by presenting the mathematical formulation of the received signal. From there, we derive the test statistic, which will be used for detection, focusing on separating the energy captured from different sources of interference. The receiver model used is based on a coherent correlation-based receiver, specifically a maximal ratio combiner (MRC)-based RAKE receiver. Since the derivation covers only interference, the test statistic is also applicable to TR receiver (since the main performance difference between RAKE and TR is the doubling of noise in TR).

The transmitted signal is a direct sequence (DS)-UWB with binary phase shift keying (BPSK) symbol. This means that the multi-user code is determined by the sequence of -1/+1 multiplied by the polarity of the pulse, and the symbol information is represented by the phase of the transmitted pulse. For binary transmission, the phase of the transmitted pulse is equal to the polarity of the pulse.

3.1 Mathematical Derivation

Based on the specified transmitter, the mathematical model for the m^{th} transmitted symbol $s_m(t)$ is given by:

$$s_m(t) = \sqrt{\frac{E_s}{N_{pps}}} \sum_{k=mN_{pps}}^{(m+1)N_{pps}-1} c_k a_m p(t - kt_c) \quad (3.1)$$

The equation is essentially the same as in (2.4), with the addition of the energy per symbol term E_s . For each symbol, N_{pps} pulses are transmitted, and the total energy per symbol is denoted by E_s . The transmitted pulse is denoted by $p(t)$. The k^{th} transmitted pulse is multiplied by the information symbol a_m and multi user code c_k .

The channel is represented by an L -tapped delay line, $h(t) = \sum_{l=0}^{L-1} g_l \delta(t - \tau_l)$, where $\delta(t)$ is the Dirac-delta function and g_l is the channel gain of the l^{th} replica which arrives with τ_l delay. In this equation, there are L number of multipath replicas. In a correlation-based receiver, the received signal is correlated with a template. The result of the correlation operation is a test statistic, upon which the decision is based. In a BPSK system, a positive test statistic result indicates that a +1 symbol was transmitted. When the test statistic result is negative, -1 symbol was transmitted.

With a perfect correlation receiver which captures all the incoming replicas and combines the energy using Maximal Ratio Combiner (MRC), the test statistic of the receiver Z_m can be represented as follows.

$$Z_m = \sum_{k=mN_{pps}}^{(m+1)N_{pps}-1} \sum_{i=0}^{L-1} g_{i,k} [r(t) \otimes v_{i,k}(t - \tau_i)] \quad (3.2)$$

The received signal $r(t)$ is the convolution of the transmitted signal $s_m(t)$ and the channel impulse response $h(t)$. The term $g_{i,k}$ denotes the channel gain of the i^{th} multipath replica from the k^{th} transmitted pulse. The operator $\otimes$ represents correlation operation. The correlator template, $v_{i,k}$, is defined as:

$$v_{i,k}(t - \tau_i) = \frac{1}{\sqrt{N_{pps}}} c_k p(t - kt_c - \tau_i) \quad (3.3)$$

The terms c_k and kt_c are the multi user code and the time delay for the k^{th} pulse respectively. The delay between the first arrival of the multipath replica and the i^{th} multipath replica is denoted by τ_i .

In a practical scenario, capturing all the replicas is expensive, and thus, the number of replicas used is generally less than L .

For a binary symbol transmission, the probability of error P_e can be expressed as:

$$\begin{aligned} P_e &= P(Z_m > 0 | a_m = -1)P(a_m = -1) + \\ &\quad P(Z_m < 0 | a_m = 1)P(a_m = 1) \end{aligned} \quad (3.4)$$

In subsequent discussions, we derive the test statistic with the objective of separating the energy from the transmitted symbol and the interfering energy.

Suppose $N_{pps} = 1$, which means one symbol is represented by one pulse transmission. In addition, let the symbol period to be larger than the channel excess delay.

Normalizing the energy per symbol E_s to 1, the m^{th} transmitted symbol can be represented as $s_m(t) = a_m p(t)$.

The test statistic of the m^{th} symbol is

$$\begin{aligned} Z_m &= \sum_{i=0}^{N_f-1} g_i [r(t) \otimes v_i(t - \tau_i)] \\ &= \sum_{i=0}^{N_f-1} g_i [a_m \sum_{l=0}^{L-1} g_l p(t - \tau_l) \otimes p(t - \tau_i)] \\ &= \sum_{i=0}^{N_f-1} g_i [a_m g_i R_p(\tau_i, \tau_i) + a_m \sum_{l=0, l \neq i}^{L-1} g_l R_p(\tau_l, \tau_i)] \\ &= \sum_{i=0}^{N_f-1} a_m g_i^2 + \sum_{i=0}^{N_f-1} a_m g_i \sum_{l=0, l \neq i}^{L-1} g_l R_p(\tau_l, \tau_i) \end{aligned} \quad (3.5)$$

where $R_p(\tau_x, \tau_y) = p(t - \tau_x) \otimes p(t - \tau_y)$. In the final form of (3.5), the test statistic can be divided into summation of two main terms. The first term $\sum_{i=0}^{N_f-1} a_m g_i^2$ represents the correlation between the templates and all the synchronized replicas arriving at the receiver from the transmission of the m^{th} symbol. There are N_f templates, and they are perfectly synchronized with the N_f multipath replicas, where $N_f \leq L$. Since all the replicas and all the templates are synchronized, the cross-correlation between them ($R_p(\tau_i, \tau_i)$) is 1 and thus the contributing energy is simply the square of the channel gain. This leaves the m^{th} symbol information a_m to determine the polarity of the first term of the test statistic. This implies that the energy contribution of the first term always has the correct polarity. Since there is no interference affecting the first term, it shall be referred to as zero interference test statistic (Z_{ZI}).

The remaining portion of the test statistic is the correlation between the template and the multipath replicas which are not synchronized to the template ($l \neq i$). Even though the UWB channel is frequency selective, there are instances where two replicas collide. Such collisions are reflected by this portion of the test statistic. It shall be referred to as current pulse interference test statistic (Z_{CPI}).

The test statistic given in (3.5) is only valid when there is a complete separation between receptions of different symbols. This happens when the replicas of the m^{th} symbol do not interfere with the $(m+1)^{th}$ symbol. In a more practical scenario, for example under 802.15.3a channel model, the channel excess delay ranges from 40 ns to 150 ns in indoor channel. This means a complete separation is only possible for transmission of 6 Mbps and below. Transmitting with data rate higher than 6 Mbps means that some replicas from previous symbols' transmission will arrive in the current symbol's correlation window.

In addition, in order to capture enough energy, the correlation period needs to be larger (or large enough) [14]. If the correlation window is larger than the symbol pe-

riod, replicas from subsequent symbols' transmission will also interfere with the current symbol's detection.

These additional interferers will contribute towards the total test statistic at the receiver. The total test statistic is thus given as.

$$Z = Z_{ZI} + Z_{CPI} + Z_{PPI} + Z_{SPI} \quad (3.6)$$

where the energy contribution from the previous pulses interference is denoted as Z_{PPI} and the energy contribution from the subsequent pulses interference is denoted as Z_{SPI} .

With the additional interferers, the received signal can be represented as (3.7).

$$r(t) = r_m(t) + \sum_{n=m-N_{PI}}^{m-1} r_n(t) + \sum_{q=m+1}^{m+N_{SI}} r_q(t) \quad (3.7)$$

r_n represents all the received signal from the preceding symbols which affects the m^{th} symbol detection. Similarly, r_q represents all the received signal from subsequent symbols which affects the m^{th} symbol detection. N_{PI} is the number of previous symbols affecting the current detection, whereas N_{SI} is the number of subsequent symbols affecting the current detection. The two values are determined by the length of the symbol period and the channel excess delay as shown in (3.8).

$$N_{PI} = N_{SI} = \left\lceil \frac{\text{channel excess delay}}{\text{symbol period}} \right\rceil \quad (3.8)$$

The impact of the additional $\sum_{n=m-N_{PI}}^{m-1} r_n(t)$ term to the current symbol's test statistic is denoted by Z_{PPI} and can be expressed as.

$$\begin{aligned}
Z_{PPI} &= \sum_{i=0}^{N_f-1} g_{m,i} \sum_{n=m-N_{PI}}^{m-1} r_n(t) \otimes v_{m,i}(t - \tau_{m,i}) \\
&= \sum_{i=0}^{N_f-1} \sum_{n=m-N_{PI}}^{m-1} \sum_{l=0}^{L-1} a_n g_{m,i} g_{n,l} R_p(\tau_{n,l}, \tau_{m,i})
\end{aligned} \tag{3.9}$$

Similarly, the impact of the additional $\sum_{q=m+1}^{m+N_{SI}} r_q(t)$ term is denoted by Z_{SPI} and can be expressed as (3.10)

$$\begin{aligned}
Z_{SPI} &= \sum_{i=0}^{N_f-1} g_{m,i} \sum_{q=m+1}^{m+N_{SI}} r_q(t) \otimes v_{m,i}(t - \tau_{m,i}) \\
&= \sum_{i=0}^{N_f-1} \sum_{q=m+1}^{m+N_{SI}} \sum_{l=0}^{L-1} a_q g_{m,i} g_{q,l} R_p(\tau_{q,l}, \tau_{m,i})
\end{aligned} \tag{3.10}$$

The extra subscript m, n, q indicate which symbol the replicas belong to. For both (3.9) and (3.10), the term $g_{m,i}$ denotes the channel gain of the i^{th} replica from the m^{th} symbol, which is the current symbol. The term $g_{n,l}$ in (3.9) denotes the channel gain of the l^{th} replica from the n^{th} symbol, which is one of the interfering symbol from the previous symbol transmissions. Similarly $g_{q,l}$ in (3.10) denotes the channel gain of the l^{th} replica from the q^{th} symbol, which is one of the interfering symbol from the subsequent symbol transmissions. The same explanation of the subscript applies to the correlation template $v_{m,i}$ and pulse delays $(\tau_{m,i}, \tau_{n,l}, \tau_{q,l})$.

For a binary symbol, when the transmitted symbol is +1, the detection is correct when $Z_m = Z_{ZI} + Z_{CPI} + Z_{PPI} + Z_{SPI} > 0$. This representation separates the test statistic into four different contributing energies. Alternatively, the total test statistic, Z_m , is the sum of the product of the template with the received signal and is given by

$$\begin{aligned}
Z_m = & \sum_{i=0}^{N_f-1} g_i \left[a_m g_i + \sum_{l=0, l \neq 1}^{L-1} a_m g_l R_p(\tau_l, \tau_i) + \right. \\
& \sum_{n=m-N_{PI}}^{m-1} \sum_{l=0}^{L-1} a_n g_{n,l} R_p(\tau_{n,l}, \tau_{m,i}) + \\
& \left. \sum_{q=m+1}^{m+N_{SI}} \sum_{l=0}^{L-1} a_q g_{q,l} R_p(\tau_{q,l}, \tau_{m,i}) \right] \tag{3.11}
\end{aligned}$$

With the additional two contributing test statistics Z_{PPI} and Z_{SPI} , the probability of error is given by

$$\begin{aligned}
Pe = & P(Z_{ZI} > -(Z_{CPI} + Z_{PPI} + Z_{SPI}) | a_m = -1) P(a_m = -1) + \\
& P(Z_{ZI} < -(Z_{CPI} + Z_{PPI} + Z_{SPI}) | a_m = +1) P(a_m = +1) \tag{3.12}
\end{aligned}$$

Relaxing all the assumptions on the number of pulse per symbol and the length of the symbol period, the test statistic is written as:

$$Z_{ZI} = \sum_{k=mN_{pps}}^{(m+1)N_{pps}-1} \sum_{i=0}^{N_f-1} \frac{\sqrt{E_s} a_m g_{k,i}^2}{N_{pps}} \quad (3.13)$$

$$Z_{CPI} = \sum_{k=mN_{pps}}^{(m+1)N_{pps}-1} \sum_{i=0}^{N_f-1} \sum_{l=0, l \neq i}^{L-1} \frac{\sqrt{E_s} a_m g_{k,i} g_{k,l}}{N_{pps}} R_p(\tau_{k,l}, \tau_{k,i}) \quad (3.14)$$

$$Z_{PPI} = \sum_{k=mN_{pps}}^{(m+1)N_{pps}-1} \sum_{i=0}^{N_f-1} \frac{\sqrt{E_s} g_{k,i}}{N_{pps}} \sum_{n=m-N_{PI}}^{m-1} \sum_{k'=nN_{pps}}^{(n+1)N_{pps}-1} a_n c_k c_{k'} \quad (3.15)$$

$$\sum_{l=0}^{L-1} g_{k',l} R_p(\tau_{k',l}, \tau_{k,i})$$

$$Z_{SPI} = \sum_{k=mN_{pps}}^{(m+1)N_{pps}-1} \sum_{i=0}^{N_f-1} \frac{\sqrt{E_s} g_{k,i}}{N_{pps}} \sum_{q=m+1}^{m+N_{SI}} \sum_{k'=qN_{pps}}^{(q+1)N_{pps}-1} a_q c_k c_{k'} \quad (3.16)$$

$$\sum_{l=0}^{L-1} g_{k',l} R_p(\tau_{k',l}, \tau_{k,i})$$

Equations (3.11) and (3.13) - (3.16) show the separation of the test statistic between the zero interference energy and the interference energy. The test statistic used for detection is the sum of these two sources of energy. In a binary system, when the test statistic produces energy with the same polarity as that of the transmitted symbol, the detection is correct. Otherwise, a detection error has occurred. It is clear that in order to improve the system's performance against interference, we need to increase the energy contribution of Z_{ZI} and reduce the energy contribution of all the other test statistics from the interference.

3.2 Analysis and Discussion

In order to further understand the impact of each different source of interference, we need to know the actual impact of each of the interference to the actual error perfor-

mance of the system. As we can see from the mathematical formulation of all the test statistics, the energy contribution of each test statistic relies heavily on the gain and the delay of each replica. These values are random values from the channel impulse response, which are determined by the channel model used. Thus to understand the actual impact, a simulation of a receiver system was conducted. Table 3.2 shows the parameters used for the simulation and figures 3.1 – 3.2 show the error performance against the length of the symbol period. Two channel models from IEEE 802.15.3a were used. The first is CM1, which is a line-of-sight (LOS) channel, and the second is CM3, which is a more severe non-line-of-sight (NLOS) channel.

Table 3.1: Simulation parameters for investigating interferences

Modulation	BPSK with 1 pulse per symbol
Pulse shape	0.5 ns second derivative of Gaussian monopulse
Receiver	RAKE with 1 finger and perfect channel estimation
Channel	CM1 and CM3 of 802.15.3a
Symbol Period	2 – 10 ns

The simulation results show that the error rates due to the inter-symbol interference (Z_{PPI} and Z_{SPI}) go down as the data rates become slower (longer symbol period). This is expected because as the symbol period gets larger, the interference from the other symbols gets weaker. However, this is not the case when Z_{CPI} alone is considered. The error rate due to Z_{CPI} remains constant for all the symbol periods used. This is also expected, since the error in this case is caused only by the replicas of the current pulse. When all the energies from all the different sources of interferences are combined, the trend of the error rates follows closely the trend of the interference caused by ISI. However, for CM1 it reaches the error floor which is defined by the interference from Z_{CPI} .

Based on the mathematical derivations and the result of the simple simulation, there

Figure 3.1: Bit error rate against symbol period for CM1 of 802.15.3a

Figure 3.2: Bit error rate against symbol period for CM3 of 802.15.3a

are three main observations:

1. The Z_{CPI} is the result of the correlation between the template and other replicas from the current pulse which are not synchronized with the RAKE fingers. Based on this definition, one way to reduce the Z_{CPI} is to increase the number of RAKE fingers. By doing so, the receiver shifts the energy contribution from Z_{CPI} to Z_{ZI} . In addition, increasing the number of RAKE fingers will not only reduce the interference from Z_{CPI} , but will also improve the robustness of the system against noise.

Another simulation was performed to investigate the impact of increasing the RAKE finger to the error performance. The simulation parameters are mostly the same as in table 3.2, however in this simulation the symbol period was set to 2 ns (corresponding to 500 Mbps) and the number of RAKE fingers was varied from 1 to 10. Figure 3.3 – 3.4 show the performance.

The results show that by increasing the number of RAKE fingers, the error rate due to Z_{CPI} drops below 10^{-4} when the number of RAKE fingers used is more than 2. However, the interference from Z_{PPI} and Z_{SPI} does not fall as quickly and it reaches the error floor at around 10^{-2} to 10^{-3} .

2. From equations (3.13) - (3.16), it is noted that there is one main difference between the Z_{ZI} and the other test statistics, which is the presence of $R_p(\tau_{k,l}, \tau_{k,i})$ in the interference test statistic. This is essentially the cross-correlation of the received pulses in different delay position. The interfering test statistic can be seen as the sum of these cross-correlations, after they are scaled with several other parameters such as the channel gain, the DS code, and the amplitude of the other interfering symbols.

In order to reduce the energy contribution from the interference test statistic, we

Figure 3.3: Bit Error Rate for Different Numbers of RAKE fingers for CM1

Figure 3.4: Bit Error Rate for Different Numbers of RAKE fingers for CM3

can reduce the scaling parameters or the cross correlation of the template and the interfering replicas. Reducing the scaling parameters is, however, not possible. The channel gain and the amplitude of the other interfering symbols are random values. The DS code is only orthogonal when the whole code sequence length is correlated. This is useful for user separation in a synchronized multiple access system, but it is not applicable in the current scenario. This leaves us only with reducing the cross-correlation value.

The cross correlation value depends on the transmitted pulse. Our goal is to reduce the cross correlation between the current symbol transmission and all the replicas which arrive within the correlation symbol period. We propose a transmitter which employs a pulse shape hopping technique to reduce the interference. Chapter 4 is dedicated to discuss this transmitter technique.

3. Equation (3.11) shows that the test statistic is the sum of N_f different energies, where each is the result of the energy capture of each individual template. With maximal ratio combining, the energy captured from each template is scaled by the synchronized channel gain, which in this case is g_i . In order to achieve correct detection, the sum of all the N_f energies must produce the same polarity as the transmitted symbol a_m . Due to the interfering energy, not all of the N_f energy captured would constructively contribute to the total energy.

One of the main strong point of a UWB system is that there is a large pool of multipath replicas from which the receiver can selectively use for detection. Instead of making use of all the replicas, our proposal is to selectively use the energy captured. The goal is to select energies which are contributing towards a constructive energy.

Our approach for energy selection at the receiver is explained in chapter 5. The

proposed selective energy capture receiver is based on a Transmitted Reference receiver. This is to alleviate the practical challenges of synchronization and channel estimation with a narrow pulse shape in performing selective energy capture using RAKE.

3.3 Summary

In this chapter we have performed a mathematical derivation of the receiver's test statistic with the objective of investigating the impact of different sources of interference to the error performance of the system. Since the actual error performance is affected by the actual channel model used, simulation results were also presented.

From the mathematical derivation and the simulation results, we came up with three observations. The first observation is on how the error due to the current pulse interference can be reduced significantly by increasing the number of RAKE fingers. This is one of the advantages of UWB system. The wide bandwidth produces fine multipath replicas, enabling better energy capture through the use of a time-diversity-based receiver. Simulation results show that although the basic RAKE receiver can significantly reduce interference due to current pulse interference, it cannot mitigate inter-symbol interference.

The remaining two observations allowed us to formulate two proposals (one for the transmitter, and one for the receiver) to reduce inter-symbol interference. The two proposals share two underlying aspects:

1. The two proposals are based on the energy capture selection.
2. The goal of the proposed approaches is interference reduction. This is as opposed to interference mitigation and interference avoidance. In interference reduction,

the goal is to reduce the amount of interfering energy without increasing the complexity of the system.

The following chapters 4 and 5 explain the transmitter and receiver proposals respectively.

Chapter 4

Reducing Interfering Energy through Pulse Shape Hopping

As discussed in chapter 3, the major differentiating factors between the contribution of the zero interference test statistic and the inter symbol interference test statistic are in the form of the scaling provided by the channel gain and the cross-correlation of the pulses. It is understood that the scaling provided by the channel gain depends on the channel impulse response, which is random in nature. This leaves the cross correlation of the pulses as a design parameter which we can use to reduce the contribution of the inter symbol interference test statistic.

In order to do so, a transmitter design which makes use of a special pulse shape is required. In this chapter, we present a pulse shape hopping technique, which utilizes both orthogonal and shift-orthogonal pulse shapes to reduce the inter-symbol interference. In IR-UWB, these types of pulse shape have been used mainly for M -ary Pulse Shape Modulation (PSM) and to represent different user in multiple access system.

In [110] the authors discuss the use of an ISI-free pulse shapes as a method to mitigate ISI. The proposed pulse shapes always have zero cross-correlation at every sampling

point and thus will never suffer from inter-pulse interference (and correspondingly ISI). However, the paper only provides a theoretical possibility of such pulse, with neither theoretical nor practical error performance analysis. The paper also acknowledges that achieving a perfect orthogonality would require the pulse width have to be infinite, which is impractical.

In this chapter, one practical implementation of shift orthogonal pulse and two orthogonal pulse shapes are used to combat ISI. The orthogonal pulse shapes are different to the ISI-free pulse shape in [110], wherein their cross-correlation is only zero when the pulses are synchronized. This means, the use of orthogonal pulse by itself does not mitigate ISI. The main contribution of this chapter is the introduction of a simple Pulse Shape Hopping (PSH) method, which achieves ISI mitigation by utilizing orthogonal pulse shapes.

Prior to explaining our proposed approach, a literature review on the pulse shape design in UWB system is first presented. After which, our proposed transmitter design [15], [111] is explained together with the improvement results. A discussion on the impact of our proposed transmitted design on the current state of pulse shape design concludes this chapter.

4.1 Pulse Shapes in UWB

Pulse shapes play a very important role in IR-UWB system. It is the width of the transmitted pulse that defines how wide the bandwidth of the system is. The shape of the pulse also defines the spectral shape of the transmitted signal.

Scholtz introduced impulse radio UWB in his paper in 1993 [4]. In this original publication, Gaussian monopulse was used as the transmitted pulse. Due to the simplicity in generating the Gaussian monopulse (achieved simply by applying a step function

current to the antenna), this pulse shape has been generally accepted as the standard pulse shape for UWB system.

When the FCC finally approved the usage of UWB in February 2002, it introduced a spectral mask which limits the maximum transmitted power of the UWB signal. As shown in figure 4.1, the spectral mask significantly limits the transmitted power of the system which in turn will reduce the robustness of the system under the ever present thermal noise.

Figure 4.1: Spectral Mask for Indoor Channel defined by the FCC

In the presence of the FCC rules and the fact that UWB system overlays with other wireless spectrum, there are two immediate impacts of the pulse design. First of all,

in order to use as much energy as possible, it is important for the spectral shape of the transmitted pulse to be as close as possible to the spectral mask defined by the FCC rules. This results in a system that has a higher energy per bandwidth and thus performs better in the presence of thermal noise. Secondly, to minimize or to avoid interferences to and by the other communication systems, the pulse shape should be robust enough so as to produce several nulls in certain frequency bands which are used by other narrow band communication systems.

Not surprisingly, most of the pulse shape design papers published so far focus on achieving high spectral utilization efficiency (SUE) and robustness against narrow band interference (NBI). The narrow band interferer considered the most is the 802.11a/g, which uses the 5 GHz spectrum.

Another popular objective of pulse shape design is to use the pulse shape as an information carrier. This is made possible by the introduction of orthogonal pulse shapes. A set of pulse shapes is considered orthogonal if the cross correlation of the pulses is zero when the pulses are fully synchronized. A set of orthogonal pulse shapes can then carry information because the receiver would be able to perform a simple demodulation to differentiate these pulses. A set of pulse shape that carries information can be used to represent an M -ary Pulse Shape Modulation (PSM) system [20] or used in a parallel transmission to increase the data rate of the system [112].

4.1.1 Pulse Shapes to Achieve Spectral Utilization Efficiency

There are many publications which cover this particular topic. Several papers actually add an additional constraint to the spectrum design such that there is a null spectrum at certain bands, especially at around 5GHz where the 802.11a/g spectrum is located [113], [114]. The pulse shapes design methods to achieve spectral utilization efficiency

(SUE) can generally be categorized into the following approaches:

1. Derivatives of Gaussian Pulse

The Gaussian monopulse introduced by Win and Scholtz does not fit the spectral mask [32]. However, several derivatives of the Gaussian monopulse can fit the spectral mask quite well. In [115], the authors have shown that the fourth and the seventh derivatives of the Gaussian pulse can fit the FCC spectral mask better than other derivatives.

In [32], the authors show that compared to the fourth and seventh derivatives of the Gaussian pulse, linear combination of several different derivatives of Gaussian monopulse can achieve a better fit to the regulatory spectral mask.

2. Utilization of Finite Impulse Response (FIR) prefilter

In this category, the approach of linearly combining the Gaussian monopulse is pushed a step further. In order to achieve an even better spectral fit, the authors in [18] and [116] designed a finite impulse response (FIR) prefilter to shape the spectrum of the Gaussian monopulse. The resulting pulse shape has a spectrum which fits the spectral mask very well.

3. Discrete shaping

Unlike the previous two categories, the design in this approach is based on the discrete representation of the pulse and every sampling point. Prolate Spheroidal based pulse shape (widely known as Parr's pulse) [21] is the only notable pulse shape in this category.

4.1.2 Pulse Shapes to Carry Information

In addition to spectrum design, there are also several papers which came up with designs for set of pulse shapes which are mutually orthogonal. Orthogonality enables M -ary or parallel transmissions.

The first orthogonal pulse shape is the Hermite-based pulse shape specified in [20]. The Hermite pulse shape is derived from the classic orthogonal polynomials. All the Hermite pulse shapes are mutually orthogonal. The pulse shape has been proposed for M -ary transmission [117] as well as to represent different users in multi-user systems [118]. In addition, the original authors have also shown the performance when the synchronization is not perfect [119], as well as the transmitter structure [120]. Another pulse design, which is also based on the classic orthogonal polynomials is the Laguerre pulse shape proposed in [121]. Of the two, Hermite pulse is a better-researched pulse shape.

Other approaches have also been used to produce orthogonal pulses such as the use of wavelet [113], [22]. In addition, the Parr's pulse design approaches explained earlier have a special characteristic that the pulses generated are mutually orthogonal.

Out of the two objectives of pulse shape design described earlier, the first objective is more essential to the UWB system. Fulfilling the spectral mask regulation is required for practical usage of UWB system.

4.2 Pulse Shape Hopping (PSH)

As shown in chapter 3, there are three sources of interference affecting the error performance in high data rate system. Figures 3.3 and 3.4 show that by increasing the

number of RAKE fingers, we can reduce the impact of the interference from the current pulse. However, the interferences from other symbols (Z_{PPI} and Z_{SPI}) do not fall as quickly as Z_{CPI} does when the number of RAKE finger is increased. In fact, the rate of performance improvement is reduced when the number of finger is higher. As mentioned earlier, increasing the number of fingers shifts the energy captured from the Z_{CPI} to Z_{ZI} . The energy of Z_{PPI} and Z_{SPI} is not affected, but as Z_{ZI} increases, the effect of interfering energy from Z_{PPI} and Z_{SPI} is reduced to a certain extent. Without performing any equalization, it is impossible to shift the energy from Z_{PPI} and Z_{SPI} into Z_{ZI} . Therefore one way to reduce the error rate is to reduce the energy from Z_{PPI} and Z_{SPI} .

We reproduce equation (3.13), (3.15), and (3.16) again in order to ease the analysis. In order to further assist the analysis, instead of showing the final mathematical derivation of the Z_{ZI} , we present an intermediate step which includes the correlation of the pulses $R_p(\tau_{i,l}, \tau_{i,l})$ (which essentially is a unity when the pulse energy is normalized).

$$Z_{ZI} = \sum_{k=mN_{pps}}^{(m+1)N_{pps}-1} \sum_{i=0}^{N_f-1} \frac{\sqrt{E_s} a_m g_{k,i}^2}{N_{pps}} \sum_{l=0}^{L-1} R_p(\tau_{k,i}, \tau_{k,i})$$

$$Z_{PPI} = \sum_{k=mN_{pps}}^{(m+1)N_{pps}-1} \sum_{i=0}^{N_f-1} \frac{\sqrt{E_s} g_{k,i}}{N_{pps}} \sum_{n=m-N_{PI}}^{m-1} \sum_{k'=nN_{pps}}^{(n+1)N_{pps}-1} a_n c_k c_{k'} \sum_{l=0}^{L-1} g_{k',l} R_p(\tau_{k',l}, \tau_{k,i})$$

$$Z_{SPI} = \sum_{k=mN_{pps}}^{(m+1)N_{pps}-1} \sum_{i=0}^{N_f-1} \frac{\sqrt{E_s} g_{k,i}}{N_{pps}} \sum_{q=m+1}^{m+N_{SI}} \sum_{k'=qN_{pps}}^{(q+1)N_{pps}-1} a_q c_k c_{k'} \sum_{l=0}^{L-1} g_{k',l} R_p(\tau_{k',l}, \tau_{k,i})$$

In order to reduce the energy from Z_{PPI} and Z_{SPI} , there are several parameters which can be modified.

1. Energy per symbol E_s , number of pulse per symbol N_{pps} , and template gain $g_{k,i}$. Reducing energy per symbol and template gain, and increasing the value of the number of pulse per symbol will reduce the energy of the interfering test statistic. However, these three terms are also part of Z_{ZI} and thus will also reduce the zero interference test statistic. In fact, it is desirable to increase these values as it increases the robustness of the system against AWGN.

This is the main difference between the AWGN mitigation and interference mitigation. In AWGN mitigation, increasing total impact of the three parameters increases the robustness of the system against the noise. In interference mitigation, doing so will increase both the desired and undesired energies.

2. Other symbol's information a_n and a_q , the coding c_k and $c_{k'}$, and the interfering replicas' channel gain $g_{k',l}$. Unlike the three preceding parameters, these parameters are not part of Z_{ZI} and thus reducing their values will reduce the interfering energy. However, the values of these parameters are not controlled by any of the design parameters.

Assuming that all the symbol information has equal distribution, the values of a_n and a_q are random and generally cannot be zero (unless zero has a meaning in the modulation). The channel gain of the interfering replicas depends solely on the channel impulse response. This gain is also a random value and is not under control of both the transmitter and the receiver.

Similarly the coding c_k and $c_{k'}$ are random values whose values depends on the channel impulse response. Although the DS codes are designed to be orthogonal, its' orthogonality is only relevant for multiple access detection.

3. This leaves us with the cross-correlation of the pulse $R_p(\tau_{k',l}, \tau_{k,i})$. A similar

expression $R_p(\tau_{k,i}, \tau_{k,i})$ is also present in the Z_{ZI} , however these two terms carry different meanings and produce different impacts to the overall test statistic. The correlation term in the Z_{ZI} is the auto correlation of the same pulse, which is the result of a fully synchronized correlation between the template and the received replicas. As explained earlier, this correlation value will result in a unity provided that the pulse energy is normalized to one. It is actually the design goal of the receiver system to produce as high an energy as possible from this correlation value.

However, for the correlation $R_p(\tau_{k',l}, \tau_{k,i})$ in the Z_{PPI} and Z_{SPI} , the opposite is true. This means that in order to reduce the interfering energy, it is desired to produce as low energy as possible for this correlation value.

Given that the two correlation values are from the same pulse $p(t)$, achieving the two opposing design goals is not possible. However, there is no requirement that the two correlation operations should be from the same pulse. By modifying the transmitter's design we can achieve the objective of producing as low energy as possible for the correlation value in Z_{PPI} and Z_{SPI} .

If $\otimes$ is a correlation operator, the correlation in the Z_{ZI} can be represented as (4.1), whereas the correlation in the Z_{PPI} and Z_{SPI} can be represented as (4.2).

$$R_p(\tau_{k,i}, \tau_{k,i}) = p_{\text{template}}(t - \tau_{k,i}) \otimes p_{\text{current symbol}}(t - \tau_{k,i}) \quad (4.1)$$

$$R_p(\tau_{k,i}, \tau_{k',l}) = p_{\text{template}}(t - \tau_{k,i}) \otimes p_{\text{other symbol}}(t - \tau_{k',l}) \quad (4.2)$$

The pulse shape of the template is the same as the pulse shape of the current symbol to achieve the highest energy capture (matched filter). From the two equations, it is

clear that fulfilling the two opposing design goals is only possible if the pulse shape used by other symbols is different from the pulse shape used by the current symbol. This can be achieved by performing a pulse shape hopping operation.

In a pulse shape hopping operation, the transmitter changes the transmitted pulse at every transmission instant.

$$S_m(t) = \sqrt{\frac{E_s}{N_{pps}}} \sum_{k=mN_{pps}}^{(m+1)N_{pps}-1} c_k a_m p_{h(k)}(t - k t_c) \quad (4.3)$$

By doing so, the correlation $(p(t - \tau_{k',l}) \otimes p(t - \tau_{k,i}))$ is changed into cross-correlation between the previous pulse shape and the current pulse shape $(p_{h(k')}(t - \tau_{k',l}) \otimes p_{h(k)}(t - \tau_{k,i}))$. The objective is then to minimize the cross-correlation value, so that under the same channel conditioning, the pulse shape hopped transmissions produce weaker interfering energy.

The hopping code sequence can be as simple as $h(k) = [1 \ 2 \ \dots \ N \ 1 \ 2 \ \dots]$, where N is the number of pulse shapes. This hopping code sequence ensures that the time duration between transmissions of two pulses with the same shape is $(N - 1) \times$ chip duration. If this time duration is greater than the channel excess delay, the interfering energy can be significantly reduced.

This method is different from PSM (Pulse Shape Modulation) proposed in [20] or combined PPM-PSM (Pulse Position Modulation - Pulse Shape Modulation) in [117]. In both methods, the pulse shape is used to represent information, whereas in our proposed method, the receiver has the knowledge of the PSH code. The objective is to make use of the pulse shape's difference to minimize Z_{PPI} and Z_{SPI} . The information can be stored in pulse position or amplitude, depending on the modulation used.

The complexity of implementing a PSH transceiver is about the same as implementing a PSM. For both approaches, a pulse shape generator is required at both the

transmitter and the receiver. The receiver requires it to generate the correlation template. In PSM, during the detection process, the receiver would have to perform M number of correlations prior to making a decision, where M is the number of pulse shape used. In PSH, the receiver would only need to perform one correlation operation based on the PSH code. An extra complexity in PSH lies in the necessity of the transmitter to inform the PSH code to the receiver.

In PSH, in addition to the number of pulses, the shape of the pulse is also very important. The two design objectives require the set of pulse shapes used to have a large autocorrelation value but low cross-correlation value among the pulses. In other words, the set of pulse shapes used must be mutually orthogonal. The following two points describe two types of pulse shape design for PSH.

Shift-orthogonal pulse shapes

Shift-orthogonality condition means that the cross-correlation value is zero for every delay position. This ensures that both Z_{PPI} and Z_{SPI} are zero, as long as the number of pulse shape used is large enough to cover the channel excess delay. In such case, the test statistic will be only $Z_{ZI} + Z_{CPI}$. Such requirement can be fulfilled only if the different pulse shapes occupy different parts of the spectrum [122]. This way, the impact of performing a pulse shape hopping is similar to performing a frequency hopping. However, instead of relying on up-conversion and down-conversion to shift the spectrum of the pulse, the design of the pulse can be used. As explained in section 4.1.1, many pulse shape design techniques were introduced to shape the spectrum of the system so that it is as close as possible to the regulatory spectral mask. These kinds of pulse design technique can be used to produce a set of pulses, where each pulse lies in a different spectrum. The pulse shape design proposed in [18] has been shown to be very flexible and can be used for this purpose.

In [18], the new pulse shape is obtained by passing a Gaussian monocycle through a Parks-McClellan digital filter. In the paper, the filter taps are designed such that the spectrum of the filtered pulse shape is as close as possible to the regulatory spectral mask. It is also shown that the filter taps can be designed to produce multiband UWB with non-overlapping spectrum.

An example of the pulse shapes with 4 spectrum division is shown in figure 4.2 and their EIRP is shown in figure 4.3. Since the pulse shapes retain their mutual orthogonality regardless of the shift in their delay position, such pulse shape is referred to as shift-orthogonal pulse shape.

Figure 4.2: Four Shift-Orthogonal Pulse Shapes

Figure 4.3: EIRP of the Four Shift-Orthogonal Pulse Shapes Against the Regulatory Spectral Mask

Orthogonal pulse shapes

The disadvantage of the shift-orthogonal pulse shape is that it divides the whole spectrum into several smaller spectrums. Increasing the number of pulse shapes requires the bandwidth to be divided further. In IR-UWB, reduction in bandwidth means increment in pulse width, and hence degradation of the multipath resolution.

Another solution for the pulse design system is through the use of orthogonal pulse shapes. Although, the use of these pulses do not reduce both Z_{PPI} and Z_{SPI} to zero,

it has several advantages. Firstly, the cross-correlation is zero at the peak value (when the two pulses are fully synchronized) and is generally weaker in other delay values. Secondly, it can use the whole bandwidth, which means finer resolution of the pulses. In this thesis, we consider the use of Hermite pulse and Parr's pulse.

Hermite pulse was originally proposed in [20] for M -ary Pulse Shape Modulation. Important features of the Hermite pulse are the pulse width and bandwidth of the Hermite pulses and their derivatives are almost the same; and in time domain Hermite pulse and its' derivatives are mutually orthogonal. However to fulfill the FCC spectral mask requirement, Hermite pulse requires a spectrum shifter.

The motivation behind Parr's pulse is to design a pulse shape whose spectrum is as close as possible to the FCC spectral mask. Parr's pulse is generated using a Prolate Spheroidal method, and the generated pulses are mutually orthogonal.

Figure 4.4 and figure 4.5 shows the correlation value of Hermite pulse and Parr's pulses respectively.

4.3 Spectral Utilization Efficiency of the Pulse Shapes Used

Prior to investigating the performance of the proposed pulse shape hopping technique, it is important first to know the spectral utilization efficiency of the pulse shapes to be used. Although the SUE is not an indicator of the pulse shape's performance under interference, it is best to understand the performance of the pulse shapes under AWGN.

In order to achieve high spectral utilization efficiency (SUE), the pulse designed must have a spectrum that is as close as possible to the spectral limit. In this section, a comparison of different types of pulse shape described in the previous section is

Figure 4.4: Autocorrelation (in solid line) and Cross-correlation (in dotted line) of Hermite Pulse

performed. Several pulse shape designs such as the pulse based on Parks-McClellan [18] and Parr's pulse [21] were designed with the objective of achieving high SUE. Other types, such as the Gaussian pulse and Hermite pulse were designed for other purposes; however, they too must fulfill the spectral mask limit. For Hermite pulse, a special method is required to shift its spectrum in order for it to fulfill the spectral mask. Figure 4.6 shows the comparison of the spectra of these pulse shapes.

With such a spectrum shape, the maximum transmission power allowed for each pulse shapes is shown in table 4.1.

Figure 4.5: Autocorrelation (in solid line) and Cross-correlation (in dotted line) of Parr's Pulse

Both figure 4.6 and table 4.1 imply that given the same transmission bandwidth, the Parks-McClellan pulse can transmit with higher energy per symbol compared to the other three pulses, while still fulfilling the spectral mask requirement. Similarly, both the Hermite pulse and the Parr's pulse can transmit with higher energy per symbol compared to the Gaussian pulse, while still fulfilling the spectral mask requirement. This is important because given the same noise level at the receiver, the signal with higher energy per symbol produces a higher signal to noise ratio (SNR), and thus is more robust against AWGN.

Figure 4.6: Spectral Utilization Efficiency of Different Pulse Shapes

Table 4.1: Parameter for Pulse Shapes Used

	Width	Max Power	Additional Info
Gaus 7 th order	0.4 ns	0.05 mW	$F_g = 6.85\text{GHz}$
Hermite	1.5 ns	0.13 mW	Shifter = 6.85GHz
Parr's	1 ns	0.13 mW	-
Parks-McClellan	1.156 ns	0.35 mW	-

Figure 4.7 illustrates this point by showing the performance for a BPSK (Binary Phase Shift Keying) system with the maximum transmission power allowed. The plot is based on probability of error $P_e = Q(\sqrt{E_b/N_o})$, where E_b is the energy per bit, N_o is the noise power, and Q is the complementary cumulative distribution function.

As expected, the Parks-McClellan pulse shape performs the best under AWGN. This is because it can fit the spectral mask very nicely. The performances of the Hermite and Parr's pulse are very similar. They are generally better than the original Gaussian pulse.

In subsequent sections, the performance of the pulse shape hopping technique will be investigated. Three pulse shapes will be used. The first one is Hermite pulse, representing a pulse shape designed only for orthogonality. The second is Parr's pulse, representing a pulse shape designed to fulfill the spectral mask, but is also mutually orthogonal. The third is the pulse shape designed using Parks-McClellan filter, which is designed to fulfill the spectral mask. This pulse will be used to represent the shift-orthogonal pulse shapes too. As the basic comparison, a Gaussian pulse is also investigated.

Compared to the basic IR-UWB transmission using Gaussian pulse, there are two additional complexities in PSH transmission. The first complexity is due to the necessity of the transmitter to inform the receiver on the PSH code used. The second complexity is the generation of the orthogonal or shift-orthogonal pulse shapes. The generation of Hermite pulse requires a special circuitry presented in [120]. It also requires a modula-

Figure 4.7: Probabilty of Error Against AWGN

tor to shift the overall spectrum to fit the regulatory spectral mask. Since Parr's pulse defines the amplitude of each sampling point of the generated pulse, pulse shape generation of Parr's pulse requires a high speed (up to 64 GHz) digital to analog converter [3]. Parks-McClellan pulse is generated by passing a Gaussian monocycle through a Parks-McClellan digital filter [18].

4.4 Performance of Pulse Shape Hopping

Monte Carlo simulations were performed to investigate the performance of the pulse shape hopping approach. Table 4.4 shows the parameters used for the simulation.

Table 4.2: Simulation Parameter for Pulse Shape Hopping

Sampling Frequency	32 GHz
Modulation	BPSK with 1 pulse per symbol
Receiver	RAKE with perfect channel estimation
Channel	CM1 and CM3 of 802.15.3a
Channel Excess Delay	CM1 $\approx$ 40 ns CM3 $\approx$ 150 ns
Symbol Period	2 ns
Pulse Width	Gaussian: 0.5 ns Hermite: 1.5 ns Parr's: 1 ns Parks-McClellan: 1 - 4 ns
PSH Codes	[1 2 3 4 ... 1 2 3 4 ...] for 4 pulse shapes and [1 2 3 4 5 6 7 ... 1 2 3 4 5 6 7 ...] for 7 pulse shapes
Number of pulse shapes	1, 4, and 7

The sampling frequency used for the simulation was 32 GHz. This is to facilitate the generation of Parr's pulse and the Parks-McClellan pulse. The frequency sampling used to generate Parr's pulse in [21] and Parks-McClellan pulse in [18] are 64 GHz and 28 GHz respectively.

The performance of the different pulse shapes under high data rate interference

with 1 RAKE finger are shown in figure 4.8 for CM1 and in figure 4.9 for CM3, and the performance under different numbers of RAKE fingers are shown in figure 4.10 for CM1 and in figure 4.11 for CM3.

Figure 4.8: Error Rates vs Symbol Period from Different Sources of Interference for CM1

The performance shown is similar to what is shown in 3.1 - 3.2. Comparing figure 4.7 and figure 4.8, it is obvious that at a high signal to noise ratio, the interference produces a error floor to the total system performance. The impact of increasing the number of RAKE fingers is the same across all different pulse shapes.

Figure 4.9: Error Rates vs Symbol Period from Different Sources of Interference for CM3

Figure 4.12 – 4.13 show the error rates of Hermite and Parr’s pulses using pulse shape hopping with 1, 4, and 7 pulses. Since the Z_{CPI} is not affected by the use of PSH, it is not shown in the figure. As expected, the error rates are reduced as the number of pulse shapes used is increased.

In practice, there is a limit on the number of orthogonal pulse shape generated. Taking the Hermite pulse as an example, in [120], the authors present an example of the circuitry required for 2 orthogonal pulse shapes. The authors explain that additional

Figure 4.10: Error Rates for Different Numbers of RAKE Fingers at 500 Mbps for CM1

Figure 4.11: Error Rates for Different Numbers of RAKE Fingers at 500 Mbps for CM3

Figure 4.12: Performance of Hermite and Parr's Pulses Using PSH for CM1 of 802.15.3a

Figure 4.13: Performance of Hermite and Parr's Pulses Using PSH for CM3 of 802.15.3a

circuitry would be required to produce additional number of pulses. However, considering that the strength of the multipath reduces with time, it is adequate to simply reduce the interference of the nearest interfering symbols. Thus it is not really necessary to have a large number of pulse shapes. In this simulation when the number of pulse is 7, the system is capable to reduce the impact of interference from 6 symbol periods prior to the current symbol period and 6 symbol periods after the current symbol period.

Figures 4.14 and 4.15 show the performance of an M -ary PSM system using Hermite pulse under CM1 and CM3 channels respectively. As expected, the results show that increasing the number of pulse shape used does not improve the bit error rate performance. Although the M -ary PSM uses the same number of orthogonal pulse shapes, without performing PSH there is no mechanism to reduce the ISI. As explained in section 4.2, the PSH tries to reduce the ISI by reducing the cross-correlation value between the templates and the interfering multipath replicas. This is achieved by performing pulse shape hopping at the transmitter. Pulse shape hopping ensures that the distance between two pulses with the same shape, which causes high cross-correlation value, is as far as possible.

Figures 4.16 and 4.17 show the error rates of Parks-McClellan pulse using pulse shape hopping with 1, 4, and 7 pulses. The performance is improved when the number of pulses is increased from 1 to 4. However, the performance is degraded as the number of pulses is increased to 7. The disadvantage of the shift-orthogonal pulse shape is that it divides the whole spectrum into several smaller spectrums. Increasing the number of pulse shapes requires the bandwidth to be divided further. Reduction in bandwidth means increment in pulse width, and hence degradation of the multipath resolution. Degradation of multipath resolution means that the interference caused by Z_{CPI} would get stronger.

Both figure 4.16 and 4.17 show that the error performance due to the Z_{CPI} increases

Figure 4.14: Performance of M-ary PSM in CM1 of 802.15.3a channel

Figure 4.15: Performance of M-ary PSM in CM3 of 802.15.3a channel

Figure 4.16: Performance of Parks-McClellan Pulse Using PSH for CM1

Figure 4.17: Performance of Parks-McClellan Pulse Using PSH for CM3

as the number of pulse shape used is increased. When the number of pulses is increased from 4 to 7, although the error performance due to Z_{PPI} and Z_{SPI} gets better, the overall error performance does not get better. The error due to the Z_{CPI} serves as the error floor to the overall system for CM1.

In Hermite pulse and Parr's pulse, all the pulses in the orthogonal pulse set share the same spectrum, i.e. there is no bandwidth division. As such, increasing the number of pulse does not reduce the bandwidth of each pulse and does not affect the error performance due to the Z_{CPI} .

Although the shift-orthogonal pulse allows complete elimination of cross-correlation (to a certain extent as limited by the number of pulse shapes used), the overall performance improvement is limited by the loss of multipath resolution.

Figure 4.18 shows the error rates under AWGN and indoor channel. The data rates used is 500 Mbps (2 ns symbol period) and the channel model used is CM1 from 802.15.3a. The noise level is kept constant for all four pulse shapes. The pulse shapes transmits the energy at its maximum allowable energy as specified in table 4.1, resulting in transmitted energy per noise ratio of 15dB, 19dB, 19dB, and 23dB for Gaussian, Hermite, Parr's, and Parks-Clellan pulses respectively. Pulse shape hopping is performed for Hermite and Parr's pulses using 7 pulses.

Comparing figure 4.18 and figure 4.8, we can conclude that under high data rate indoor channel, high data rate interference is more prominent than AWGN in causing detection error. We can also observe that although the Parks-McClellan pulse has the highest energy per bandwidth, the performance of Hermite and Parr's pulses with pulse shape hopping is almost as good in this condition.

Figure 4.18: Performance under AWGN and CM1 of 802.15.3a

4.5 Summary

In this chapter, we have presented one of our interference reduction techniques, the pulse shape hopping technique. Aside from explaining the structure of the pulse shape hopping technique, we have also explained the rationale behind the design of the technique.

Pulse shape hopping can be used for both orthogonal and shift orthogonal pulse shapes. The separation of the sources of interference helps us to understand the performance of the shift-orthogonal pulse shape. Although the shift orthogonal pulse shape can completely eliminate the undesired cross correlation value, it comes with a price of reducing the fine multipath resolution. Using the orthogonal pulse shape, the pulse shape hopping technique shows continuous improvement of the system performance as the number of pulses used is increased.

The simulation results show that PSH using orthogonal pulse is able to improve the error performance of the receiver. The results also show that increasing the number of orthogonal pulse produces better interference reductions.

In the next chapter, we present our second interference reduction technique, which is to be done at the receiver. The proposed technique can be combined with the PSH to further reduce the impact of the interference to the receiver.

Chapter 5

Reducing Interfering Energy through Selective Transmitted Reference

In our analysis so far, the receiver system used has been the RAKE receiver. As the RAKE fingers are synchronized to the strongest replicas arriving at the receiver, and since the time interval between the arrivals of these replicas is usually less than the chip period used, the RAKE receiver used is considered as the fractionally spaced RAKE (FS-RAKE) receiver. As reported in [41], due to the fine multipath resolution of IR-UWB, the use of FS-RAKE receiver is crucial to increase the energy capture. However, the use of FS-RAKE receiver is expensive as it necessitates complex channel estimation and synchronization process. Unlike symbol spaced or chip spaced RAKE receiver, the FS-RAKE receiver requires the channel estimator to have a high sampling frequency in a search for a more accurate channel gain which will then be used for the template gain.

In IR-UWB systems, a popular alternative for the RAKE receiver is the Transmitted

Reference (TR) receiver. The biggest advantage of a TR receiver is that the receiver does not need to perform any channel estimation. The drawbacks of TR receiver are the reduction in the bandwidth of the system and the noise enhancement. In addition there are only a few available papers [58],[59], [60], [61] which discuss the performance of TR receiver under high data rate system. In [123], the authors derived a mathematical model which shows that high data rate interference has a significant impact on the performance of the system, and the impact is mostly determined by the channel model. The authors also explained that despite this, the investigation on the performance of TR receiver under high data rate interference has been mostly neglected. However, in order to improve the simplicity and the practicality of a UWB system, the use of a TR receiver is highly desirable.

The objective of this chapter is to obtain a robust high data rate receiver based on TR. In the next section, we present our proposed approach for the high data rate interference reduction based on a TR receiver design. The mathematical derivation in chapter 3 is used as the source of inspiration. The performance of the new system against several other high data rate interference reduction technique is then presented. We then present the performance of the system when both the proposed pulse shape hopping and selective transmitted reference receiver are used.

5.1 Partial RAKE Receiver

Recently, a simpler FS RAKE receiver has been proposed in [124]. The receiver is termed Partial RAKE receiver (P-RAKE). In many system model (including our own in section 3.1), to reduce the complexity of the system, normally the number of fingers used for the RAKE receiver is less than the number of replicas in the channel impulse response. The selected fingers are normally from the strongest replicas. In practice, the

channel estimation process of selecting the strongest replicas from the channel impulse response is also an expensive process.

In P-RAKE receiver, the channel estimation is designed not to search the strongest replicas from the whole channel impulse responses. Instead it only selects the first N_f replicas arriving at the receiver. It is generally assumed that the strongest replicas are always the first few replicas. However, this is not the case for several channel models provided by the 802.15.3a or the 802.15.4a. This is especially true for a non line of sight (NLOS) channels.

A simulation was performed to compare the performance of the P-RAKE receiver against the selective RAKE receiver. For this simulation, CM2 channel model from 802.15.3a was used. This channel model was selected because it is a NLOS channel. The pulse shape used was the first order of Hermite pulse with width = 1.5 ns. In order to simulate a high-data-rate interference, a 2 ns symbol period was used. Figure 5.1 shows the performance for different number of fingers.

This simulation shows that although a P-RAKE receiver can reduce the complexity of the channel estimation used by the RAKE receiver, it does not perform as well as the selective RAKE receiver. This motivates us to conduct further research on the TR receiver.

5.2 Selective Transmitted Reference

We reproduce the mathematical formula (3.11) from chapter 3 to ease the analysis.

Figure 5.1: Performance of Partial RAKE Against Selective RAKE

$$\begin{aligned}
Z_m = & \sum_{i=0}^{N_f-1} g_i \left[a_m g_i + \sum_{l=0, l \neq i}^{L-1} a_m g_l R_p(\tau_l, \tau_i) + \sum_{n=m-N_{PI}}^{m-1} \sum_{l=0}^{L-1} a_n g_{n,l} R_p(\tau_{n,l}, \tau_{m,i}) + \right. \\
& \left. \sum_{q=m+1}^{m+N_{SI}} \sum_{l=0}^{L-1} a_q g_{q,l} R_p(\tau_{q,l}, \tau_{m,i}) \right] \quad (5.1)
\end{aligned}$$

Equation 5.1 can be seen as a sum of N_f fingers with weight g_i , multiplied by the summation of four terms. Looking back to equation 3.13 - 3.16, and letting $E_S = 0$ and $N_{pps} = 0$, it can be seen that these four terms are actually Z_{ZI} , Z_{CPI} , Z_{PPI} , and Z_{SPI} divided by N_f fingers. In other words, the equation 5.1 can be expressed as.

$$\begin{aligned}
Z_m &= \sum_{i=0}^{N_f-1} g_i [Z_{ZI}(i) + Z_{CPI}(i) + Z_{PPI}(i) + Z_{SPI}(i)] \quad (5.2) \\
\text{where} \quad Z_{ZI}(i) &= a_m g_i \\
Z_{CPI}(i) &= \sum_{l=0, l \neq i}^{L-1} a_m g_l R_p(\tau_l, \tau_i) \\
Z_{PPI}(i) &= \sum_{n=m-N_{PI}}^{m-1} \sum_{l=0}^{L-1} a_n g_{n,l} R_p(\tau_{n,l}, \tau_{m,i}) \\
Z_{SPI}(i) &= \sum_{q=m+1}^{m+N_{SI}} \sum_{l=0}^{L-1} a_q g_{q,l} R_p(\tau_{q,l}, \tau_{m,i})
\end{aligned}$$

Figure 5.2 provides an illustration of the equation. From this figure, we can see that the sum of $Z_{ZI}(i)$, $Z_{CPI}(i)$, $Z_{PPI}(i)$, and $Z_{SPI}(i)$ for a particular value of i contributes to one of the fingers in the correlation-based receiver. The result of all these N_f fingers is then combined which will then produce the test statistic. Our approach presented in chapter 4, pulse shape hopping, reduces the interference level by reducing the interfering energy $Z_{PPI}(i)$ and $Z_{SPI}(i)$ on each finger. By reducing the cross-correlation of the pulse of the current symbol and the pulses of other symbols, all the interfering energies in all

Figure 5.2: Separation of Energy Capture

the fingers will be reduced.

We would like to further improve the performance of the system by filtering the energy captured. If the pulse shape hopping focuses only on interference reduction on each finger, in this chapter we would like to focus on reducing the interference from the whole correlation and combining process.

If the correlation operation covers all the multipath replicas, each of the fingers represents one replica in the channel impulse response. The strength of each replica depends on the channel condition, which is a random variable. It is clear that not all of the synchronized replicas are strong. Assuming that no pulse shape hopping operation is performed, for some fingers, the sum of the interfering energy might have been stronger than the energy of the synchronized replicas. In other words, if the interfering energy in the m^{th} finger is stronger, then $Z_{CPI}(m) + Z_{PPI}(m) + Z_{SPI}(m) > Z_{ZI}(m)$. From section 3.1, we know that $Z_{ZI}(i)$ always have the same polarity to that of the transmitted symbol. Thus in this case, the sum of the four terms would produce an incorrect polarity. In order to reduce the overall effect of the interfering energy, it is desirable to remove the contribution from such fingers. In other words, instead of making use of the energy

from all the fingers, the receiver will selectively choose which finger to be used.

Selective energy capture has previously been researched with the objective of reducing high data rate interference. In [77], the authors show that by delaying the energy capture by half a symbol period, the error performance of the receiver is improved. In [125], a more advanced concept, termed the shift window, where the receiver performs a search on the best delay period is presented. The receiver is targeted for inter chip wireless network and it was shown to have achieved a good result. The shift window approach is very close to what we try to achieve, however there are several limitations of the shift window approach which makes it not viable for the WPAN channel. We will first provide a short description of the shift window approach and explain the limitation of the system. A simple mathematical derivation of IR-UWB is presented to help in understanding the system. Afterwards, we will present our generalized form of the shift window approach [126], [127].

5.2.1 Shift Window (SW) Approach

In the simplest form, a transmitted signal in IR-UWB can be modeled as $S_m(t) = a_m p(t - mt_s)$. This simple form is devoid of any multiple access terms, which are normally present. A binary phase modulation is considered, i.e. $a_m = [-1/+1]$ with symbol period t_s .

UWB channel is a frequency selective fading channel, which can be modeled as the following tapped delay line channel, $h_t = \sum_{l=0}^{L-1} \alpha_l(t - \tau_l)$. There are L number of taps, each with strength α_l and delay τ_l . The received signal can therefore be modeled as $R_m(t) = a_m \sum_{l=0}^{L-1} \alpha_l p(t - mt_s - \tau_l) + n(t)$, where $n(t)$ is the additional white Gaussian noise. This equation is only true when there is no ISI. When any of the τ_l is longer than t_s , some of the replicas of the m^{th} symbol will interfere with the $(m+1)^{th}$ received sym-

bol. With ISI, the received signal can be modeled as (5.3). Aside from the replicas of the m^{th} symbol, there are additional replicas from NI previous symbol transmissions. NI denotes the number of interfering replicas which is defined as $\lceil \text{channel excess delay}/t_s \rceil$.

$$R_m(t) = a_m \sum_{l=0}^{L-1} \alpha_l p(t - mt_s - \tau_l) + \sum_{n=m-NI}^{m-1} a_n \sum_{l=0}^{L-1} \alpha_l p(t - nt_s - \tau_l) + n(t) \quad (5.3)$$

Eq. (5.3) assumes that the channel remains invariant for $NI + 1$ symbols. For a correlation-based receiver, the severity of the interference depends on the number and the strength of unwanted replicas within the correlation window. The whole idea of SW is to perform correlation only within a certain time period where the impact of the interference from previous symbols' transmission is low. The underlying assumption is that the interfering energy from previous pulse would gradually get weaker, to the point that the energy would not interfere with the current symbol's detection. In [125], the author presented a flow chart on how to obtain the desired correlation period. The process involves transmitting $2^{NI/2}$ combination of training symbols, on which the derivation of optimum time shift is based. After obtaining the desired correlation period, a RAKE receiver is used to perform the correlation which produces a test statistic (5.4) to be used for detection.

$$Z_m = \sum_{ls}^{le} \alpha_l v(t - \tau_l) \otimes R_m(t) \quad (5.4)$$

The template used for the RAKE finger is $v(t)$ and the correlation operation is

denoted by $\otimes$. The desired correlation window is defined by the arrival time of the l_s^{th} and the l_e^{th} replicas, and for an All-RAKE receiver l_e is $L - 1$.

In summary, SW can be characterized by 2 processes, the derivation of the optimum time shift and the selective correlation based on the derived time shift. The WPAN has a more severe channel condition compared to the inter chip wireless network, thus applying SW to reduce ISI in WPAN is impractical due to the following factors:

- The channel excess delay in WPAN channel is significantly longer than the WCAN. This would make the requirement of transmitting $2^{NI/2}$ training symbol to be impractical. In addition, the use of All-RAKE receiver would also make the receiver system expensive.
- The SW approach limits its time shift search to be within the current symbol period. Under a non line of sight (NLOS) channel (as shown in figure 5.3), the peak energy may fall in the next symbol period. Thus under NLOS channel, the time shift produced may be not optimal.
- One of the characteristics of the indoor WPAN channel is the cluster-based arrival. The implication of this is that the energy of the replicas does not necessarily grow weaker.

Figure 5.3: Severe Inter-Symbol Interference

5.2.2 Generalization of Shift Window

Based on the limiting factors specified in the previous section, obtaining good ISI reduction using SW under severe multipath is impractical. In order to overcome the limitations, we would like to abstract SW into a generalized form of ISI reduction.

SW essentially involves two main steps. Initially pilots are transmitted to train the system to obtain the preferred correlation window. Subsequently the receiver performs correlation to the preferred correlation window to obtain the test statistic. Figure 5.4 shows a generalized view of the ISI reduction.

Figure 5.4: Generalized View of ISI Reduction

While still maintaining the objective of capturing as much wanted energy as possible for the desired symbol, there are three ways by which SW can be generalized.

1. The number of correlators can be more than one. This is to handle situations where there are multiple peaks, which occur in a cluster-based channel.
2. The correlator can be a selective RAKE (where the $le \leq L - 1$) or a transmitted reference (TR) receiver [43].
3. The algorithm for the correlation window selection can be replaced by a different optimization technique.

From this generalization, we can come up with a new transceiver which can perform better under severe multipath.

Since a RAKE receiver requires channel estimations, in order to reduce the complexity of the system, TR-based receiver should be used. There are two main differences for a TR-based approach. Firstly the TR-based receiver uses a noisy template for correlation and secondly synchronization to the arrival time for each replica is not required.

More than one correlator can be used for WPAN channel in order to take advantage of the cluster-based channel. Generally the number of correlators should be close to the number of clusters and the correlation window period should be close to the average cluster length.

In order to avoid the lengthy training process required by the SW approach, the correlation window selection algorithm can be replaced by a simple energy detector.

The proposed new transceiver system is defined as follows:

- The transmitter transmits N_p pilot symbols. Using an energy detector, the correlation window selector then measures and stores the energy of different window regions of the pilot. Dividing the window region can be done in two ways. One is to perform shift window as in [125]. A simpler way is to fix the window region period (e.g. to 2 ns) and divide the received pilot signal by this period. Using this approach, the number of window region is $\lceil \text{channel excess delay} / \text{window region period} \rceil$. The 2nd approach is used for the numerical result investigation.
- The correlation window selector selects one or more regions which have the highest energy among all the regions. These will be the correlator templates used for the next N_d data symbols.
- When the data symbols arrive, the receiver will correlate and sum all the correlation results to produce the test statistic. The first data symbol is transmitted only after all the replicas of the pilot symbol arrived at the receiver.

To further simplify the system, a single reference TR [45] (where $1 \leq N_p < N_d$) is used. The purpose of having $N_p > 1$ is not to train the correlation window selector, but to reduce the noise introduced by the template. Thus N_p can be set to be much less than NI from (5.3). For the numerical investigation result shown in the next section, N_p is set to be 1.

Referring back to figure 5.2, in the generalized SW approach, the transmitter first transmits a pilot. Since the first data symbol is transmitted only after all the replicas of the pilot symbol arrived at the receiver, this means all the $Z_{PPI}(i)$ and $Z_{SPI}(i)$ in all the fingers are zero. Thus, during the energy detection and finger selection, the receiver chooses the fingers which have the strongest cumulative energy of $Z_{ZI}(i)$ $Z_{CPI}(i)$. These fingers will then be used for the overall detection operation because these fingers are more capable of combating the destructive energy of the interference $Z_{PPI}(i)$ and $Z_{SPI}(i)$. For a TR based receiver, figure 5.2 can be represented as figure 5.5.

Figure 5.5: Separation of Energy Capture in TR Receiver

In TR receiver, the fingers are replaced by the correlation window. The whole channel excess delay is divided into N_W correlation window. For the n^{th} correlation window, the index of the replicas included is from $W(n-1)$ to $(W(n)-1)$, where $W(n)$ is the index of the first replica in the n^{th} correlation window. The first index of the first correlation window is 0 and thus $W(0) = 0$.

Since the overall detection is based on several selected correlation window, we name the generalized SW approach as the Selective Transmitted Reference receiver.

5.2.3 Selective TR vs RAKE Receiver

One of our design goals is to have the performance of selective TR comparable to the selective RAKE without having the complexity of a RAKE receiver. The differences between the two approaches are shown in table 5.2.3.

Table 5.1: Differences between S-RAKE and S-TR

	S-RAKE	S-TR
Sampling Frequency	Faster than Symbol Rate	Symbol Rate
Combining Method	MRC	MRC
Finger/Frame Selection Technique	Maximum Likelihood, Successive Cancellation, Sliding Window [128]	Energy Detector

A simulation with the same parameter as in section 5.1 was conducted and the result is shown as the solid line in figure 5.6. For the CM2 channel, the total number of frames is more than 30. The result shows that by using the 15 strongest frames the performance is almost the same as the S-RAKE receiver. This is achieved without having to perform channel estimation and synchronization at faster than symbol rate sampling frequency. Moreover the frame selection is performed using only a simple energy detector.

Figure 5.6: Error Rate Performance of Selective TR

5.3 Performance Results

Monte Carlo simulations were performed to analyze the selective transmitted reference and to compare its performance against the original SW and two other ISI reduction techniques, ISI-Cancellation (ISI-C) [39] and Received Response Code Sequence (RR) [76]. These two techniques were selected because they share the same ISI reduction objective, which is to reduce the impact of the interference without using complex equalization. Two test scenarios were considered: the severity of ISI (determined by the symbol period) and whether the channel is LOS. The simulation parameters are

defined in table 5.3.

Table 5.2: Simulation Parameter for Selective Transmitted Reference

	SW	STR	ISI-C	RR
Receiver Structure	TR	STR	Energy Detector	RAKE
Correlation Period	1 symbol period			12 fingers
Channel	CM1 and CM2 from 802.15.3a			
SNR	20 dB			
Pulse Shape	0.5 ns second derivative of Gaussian Pulse			

Figure 5.7 shows the performance of STR against the original Shift-Window approach, whereas figure 5.8 shows the performance of STR against other interference reduction techniques. Both figures show that the proposed STR consistently outperforms all the other three techniques. The original SW is also shown to perform better than the RR and the ISI-C techniques.

Figure 5.8 shows that the ISI-C performs better in a LOS channel (CM1). In NLOS channel (CM2), there is no significant improvement on the error performance for data rate 200 Mbps - 500 Mbps. The result shows that although the ISI-C offers the simplest ISI reduction techniques, as the symbol period gets shorter (and the interference gets stronger), the desired energy capture and the interference canceller become weaker.

In the original paper [76], the RR was shown to produce interference reduction for a system with data rate of up to 83.3 Mbps. Figure 5.8 shows that the interference reduction has reached the error floor for data rate of 200 Mbps and above. RR attempts to amplify the energy capture of dominant paths by transmitting more pulses at a predetermined delay. But by doing so, the inter-chip interference will also get magnified.

Figure 5.7: Performance of STR against the original Shift-Window (SW) approach

Figure 5.8: Performance of STR against other interference reduction approaches

Another interesting observation is that the performance of RR in CM2 is better than in CM1. This is also reported in the original paper [76] where the performance in CM4 is better than in CM1. This is because the RR receiver captures just a few dominant paths. In the 802.15.3a channel model, the more severe the channel condition, the stronger the dominant paths. This explains why performance in CM2 is better than in CM1.

Figure 5.7 shows that the STR consistently outperforms the SW approach for both LOS channel (CM1) and NLOS channel (CM2). This is achieved without having to transmit $2^{N/2}$ training symbols. There are several factors contributing to the performance gain of the new approach. The SW limits its optimum correlation window search to only one symbol period. In WPAN, the channel excess delay is much longer than the symbol period, thus such a limitation would produce a non-optimum selection. This is especially true in the case of NLOS, contributing to the poor performance of SW in CM2. The cluster-based WPAN channel implies that the strength of replicas fluctuates throughout the channel response. Thus a multi-correlation window system would perform better in selecting and capturing the desired energy. As shown in figure 5.7, the performance of the new approach is improved as the number of correlators is increased. There is bound to be a limit in the performance improvement with respect to the number of correlators, however we leave the investigation to future work.

5.4 Pulse Shape Hopping and Selective Transmitted Reference

We end this chapter by presenting the performance of the combined pulse shape hopping and selective TR approach. Structurally, the pulse shape hopping approach requires a

modification mostly at the transmitter part, whereas the selective TR approach requires modification exclusively at the receiver part. This means that the combination of these approaches can be done with relative ease.

As explained previously, although the objective of the two approaches is the same, the way they solve the problem is different. The receiver system combined the energy from multiple correlation windows (or fingers in RAKE receiver). The pulse shape hopping focuses on reducing the interfering energy in each correlation window. The selective TR on the other hand focuses on reducing the contribution of the interfering energy in the combiner operation. Theoretically, the performance gain provided by each of these approaches is independent. Thus, combining these two approaches would produce a good high data rate interference reduction.

To investigate the performance of a system which performed the two approaches, we performed a Monte Carlo simulation for a high data rate condition with a severe channel condition. So far, the simulations performed are based on CM1 and CM2 of the 802.15.3a. For this experiment, a more severe CM3 NLOS channel is used. The data rate used is 500 Mbps, which corresponds to 2 ns symbol period. In order to support pulse shape hopping, the pulse shape used is the Hermite pulse shape. The number of pulse per symbol used is 1. The error performance of the system for different number of correlation windows is shown in figure 5.9.

The performance of the system with a normal TR is shown to be very poor. When the number of correlation window used is 1, the error rate is 0.5, which is basically the same as a coin toss. The slope of improvement from 1 correlation window to 8 correlation windows is not good either. Introducing a selective TR produces a significant improvement to the overall performance of the system. At 8 correlation windows, the error rate performance is roughly 20 dB better than the normal selective TR. Finally, as expected, by introducing a pulse shape hopping with 4 pulses produces a significant

Figure 5.9: Performance of Combined Selective TR and Pulse Shape Hopping

improvement over the normal TR. At 8 correlation windows, the error rate is almost at 10^{-5} , which is almost a 40 dB improvement over the normal TR.

The gain obtained by performing the selective TR and the pulse shape hopping is independent and thus combining both approaches produces a good high data rate interference reduction. This is achieved while still maintaining the simplicity of the system and without having to perform any complex equalization.

5.5 Summary

In this chapter, our focus is on achieving a TR based receiver system that is robust against high data rate interference. We presented our selective TR receiver, which generalizes the shift window approach to combat ISI mitigation in inter chip wireless communication. The selective TR performs better than other ISI reduction techniques, especially in the NLOS channel. From the mathematical derivation, we can see that the performance gain from the selective TR approach and the pulse shape hopping approach are independent. We closed the chapter by showing a simulation result from a system which combines the two proposed approaches.

The result shows that the performance of the combined approaches is very good, even when under a severe channel condition. This is achieved while still maintaining the simplicity of the IR-UWB system.

Chapter 6

High Data Rate Wireless Sensor Network Utilizing Cooperative Communication UWB

In this chapter, we would like to expand the thesis to cover the high data rate in cooperative communication UWB. Cooperative communication system achieves spatial diversity through the use of multiple relays in place of the usual multiple antennas in MIMO (Multiple Input Multiple Output) system. Such system is especially useful for wireless system where the transceiver nodes are meant to be lightweight or energy efficient, such as the Wireless Sensor Network (WSN). The use of cooperative communication in WSN has the potential to improve the overall performance in energy efficiency, data rates, and distance coverage [87].

IR-UWB has been considered as one of the physical layers for WSN due to its simplicity [129]. Correspondingly, there have been numerous works on the implementation of cooperative communication for IR-UWB. These works, which are discussed in section 2.6.2, study different aspects of cooperative communication IR-UWB, including

the physical and network layer techniques, as well as the impact of cooperative communication to UWB system. However, to the best of our knowledge, there has been no research on cooperative communication usage for high data rate UWB. Although in general WSN is mainly targeted towards low data rate system, recent application such as video surveillance [130] and oil exploration [9] have shown that there are rising interests in high data rate WSN. Since high data rate system introduces additional interference to the receiver system in the form of inter-symbol interference (ISI), it adds significance challenge to the cooperative communication system, which is already suffering from the interference coming from different relays. If left unmitigated, the ISI would affect the overall bit error rate performance of the system.

The objective of this chapter is to provide a better understanding on the impact of ISI to cooperative communication. This is done through a mathematical derivation of the test statistic. From the test statistic, it is shown that both the inter-relay interference (IRI) and the ISI are in the form of inter pulse interference. This means that the use of our proposed approaches (STR and PSH) would be able to mitigate the interferences. Monte Carlo simulations were performed to investigate the performance of the proposed approaches in high data rate cooperative communication.

This chapter starts with a discussion on why cooperative communication is suitable for a Wireless Sensor Network (WSN). A mathematical formulation of the test statistic at the receiver is then derived to show the different sources of interference. We then present a transceiver system utilizing both the selective Transmitted Reference (STR) and Pulse Shape Hopping (PSH) to combat both the IRI and the ISI.

6.1 Cooperative Communication in Wireless Sensor Network

A WSN normally involves a deployment of a large number of sensor nodes. In a very simplistic sense, the objective of the whole network is to sense a phenomenon and report it back to the data sink. Several prominent characteristics of a WSN involve a distribution of a large number of nodes over a large area, transmission of information requiring multihop to reach the destination, and limited power source for the nodes [131]. With the objective of collecting data to the data sink, and with a large number of nodes, a WSN involves many convergecast (as opposed to unicast or broadcast) transmissions where multiple nodes try to transmit data to a single node. Figure 6.1 shows an illustration of a convergecast scenario. Such scenario requires an advanced multi access protocol.

Another important characteristic of a WSN, which can also be observed in figure 6.1, is that there are many nodes which are inactive even when many nodes around them are actively transmitting data. One of the basic features of a wireless communication, as opposed to the wired communication, is that the transmission of data in a wireless communication is generally a broadcast transmission. This is especially true when an omnidirectional antenna is used. There is one important implication of this. The inactive nodes which are situated near the actively transmitting nodes would overhear the transmitted signal. Instead of staying inactive, these nodes can instead act as relay nodes, which will then help to transmit the data to the intended recipient. This is the basic premise of cooperative communication [132]. Figure 6.2 shows an illustration on how cooperative communication can be performed.

The use of cooperative communication in WSN allows spatial diversity and better energy capture, which will produce a higher SINR. In addition, in some WSN applica-

Figure 6.1: An Illustration of Wireless Sensor Network Transmission

tions, e.g. industrial automation [133] and wireless sensor network for the active aircraft [134], redundancy of transmission link is required.

6.2 Mathematical Derivation of Test Statistic

In order to fully understand the physical layer performance of high data rate cooperative communication IR-UWB, we perform a mathematical derivation to the test statistic of the receiver. The goal is to investigate the error performance of a receiver when the received signal comes from multiple relays. As such, a simple system model as shown in the figure 6.3 would be used throughout this chapter. The transmission of data

Figure 6.2: Cooperative Communication. The dashed lines indicate cooperative communication through relay nodes, which are indicated by the filled circle.

from the source to the destination takes two time slots. The first time slot is for the transmission from the source to the three relay nodes. The second time slot is for the transmission from the relay nodes to the destination. We assume that TDMA is used and thus within the specified time frame, the communication channel is used only by the transmitter node, the relay nodes, and the intended recipients. The mathematical analysis only analyzes the performance of the receiver at the destination.

Similar to what we have done in chapter 3, the mathematical derivation is separated into several steps where in the first step, it is assumed that the number of transmitted pulse per symbol is one and the symbol period is larger than the channel excess delay.

Figure 6.3: A simple relay system with 1 source (S), 1 destination (D), and 3 relay nodes (R1, R2, and R3).

The assumption would then be relaxed. The mathematical derivation presented here follows the symbols introduced in chapter 3. The transmitted signal is as shown in (3.1) and the channel impulse response is $h(t) = \sum_{l=0}^{L-1} g_l \delta(t - \tau_l)$. The receiver system considered here is the coherent correlation-based receiver.

Reproducing equation 3.5 from Chapter 3, for a system with $N_{pps} = 1$, when there is no relay, the test statistic of the symbol m is represented as Z_m .

$$\begin{aligned}
 Z_m(t) &= \sum_{i=0}^{N_f-1} r(t) \otimes g_i v_i(t - \tau_i) \\
 &= \sum_{i=0}^{N_f-1} a_m g_i^2 + \sum_{i=0}^{N_f-1} a_m g_i \sum_{l=0, l \neq i}^{L-1} g_l R_p(\tau_l, \tau_i)
 \end{aligned} \tag{6.1}$$

Once again, for easy referencing, the first component is denoted as Z_{ZI} (zero interference) and the second component is denoted as Z_{CPI} (current pulse interference).

For cooperative communication, the received signal comes from more than one relay nodes. Assuming there are two relay nodes, node i and node j , which are cooperatively transmitting to the receiver, the test statistic for the correlation based receiver can be expressed as follows.

$$\begin{aligned}
Z_m &= \sum_{i,j} [(r_i(t) + r_j(t)) \otimes (g_i v(t - \tau_i) + g_j v(t - \tau_j))] \\
&= a_m \left[\sum_{i=0}^{N_f-1} g_i^2 + \sum_{i=0}^{N_f-1} g_i \sum_{l=0, l \neq i}^{L(i)-1} g_l R_p(\tau_l, \tau_i) \right] + \tag{6.2}
\end{aligned}$$

$$\begin{aligned}
& a_m \left[\sum_{j=0}^{N_f-1} g_j^2 + \sum_{j=0}^{N_f-1} g_j \sum_{l'=0, l' \neq j}^{L(j)-1} g_{l'} R_p(\tau_{l'}, \tau_j) \right] + \tag{6.3}
\end{aligned}$$

$$\begin{aligned}
& \sum_{i=0}^{N_f-1} a_m g_i \sum_{l'=0}^{L(j)-1} g_{l'} R_p(\tau_{l'}, \tau_i) + \tag{6.4}
\end{aligned}$$

$$\begin{aligned}
& \sum_{j=0}^{N_f-1} a_m g_j \sum_{l=0}^{L(i)-1} g_l R_p(\tau_l, \tau_j) \tag{6.5}
\end{aligned}$$

The first two terms (6.2), (6.3) are exactly the same of (6.1). These represent the individual energy contribution of the two relays to the overall test statistics. The remaining two terms (6.4) and (6.5) represent the contribution of the inter-relay interference (IRI) to the test statistic. These are the result of the cross-correlation between the pulses arrived from a relay node and the templates obtained from other relay nodes. The sum of (6.4) and (6.5) is denoted as Z_{RI} (relay interference).

Under high data rate system, the multipath replicas from previous and subsequent symbols may arrive at the current symbol's correlation period, and thus affecting the overall test statistic. With the additional interferers, the received signal can be represented as $r(t) = r_m(t) + \sum_{n=m-N_{PI}}^{m-1} r_n(t) + \sum_{q=m+1}^{m+N_{SI}} r_q(t)$. $r_m(t)$ represents all the received signal from the current symbol, whereas r_n represents all the received signal from the preceding symbols which affects the m^{th} symbol detection. Similarly, r_q represents all the received signal from subsequent symbols which affects the m^{th} symbol detection. N_{PI} is the number of previous symbols affecting the current detection, whereas N_{SI} is the number of subsequent symbols affecting the current detection. The

two values are determined by the length of the symbol period and the channel excess delay: $N_{PI} = N_{SI} = \lceil \frac{\text{channel excess delay}}{\text{symbol period}} \rceil$

The impact of the additional $\sum_{n=m-N_{PI}}^{m-1} r_n(t)$ to the current symbol's test statistic can be represented as Z_{PPI} (previous pulses' interference).

$$\begin{aligned} Z_{PPI} &= \sum_{i=0}^{N_f-1} g_{m,i} \sum_{n=m-N_{PI}}^{m-1} r_n(t) \otimes v_{m,i}(t - \tau_{m,i}) \\ &= \sum_{i=0}^{N_f-1} \sum_{n=m-N_{PI}}^{m-1} \sum_{l=0}^{L-1} a_n g_{m,i} g_{n,l} R_p(\tau_{n,l}, \tau_{m,i}) \end{aligned} \quad (6.6)$$

Similarly, the impact of the additional $\sum_{q=m+1}^{m+N_{SI}} r_q(t)$ can be represented as Z_{SPI} (subsequent pulses' interference).

$$\begin{aligned} Z_{SPI} &= \sum_{i=0}^{N_f-1} g_{m,i} \sum_{q=m+1}^{m+N_{SI}} r_q(t) \otimes v_{m,i}(t - \tau_{m,i}) \\ &= \sum_{i=0}^{N_f-1} \sum_{q=m+1}^{m+N_{SI}} \sum_{l=0}^{L-1} a_q g_{m,i} g_{q,l} R_p(\tau_{q,l}, \tau_{m,i}) \end{aligned} \quad (6.7)$$

For a non-cooperative system, the overall test statistic is the sum of the following test statistic $Z = Z_{ZI} + Z_{CPI} + Z_{PPI} + Z_{SPI}$. For high data rate cooperative system, aside from the additional Z_{RI} , there would be additional interference which comes from the previous and subsequent symbols of other relay nodes. The total interference from previous symbols and subsequent symbols can be represented as Z_{TPI} (total previous symbols interference) and Z_{TSI} (total subsequent symbols interference) respectively.

$$\begin{aligned}
Z_{TPI} &= \sum_{i,j} \sum_{n=m-N_{PI}}^{m-1} [(r_{i,n}(t) + r_{j,n}(t)) \otimes \\
&\quad (g_{i,m}v_{i,m}(t - \tau_{i,m}) + g_{j,m}v_{j,m}(t - \tau_{j,m})) \\
&= a_n \sum_{n=m-N_{PI}}^{m-1} [\\
&\quad \sum_{i=0}^{N_f-1} \sum_{l=0}^{L(i)-1} g_{i,m}g_{l,n}R_p(\tau_{i,m}, \tau_{l,n}) + \tag{6.8}
\end{aligned}$$

$$\sum_{j=0}^{N_f-1} \sum_{l'=0}^{L(j)-1} g_{j,m}g_{l',n}R_p(\tau_{j,m}, \tau_{l',n}) + \tag{6.9}$$

$$\sum_{i=0}^{N_f-1} \sum_{l'=0}^{L(j)-1} g_{i,m}g_{l',n}R_p(\tau_{i,m}, \tau_{l',n}) + \tag{6.10}$$

$$\sum_{j=0}^{N_f-1} \sum_{l=0}^{L(i)-1} g_{j,m}g_{l,n}R_p(\tau_{j,m}, \tau_{l,n})] \tag{6.11}$$

$$\begin{aligned}
Z_{TSI} &= \sum_{i,j} \sum_{q=m+1}^{m+N_{SI}} [(r_{i,q}(t) + r_{j,q}(t)) \otimes \\
&\quad (g_{i,m}v_{i,m}(t - \tau_{i,m}) + g_{j,m}v_{j,m}(t - \tau_{j,m})) \\
&= a_q \sum_{q=m+1}^{m+N_{SI}} [\\
&\quad \sum_{i=0}^{N_f-1} \sum_{l=0}^{L(i)-1} g_{i,m}g_{l,q}R_p(\tau_{i,m}, \tau_{l,n}) + \tag{6.12}
\end{aligned}$$

$$\sum_{j=0}^{N_f-1} \sum_{l'=0}^{L(j)-1} g_{j,m}g_{l',q}R_p(\tau_{j,m}, \tau_{l',q}) + \tag{6.13}$$

$$\sum_{i=0}^{N_f-1} \sum_{l'=0}^{L(j)-1} g_{i,m}g_{l',q}R_p(\tau_{i,m}, \tau_{l',q}) + \tag{6.14}$$

$$\sum_{j=0}^{N_f-1} \sum_{l=0}^{L(i)-1} g_{j,m}g_{l,q}R_p(\tau_{j,m}, \tau_{l,q})] \tag{6.15}$$

Similar to the low data rate cooperative system, the first two terms (6.8) and (6.9) for the Z_{TPI} are exactly the same as the Z_{PPI} . The additional two terms (6.10) and (6.11) are the interference caused by the previous symbols from other relay nodes. The sum of these two terms is denoted as Z_{PIR} (previous symbols interference from other relays). The exact same thing applies to the subsequent symbol interference. The sum of the last two terms of the Z_{TSI} , (6.14) and (6.15) is denoted as Z_{SIR} (subsequent symbols interference from other relays).

For a non-cooperative system, the overall test statistic is the sum of the following test statistic $Z = Z_{ZI} + Z_{CPI} + Z_{PPI} + Z_{SPI}$. For a cooperative system, the overall test statistic is the sum of the following test statistic $Z = Z_{ZI} + Z_{CPI} + Z_{RI} + (Z_{PPI} + Z_{PIR}) + (Z_{SPI} + Z_{SIR})$.

Observing all the test statistics, it is clear that both the IRI and the ISI are both in the form of an inter-pulse interference (IPI). There are two main implications of this. Firstly, the interference only occurs when there are collisions among different pulses from different relays or different symbols. Since UWB has a fine multipath resolution, the possibility of collisions is reduced. In fact in [84] and [135], the authors argue that due to the fine multipath resolution, IR-UWB is immune to the IRI. However, no physical layer performance comparison was done to prove this point. In section 6.4, the error performance of IR-UWB without any IRI mitigation is investigated.

The second implication is that if different pulse shapes are used among different relays and symbols, and the cross-correlation among these pulses are zero (or at least weaker than its autocorrelation), the interference will be mitigated.

6.3 Proposed Approaches

As we can see from the mathematical model presented in the 6.2, much of the interfering energy actually comes from the high data rate interference from the previous symbols. This interference comes not only from the transmitter, but also from the relay nodes, causing further performance degradation to the receiver's performance. As explained in [90], the space time block coding (STBC) and its variant distributed space time block coding (DSTBC) were designed only to remove the MIMO or cooperative communication interference. In [90], it is also noted that most proposal to handle high data rate interference in MIMO system is by performing a parallel transmission (e.g. OFDM), so that the symbol period can be lengthened. In other words, the STBC and DSTBC are not designed to handle the high data rate interference.

From the test statistic, we can see that the source of the performance degradation is similar to that of the single user system. The high data rate interference consists of the cross correlation of the pulse from the current symbol's template and the pulses from other symbols. This means, performing a pulse shape hopping will reduce the contribution of the interfering energy to the total test statistic.

In the single user system, the selective TR selects the strongest energy from all the Z_{ZI} and the Z_{CPI} , with the goal of selecting only the correlation results which will constructively add to the test statistic. Similarly, in a cooperative communication, the selective TR will select the strongest energy from the cumulative sum of energy (6.2) + (6.3) + (6.4) + (6.5).

Our proposal is that instead of performing a DSTBC, we will perform a combined selective TR and pulse shape hopping for cooperative communication. The main objective is to obtain the performance gain from the cooperative communication, by reducing all the interference present in the received signal

In order to perform the combined selective TR, all the relay nodes regularly send a pilot to the intended recipient. This is done simultaneously by all the relay nodes. The receiver would then combine all the pilots and perform the energy selection. Since the pilots are transmitted at the same time, the signal that arrives to the receiver is the sum of all these pilots. One important point is that the energy selection is performed to the sum of all the pilot symbols. This is to ensure that the selection has considered the effect of the collision among replicas from different relays. If the template is selected without considering the collision among replicas from different relays, during the actual correlation to the information symbol, the resulting energy may be weaker due to the destructive contribution from the collision from different relays. Once the strongest templates are selected, the transmitter and the relay node can start sending the information symbols.

To implement the pulse shape hopping, all of the nodes must be able to generate the supported pulse shapes. As with any WSN system that support TDMA, all the nodes should be synchronized in time (at least all the nodes in the piconet). During initialization, all the transmitters are reset to using the first pulse shape in the set. At every symbol period, the transmitter should change its pulse shape. At every time instant, all the nodes that are transmitting, transmit the same pulse shape. This ensures that during the transmission of one symbol the same pulse shape is used by both the transmitter and the relay nodes. The receiver can then make use of this pulse shape as a template for all the incoming signals, thereby reducing all the inter-symbol interference present.

The advantage of the proposed system compared to the DSTBC is as follows:

- Generation of the STBC code is not easy and not all number of relays can be supported. In addition, the distribution of the code also remains as one of the

challenges of cooperative communication [83]. In our proposed approach, we only use a repetition coding. This means no generation or distribution of code is required.

- Most importantly, this approach focuses in minimizing the high data rate interference in the system. The DSTBC on the other hand does not consider the impact of high data rate interference.

In the following two sections, the performance of the proposed system is analyzed through the use of Monte Carlo simulations. Firstly, we investigate if our proposed system can still achieve spatial gain without the use of DSTBC. This is followed by the investigation on the ISI mitigation of the proposed system.

6.4 Spatial gain of the proposed approach

Ever since the introduction of the cooperative communication, and even the MIMO system, which precedes it, the use of some form of coding to mitigate the interference from different relays, are always considered. This is usually in the form of space-time block coding (STBC) for MIMO and Distributed STBC (DSTBC) in cooperative communication.

This coding technique, however, was introduced for a flat fading system where collisions at the receiver are inevitable. In the case of UWB system, the frequency selective fading implies that the multipath replicas are separable from one another. Depending on the channel impulse response, this might lead to a less possibility of collisions.

Since the channel impulse response plays an important role in determining the bit error rate, Monte-Carlo simulations were performed to simulate receivers performance. Since the goal of both MIMO and cooperative system is to achieve the same bit error

rate performance as Maximal Ratio Combining (MRC) [90], the receivers performance is then compared to that of MRC receiver. The model of the MRC receiver is based on [91]. The received signal from different nodes are demodulated separately and the resulting test statistic is then combined.

For the simulation, a system model as shown in figure 6.3 is used. Throughout the simulation, the number of pulse per symbol used is 1 and the energy of the transmitted pulse is normalized to one. In a system using DSTBC with M relay nodes, for every symbol received by the relay nodes, the relay nodes will send a train of M symbols multiplied by the DSTBC code. Similarly in our system, the relays will send a train of M symbols; however no coding is used.

The channel model used is the 802.15.3a [35], where 4 different channel models (CM1 - CM4) are defined. CM1 and CM3 are used for the simulation. CM1 represents a line-of-sight (LOS) channel and CM3 represents non-line-of-sight (NLOS) channel with a more severe multipath.

The pulse shape used is a Hermite-based pulse shape as proposed in [117], with pulse width = 1.5 ns. This is used to facilitate our discussion in the next section where orthogonal pulse shape is used. The receiver used is the STR receiver presented in chapter 5. STR is used because it performs well for a NLOS channel, especially for 802.15.3a channel model where there is a clustering phenomenon. As explained earlier, STR receiver divides the channel excess delay period into smaller correlation period. The receiver then chooses N correlation period which has the strongest energy. This is to ensure that the strongest clusters are used for detection process. For this simulation, the receiver uses 2 correlation period with width = 2 ns.

Figure 6.4 and 6.5 show the performance of the system for CM1 and CM3 channel model respectively. The simulation result shows that even without any IRI mitigation, UWB system can achieve the spatial gain. This validates the presumption held in [84]

and [135], that the fine multipath resolution of IR-UWB renders the Z_{RI} insignificant.

Figure 6.4: Bit error rate against SNR (in dB) for CM1

6.5 Orthogonal pulse shape to mitigate inter pulse interference

There are two methods in which the orthogonal pulse shape can be utilized. The first method is to use different pulse shapes for different relays. The objective of this is to reduce the IRI at the receiver. The second method is to implement a PSH at all the relays in order to reduce the ISI at the receiver. Although we introduced PSH for non-

Figure 6.5: Bit error rate against SNR (in dB) for CM3

cooperative communication, it can easily be adapted to cooperative communication. During initialization of the network, all the relay nodes will have to be notified on the hopping sequence. As shown in [15], the most effective hopping sequence is a simple repeating sequence $[1, 2, \dots, N_p, 1, 2, \dots, N_p, \dots]$ where N_p is the number of pulse shape used. Since the hopping sequence is repeating, after the initialization, all the relay nodes can determine the next hopping sequence independently.

Once again, Monte-Carlo simulations are performed to investigate the performance of the two methods. The simulation setups are the same as in section 6.4, with SNR = 10 dB. Hermite based orthogonal pulse shape is used. Figure 4 and 5 show the

performance under CM1 and CM3 respectively.

Figure 6.6: Bit error rate against number of relays for CM1

The MRC is the baseline used, in which there is no IRI affecting the detection. This means the MRC does not need to mitigate the energy contribution of the Z_{RI} . However, the MRC does not mitigate ISI.

The use of different orthogonal pulse shape at different relays mitigates all the interference from different relays. This includes the Z_{RI} , Z_{PIR} , and Z_{SIR} . Based on the simulation result, the performance of this technique is more or less the same to that of the MRC. Such results imply that the effect of Z_{PIR} and Z_{SIR} to the overall error performance is low.

Figure 6.7: Bit error rate against number of relays for CM3

The use of PSH mitigates all the interference from other symbols. This includes the Z_{PPI} , Z_{SPI} , Z_{PIR} , and Z_{SIR} . Based on the simulation result shown in section 6.4, Z_{RI} in IR-UWB is not significant to the overall test statistic. Thus the overall test statistic for PSH will be just $Z = Z_{ZI} + Z_{CPI}$, implying that most of the interference have been mitigated. As expected, the simulation results show that the PSH outperforms both the MRC and the use of different orthogonal pulse for different relays. The performance is shown to be improved when more orthogonal pulse shape is used. This is an additional advantage over using different orthogonal pulse for different relays because in the later technique, the number of orthogonal pulse used is limited to the number of relays.

In addition to showing that the use of PSH is an effective way to attain good error performance in high data rate cooperative communication, these simulation results also imply that in IR-UWB, it is more effective to spend more resource to mitigate the ISI as opposed to mitigating the IRI.

6.6 Performance under Timing Jitter

One of the practical implementation issues for a coherent-based receiver is the sensitivity to timing synchronization. This is especially true in cooperative communication, where there are multiple relay nodes transmitting to the same destination. Any timing jitter at any of the relay nodes would cause the loss of synchronization.

A simulation study was performed to understand the performance of the proposed system when up to 2 relay nodes are out of synchronization. A transceiver using STR and PSH with 4 Hermite pulse shapes was simulated with 2 ns symbol period under CM3 channel. The timing jitter is modeled as a normal distribution with zero mean. Two standard deviation σ values, 0.01 ns and 0.1 ns, are considered. Figures 6.8 and 6.9 show the simulation results.

The results show that the presence of timing jitter degrades the performance of the system. The results also show that the highest degradation happens between a system with full synchronization and a system with one relay node experiencing jitter. Comparatively, the performance gap between 1 relay node experiencing jitter and 2 relay nodes experiencing jitter is much smaller. Another observation is that even with the presence of timing jitter, the system is still able to obtain performance gain when the number of relays is increased.

The possibility of timing jitter occurring in the proposed system is actually low. This is because the receiver used is based on the Transmitted Reference (TR) receiver.

Figure 6.8: Performance under timing jitter with $\sigma = 0.01$

In TR receiver, timing jitter occurs only when there is a clock drift at the transmitter after it sends the pilot but before it sends the data. Such clock drift causes the loss of synchronization between the template (which is really the pilot) and the received signal. In TR receiver, due to the periodic transmission of the pilot to the receiver, the possibility of timing jitter is low.

6.7 Impact and Potentials

In WSN, there are three types of communication paradigms, namely the node centric, the location centric, and the data centric [136]. The node centric approach is the usual

Figure 6.9: Performance under timing jitter with $\sigma = 0.1$

point-to-point communication, which is widely used by the internet protocol (IP). In node centric, when a node wants to transmit a data, the node has to provide the address of the intended recipient. A location centric makes use of the actual location and positioning of the nodes in order to transmit the information. This is very relevant in a WSN environment where the objective of most of the nodes is to transmit to a sink node. In a location centric approach, when a node wants to transmit a data, it will target the neighboring nodes which are geographically closer to the final intended recipient. In a data centric approach, the transmitting node will look for the neighboring nodes which are in the path to the data sink that is interested in the information it

is carrying. This data centric approach is also relevant to the WSN, where the whole sensor network is monitoring different types of phenomenon. Although node centric approach is widely accepted, the location and the data centric approaches are more suitable for WSN.

The use of our proposed system model presented in this chapter would enable the data centric and location centric networks to exploit the use of cooperative communication. For example, when three nodes observe a certain phenomenon in a certain area, these three nodes would then try to transmit this same information to the data sink. In a TDMA-based data centric WSN, instead of allocating a time period for transmission to a certain node, the system can allocate different time periods for different types of data. When the time slot for the intended data arrives, the three nodes that observe the same phenomenon can start broadcasting the data to the neighboring nodes. Any node whose duty is to propagate this kind of information can capture the information from the three nodes cooperatively.

Without the need to design and distribute the DSTBC code and with a jitter robust system, our proposed approach is very suitable to support this architecture. It would enable the data centric and location centric system to better exploit the use of cooperative communication in WSN.

6.8 Summary

In this chapter we have presented the application of our proposed approaches in high data rate WSN utilizing cooperative communication. We have shown that a robust high data rate cooperative IR-UWB system can be achieved through the utilization of our proposed energy capture selection transceivers. Firstly the STR is used to exploit the fine multipath resolution of the IR-UWB. This enables the system to achieve good

spatial diversity even without performing complex DSTBC. Secondly the use of PSH is shown to be an effective way to mitigate the interference coming from ISI. Mathematical derivation of the test statistic shows that the both inter-relay interference and inter-symbol interference are, in essence, caused by inter-pulse interference. We have shown that although the use of orthogonal pulse can be targeted towards the mitigation of IRI or ISI, it is more effective to use it to mitigate ISI.

Our proposed system model would also enable the data centric and location centric WSN architectures to exploit cooperative communication.

Chapter 7

Conclusions and Future Works

7.1 Conclusions

In this thesis, we have shown that by selectively choosing which energy to be used for detection, we are able to reduce the impact of interference in a high data rate system. Through a mathematical derivation of the test statistic, we have shown that the overall energy captured by the receiver is actually a combination of the energy from the wanted signal and the energy from the interferences.

We have presented two methods, the Pulse Shape Hopping (PSH) transmitter and the Selective Transmitted Reference (STR) receiver, utilizing the energy capture selection concept. By combining both methods, we have shown that the high data rate interference both in single user system and in cooperative communication system can be mitigated.

In PSH, the unwanted energy contribution from the inter-symbol interference is mitigated by transmitting different pulse shapes at different symbol period. The usage of two types of pulse shapes, orthogonal and shift-orthogonal, is presented. Through Monte Carlo simulations, it is shown that performing PSH using orthogonal pulse is

more scalable in reducing ISI. Increasing the number of pulse shape in shift-orthogonal pulse reduces the bandwidth of each symbol and thus increases the error due to the current pulse interference.

The STR is a generalization of the shift window method, which was proposed for an inter-chip wireless network. It focuses the energy capture only to a few strongest correlation windows. The proposed STR is especially useful for a channel with clustering phenomenon.

In high data rate cooperative communication system, aside from the ISI, the system also suffers from inter-relay interference (IRI). We have proposed a system model utilizing both PSH and STR, which is shown to be effective in combating both forms of interference.

The wide bandwidth of UWB results in a fine multipath resolution and the spread of the energy beyond the transmitted symbol period. Without any special handling, these features of UWB produce interference to the receiver system in the form of inter symbol interference. The pulse shape hopping and selective transmitted reference receiver perform a special handling on these features by selectively capturing the desired energy. These proposed techniques have achieved the objective of reducing the impact of interference in a high data rate system, for both single user system and cooperative communication system.

7.2 Future Works

Pulse shape hopping and selective transmitted reference have been shown to provide a good error performance in a high data rate WSN with cooperative communication. In addition, using these two techniques enables an implementation of cooperative communication in data centric and location centric WSN. In a layered networking perspective,

these fulfill the two main objectives of the two lowest layers (PHY and MAC).

First of all, the impact of using the proposed approaches to the actual system parameters will be investigated. This includes the average lifetime and the average throughput of the network.

The next logical step is to investigate the system design in the network layer. The challenges in the network layer of WSN include the handling of the routing and the relay selection, while still ensuring the low overall energy consumption of the system. As explained earlier in section 6.7, the proposed approaches enable a different paradigm in routing and relay selection. This capability, together with the capability of achieving high data transmission, open up possibilities of new network layer designs. For example, a robust high data rate system would enable nodes to do a quick bursty transmission, before going back to sleep.

WSN is commonly attributed as an ad-hoc network. However, there are applications where the WSN is based on an infrastructure, e.g. industrial plant monitoring system or aircraft control system. In an infrastructure-based network, the network topology plays an important role in the system's performance. The impact of implementing the proposed approaches on different topology can be investigated, with the goal of finding the best topology which can exploit the impact of the proposed approaches.

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List of Publications

1. W. C. Tjhi, C. T. Lau, and A.B. Premkumar “A generalization of shift-window approach for UWB ISI reduction,” published in *IEEE Communication Letters*, Vol. 14, No. 7, pp. 602 – 604, 2010.
2. W. C. Tjhi, C. T. Lau, and A.B. Premkumar “A novel selective transmitted reference transceiver for high data rate UWB,” published in *Proceedings of IEEE Vehicular Technology Conference (VTC Spring 08)*, pp. 464 – 467 2008.
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