A WAVELET-BASED ARCHITECTURE FOR ULTRA WIDEBAND SYSTEM WITH SPECTRUM SENSING

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To my beloved parents

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ABSTRACT

Ultra Wideband (UWB) system possesses attractive features such as high data rate, low cost, and low power consumption. However, UWB wide range of frequency band causes mutual interference with other narrowband systems. The main goal of the work is to develop UWB system that can mitigate interference. In this thesis a Wavelet Cognitive UWB System has been designed that can minimize interference and enhance system performance. The proposed system is composed of Wavelet Packet Multicarrier Modulation (WPMCM), wavelet spectrum sensing, and spectrum and power allocation. WPMCM is deployed since it is flexible and inherently robust against interference mitigation. The WPMCM employs Inverse Wavelet Packet Transform (IWPT) and WPT engine to play the same role as Inverse Fast Fourier Transform (IFFT) and FFT in Orthogonal Frequency Division Multiplexing (OFDM) system. Wavelet Spectrum Sensing is designed to minimise interference by sensing the whole spectrum band and make decision to deactivate the occupied subcarriers. The proposed wavelet spectrum sensing has the capability to detect interfering occupied subcarriers. It uses energy detection for spectrum analysis and decision. Enhanced Forward Consecutive Mean Excision (E-FCME) algorithm is used to provide decision threshold whether to use the subcarriers. Spectrum and power allocation has been developed to allocate the transmission power to the selected subcarriers according to channel estimation gain. In addition, an efficient pilot pattern strategy is employed in the channel estimation to enhance the estimated channel gain. The optimum power allocation is derived by Lagrange multiplier method to minimize the Bit Error Rate (BER) at the constraint of UWB power limit. As a benchmark, the proposed system is compared to the conventional FFT based system in different UWB channel models (CM1-CM4) using MATLAB simulation. Simulation results show enhancement in side-lobes suppression of WPMCM about $20dB$. The result proves significant improvements, while primary and secondary links are subjected to multipath fading and noise. The probability of detection average is increased from 0.87 to 0.99, and probability of false alarm is reduced and controlled around 0.02 in the spectrum sensing phase. At $SNR = 25dB$, the achieved average BER is reduced from 4.4×10^{-3} to 3.95×10^{-4} for the proposed spectrum and power allocation. In general, the numerical results verify that the proposed system outperforms the traditional system with various metrics of performance analysis.

ABSTRAK

Sistem Ultra Jalur-Lebar (UWB) mempunyai ciri-ciri menarik seperti kadar penghantaran data yang tinggi, kos yang rendah, dan penggunaan kuasa yang rendah. Walau bagaimanapun, liputan jalur frekuensi yang besar dalam UWB menyebabkan gangguan kepada sistem jalur sempit yang lain. Matlamat utama kerja adalah untuk membangunkan sistem UWB yang boleh mengurangkan gangguan. Dalam tesis ini sistem Wavelet Kognitif UWB telah direka bagi meminimumkan gangguan dan meningkatkan prestasi sistem. Sistem yang dicadangkan adalah terdiri daripada modul modulasi wavelet paket berbilang pembawa (WPMCM), modul wavelet pengesan spektum, dan modul spektrum dan peruntukan kuasa. WPMCM dibangunkan kerana ia adalah fleksibel dan sememangnya teguh terhadap pengurangan gangguan. Modul WPMCM menggunakan jelmaan songsang wavelet paket (IWPT) dan enjin WPT bagi memainkan peranan yang sama seperti jelmaan songsang Fourier cepat (IFFT) dan FFT dalam sistem pembahagian frekuensi pemultipleksan (OFDM). Wavelet pengesan spektrum direka untuk meminimumkan gangguan dengan mengesan keseluruhan jalur spektrum dan membuat keputusan untuk menyahaktifkan subpembawa yang sedia ada. Modul wavelet pengesan spektrum yang dicadangkan mempunyai keupayaan untuk mengesan gangguan subpembawa yang sedia ada. Ia menggunakan pengesanan tenaga untuk menganalisis spektrum dan membuat keputusan. Algoritma peningkatan min pemotongan ke hadapan berturutan ((E-FCME) digunakan untuk menyediakan ambang keputusan sama ada untuk menggunakan subpembawa. Modul spektrum dan peruntukan kuasa telah dibangunkan untuk memperuntukkan penghantaran kuasa kepada subpembawa yang telah dipilih berdasarkan gandaan saluran penganggar. Di samping itu, corak strategi pilot yang cekap digunakan dalam saluran penganggar untuk meningkatkan anggaran gandaan saluran. Peruntukan kuasa optimum yang diperolehi dari kaedah pengganda Lagrange untuk meminimumkan BER pada kekangan had kuasa UWB. Sebagai penanda aras, sistem yang dicadangkan dibanding dengan sistem konvensional berasaskan FFT dalam model saluran UWB (CM1-CM4) yang berbeza menggunakan simulasi MATLAB. Keputusan simulasi menunjukkan peningkatan dalam penindasan cuping sisi WPMCM sebanyak 20dB. Keputusan ini membuktikan peningkatan yang ketara, meskipun penghubung utama dan sekunder adalah tertakluk kepada pemudaran dari pelbagai laluan dan bunyi. Kebarangkalian pengesanan purata meningkat dari 0.87 hingga 0.99, dan kebarangkalian penggera palsu dikurangkan dan dikawal sekitar 0.02 dalam fasa pengesanan spektrum. Pada SNR = 30dB, BER yang dicapai dapat dikurangkan dari 4.4×10^{-3} hingga 3.95×10^{-4} bagi spektrum dan peruntukan kuasa yang dicadangkan. Secara umum, keputusan berangka mengesahkan bahawa sistem yang dicadangkan mengatasi prestasi sistem tradisional dengan pelbagai metrik untuk analisis prestasi.

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LIST OF ABBREVIATIONS

AIC	-	Active Interference Cancellation
AMC	-	Automatic Modulation Classifier
ANN	-	Artificial Neural Network
AWGN	-	Additive White Gaussian Noise
BER	-	Bit Error Rate
BPSK	-	Binary Phase Shift Keying
CE	-	Consumer Electronics
CFAR	-	Constant False Alarm Rate
CIR		Channel Impulse Response
CME		Consecutive Mean Excision
CP	-	Cyclic Prefix
CR	-	Cognitive Radio
CSCG	-	Circularly Symmetric and Complex Gaussian
CSD	-	Cyclostationary Detection
CSI	-	Channel State Information
CTS	-	Clear-To-Send
CU	-	Cognitive User
CWT	-	Continuous Wavelet Transform
DFT	-	Discrete Fourier Transform
DPC	-	Dirty Paper Coding
DS	-	Direct Sequence
DWT	-	Discrete Wavelet Transform
ED	-	Energy Detection
E-FCME	-	Enhanced Forward Consecutive Mean Excision
EM	-	Expectation Maximization
FC	-	Fusion Centre
FCC	-	Federal Communications Commission

FCME	-	Forward Consecutive Mean Excision
FFT	-	Fast Fourier Transform
FIR		Finite Impulse Response
GI		Guard Interval
GPS	-	Global Positioning System
GSM		Global System for Mobile communication
ICI	-	Inter Carrier Interference
IFFT	-	Inverse Fast Fourier Transform
INR	-	Interference to Noise Ratio
ICI	-	Inter Carrier Interference
IR		Impulse Radio
ISI	-	Inter Symbol Interference
IWPT	-	Inverse Wavelet Packet Transform
LDPC		Low-Density Parity-Check
LRT	-	Likelihood Ratio Test
LS	-	Least Squares
MB	-	Multiband
MCM	-	Multicarrier Modulation
MCS	-	Modulation and Coding Scheme
MF	-	Match Filtering
MIMO	-	Multiple Input-Multiple Output
ML	-	Expectation Maximization
MMSE	-	Minimum Mean Squared Error
MRC	-	Maximum Ratio Combining
MSE	-	Mean Squared Error
NBI	-	Narrowband Interference
NMSE	-	Normalized Mean Square Error
OFDM	-	Frequency Division Multiplexing
PACE	-	Pilot Aided Channel Estimation
PAPR	-	Peaks to Average Power Ratio
PBI	-	Partial Band Interference
PDF	-	Probability Distribution Function
PLC	-	Power Line Communication

PSD	-	Power Spectral Density
PU	-	Primary User
QAM	-	Quadrature Amplitude Modulation
QMF	-	Quadrature Mirror Filter pair
QPSK	-	Quadrature Phase Shift Keying
RMT		Random Matrix Theory
RMS		Root Mean Square
RTS	-	Request-To-Send
SDR	-	Software Defined Radio
SFH	-	Slow Frequency Hopping
SINR	-	Signal to Interference and Noise Ratio
SNR	-	Signal to Noise Ratio
S-V model		Saleh-Valensuela model
TFC	-	Time Frequency Code
UWB	-	Ultra Wideband
V-BLAST	-	Vertical Bell Laboratories Layered Space Time
WBAN		Wireless Body Area Network
WLAN	-	Wireless Local Area Network
WPAN	-	Wireless Personal Area Networks
WPMCM	-	Wavelet Packet Based Multicarrier Modulation
WPT	-	Wavelet Packet Transform
WSN	-	Wireless Sensor Network
ZP	-	Zero Padding

LIST OF SYMBOLS

P_i	-	Assigned power for i-th subcarrier
$V_{m,k}$	-	AWGN at m-th subcarrier data and k-th symbol
BER_i	-	BER in the i-th subcarrier
B_i	-	Bit number of the i-th subcarrier
H_{ij}	-	Channel gain
H	-	Channel impulse response
H_i	-	Channel impulse response for i-th subcarrier
$\{\alpha_{c,l}^r\}$	-	Coefficient of the gain for multipath cases
Bc	-	Cognitive base station
Rx_c	-	Cognitive receiver
Tx_c	-	Cognitive transmitter
S_c	-	Cognitive user's transmitted signal
V_c	-	Complex Gaussian noise at cognitive receiver
V_p	-	Complex Gaussian noise at primary receiver
$\{T_c^r\}$	-	Delay of the c-th cluster for the r-th channel realization
$\{\tau_{c,l}^r\}$	-	Delay of the l-th multipath component within the c-th cluster for the r-th channel realization
$P_{l,fa}$	-	Desired probability of false alarm at lower
$P_{u,fa}$	-	Desired probability of false alarm at upper threshold
h_{hi}^{dec}	-	Dilatation decomposition filter
h_{hi}^{rec}	-	Dilatation reconstruction filter
$\delta(.)$	-	Dirac delta function
$\hat{B}$	-	Estimated bandwidth
$\hat{H}_{m,k}$	-	Estimated channel impulse response at m-th subcarrier data and k-th symbol

T_{CME}	-	FCME parameter
T_{FFT}	-	FFT/IFFT period
T_{GI}	-	Guard interval duration
T_{GT}	-	Guard time
X	-	Input data stream
Γ	-	Lagrange factor
f_L	-	lower frequency measured at -10 dB below the peak emission point
T_l	-	Lower threshold
ϕ_k	-	Modulated waveform matrix
V	-	Noise
N_D	-	Number of data subcarriers
N_P	-	Number of pilot subcarriers
J	-	Number of wavelet packet levels
T_{SYM}	-	OFDM symbol duration
$\psi_{j,k}$	-	Orthogonal waveform coefficient
$\varphi_{j,k}$	-	Orthogonal waveform for scaling coefficient
φ_m	-	Orthogonal waveforms
$Df\ (wi, j\ )$	-	Packet interval in frequency domain
$Dt\ (wi, j\ )$	-	Packet interval in time domain
S_k	-	Parallel symbols
P_{total}	-	Power constraint
P_{y_c}	-	Power of the received signal
Bp	-	Primary base station
Rx_p	-	Primary receiver
Tx_p	-	Primary transmitter
S_p	-	Primary user's transmitted signal
P_d	-	Probability of detection
P_{fa}	-	Probability of false alarm
r_c	-	Radius of the cognitive user coverage
r_p	-	Radius of the primary user coverage
$I_{m,k}$	-	Received interference signal at m-th subcarrier data
R	-	Received signal

$R_{m,k}$	-	Received signal at m-th subcarrier data and k-th symbol
Fs	-	Sampling frequency
$a_{j,k}$	-	Scaling coefficient
h_{lo}^{dec}	-	Scaling decomposition filter
h_{lo}^{rec}	-	Scaling reconstruction filter
Y_c	-	Signals at cognitive receiver
Y_p	-	Signals at primary receiver
ΔF	-	Subcarrier frequency spacing
$T(y_c)$	-	Test statistic
$\hat{l}_{1,c}$	-	The number of correctly detected subcarriers in c-th cluster
$\hat{l}_{0,c}$	-	The number of falsely detected subcarriers in c-th cluster
λ	-	Threshold value
B_{total}	-	Total bit number
N_{FFT}	-	Total number of subcarriers (FFT size)
N_T	-	Total of subcarriers used
Y	-	Transmitted signal
$Y_{m,k}$	-	Transmitted signal at m-th subcarrier data and k-th symbol
f_H	-	Upper frequency measured at -10 dB below the peak emission point
T_u	-	Upper threshold
σ^2	-	Variance
$d_{j,k}$	-	Wavelet coefficient
$W_{j,n}$	-	wavelet packet in the position of (j,n)

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CHAPTER 1

INTRODUCTION

1.1 Background

Ultra wideband (UWB) radio has an inherent potential to fulfil the demand of high data rate wireless links [1]. Under the current federal communications commission (FCC) regulation, multiband UWB is a promising technology for future short and medium range wireless communication networks with a variety of throughput options[2]. Multiband UWB is more resistant to narrowband interference and has selectivity for band implementation. Traditional UWB was based on impulse radio (IR) with extremely short and low power pulses. Recent UWB technology uses multiband frequency division multiplexing (OFDM) which is more resistant to narrowband interference and has selectivity of band implementation. OFDM is a type of multicarrier modulation (MCM) based on Fourier transform which uses inverse fast Fourier transform (IFFT) in the transmitter and fast Fourier transform (FFT) in the receiver side [3].

Recently wavelet transform has also been proposed, as an alternative to Fourier transform, in the design of communication systems. Wavelets have been applied in almost all aspects of digital wireless communication systems including data compression, source and channel coding, signal denoising, channel modeling and design of transceivers [4]. Wavelets have advantages such as transform flexibility, lower sensitivity to channel distortion and interference and better utilization of spectrum. Moreover the wavelet transform, with longer basis functions, can offer a higher degree of sidelobe suppression in MCM systems compared to OFDM [5]. These characteristics have made wavelet technology as a significant candidate for UWB communication.

Cognitive radio is a new concept in wireless communications features that is aware of the radio environment conditions and can adapt accordingly. Cognitive radio can accommodate the demand for higher capacity with new ways of exploiting the available radio spectrum thus leading to better usage of available natural resources such as power and available spectrum. In UWB environment, cognitive radio features can be considered due to its underlay characteristic and fading nature [6]. Cognitive UWB can dynamically select operating configurations, based on environment aspects, goals, profiles, and preferences. The integral element of cognitive UWB may include the adaptation to optimize the system performance, and utilize the available resources in an efficient manner.

In this thesis, Wavelet Cognitive UWB System is proposed. The design exploits wavelet packet based MCM (WPMCM), cognitive radio technology, and power allocation strategy to enhance the UWB performance. WPMCM combined with UWB system can be an efficient solution to meet adaptive and cognitive goals. WPMCM using MCM is expected to improve Wavelet Cognitive UWB System performance specifically against channel effects due to fading. The proposed Wavelet Cognitive UWB System solves the major problems of existing UWB system, as addressed in the next section.

1.2 Problem Statement

In order for UWB technology to truly succeed in commercial deployment there are still several technical obstacles that must be tackled. The main challenge in enhancing UWB system performance is to ensure that UWB system can mitigate interference from licensed users (primary users) as well as UWB and other users (cognitive users) within the same spectrum band. The research problems are further explained as below;

i) Current UWB system employs OFDM modulation with cyclic prefix or guard intervals to eliminate inter symbol interference (ISI) and inter carrier interference (ICI). Using cyclic prefix wastes the spectrum of data transmission and reduces the capacity. Additionally, OFDM implementation is using the rectangular windows which create high sidelobes [7]. In fact, the pulse shaping function used to modulate each subcarrier extends to infinity in the frequency domain. High sidelobes can lead to high interference and lower performance levels [4]. Thus there is a need to use a modulation that avoids using guard interval and pulse shaping but still can minimise interference.

ii) The other challenge of UWB is the possibility of mutual interference with adjacent primary users. Moreover, licensed systems with narrow bandwidths are potentially capable to interfere with UWB users. Coexistence with these primary users is the major issue in UWB system design. Thus, the inherent interference is an essential issue to be solved [8].

iii) The other problem is the power limitation of UWB transmission which may produce difficulties to achieve desired performance. Channel estimation is also a critical factor for UWB receiver, because of its multipath fading channel [2]. The interfering primary users prevent accurate channel estimation in UWB. Thus, precise channel estimation is vital for power allocation and optimization of UWB system performance.

1.3 Objectives of the Research

The main goal of the work is to design a UWB system that can mitigate the interference and enhance system performance in UWB system. The proposed system should be able to sense the environment, mitigate the interference from primary users, and adapt the transceiver according to the channel condition. The main objectives of the research are to design a UWB system with the following features.

i) to develop wavelet based MCM for UWB system that can achieve high degree of sidelobe suppression, greater flexibility, and improved robustness against various types of interferences , such as ISI, ICI, sidelobes, and primary user signal.

ii) to include cognitive features that can sense the environment, decide and mitigate interference from primary users by allocating the spectrum usage.

iii) to propose spectrum and power allocation that can properly configure the assigned subcarriers and adapt their power level,

The proposed UWB system is defined as Wavelet Cognitive UWB System. In this system, wavelet based MCM is implemented as the modulation scheme. Wavelet based spectrum sensing is also deployed to avoid interference with minimum modification and better performance. A novel spectrum and power allocation is used to assign the power within subcarriers due to occupied channels by primary users, and the power limitation of UWB.

1.4 Scope of the Research

This research mainly focuses on UWB transmission which is highly subjected to interference. In this work, we attempt to design a new UWB architecture and integrate the benefits of wavelet transform, cognitive features, and efficient spectrum and power allocation in order to mitigate interference due to narrowband interference (NBI). Analytic schemes are derived for a robust UWB architecture against interference and channel impairments.

In this research, multiband UWB has been considered of which every band has a bandwidth equal to 528 MHz and 128 subcarriers. The space of adjacent subcarriers is 4.125MHz based on IEEE 802.15.3a standard. Narrowband interfering systems such as IEEE 802.11a are considered to be suppressed. In simulations, the interference bandwidth varies from 4% to 24% of the entire bandwidth of cognitive signal which is calculated as about 6 to 31 subcarriers of the total number of 128 tones. The number of symbols is large enough to follow central limit theorem and the system simulation has been accomplished by MATLAB codes for three contributions.

1.5 Research Contributions

The proposed Wavelet Cognitive UWB System mitigates the interference and enhances the performance in different aspects. The proposed design consists of three contributions; baseband processing that is designing of WPMCM, cognitive radio features with wavelet spectrum sensing, and spectrum and power allocation strategy.

i) **WPMCM:** The first contribution is using WPT instead of FFT in MCM to design WPMCM transceiver. The new design reduces the impacts of interferences such as ICI, ISI, and NBI. WPMCM divides the stream of the data into orthogonal and parallel modulated sub streams with lower bit rate and longer symbol time than the channel delay spread. Unlike OFDM signals, which only are overlapped in the frequency domain, the wavelet packet signals are overlapped in both time and frequency, and the orthogonality is provided by orthogonal wavelet filters (filter banks). Due to this time overlapping, WPMCM schemes don't use cyclic prefix or any kind of guard interval that is commonly used in OFDM systems. This enhances the bandwidth efficiency comparing to the conventional OFDM systems.

ii) **Wavelet Spectrum Sensing**: The second contribution is wavelet spectrum sensing design by employing WPT and adaptive thresholding in energy detector. To avoid mutual interference with licensed users, proposed method performs spectrum sensing, i.e., detects primary users by wavelet based energy detector (ED) and vacates the occupied channels at a certain period of time. Proper thresholding is a major challenge of ED. The forward consecutive mean excision (FCME) combined with frequency localization based on double thresholding algorithm is applied.

iii) **Spectrum and Power Allocation**: The third contribution is developing spectrum and power allocation for the proposed system. In this phase, the occupied spectrum can be manipulated to avoid mutual interference to the other users. The power allocation is performed by Lagrange multiplier with the aim of BER minimization.

Finally, the performance of the novel system has been investigated under different UWB channel models using MATLAB programming. Bit error rate, probability of detection, and probability of false alarm are some the metrics served for the performance analysis.

1.6 Significance of the Research

Wavelet cognitive UWB offers a solution to heavily spectral crowding problem by the opportunistic usage of frequency bands. In other word, the proposed system exploits the available radio spectrum. UWB increases capacity without increasing bandwidth, since its spectrum is flexible to avoid mutual interference with primary users. The stringent UWB transmitted power constraint allows negligible interference to licensed and unlicensed users.

UWB allows flexible data rate for wide variety of transmissions such as video, data, ranging, etc. It is potentially proper for usage in wireless personal area networks (WPAN), wireless body area network (WBAN), wireless telemetry, telemedicine, and wireless sensor networks. UWB provides a high capacity transmission such as high resolution images for short-range applications. Several imaging UWB applications include ground penetration radars, wall radar imaging, surveillance systems, and medical imaging. Positioning location and relative positioning are other significant applications of UWB. Other possible uses are wireless home networking, high-density use in office buildings and business cores, UWB wireless mouse, keyboard, wireless speakers, and wireless USB.

1.7 Organization

The outline of the thesis is as follows; Chapter 2 is literature review on the UWB system, multicarrier modulation, cognitive radio concept, and wavelet transform. The chapter presents the challenges of UWB including interference problem. Wavelet transform, its applications and advantages are described consequently. Cognitive radio and corresponding spectrum sensing is explained as a solution to interference. Power allocation and related channel estimation is also defined in this chapter. Finally, the initial investigation of multiband OFDM UWB is provided. Chapter 3 elaborates the proposed design of Wavelet Cognitive UWB

System. The Wavelet Cognitive UWB System consists of WPMCM, wavelet spectrum sensing, spectrum and power allocation. The applied network model is defined at the end. Chapter 4 defines the design of proposed WPMCM in terms of mathematical analysis and block diagrams. Then, the chapter evaluates its performance in the terms of power spectral density and bit error rate under different wavelet families and channel models. Chapter 5 develops the mathematical analysis of the proposed wavelet spectrum sensing. The wavelet spectrum sensing mechanism is integrated into WPMCM system to provide cognitive features in Wavelet Cognitive UWB System. Energy detector based on WPT is developed and adaptive thresholding algorithm is applied.

Finally, the performance of wavelet spectrum sensing is investigated. Then, the proposed spectrum sensing has been applied for WPMCM and overall system is evaluated. In chapter 6, a novel spectrum and power allocation is employed for the proposed wavelet cognitive UWB system. We consider both UWB power limit and channel knowledge for the design of spectrum and power allocation. Finally, the thesis is concluded in chapter 7, and the perspective works are explained.

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