UNIVERSITI PUTRA MALAYSIA

PEAK TO AVERAGE POWER RATIO REDUCTION AND BIT ERROR RATE IMPROVEMENT IN WIRELESS ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING COMMUNICATION SYSTEMS

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By

WISAM FAHMI AL-AZZO

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

March 2009

Dedicated to

The memory of my father and mother,

for their unconditional love and support throughout my life

To my wife and

my beloved children,

Sidra, Mustafa, Yasmeen, and AbdulRahman

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

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March 2009

Chair: **Professor Borhanuddin Mohd. Ali, PhD**

Faculty: **Engineering**

Orthogonal frequency division multiplexing (OFDM) offers high data rate transmission with high spectral efficiency, immunity to multipath fading, and simple implementation using fast Fourier transform (FFT). OFDM is readily implemented by present day processors in many high speed networks. However, one of the major drawbacks of OFDM systems is the high peak-to-average power ratio (PAPR); this can result in poor power efficiency, degradation in bit-error-rate (BER) performance, and spectral spreading. The effective PAPR reduction of OFDM signals by simple processing has been a challenge for the limited power and processing capability of portable OFDM applications.

This thesis investigates the problem of high PAPR in OFDM systems and presents many simple implementation PAPR reduction techniques, and one error-resilient technique.

The first part of this thesis presents two time-domain PAPR reduction techniques, viz, square-rooting the envelope of the OFDM output signals, and the smoothing technique. The square-rooting process changes the statistical distribution of the OFDM output signals from Rayleigh to Gaussian-like distribution and reduces the differences between the values of peak and average power, which consequently reduces the PAPR significantly. About 6 dB reduction in PAPR is achieved with moderate degradation in BER performance. For the smoothing process, which is derived from the image enhancement technique, the smoothing applied on the OFDM signals mitigates the PAPR due to its averaging effect. Up to 2.5 dB reduction is achieved by smoothing.

Two new probabilistic based non-iterative frequency-domain PAPR reduction techniques are introduced in the second part of the thesis. These techniques reduce PAPR by changing the statistical distribution of the OFDM modulated symbols from uniform distribution to Gaussian-like distribution. This task is performed by two different methods in two different PAPR techniques. The first method of PAPR reduction is done by the addition of complex Gaussian random signals, while the second one is done by insertion of dummy Gaussian subcarriers. The two techniques provide PAPR reduction in the order of 5 dB for PSK-OFDM systems with no out-of-band radiation. The adaptive operation of these techniques enhances significantly both the BER performance and reduce the transmission power.

The last part of this thesis presents a new modulation-based error resilient technique referred to as multi-dimensional modulation technique (MDM). In this technique concatenation of digital modulators of decreasing modulation orders are employed. The MDM technique improves the BER performance linearly with increased size of modulation order; up to 12 dB improvement in E_b/N_o ratio is achieved relative to the conventional OFDM systems at high modulation orders, $M \geq 1024$. Also, the MDM technique offers both error resilience and PAPR reduction when it is combined with the conventional OFDM systems in time domain.

As a conclusion, the proposed techniques described above offer new solutions to the problem of high PAPR in OFDM systems, and for one of them offer improvement of BER performance at the same time. Besides, they can be applied for different systems parameters and applications requirements. Moreover, the PAPR reduction techniques proposed in this thesis are data-independent and can be implemented in one-shot; while the MDM technique uses only digital modulation and dc-offset signal processing, which can be implemented by simple circuits and/or processors.

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

NISBAH KUASA PUNCAK KE PURATA DAN PENAMBAHBAIKAN KADAR RALAT BIT DALAM SISTEM KOMUNIKASI PEMULTIPLEKSAN PEMBAHAGI FREKUENSI ORTHOGONAL TANPA WAYER

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Pemultipleksan pembahagi frekuensi orthogonal (OFDM) menawarkan penghantaran kadar data tinggi dengan kecekapan spectrum yang tinggi, kekebalan terhadap pemudaran berbilang laluan, dan pelaksanaan mudah menggunakan Penjelmaan Fourier Pantas (FFT). OFDM mudah diterapkan menggunakan pemproses semasa dalam rangkaian kelajuan tinggi. Bagaimanapun, satu kelemahan utama sistem-sistem OFDM adalah tingginya nisbah kuasa puncak ke purata (PAPR); ini boleh mengakibatkan lemahnya kecekapan kuasa, penurunan prestasi kadar ralat bit (BER), dan pengembangan spektrum. Pengurangan berkesan PAPR untuk isyarat OFDM dengan pemprosesan mudah telah menjadi satu cabaran kepada kebolehalihan aplikasi aplikasi OFDM dengan kuasa terhad dan keupayaan pemprosesan.

Tesis ini mengkaji beberapa masalah PAPR yang tinggi dalam sistem-sistem OFDM dan mempersembahkan pelaksanaan mudah teknik-teknik pengurangan PAPR, dan satu teknik ketahanan ralat.

Bahagian pertama tesis ini mempersembahkan dua teknik pengurangan PAPR domain masa, iaitu, punca kuasa dua sampul isyarat keluaran OFDM, dan teknik pelicinan. Proses punca kuasa dua mengubah taburan statistik isyarat keluaran OFDM dari taburan Rayleigh kepada taburan seakan Gauss dan mengurangkan perbezaan di antara nilai-nilai kuasa puncak dan purata, dan seterusnya mengurangkan PAPR dengan berkesan sekali. Lebih kurang 5 dB pengurangan dapat dicapai dengan penurunan sederhana prestasi BER. Untuk proses pelicinan yang berpaksi pada teknik peningkatan imej, pelicinan yang diterapkan pada isyarat OFDM mengurangkan PAPR disebabkan oleh kesan pemurataannya. Pengurangan sehingga 2.5 dB adalah diperolehi dengan pelicinan.

Dua teknik baru berpaksikan kebarangkalian pengurangan PAPR domain frekuensi tidak berulang adalah diperkenalkan dalam bahagian kedua tesis ini. Teknik-teknik ini mengurangkan PAPR dengan mengubah taburan statistik simbol dimodulatkan dengan OFDM dari taburan sekata kepada taburan seakan Gauss. Tugas ini dilakukan menggunakan dua kaedah PAPR yang berlainan. Kaedah pertama pengurangan PAPR adalah dilakukan dengan penambahan isyarat rawak Gauss kompleks, manakala kaedah kedua dilakukan dengan memasukkan isyarat Gauss *dummy*. Kedua-dua kaedah tersebut memberikan pengurangan PAPR dalam order 4 dB untuk system-sistem PSK-OFDM tanpa sinaran di luar jalur. Pengendalian adaptif meningkatkan dengan jelas kedua-dua prestasi BER dan mengurangkan kuasa penghantaran.

Bahagian terakhir tesis ini mempersembahkan satu teknik ketahanan ralat berpaksikan modulasi yang dikenali sebagai teknik modulasi berbilang dimensi (MDM). Dalam teknik ini penyambungan pemodulat digital dengan order modulasi yang menurun adalah digunakan. Teknik MDM meningkatkan prestasi BER secara lelurus dengan peningkatan saiz order modulasi; peningkatan sehingga 12dB dalam nisbah E_b/N_o telah dicapai berbanding dengan sistem OFDM lazim. Juga, teknik MDM menawarkan kedua-dua ketahanan ralat dan pengurangan PAPR apabila ia digabungkan dengan sistem-sistem OFDM lazim dalam domain masa.

Sebagai rumusan, teknik cadangan ini sebagaimana yang diperihalkan di atas menawarkan penyelesaian baru kepada masalah PAPR tinggi dalam sistem-sistem OFDM, dan satu dari mereka, menawarkan peningkatan prestasi BER dalam masa yang sama. Selain dari itu, mereka boleh diaplikasikan untuk parameter-parameter sistem dan keperluan aplikasi yang berlainan. Lebih-lebih lagi teknik pengurangan PAPR yang dicadangan dalam tesis ini adalah bebas data dan boleh dilaksanakan sekali gus, manakala teknik MDM hanya menggunakan modulasi digital dan pemprosesan isyarat offset-dc, yang boleh dilaksanakan dengan litar mudah dan/atau pemproses.

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I certify that an Examination Committee has met on 20/3/2009 to conduct the final examination of Wisam Fahmi Al-Azzo on his Doctor of Philosophy thesis entitled "Peak to Average Power Ratio Reduction and Bit Error Rate Improvement in Wireless OFDM Communication Systems" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The committee recommends that the student be awarded the Doctor of Philosophy degree.

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Data: 9 July 2009

DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institution.

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(Wisam Fahmi Al-Azzo)

Date: 26 May 2009

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LIST OF ABBREVIATIONS

3G	Third Generation
4G	Fourth Generation
ACE	Active Constellation Extension
ACI	Adjacent Channel Interference
ADRG	Addition of Random Gaussian Signals
ADSL	Asymmetric Digital Subscriber Line
A/D	Analog to Digital Conversion
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
bps	bit per second
CCDF	Complementary Cumulative Distribution Function
CDMA	Code Division Multiple Access
CODFM	Coded Orthogonal Frequency Division Multiplexing
CP	Cyclic Prefix
CR	Clipping Ratio
D/A	Digital to Analog Conversion
DAB	Digital Audio Broadcasting
dB	decibels
dc	direct current (0 Hz)
DFT	Discrete Fourier Transform
DMT	Discrete Multi-Tone
DSI	Dummy Sequence Insertion

DSP	Digital Signal Processing
DSR	Dummy Subcarriers Ratio (no. of dummy to no. of data subcarriers ratio)
DVB	Digital Video Broadcasting
$\mathbf{E_b/N_o}$	Bit Energy-to-Noise Density Ratio
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction
FFT	Fast Fourier Transform
GMSK	Gaussian Minimum Shift Keying
GSM	Global System for Mobile communications
PA	Power Amplifier
IBO	Input Back-Off
ICI	Inter-Carrier Interference
IDRG	Insertion of Dummy Random Gaussian Subcarriers
i.i.d.	independent identically distributed
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
ISI	Inter-Symbol Interference
ITU-R	International Telecommunication Union-Radio
M_2/ M_1	Modulation orders ratio (inner-to-outer modulators in MDM technique)
Mbps	Mega bits per second
MCM	Multi-Carrier Modulation
MDM	Multi-Dimensional Modulation
OBO	Output Back-Off
OFDM	Orthogonal Frequency Division Multiplexing
P/S	Parallel-to-Serial Conversion

PAPR	Peak to Average Power Ratio
pdf	probability density function
PSD	Power Spectral Density
PSK	Phase Shift Keying
PTS	Partial Transmit Sequences
QAM	Quadrature Amplitude Modulation
S/P	Serial-to-Parallel Conversion
SLM	Selective Mapping
SNR	Signal to Noise Ratio
SPR	Signal Power Ratio (random to data signals power ratio)
SQRT	Square Rooting
TI	Tone Injection
TPR	Transmitted Power Ratio
WLAN	Wireless Local Area Network

LIST OF SYMBOLS

T_D	Data sample duration
T_s	OFDM symbol duration
T_g	Guard period
$\tau_{\max}$	maximum channel delay
f_n	OFDM subcarrier frequency
Δf	OFDM subchannel bandwidth
BW_{SC}	Bandwidth of single-carrier system
BW_{OFDM}	Bandwidth of OFDM system
N	Number of subcarriers in one OFDM block
K	Number of data subcarriers in one OFDM block
L	Number of dummy subcarriers in one OFDM block
N_{sg}	Number of signals in smoothing sub-blocks
J	Oversampling factor
S_k	modulated symbol in OFDM frequency domain
s_n	OFDM output signal
ϕ_n	Phase factor of OFDM output signal
P_{Peak}	Peak power in OFDM block signals
P_{Avg}	Average power of OFDM block signals
$E\{\cdot\}$	Expected value