



**UNIVERSITI PUTRA MALAYSIA**

***PEAK TO AVERAGE POWER RATIO REDUCTION BASED ON OPTIMUM  
PHASE SEQUENCE IN ORTHOGONAL FREQUENCY DIVISION  
MULTIPLEXING SYSTEMS***

**SOMAYEH MOHAMMADY**

**FK 2012 20**

**PEAK TO AVERAGE POWER RATIO REDUCTION BASED ON  
OPTIMUM PHASE SEQUENCE IN ORTHOGONAL FREQUENCY  
DIVISION MULTIPLEXING SYSTEMS**

By  
SOMAYEH MOHAMMADY

Thesis Submitted to the Graduate Studies, Universiti Putra Malaysia, in fulfillment of  
the requirement for the Degree of Doctor of Philosophy

January 2012

## DEDICATION

This thesis is dedicated to my husband Pooria and his helps are deeply appreciated. This thesis is also dedicated to my dear father and mother for all the encouragements and supports.



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

**PEAK TO AVERAGE POWER RATIO REDUCTION BASED ON OPTIMUM  
PHASE SEQUENCE IN ORTHOGONAL FREQUENCY DIVISION  
MULTIPLEXING SYSTEMS**

By

**SOMAYEH MOHAMMADY**

**January 2012**

**Chairman: Assoc. Prof. Roslina binti Mohd. Sidek, PhD**

**Faculty: Engineering**

Orthogonal Frequency Division Multiplexing (OFDM) is a form of a Frequency Division Multiplexing (FDM) scheme that is used in recent broadband wireless communication systems. The main advantage of OFDM systems is immunity against the fading phenomena caused by natural multipath environment. However, there is a major drawback of high Peak-to-Average Power Ratio (PAPR). Signal with high PAPR forces the Power Amplifier (PA) to work in its nonlinear region, which generates distortions. The PA has to be operated with back-off to avoid high PAPR, which decreases the power efficiency. To overcome the PAPR problem in OFDM systems, several techniques are introduced such as Conventional Selected Mapping (C-SLM) and Dummy Sequence Insertion (DSI). In C-SLM method, by increasing the number of Inverse Fast Fourier Transform (IFFT) blocks, the PAPR performance is enhanced at the expense of complexity and side information, which results in high cost and spectrum efficiency degradation. In DSI method, inserting the dummy signals degrades the spectrum efficiency and also exhibits data rate loss.

In this thesis, two schemes have been proposed in order to reduce PAPR. The first proposed scheme is called DSI-SLM, which combines the modified dummy sequence of the DSI with the phase sequence of the SLM. As a result of applying this scheme, the PAPR performance is enhanced and the complexity is reduced compared to C-SLM. The second proposed method is named Optimum Phase Sequence with Dummy Sequence Insertion (OPS-DSI) that is designed to improve the DSI-SLM method in terms of complexity and side information. In OPS-DSI method, the optimum phase sequence is applied while only one IFFT is performed and the side information can be placed within the dummy signals.

In order to demonstrate the feasibility of these methods in actual systems, the prototype of DSI-SLM and OPS-DSI methods are carried out in Field Programmable Gate Array (FPGA). The implementation results are comparable with simulation results. However, there is less than 0.1dB difference which is due to the constraints of the FPGA input and output bit resolutions. Finally, these methods are integrated with Digital Predistortion (DPD) and actual PA to represent an OFDM transmitter system. This results in Power Added Efficiency (PAE) enhancement by an average of 17%, which leads to less power consumption and prolonged battery life. This system is simulated based on IEEE 802.11e standard and the results are numerically analyzed and compared with various numbers of dummy signals and candidate signals. The DSI-SLM method reduces PAPR by 3.6dB. Almost 76% reduction in total complexity is also achieved compared to C-SLM, meanwhile OPS-DSI method enhances PAPR performance by 4.2dB and total complexity reduction by 95%. Hence, OPS-DSI outperforms DSI-SLM in terms of PAPR and complexity. Their Bit Error Rates (BERs) are in acceptable range of  $10^{-4}$  at  $S_b/N_b=14$  dB.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia Sebagai memenuhi keperluan untuk ijazah Doctor Falsafah

**PENGURANGAN NISBAH KUASA PUNCAK KEPADA  
PURATA BERDASARKAN JUJUKAN FASA OPTIMUM DALAM SISTEM-  
SISTEM PEMULTIPLEKSAN PEMBAHAGIAN FREKUENSI ORTOGON**

Oleh

**SOMAYEH MOHAMMADY**

**Januari 2012**

**Pengerusi: Assoc. Prof. Roslina binti Mohd. Sidek, PhD**

**Fakulti: Kejuruteraan**

Pemultipleksan Pembahagian Frekuensi Ortogon (OFDM) ialah satu bentuk Pemultipleksan Pembahagian Frekuensi (FDM) yang digunakan dalam sistem jalur lebar komunikasi tanpa wayar terkini. Kelebihan utama sistem-sistem OFDM ialah ketahanan terhadap fenomena pemudaran disebabkan oleh persekitaran berbilang lorong semula jadi. Bagaimanapun terdapat satu kelemahan utama, iaitu Nisbah Kuasa Puncak Kepada Purata (PAPR) yang tinggi. Isyarat PAPR yang tinggi memaksa Penguat Kuasa (PA) bekerja dalam kawasan tak linear yang akan menghasilkan pemesongan. PA perlu dikendalikan secara undur balik yang akan mengurangkan kecekapan kuasanya. Untuk mengatasi masalah PAPR dalam sistem OFDM, beberapa teknik telah diperkenalkan seperti Pemetaan Terpilih Konvensional (C-SLM) dan Sisipan Jujukan Tiruan (DSI). Dalam kaedah C-SLM, dengan penambahan jumlah blok Jelmaan Fourier Pantas Songsang (IFFT), prestasi PAPR bertambah baik tetapi akan menjadi lebih rumit dan memerlukan lebih maklumat sisi yang menyebabkan peningkatan kos dan penurunan spektrum. Dalam kaedah DSI, memasukkan isyarat tiruan akan menurunkan kecekapan spektrum dan menyebabkan kehilangan kadar data.

Dalam tesis ini, dua kaedah telah dicadangkan untuk mengurangkan PAPR. Kaedah pertama yang dicadangkan dipanggil DSI-SLM yang menggabungkan jujukan tiruan terubahsuai DSI dengan jujukan fasa SLM. Penggunaan kaedah ini meningkatkan prestasi PAPR dan mengurangkan kerumitan berbanding dengan C-SLM. Kaedah yang kedua dinamakan OPS-DSI yang direka untuk memperbaiki kaedah DSI-SLM dari segi kerumitan dan maklumat sisi. Dalam kaedah OPS-DSI, jujukan fasa optimum digunakan manakala hanya satu IFFT digunakan dan maklumat sisi boleh ditempatkan dalam isyarat tiruan.

Untuk menunjukkan kaedah ini boleh dilaksanakan dalam sistem sebenar, skema DSI-SLM dan OPS DSI dilaksanakan pada Tatasusunan Get Boleh Aturcara Medan (FPGA). Keputusan pelaksanaan setanding dengan keputusan simulasi. Bagaimanapun, terdapat perbezaan kurang daripada 0.1dB yang disebabkan oleh resolusi bit masukan dan keluaran FPGA. Akhirnya kaedah-kaedah ini digabungkan dengan model Praherotan Digit (DPD) dan PA untuk mewakili sistem pemancar OFDM. Ia menghasilkan peningkatan Kecekapan Tambahan Kuasa (PAE) sebanyak 17% yang mana akan mengurangkan penggunaan kuasa dan memanjangkan hayat bateri. Sistem ini disimulasi berdasarkan piawai IEEE 802.16e dan keputusan berangka dianalisis dan dibandingkan dengan pelbagai bilangan isyarat tiruan dan isyarat calon. Kaedah DSI-SLM dapat mengurangkan PAPR sebanyak 3.6dB. Hampir 76% pengurangan jumlah kerumitan dicapai berbanding C-SLM, sementara skim OPS-DSI prestasi PAPR sebanyak 4.2dB dan mengurangkan kerumitan sebanyak 95%. Maka, OPS-DSI mengatasi DSI-SLM dari segi prestasi PAPR dan kerumitan. Kadar Ralat Bit (BER) kedua-duanya berada didalam julat yang boleh diterima iaitu  $10^{-4}$  pada  $S_b/N_b=14$ dB.

## ACKNOWLEDGEMENTS

I would like to acknowledge the advice and guidance of Assoc. Prof. Dr. Roslina b. Mohd Sidek, committee chairman. I also thank the members of my supervisory committee, Dr Mohd. Nizar b. Hamidon and Dr Nasri Sulaiman for their encouragement, guidance and assistance. I also would like to thank the faculty, and staff of Engineering Faculty for their assistance during my stay at UPM.

I would like to thank my husband, Dr Pooria Varahram for caring, supporting and encouraging me to pursue this degree. Without his encouragement, I would not have finished the degree.

I also want to express my gratitude to my parents, sister, and brothers for their understanding and cheering through the duration of my studies.

-----  
Somayeh Mohammady

Date: February 2012



I certify that an Examination Committee has met on \_\_\_\_\_ to conduct the final examination of Somayeh Mohammady on her doctor of philosophy thesis entitled "Peak To Average Power Ratio Reduction Based On Optimum Phase Sequence In Orthogonal Frequency Division Multiplexing Systems" 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:

**Professor Ir. Dr. Norman b. Mariun, PhD**

Professor  
Faculty of Graduate Studies  
Universiti Putra Malaysia  
(Chairman)

**Dr. Suhaidi B. Shafie, PhD**

Professor  
Faculty of Graduate Studies  
Universiti Putra Malaysia  
(Internal Examiner)

**Dr. Izhal b. Abdul Halin, PhD**

Professor  
Faculty of Graduate Studies  
Universiti Putra Malaysia  
(Internal Examiner)

**Professor Dr. Mahmood Ismail, PhD**

Professor  
Faculty of Graduate Studies  
Universiti Putra Malaysia  
(External Examiner)

---

**Bujang Kim Huat, PhD**

Professor/Deputy Dean  
School of Graduate Studies  
Universiti Putra Malaysia  
Date:

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

**Roslina binti Mohd. Sidek, PhD**

Associate Professor  
Faculty of Engineering  
University Putra Malaysia  
(Chairman)

**Mohd Nizar B. Hamidon, PhD**

Associate Professor  
Faculty of Engineering  
University Putra Malaysia  
(Member)

**Nasri Sulaiman, PhD**

Senior Lecturer  
Faculty of Engineering  
University Putra Malaysia  
(Member)

---

**BUJANG BIN KIM HUAT, PhD**

Professor and Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date:

## 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.



-----  
**SOMAYEH MOHAMMADY**

Date: 11 January 2012

## TABLE OF CONTENTS:

	Page
<b>DEDICATION</b>	<b>ii</b>
<b>ABSTRACT</b>	<b>iii</b>
<b>ABSTRAK</b>	<b>v</b>
<b>ACKNOWLEDGEMENTS</b>	<b>vii</b>
<b>APROVAL</b>	<b>viii</b>
<b>DECLARATION</b>	<b>x</b>
<b>LIST OF TABLES</b>	<b>xiv</b>
<b>LIST OF FIGURES</b>	<b>xvi</b>
<b>LIST OF ABBREVIATIONS</b>	<b>xxi</b>
<b>CHAPTER</b>	
<b>1 INTRODUCTION</b>	<b>1</b>
1.1.1 OFDM Systems	2
1.1.2 OFDM Orthogonality	3
1.1.3 Peak-to-Average Power Ratio (PAPR) in OFDM signal	3
1.2 Related Work	5
1.4 Thesis Objective	8
1.5 Research Methodology and Scope	8
1.6 Thesis Contribution	11
1.7 Thesis Organization	12
<b>2 LITERATURE REVIEW</b>	<b>14</b>
2.1 Introduction	14
2.2 OFDM Basics	14
2.3 Channel and Receiver in OFDM system	17
2.4 Advantages and Drawbacks of OFDM	19
2.5 PAPR Parameters	20
2.6 Distortion Based PAPR Reduction Techniques	22
2.6.1 Clipping Method	22
2.6.2 Windowing method	24
2.6.3 Companding Method	24
2.7 Distortionless based PAPR reduction methods	25
2.7.1 Coding Method	27
2.7.2 Active Constellation Extension (ACE)	27
2.7.3 Partial Transmit Sequence (PTS)	28
2.7.4 Selected Mapping (SLM) Method	30
2.7.5 Tone Reservation (TR) Method	37
2.7.6 Dummy signal insertion (DSI) Method	38

2.8	Discussion of the current PAPR reduction solutions	42
2.9	Power Amplifier in OFDM transmitter	43
2.9.1	Power Amplifier Memory effects	47
2.9.2	Need For Linearity	49
2.10	Linearization Methods	50
2.10.1	Digital Predistortion Linearization method	50
2.10.2	Complex Gain Memory (CGMP) Predistortion	51
2.10.3	Advantages and Disadvantages of the CGMP Method	53
2.11	Summary	54
<b>3</b>	<b>DESIGN OF THE PROPOSED DSI-SLM SCHEME</b>	<b>56</b>
3.1	Introduction	56
3.2	The proposed DSI-SLM method	56
3.3	The Advantages and Disadvantages of the DSI-SLM	62
3.4	DSI-SLM system performance	63
3.4.1	DSI-SLM Side Information	64
3.4.2	DSI-SLM Computational Complexity	64
3.4.3	Simulation results and analysis	69
3.4.4	Results Discussion	82
3.5	Summary	83
<b>4</b>	<b>OPTIMUM PHASE SEQUENCE WITH DUMMY SEQUENCE INSERTION (OPS-DSI) SCHEME</b>	<b>84</b>
4.1	Introduction	84
4.2	Design of OPS-DSI scheme	84
4.3	System performance of the OPS-DSI scheme	94
4.3.1	OPS-DSI Side Information	94
4.3.2	Advantages and Disadvantages of the proposed OPS-DSI	94
4.3.3	OPS-DSI Computational Complexity	95
4.3.4	Simulation results and analysis	96
4.3.5	Results Discussion	100
4.4	Summary	101
<b>5</b>	<b>HARDWARE IMPLEMENTATION</b>	<b>103</b>
5.1	Introduction	103
5.2	Field Programmable Gate Array (FPGA)	104
5.2.1	System Generator Tool	105
5.2.2	System Generator Design Flow	105
5.3	FPGA Implementation of the DSI-SLM method	106
5.3.1	Implementation of the IFFT	107
5.3.2	Using AccelDSP software for implementing IFFT	109
5.3.3	Implementation of C-SLM method	111
5.3.4	Implementation of DSI-SLM method	114
5.3.5	Hardware resource consumption	119
5.4	FPGA implementation of the OPS-DSI scheme	124
5.4.1	Implementation of OPS-DSI Transmitter	124
5.4.2	Implementation of OPS-DSI Receiver	129

5.4.3 Implementation of Complex Division in receiver	136
5.4.4 Hardware resource consumption of the OPS-DSI scheme	146
5.5 Summary	147
<b>6 INTEGRATION OF DSI-SLM/OPS-DSI IN PREDISTORTED POWER AMPLIFIER</b>	<b>148</b>
6.1 Introduction	148
6.2 Power Amplifier Characteristics	149
6.3 Digital Predistortion (DPD) Technique	153
6.4 Integration of DSI-SLM/OPS-DSI in predistorted PA	157
6.5 Summary	165
<b>7 CONCLUSION</b>	<b>166</b>
7.1 Conclusion	166
7.1.1 Design of DSI-SLM Scheme	167
7.1.2 Design of DSI-OPS method	167
7.1.3 Integration of DSI-SLM/DSI-OPS technique in CGP	168
7.1.4 FPGA Implementation of the proposed techniques	169
7.2 Suggestions for Future Works	169
<b>REFERENCES</b>	<b>170</b>
<b>APPENDICES</b>	<b>183</b>
<b>BIODATA OF STUDENT</b>	<b>208</b>
<b>LIST OF PUBLICATIONS</b>	<b>209</b>