A SCHEME FOR SPACE-TIME-FREQUENCY CODING AND ADAPTIVE MULTIPLE ANTENNA SELECTION FOR IMPROVING THE PERFORMANCE OF MULTIPLE-INPUT SINGLE-OUTPUT OFDM SYSTEM

By

NOR KAMARIAH NOORDIN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,
in Fulfilment of the Requirement for the Degree of Doctor of Philosophy

November 2006

DEDICATION

To my children,

Nadiah Husseini, Hilal Husseini and Hafeez Husseini

To the memory of my beloved husband,

Assocociate Professor Dr. Zainol Abidin Bin Abdul Rashid
[2 Feb 1962 – 8 October 2006]

and

To the memory of my parents,

Hj Noordin Hj Yacob [1914 – 6 Nov 2005]
Esah Mohamed [1921 – 15 March 1989]

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment the requirement for the degree of Doctor of Philosophy.

A SCHEME FOR SPACE-TIME-FREQUENCY CODING AND ADAPTIVE MULTIPLE ANTENNA SELECTION FOR IMPROVING THE PERFORMANCE OF MULTIPLE-INPUT SINGLE-OUTPUT OFDM SYSTEM

By

NOR KAMARIAH NOORDIN

November 2006

Chairman: **Professor Borhanuddin Mohd Ali, PhD**

Faculty: **Engineering**

In this thesis, issues such as link adaptation that include adaptive spatial mode in the context of orthogonal frequency division multiplexing (OFDM) is addressed, particularly in a multiple-input single-output (MISO) configuration suitable for mobile communications. The performances of ST- and SF-OFDM incorporating channel coding are extensively investigated in the presence of channel fading and noise. Realizing that ST and SF behave differently in different environments, a new adaptive spatial mode (ASM)-OFDM is proposed. This scheme selects the mode of transmission based on the instantaneous signal to noise ratio (SNR) for a 2×1 MISO system. A new adaptive multiple antenna selection (AdMAS) using second-order moment of the channel impulse response between multiple transmitting antennas and a single receiver MISO-OFDM configuration is also proposed as a major contribution. This scheme employs a 4×1 space-time-frequency coding with a symbol rate of ¾, using orthogonal signals, to avoid high complexity in detection. In the proposed AdMAS scheme the worst faded channel(s) is(are) adaptively turned off based on the calculated second-order moment of the channel impulse response. Findings show that the proposed scheme outperforms other multiple antenna schemes such as the one based on the mean of the channel impulse response, especially at higher order modulation. Throughout the simulation, channel state information (CSI) is assumed to be known both by the transmitter and the receiver which may be achieved via a dedicated feedback channel or through the reciprocity of the channel such as that found in time division duplex (TDD) system.

Minor contribution of this thesis includes a simplified sphere decoding algorithm for MIMO that forms part of the detection scheme at the receiver. A maximum achievable diversity order of the 4×1 MISO-OFDM has also been derived analytically and proved through simulation. A diversity gain of more than 10 dB can be achieved with Binary Phase Shift Keying modulation when compared to Alamouti's Space-Time Block Code (STBC) at a bit error rate (BER) of 10^{-3}. This makes the proposed scheme a potential scheme to be considered for the future high data rate communication. The proposed schemes are tested through simulations in different types of practical channels such as Wireless Local Area Network (WLAN) IEEE 802.11, Rayleigh fading with various delay spreads, as well as the most recent Fixed Broadband Wireless Access (FBWA) IEEE 802.16 Stanford University Interim channels, or better known as the WiMAX channels.

Abstrak tesis dikemukakan kepada Senat Universiti Putra Malaysia sebagai
memenuhi syarat keperluan untuk ijazah Doktor Falsafah

SKIMA BAGI PENGEKOD RUANG-MASA-FREKUENSI DAN PEMILHAN ANTENNA BERBILANG MUDAH SUAI UNTUK MEMBAIKI PRESTASI BERBILANG-MASUKAN SATU-KELUARAN OFDM

Oleh

NOR KAMARIAH NOORDIN

Mei 2006

Pengerusi: **Profesor Borhanuddin Mohd Ali, PhD**

Fakulti: **Kejuruteraan**

Dalam tesis ini, isu seperti mudah-suai hubungan termasuk mod mudah-suai ruang dalam konteks OFDM diberi tumpuan, terutamanya dalam konfigurasi berbilang masukan satu keluaran (MISO) yang sesuai untuk sistem komunikasi bergerak. Prestasi ST dan SF-OFDM yang dilengkapi dengan pengkodan saluran dikaji secara menyeluruh dalam kedaaan saluran pudar dan hingar. Memandangkan skema ST dan SF menunjukkan sifat yang berbeza dalam keadaan saluran yang berbeza, satu skema mudah-suai mod ruang (ASM) yang baru telah disarankan. Skema ini memilih mod dengan memudah-suaikan mod penghantaran berdasarkan nisbah ketika isyarat kepada hangar (SNR) bagi konfigurasi MISO 2×1. Satu lagi skema baru yang dicadangkan adalah skema mudah-suai pemilihan berbagai antenna (AdMAS) dengan menggunakan momen aturan kedua bagi sambutan denyut saluran di antara penghantar berbilang antenna dengan penerima satu antenna. Skema ini merupakan sumbangan utama tesis ini. Skema ini menggunakan 4×1 pengkodan ruang-masa-

frekuensi (STF)-OFDM dengan kadar simbol sebanyak ¾, menggunakan isyarat ortogonal, bagi mengelakkan kesukaran pengesanan. Dalam skema AdMAS yang di cadangkan ini, saluran yang paling pudar akan diabaikan dengan mematikan antenna penghantar tersebut. Ini dilakukan secara mudah-suai berdasarkan momen aturan kedua sambutan denyut saluran yang telah dikira terlebih dahulu. Ini boleh dilakukan dengan tanggapan keadaan informasi saluran (CSI) diketahui oleh kedua-dua penghantar dan penerima yang boleh dicapai melalui saluran penghantaran balik atau melalui saluran pengkosian sebagaimana terdapat dalam sistem dupleks pembahagian masa (TDD).

Sumbangan kecil yang juga terdapat dalam tesis ini termasuklah algoritma penyahkodan sphere yang dimudahkan, yang membentuk sebahagian dari skema pengesanan simbol dalam penerima. Aturan diversiti maksimum yang boleh dicapai juga telah dikeluarkan bagi konfigurasi 4×1 MISO STF-OFDM dan dibuktikan melalui simulasi. Gandaan diversiti sebanyak 10 dB telah diperolehi dengan modulasi Kekunci Anjakan Fasa Binari (BPSK) berbanding dengan kaedah Kod Blok ST Alamouti pada kadar ralat (BER) 10^{-3}. Ini membuatkan skema yang dicadangkan berpotensi untuk menjadi skema pilihan untuk sistem komunikasi akan datang. Skema-skema yang dicadangkan di atas telah diuji melalui simulasi dalam saluran praktikal yang berbeza seperti saluran Rangkaian Setempat Wayarles (WLAN) IEEE 802.11, pemudaran Rayleigh dengan nilai-nilai serakan lengah yang berbeza, serta saluran IEEE 802.16e Stanford Univerity Interim (SUI) bagi sistem Capaian Wayarles Jalur Lebar Tetap (FBWA) atau lebih dikenali sebagai WiMAX.

ACKNOWLEDGEMENTS

First of all, I would like to thank Allah, the Almighty for giving me the strength and courage to finish this work. I would also like to take this opportunity to thank my supervisor, Professor Borhanuddin Mohd Ali, for his guidance and for introducing me to OFDM in 2001. He has helped me find a good topic to work with, with the helps of his many reputable friends. The same goes to my supervisory committee members, Professor Sudhansu Shekar Jamuar, who always keep me on my toes, Professor Tharek Abdul Rahman and Associate Professor Dr. Mahamod Ismail.

I am also grateful to the discussion and technical chat that I have with fellow PhD students, particularly Chee Kyun. My sincere thanks also go to all my colleagues at the Department of Computer and Communication Systems Engineering, particularly Haniff for sharing his grant with me so that I can present some of my findings, and Roslizah for letting me use her Matlab dongle.

I also would like to express my gratitude and love to my family, especially my husband, my children, Nadiah, Hilal and Hafeez for being there with me when my mood was not that tolerable. Also my sincere appreciation and love to my late parents, Haji Noordin Haji Yacob and Esah Mohamed. The same goes to my brothers and sisters for their constant du'a.

Last but not least a thank you note to my former Dean, Professor Radin Umar Radin Sohadi, who has persuaded me to embark in this PhD journey. Thank you all so much.

I certify that an Examination Committee met on 2nd of November 2006 to conduct the final examination of Nor Kamariah Noordin, on her Doctor of Philosophy thesis entitled “A Scheme for Space-Time-Frequency Coding and Adaptive Multiple Antenna Selection for Improving the Performance of Multiple-Input Single-Output OFDM System” in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

Mohd Khazani Bin Abdullah, PhD
Associate Professor
Department of Computer and Communication Systems Engineering
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Sabira Khatun, PhD
Associate Professor
Department of Computer and Communication Systems Engineering
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mohd Adzir Mahdi, PhD
Associate Professor
Department of Computer and Communication Systems Engineering
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Farid Ghani, PhD
Professor
School of Electrical and Electronic Engineering
Universiti Sains Malaysia
(Independent Examiner)

HASANAH MOHD. GHAZALI, Ph.D
Professor
Deputy Dean (Science and Engineering)
School of Graduate Studies
Universiti Putra Malaysia

Date:

This thesis submitted to the Senate of Universiti Putra Malaysia has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the supervisory Committee are as follows:

Borhanuddin Bin Mohd Ali, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Sudhansu Shekar Jamuar, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Tharek Bin Abdul Rahman, PhD
Professor
Faculty of Electrical Engineering
Universiti TeknologiMalaysia
(Member)

Mahamod Bin Ismail, PhD
Associate Professor
Faculty of Engineering
Universiti Kebangsaan Malaysia
(Member)

AINI IDERIS, PhD
Professor/Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 16 JANUARY2007

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

(NOR KAMARIAH NOORDIN)

Date: 5 DECEMBER 2006

TABLE OF CONTENTS

Page

CHAPTER

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

4G	Fourth Generations
AdMAS	Adaptive Multiple Antenna Selection
ASM	Adaptive Spatial Mode
AWGN	additive white Gaussian noise
BC	Block Coding
BER	Bit Error Rate
BLAST	Bell Labs Layered Space-Time
bps	bits per second
BPSK	Binary Phase Shift Keying
BWA	Broadband Wireless Access
CIR	Channel Impulse Response
CL	Chan-Lee
Code A	Convolutional code with code rate of ¼ and length of 10
Code B	Convolutional code with code rate of 1/3 and length of 8
Code C	Convolutional code with code rate of ½ and length of 7
Code D	Convolutional code with code rate of ½ and length of 5
COFDM	Coded Orthogonal Frequency Division Mulitplexing
CP	Cyclic Prefix
CSI	Channel State Information
DAB	Digital Audio Broadcasting
dB	decibels
DFT	Discrete Fourier Transform
DVB	Digital Video Broadcasting

ETSI	European Telecommunication Standards Institute
FBWA	Fixed Broadband Wireless Access
FEC	Forward Error Corrections
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
GHz	Giga Hertz
Hz	Hertz
i.i.d	independent and identically distributed
ICI	Inter Carrier Interference
IDFT	Inverse Discrete Fourier Transform
IEEE	Institute of Electricla and Electronic Engineers
IFFT	Inverse Fast Fourier Transform
ISI	Inter Symbol Interference
ITU	International Telecommunication Union
kHz	kilo Hertz
LA	Link Adaptation
LOS	Line of Sight
MatLab	Matrix Laboratory
Mbps	Mega bits per second
MCMC	Malaysian Communications and Multimedia Commision
MHz	Mega Hertz
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
ML	Maximum Likelihood
MRC	Maximum Ratio Combining

MRRC	Maximal-Ratio Receive Combining
NLOS	Non Line of Sight
ns	nano seconds
OFDM	Orthogonal Frequency Division Multiplexing
pdf	probability density function
PSD	power spectral density
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QR	Cholesky’s factorisation
QO-STBC	Quasi Orthogonal Space-Time Block Code
QPSK	Quadrature Phase Shift Keying
rms	root mean square
Rx	Receiver
SER	Symbol Error Rate
SF	Space-Frequency
SIMO	Single Input Multiple Output
SISO	Single Input Single Output
SNR	Signal to Noise Ratio
ST	Space-Time
STBC	Space-Time Block Code
STC	Space-Time Coding
STF	Space-Time-Frequency
STTC	Space-Time Trellis Coding
SUI	Stanford University Interim
Tx	Transmitter

VB	Viterbo-Boutrous
VSAT	Very Small Aperture Terminal
WATM	Wireless Asynchronous Transfer Mode
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

LIST OF SYMBOLS

$h(\tau,t)_l$	time-varying channel impulse response with order l
f_c	carrier frequency
$\alpha_l(t)$	attenuation factor for the l-th path
$\tau_l(t)$	propagation delay for the l-th path
A	the envelope of the channel impulse response $h(\tau,t)_l$
$p_A(a)$	probability density function of A
$\overline{\tau}$	mean access delay
σ_τ	root mean square (rms) delay spread
$P(\tau_k)$	power delay profile
T_C	channel coherence time
T_s	symbol period
B_C	coherence bandwidth
$\Delta\tau$	differential delay between the time of the direct path and the next path
$H(j\omega)$	system transfer function
N_T	number of transmit antennas
N_R	number of receive antennas

ρ_{ij}	fading correlation between antennas i and j
$J_0^{\,2}(.)$	Bessel function of the first kind with zero-th order
d_{ij}	separation between antennas i and j in meters
λ	wavelength of the operating frequency
Λ	angular spread of the incoming signal intercepted by an array of omnidirectional antennas
$\mathbf{\Sigma}_{\mathrm{TX}}$	correlation matrix of the transmit antenna arrays
$\mathbf{\Sigma}_{\mathrm{RX}}$	correlation matrix of the receive antenna arrays
$\mathbf{H}$	$(N_T \times N_R)$ correlated MIMO channel matrix
$\mathrm{vec}\{.\}$	the vector operation of stacking the columns of a matrix into a single column vector
$\otimes$	Kronecker product
$\mathbf{G}$	$(N_T \times N_R)$ uncorrelated MIMO channel matrix
$\mathcal{N}(0,\frac{\sigma_k^2}{2})$	zero mean Gaussian random variable with variance $\frac{\sigma_k^2}{2}$
T_{rms}	delay spread of the channel
b_k	data sequence
$s_t^{(k)}$	M-QAM or M-PSK symbol represents a $\log_2 M$ bits per symbol transmitted over k-th subcarrier during t-th OFDM symbol (frame) resulted after the IFFT operation
N_{ch}	independent QAM/PSK channels, each operating at the same symbol rate $1/T$, but each having a distinct QAM/PSK constellation
$S_t^{(k)}$	complex-valued signal points corresponding to the information symbols on the subcarriers
$s(t)$	transmitted signal waveform resulted from passing the signal samples $\{s^{(k)}\}$ through a digital-to analog converter
$y(t)$	the received signal (or the output of the channel)

$n(t)$	additive white Guassian noise in the channel
$*$	convolution operator
Δf	bandwidth of each subchannel
$Y^{(k)}$	the N-point of discrete Fourier transform (DFT) of the received samples $y^{(k)}$
$\hat{b}_k$	estimated output sequence
$\mathbf{F}$	an $N \times N$ Fourier transformation matrix
N_0	variance of the additive white Gaussian noise $n_t^{(i)}$.
T_{OFDM}	OFDM symbol duration
T_{CP}	cyclic prefix duration
R_{STBC}	rate of a space-time block code
$\hat{\mathbf{X}}$	estimated symbol $\mathbf{X}$
$[\cdot]^{\mathcal{H}}$	denotes Hermitian of a matrix and
$\lVert\cdot\rVert_F$	denotes the Frobenius norm of an expression
r	denotes the rank of matrix $(\mathbf{X}-\hat{\mathbf{X}})$
$\lambda_1,\lambda_2,\ldots\lambda_r$	the nonzero eigenvalues of $(\mathbf{X}-\hat{\mathbf{X}})^{\mathcal{H}}(\mathbf{X}-\hat{\mathbf{X}})$.
$\prod_{i=1}^{r}\lambda_i$	the products of non zero eigenvalues $\lambda_1,\lambda_2,\ldots\lambda_r$ over all pairs of distinct codewords $\mathbf{X}$ and $\hat{\mathbf{X}}$
$\mathbf{C}_4$	4×4 transmission matrix
$\mathcal{A}$	signal constellation of either M-QAM or M-PSK
δ_1	a phase delay applied to signal $s(n)$
c_i	combining weights applied to the received signals at receive antenna $i = 1, 2, \ldots, N_R$

ε	energy of $s(n)$
N_0	noise power spectral density of additive white Gaussian noise, $\nu(n)$
L_T	the number of transmit antenna chosen by the system out of N_T available antennas that yield the best performing signals
L_R	the number of receive antenna chosen by the system out of N_R available antennas that yield the best performing signals
$\mathbf{s}_p$	resulting sequence of modulated signal after adding the cyclic prefix of length P
$\mathbf{X}_1$	the M-th block data symbol vector
$\mathbf{X}_2$	the (M+1)-th block data symbol vector
$\mathbf{I}$	identity matrix
$\mathbf{X}_e$	the even component of data symbol $\mathbf{X}$
$\mathbf{X}_o$	the odd component of data symbol $\mathbf{X}$
$\mathbf{X}_{1,e}$, $\mathbf{X}_{2,e}$	the even component vectors of $\mathbf{X}_1$ and $\mathbf{X}_2$
$\mathbf{X}_{1,o}$, $\mathbf{X}_{2,o}$	the odd component vectors of $\mathbf{X}_1$ and $\mathbf{X}_2$
N	number of subcarriers
BW	broadband bandwidth,
$\mathbf{A}_4$	4×4 orthogonal transmission matrix of rate ¾
$\mathbf{S}_{i,t}$	correspond to data symbol vectors transmitted during the t-th time from the i-th transmitting antenna
$\mathbf{S}_{i,t,e/o}$	denotes the data symbol vectors transmitted on the even/odd subcarrier of the t-th time slot from the i-th antenna
$\mathbf{H}_{i,t,e/o}$	denotes the channel frequency response of the even/odd subcarrier of the t-th time slot from the i-th antenna
K	constraint length of a convolutional code

k/n	convolutional code rate, expressed as a ratio of the number of bits (*k)* into the convolutional encoder to the number of channel symbols output, (*n*) by the convolutional encoder in a given encoder cycle
m	memory length of the convolutional encoder.
N_M	number of QAM/PSK symbols in the block vector $\mathbf{S} = [S(0)\ S(1)\,\Lambda\ \ S(N_M - 1)]^T$
N_S	number of OFDM symbols
$R_{STF-OFDM}$	the proposed STF code rate