DESIGN AND EVALUATION OF MULTIDIMENSIONAL TURBO PRODUCT CODED MIMO-OFDM SYSTEM

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

JANUARY 2007

ABSTRACT

Multiple inputs multiple outputs (MIMO) realized through employing multiple antennas at both transmitter and receiver provides low bit error rate and high transmission rate as required by future digital wireless communication systems. Space time coding and spatial multiplexing are the two approaches in exploiting MIMO channel. This project proposes a new multiple inputs multiple output-orthogonal frequency division multiplexing (MIMO-OFDM) system employing single parity check multidimensional turbo product codes (MDTPC) that will provide high bit rate transmission with low bit error rate over correlated frequency selective fading channels. The initial work is developing the dimensional-based reading order (DBRO) algorithm for generating the MDTPC codeword sequences. The MDTPC codeword sequence is then applied to MIMO-OFDM system that exploits space, time, and frequency diversity and provides full-rate transmission. The system provides diversity gain of 2.5 dB in signal to noise ratio (SNR) and coding gain of 3 dB. Spatial multiplexing space-time coded MDTPC-MIMO-OFDM system with antennas grouping (AG-SMST-SPC-MDTPC-MIMO-OFDM) is then developed to increase the transmission rate. The result shows that the system provides a high transmission rate of 8 bps/Hz at SNR of 10 dB using two groups of four transmit antennas. The final task is designing the accurate channel estimation for the AG-SMST-MDTPC-MIMO-OFDM system employing pilot symbol assistance and least square estimation using mean-square error criterion. The channel estimator achieves mean-square error of 7×10^{-4} which is highly accurate. The proposed system provides high transmission bit rate of 120 Mbps with bit error rate of 10^{-5} at SNR of 18 dB for two groups of four transmit antennas. It can be implemented in wireless local area network (WLAN) and can also be deployed in any broadband wireless system.

ABSTRAK

Masukan berganda keluaran berganda (MIMO) wujud dengan penggunaan antena berganda pada kedua-dua pemancar dan penerima bagi menyediakan kadar ralat bit rendah dan kadar penghantaran tinggi sebagaimana yang diperlukan oleh sistem-sistem perhubungan digital wayarles masa hadapan. Pengekodan ruang masa dan gandaan mengikut ruang adalah dua pendekatan penggunaan saluran MIMO. Projek ini mencadangkan sebuah sistem masukan berganda keluaran berganda-pemultiplek pembahagi frekuensi ortogonal (MIMO-OFDM) yang baru bagi menjalankan pemeriksaan persamaan tunggal pengekodan sejajar turbo dimensi rantaian (MDTPC) yang akan menyediakan kadar penghantaran bit tinggi dengan kadar ralat bit rendah sepanjang saluran berpudar berkaitan frekuensi terpilih. Kerja awal adalah membangunkan algoritma berdasar dimensi pembacaan urutan (DBRO) untuk menjana urutan-urutan kod MDTPC. Urutan-urutan kod MDTPC kemudian digunakan kepada sistem MIMO-OFDM yang mengeksploitasikan kepelbagian ruang, masa, dan frekuensi dan menyediakan kadar penghantaran penuh. Sistem ini menyediakan kepelbagian gandaan 2.5 dB dalam nisbah isyarat hingar (SNR) dan pengekodan gandaan 3 dB. Gandaan ruang bagi ruang-masa berkod sistem MDTPC-MIMO-OFDM dengan antena berkumpul (AG-SMST-MDTPC-MIMO-OFDM) kemudian dibangunkan untuk meningkatkan kelajuan penghantaran. Hasil kerja menunjukkan bahawa sistem menyediakan kadar penghantaran yang tinggi iaitu 8 bps/Hz pada SNR 10 dB dengan menggunakan dua kumpulan yang terdiri daripada empat antena. Kerja terakhir adalah merekabentuk pengiraan saluran bagi sistem AG-SMST-MDTPC-MIMO-OFDM dengan menggunakan pembantu simbol berpandu dan penganggaran ganda dua terkecil menggunakan kriteria purata ralat ganda dua. Penganggar saluran memperolehi purata ralat ganda dua 7×10^{-4} yang mana adalah ketepatan yang tinggi. Sistem yang dicadangkan mencapai kadar penghantaran 120 Mbps dengan kadar ralat bit 10^{-5} pada SNR 18 dB untuk dua group dari empat antena penghantar. Ianya boleh digunakan dalam aplikasi rangkaian kawasan tempatan wayarles (WLAN) dan boleh juga digunakan dalam mana-mana sistem jalur lebar wayarles.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AWGN	-	Additive White Gaussian Noise
BPSK	-	Binary Phase Shift Keying modulation
CWEF	-	Conditional Weight Enumerating Function
dB	-	decibel
IOWEF	-	Input-Output Weight Enumerating Function
LLR	-	Log-likelihood Ratio
LOS	-	Line Of Sight
LS	-	Least Square
MDTPC	-	Multidimensional Turbo Product Codes
MIMO	-	Multiple Input Multiple Output
MISO	-	Multiple Input Single Output
ML	-	Maximum Likelihood
MSE	-	Mean Square Error
OFDM	-	Orthogonal Frequency Division Multiplexing
TPC	-	Turbo Product Code
PEP	-	Pairwise Error Probability
PSA	-	Pilot Symbol Assisted
QAM	-	Quadrature Amplitude Modulation
RLS	-	Recursive Least Square
SIMO	-	Single Input Multiple Output
SISO	-	Single Input Single Output
SNR	-	Signal to Noise Ratio
SPC	-	Single Parity Check code
STBC	-	Space Time Block Codes
STTC	-	Space Time Trellis Codes
ZF	-	Zero Forcing

LIST OF SYMBOLS

$A(.)$	-	IOWEF, input output weight enumerating function
B_h	-	Bit error multiplicity
$\mathbf{b}$ b	-	Information bits
C	-	The link level capacity, channel capacity
D	-	Number dimension of multi dimensional turbo product code
E_s	-	Energy of transmitted symbol
$E\{.\}$	-	Expectation function, running time mean
F	-	Frame length of transmitted block (symbols)
$\mathbf{H,h}$	-	Channel response
$H(.)$	-	Entropy
$\mathbf{I}$	-	Identity matrix
$I(.)$	-	Mutual information
j	-	Imaginary sign of complex number
k_d	-	Information block length, encoder input length
k	-	Constellation component order
M	-	Modulation level, number of constellation components
m, n, t	-	Order for transmit antenna, order for receive antenna, and order of transmitted symbol
N	-	Codeword length of a product code (bits)
N_0	-	Power of additive noise
N_T	-	Number of transmit antennas
N_R	-	Number of receive antennas
N_G	-	Number of antenna groups
n_d	-	Codeword length of component code at d^{th} dimension

P_e	-	Probability of bit error
Pr$(.)$	-	Probability of an event
$p(.)$	-	Conditional probability
$\mathbf{s}$	-	Transmitted signal
s_k	-	Constellation components, transmitted symbols
W,w	-	AWGN noise
X, X	-	Coded bits
Y,y	-	Received signal matrix
δ_d	-	Hamming distance of a codeword
$\mathbb{C}$	-	Complex number set
$\mathbb{R}$	-	Real number set
$\Re(.)$		Real part of complex number
$\mathbb{Z}$		Integer number set
$(.)^T$	-	Matrix transpose
π	-	Pi = 22/7 = 3.14159
ξ	-	DBRO mapping function
$\Lambda(.)$	-	LLR = log-likelihood ratio
Λ_e	-	Extrinsic information
Λ_c	-	Soft channel output
$\mathcal{O}(.)$	-	Computational complexity
$\mathcal{S}$	-	Set of constellation components
$\mathcal{C}(.)$	-	Component code of multidimensional product code
$(.)^{\mathcal{H}}$	-	Hermitian matrix
$(.)^*$	-	Complex conjugate
$(.)^{-1}$	-	Matrix inverse
$(.)^{\dagger}$	-	Moore-Penrose pseudo-matrix inverse

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Orthogonal frequency division multiplexing (OFDM) has become a popular technique for transmission of signal over wireless channel. OFDM converts a frequency-selective channel into a parallel collection of frequency flat channels. The sub-carriers have the minimum frequency separation required to maintain orthogonality of their corresponding time domain waveforms, yet the signal spectra corresponding to different sub-carriers overlap in frequency. Based on these advantage, OFDM has been adopted in several wireless standards such as digital audio broadcasting (DAB), digital video broadcasting (DVB-T), the IEEE802.11a (IEEE, 1999) local area network (LAN) standard and the IEEE 802.16a (IEEE, 2003) metropolitan area network (MAN) standard. OFDM is also being pursued for dedicated short-range communications (DSRC) for road side to vehicle communications and as potential candidate for fourth-generation (4G) mobile wireless systems.

The IEEE 802.11a LAN standard operates at raw data rates up to 54 Mbps (channel condition permitting) with a 20 MHz channel spacing, thus yielding a bandwidth efficiency of 2.7 bps/Hz (IEEE, 1999). The actual throughput is highly dependent on the medium access control (MAC) protocol. Likewise, IEEE802.16a operates in many modes depending on channel conditions with a data rate ranging from 4.20 to 22.91 Mbps in typical bandwidth of 6 MHz, translating into bandwidth efficiency of 0.7 to 3.82 bps/Hz (IEEE, 2003). Recent development of OFDM combined with multiple input multiple output (MIMO) techniques promise a significant performance boost. Broadband MIMO-OFDM systems with bandwidth efficiency of the order of 10 bps/Hz are feasible for LAN/MAN environments (Stubber *et al.*, 2004).

MIMO system is an arrangement of multiple antennas that can be used at transmitter and receiver. A MIMO system takes advantage of the spatial diversity that is obtained by spatially separated antennas in a dense multi-path scattering environment. MIMO systems may be implemented in a number of different ways to provide a diversity gain and combat signal fading in order to obtain a capacity gain. Generally, there are three different ways in exploiting MIMO system. The first reason is to improve the power efficiency by maximizing spatial diversity. This approaches provides low bit error rate at low signal to noise ratio (SNR). Such techniques include delay diversity (Wittneben, 1993), space–time block codes (STBC) (Alamouti, 1998; Tarokh *et al.*, 1999) and space–time trellis codes (STTC) (Tarokh *et al.*, 1998). The second method uses a layered approach (spatial multiplexing) to increase capacity. One popular example of such a system is V-BLAST suggested by (Wolniansky *et al.* 1998) where full spatial diversity is usually not achieved. Finally, the third type exploits the knowledge of channel at the transmitter to maximize the link level capacity relate to capacity gain. It decomposes the channel coefficient matrix using singular value decomposition (SVD) and uses these decomposed unitary matrices as pre- and post-filters at the transmitter and the receiver to achieve near capacity (Ha *et al.*, 2002). This approach requires a feedback channel from receiver to transmitter to send the channel parameters experienced by the transmitted signals.

Spatial diversity improves the MIMO system in term of link reliability and error-rate performance of the system (Bliss *et al.*, 2004; Ajib and Haccoun, 2005). STTC give high transmission rate with low error-rate at the cost of receiver complexity that increased exponentially as the number of antenna increase. STBC require linear decoding thus it is less complex. However, STBC does not provide coding gain. Another disadvantage of STBC is that these code decrease the transmission rate when the number of transmit antenna are more than two. Both STTC and STBC are designed for flat fading channel and are not suitable for fast and selective fading channel (Alamouti, 1998; Tarokh *et al.*, 1998). On the other hand, layered MIMO techniques are addressed to provide high transmission rate but sacrifice the error rate performance. Since the distinct symbol streams are transmitted from multiple transmit antennas, they will interfere each other that introduce errors during transmission. To improve the error rate performance of the layered MIMO, powerful coding techniques have to be used, such as turbo codes (Jameel and Yu, 2003) and turbo product code (TPC) (Du and Chan, 2004). Turbo code has high error correction capability among the error correcting codes. The encoder and decoder of turbo codes are very complex since they work based on the trellis diagram (trellis-based codes). TPC warrants less competent error correction capability compared to turbo code with less complex encoder and decoder processing. The existing decoder of TPC experiences the local minima in the convergence region and converges gradually at slow rate.

1.2 Problem Statement

The existing space-time codes enhance the error rate performance of the wireless transmission system over MIMO channels at the cost of decreasing the transmission rate. Both STBC and STTC that employ several transmit antennas produce maximum rate of only 3/4 symbol/s/Hz. The encoding and decoding of STBC is simple, but STBC does not grant coding gain. On the other hand, STTC provides coding gain but its encoding and decoding is complex. Furthermore, the performance of these codes will degrade greatly when the fading is changing rapidly within one transmitted symbol duration since the codes were designed for slow time varying fading channel.

The performance of spatial multiplexing MIMO system can be enhanced through the use of robust error correcting codes (Kothandaraman, 2002; Li *et al.*, 2003; Lee *et al.*, 2003; Gidlund and Ahag, 2003; Du and Chan, 2005). The performance enhancement can also be obtained by applying space-time codes onto spatial multiplexing MIMO system (Mao and Motani, 2005; Wu *et al.*, 2002). Other means include developing accurate symbol detection at the receiver (Artes *et al*., 2003), improving the signal shaping at the transmitter (Clerckx *et al.*, 2004), and grouping the transmitter antennas combined with space-time coding (Chen and Haimovich, 2004; Xia *et al.*, 2005). These approaches usually decrease the overall transmission rate of the system. The usage of OFDM on spatial multiplexing MIMO system will not only mitigate the effect of frequency-selectivity of the faded channels but also enhance the spectrum efficiency of the channel. The OFDM signal will divide the frequency-selective channel bandwidth into narrower flat channel bandwidth since OFDM employs several narrowband subcarriers.

The performance of the MIMO-OFDM system is highly dependent on the accuracy of the channel estimation schemes. The task on this issue is how to design accurate channel estimation with low complexity and low symbol overhead on the transmission. The most accurate channel estimation is pilot-symbol assisted (PSA) channel estimation where the known symbol sequences at receiver are distributed along the transmitted frame. This technique introduces high overhead when applied to MIMO system since the pilot symbols are inserted at every transmitted frame. Finding the optimal pilot training sequences for MIMO system is another issue that should be explored. The optimization criteria are in terms of overhead and energy consumption.

1.3 Objective of the Research

In order to increase the transmission rate and to improve the error rate performance of MIMO-OFDM over wireless correlated frequency-selective fast fading channels, the challenge is how to design the coding techniques that exploit the space, time, and frequency diversity whilst providing full transmission rate (1 symbol/s/Hz). Another challenge is how to increase the channel capacity of the MIMO OFDM system over time varying and frequency-selective fading channel. In real system, the receiver of MIMO OFDM system requires the channel information to perform detection and decoding, therefore the channel estimation of the full-rate space-time coded MIMO OFDM system is another issue that should be investigated.

The objective of the research is to develop a MIMO-OFDM system design that consist of channel coding, interleaving, space-time-frequency coding, spatial multiplexer, and channel estimation. The design should fulfill the following features.

(i) Powerful channel code with high code rate and simple encoding and decoding processes
(ii) Exploit space, time, and frequency diversity that will provide full rate transmission
(iii) Employ spatial multiplexing to provide high transmission rate
(iv) Deploy low complexity MIMO detector with accurate channel estimation and low overhead

The MIMO-OFDM system should achieve low bit error rate at low power transmission (SNR).

1.4 Scope of the Research

The research will develop the MIMO-OFDM system that will function well in correlated multipath frequency selective fast fading wireless channel. High rate multidimensional turbo product code (MDTPC) will be used as error correcting code and also for granting space, time, and frequency diversity in the system. Amplitude modulator is used to convert the coded bit to the modulated symbols and then transform to sub-carriers in OFDM block using inverse fast Fourier transformation. These OFDM symbols will be transmitted trough multiple transmit antenna.

Multiple antennas are also employed at the receiver with OFDM demodulator at each branch. Fast Fourier transformation (FFT) is used to convert the OFDM symbols (time domain) to modulated symbols (frequency domain). These modulated symbols composed of transmitted symbols from all transmit antennas and MIMO detector will be used to separate them again. After computing the soft detected coded bits, soft iterative decoding will be performed using parallel MDTPC decoder. The recovery information bits will be obtained by applying hard decision. These bits will be used for investigating the behavior and performance of the system

The development of the above system consists of several phases. The first phase is designing high rate MDTPC. Single parity check code (SPC) has been selected to be used as component code of MDTPC to provide high code rate. The possible codewords are generated from MDTPC and the mapping functions are derived. The performance of MDTPC has been improved by developing parallel iterative MDTPC decoder with weighting feedback. Mathematical analysis and computer simulation using MATLAB has been developed to study the performance of MDTPC over additive white Gaussian noise channel (AWGN) and Rayleigh fading channel.

The second phase is to provide the space, time, and frequency diversity in MIMO OFDM system by employing the possible codeword sequences of MDTPC. Space and time diversity has been exploited by transmitting the possible codeword sequences through different transmit antennas. Frequency diversity is obtained by employing OFDM modulator at the transmitter. These space-time codes ST-MDTPC provides full transmission rate (1 symbol/s/Hz). In order to increase the transmission rate, the spatial multiplexing with antenna grouping defined as AG-SMST-MDTPC-MIMO-OFDM has been developed. Optimum MIMO detector has been developed using maximum likelihood (ML) decision criteria, while, sub optimum detector was designed using zero forcing (ZF) detection. Mathematical models and computer simulation has been expanded to investigate the system performance in frequency selective multipath fading channel. The channel response samples are assumed to be perfectly estimated and available at the receiver.

The final phase of the work is developing the channel estimation for AG-SMST-MDTPC-MIMO-OFDM system employing pilot symbol sequences. The search of optimum pilot sequences for least square (LS) adaptation algorithm with regard to mean square error (MSE) criteria has been performed. A recursive LS (RLS) algorithm is used to enhance the performance of the overall system. Mathematical model and simulation using MATLAB is extended to investigate the channel estimation performance and the system performance. The channel is assumed to be frequency selective fast fading channel and the response samples of these channels are correlated and Rayleigh distributed random variables.

1.5 Significance of the Work

The proposed AG-SMST-MTDC-MIMO-OFDM system is a baseband processing part of a transmission (and receiver) system that can be applied to any existing standard such as the IEEE 802.11a WLAN Standard. The significant works in this research is developing that can be stated as follows:

- Generating possible codeword sequences of the MDTPC codes and developing the corresponding mapping functions.
- Developing the full rate space-time code using the possible codeword sequences of MDTPC for any number of transmit antennas. When combining with OFDM transmission, the frequency diversity will be available at the system.
- Developing the spatial multiplexing with antennas grouping while providing space, time, and frequency diversity.
- Developing the channel estimation by employing pilot symbol assisted sequences for AG-SMST-MDTPC-MIMO-OFDM system in correlated and frequency selective fading channel. Optimum pilot sequences criteria are derived in terms of overhead and energy consumption. Recursive adaptation algorithm is developed.

The proposed system will generate wireless transmission system with high transmission rate at multiple the numbers of antenna groups. Furthermore, the system will endure low bit error rate and require low power transmission at high transmission rate. The system can be easily extended to be applicable to any wireless communication system standards such as WLAN, DAB, DVB, and DSRC.

1.6 Thesis Outline

The thesis is organized and distributed into seven chapters. **CHAPTER 1** introduces to the general idea of the research and provides an overview of the thesis that includes the background, problem, objective, and scope of the research. **CHAPTER 2** studies and reviews the previous works related to this research. The study covers state of the art of the developing system and also the recent related works in references. Some important findings are presented and analyzed.

CHAPTER 3 describes the proposed MDTPC and its parallel decoder. In this chapter, the possible codeword sequences of MDTPC are generated based on the dimension-based reading order. The mapping functions for generating the possible codeword from MDTPC codeword sequences are derived. Parallel MDTPC decoder with weighting extrinsic information feedback is proposed. The performance of the single parity check MDTPC with parallel decoder is studied through mathematical analysis and computer simulation using MATLAB.

CHAPTER 4 designs a new space-time multidimensional product coded (ST-MDTPC) system employing the possible codeword of MDTPC. The MIMO receiver using ML detector and ZF detector are developed and analyzed. The analytical link channel capacity is derived. Application of the ST-MDTPC in OFDM system is investigated in frequency selective fading channel.

CHAPTER 5 presents the spatial multiplexing ST-MDTPC-MIMO scheme which is an extension of the ST-MDTPC schemes (chapter three) with multiple groups of transmit antennas (AG-SMST-MDTPC-MIMO). The analytical channel capacity is derived. Application over OFDM channel is performed and investigated.

CHAPTER 6 presents the channel estimation of the AG-SMST-MDTPC-OFDM system using adaptive LS algorithm based on MSE criteria. The optimum pilot training criteria are derived for distinct pilot symbols types. Channel estimation enhancement is developed using recursive LS and frequency domain analysis is presented.

CHAPTER 7 concludes the thesis report and suggests the potential and possible future works.

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