UNIVERSITI PUTRA MALAYSIA

POWER AMPLIFIER MEMORY POLYNOMIAL PREDISTORTER FOR LONG TERM EVOLUTION APPLICATION

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POWER AMPLIFIER MEMORY POLYNOMIAL PREDISTORTER FOR LONG TERM EVOLUTION APPLICATION

By

HOSSEIN MAZIDI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

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DEDICATIONS

In the name of Allah, Most Gracious, Most Merciful
This thesis is dedicated to:

Father & Mother
Family & Friends

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

POWER AMPLIFIER MEMORY POLYNOMIAL PREDISTORTER FOR LONG TERM EVOLUTION APPLICATION

By

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February 2015

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In Radio Frequency (RF) Front-End wireless communications systems, the power amplifier should be efficient in order to support more users and leads to decrease the costs of energy, and to extend the duration of the battery life, accordingly. Modern digital modulated signals like: Long Term Evolution (LTE) and Universal Mobile Telephone System (UMTS) exhibit difficult challenging concerns on the efficiency of the radio frequency power amplifiers and their design. Despite the spectral efficiency of these new modulated schemes, the RF PAs which are excited by the modulated signals like LTE, can experience nonlinear and unstable situation. These situations cause distortions and then result in lots of drawbacks like: power loss or heating. Therefore, some linearization techniques have been proposed to overcome the effects of nonlinearity. The designer can implement the digital predistortion and apply it to the input of the amplifiers for the top speed digital processors. This solution represents a significant paradigm shift for design and compensation of the nonlinear RF PAs. In this thesis, some behavioral modeling approaches of the nonlinear dynamic distortions in the wireless communication systems are investigated to model RF nonlinear PAs in order to compensate the memory effects as terms of their nonlinearity. A brief description of some characterization techniques will be explained. These nonlinear modeling techniques can be applied to the design of successful predistortion algorithms. The overall structure of a linearized transmitter using Memory Polynomial Digital Predistortion (MP DPD) architecture is represented to obtain both linearity and efficiency of the nonlinear PAs. The results are obtained by simulations through MATLAB. An open loop test bench is set up by using ZVE-8G+ power amplifier and Agilent equipment such as Agilent vector signal generator (VSG)EXG-D series and Agilent vector signal analyzer (VSA) PXI series in order to generate LTE down-link signal with 5 MHz bandwidth. Then, the test bench's output signal is given in arbitrary waveform format (I/Q) to the MATLAB software as the input.

In conclusion, MP DPD is resulted in as improvement between 15 to 20 dB in the adjacent channel power ratio (ACPR). Therefore, the characteristics of the realized amplifiers are measured to satisfy the Error Vector Magnitude (EVM) and desired power spectral density (PSD) is plotted as requirements for Wide-band Code Division Multiple Access (WiMAX) base stations and LTE down-link signal. Effect of some elements like: number of iterations, input power back-off (IBO) points, the memory effect modeling ration (MEMR) matric for different PAs with memory effects and memory-less respectively, on the performance of predistorter, are investigated.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

POWER AMPLIFIER MEMORY POLYNOMIAL PREDISTORTER UNTUK APLIKASI EVOLUSI JANGKA PANJANG

Oleh

HOSSEIN MAZIDI

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Dalam Radio Frekuensi (RF) Front-End sistem komunikasi tanpa wayar, penguat kuasa perlu cekap bagi menyokong lebih ramai pengguna dan dapat mengurangkan kos tenaga, dan memanjangkan tempoh hayat bateri. Isyarat termodulat digital moden seperti : Evolusi Jangka Panjang (LTE) dan Universal Sistem Telefon Mudah Alih (UMTS) menunjukkan kebimbangan pada kecekapan penguat kuasa frekuensi radio dan reka bentuk mereka. Walaupun dengan kecekapan spektrum skim termodulat baru ini, PA RF yang teruja dengan isyarat termodulat seperti LTE, boleh mengalami keadaan tidak linear dan tidak stabil. Situasi ini menyebabkan kekurangan dan kemudian menyebabkan banyak keburukan seperti: kehilangan kuasa atau pemanasan. Oleh itu, beberapa teknik linear telah dicadangkan untuk mengatasi kesan tidak linear. Pereka bentuk boleh melaksanakan pra-penyelewengan digital dan gunakan kepada input penguat untuk mendapatkan kelajuan maksimum pemproses digital. Penyelesaian ini mewakili satu anjakan paradigma yang besar untuk reka bentuk dan penyelesaian daripada PA RF tidak linear. Dalam tesis ini, beberapa pendekatan model tingkah laku gangguan dinamik tidak linear dalam sistem komunikasi tanpa wayar disiasat untuk model PA RF tidak linear untuk mengimbangi kesan memori segi tidak linear. Penerangan ringkas mengenai beberapa teknik pencirian akan diterangkan. Teknik-teknik pemodelan linear boleh digunakan untuk reka bentuk berjaya algoritma pra-penyelewengan. Struktur keseluruhan sebuah pemancar terlinear menggunakan seni bina memori polinomial Digital Pre-penyelewengan (MP DPD) digunakan untuk mendapatkan kedua-dua kelinearan dan kecekapan PA tak linear. Keputusan yang diperolehi oleh simulasi melalui MATLAB. Ujian gelung terbuka dijalankan dengan menggunakan penguat kuasa ZVE-8G + dan peralatan Agilent seperti penjana isyarat vektor (VSG) Siri EXG-D Agilent dan isyarat vektor penganalisa (VSA) Siri PXI Agilent untuk menjana LTE turun-link isyarat dengan jalur lebar 5 MHz. Kemudian, isyarat keluaran ujian ini diberikan

dalam bentuk format gelombang (I/Q) kepada perisian MATLAB sebagai input. Kesimpulannya, AP DPD yang mengakibatkan peningkatan dalam nisbah kuasa saluran bersebelahan (ACPR) antara 15 hingga 20 dB. Oleh itu, ciri-ciri penguat diukur untuk mematuhi Magnitud Ralat Vektor (EVM) dan ketumpatan kuasa spektrum (JPA) yang dikehendaki diplotkan sebagai keperluan bagi stesen pangkalan untuk Wideband Code Division Multiple Access (WiMAX) dan LTE turun- link isyarat. Kesan beberapa elemen seperti: bilangan lelaran, titik kuasa input back- off (IBO), pemodelan kesan memori catuan (MEMR) matrik untuk PA yang berbeza dengan kesan memori dan tiada memori, kepada prestasi sebelum distorter , adalah disiasat.

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I certify that a Thesis Examination Committee has met on 12 February 2015 to conduct the final examination of Hossein Mazidi on his thesis entitled "Power Amplifier Memory Polynomial Predistorter for Long Term Evolution Application" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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LIST OF ABBREVIATIONS

$3G$	Third Generation
$3GPP$	Third Generation Partnership Project
$4G$	Forth Generation
AM	Amplitude Modulation
$ACEPR$	Adjacent Channel Error Power Ratio
ACI	Adjacent Channel Interference
$ACLR$	Adjacent Channel Leakage Ratio
$ACPR$	Adjacent Channel Power Ratio
ADC	Analog to Digital Converter (A/D)
ADS	Advanced Design System
BB	Base-band
BW	Bandwidth
BER	Bit Error Rate
BPF	Band Pass Filter
CP	Cyclic Prefix
CFB	Cartesian-loop Feedback
DAC	Digital to Analog Converter (D/A)
DC	Direct Current
DPD	Digital Predistortion
DUT	Device Under Test
$EDGE$	Enhanced Data for GSM Evolution
EFB	Envelope Feedback
EPA	The Error Power Amplifier
ESG	The Electrical Signal Generator

EVM	Error Vector Magnitude
FB	Feedback
FDD	Frequency Division Duplexing
FET	Field Effect Transistor
FF	Feed-forward
FIR	Finite Impulse Response
GA	Generic Adaptation
HF	High Frequency
I/Q	Inphase/Quadrature
IBO	Input Back-off Point
IF	Intermediate Frequency
IMD	Intermodulation Distortion
$LINC$	Linear Amplification with Nonlinear Component
LMS	Least Mean Square
LPF	Low Pass Filter
LTE	Long Term Evolution
$LUTPD$	Look-Up Table based Predistortion
$MEMR$	Memory Effects Modeling Ratio
$MPDPD$	Memory Polynomial Digital Predistortion
$NMSE$	Normalized Mean Square Error
$OFDM$	Orthogonal Frequency Division Multiplexing
$OFDMA$	Orthogonal Frequency Division Multiple Access
P_{diss}	Dissipated Power
P_{Max}	Maximum Power
$PINV$	Moore-Penrose pseudo inverse of matrix
PA	Power Amplifier

PAE	Power Added Efficiency
PM	Phase Modulation
$PAPR$	Peak to Average Power Ratio
PSD	Power Spectrum Density
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
$QPSK$	Quadrature Phase Shift Keying
R_{th}	Thermal Resistance
RAM	Random Access Memory
RF	Radio Frequency
$RMSE$	Root Mean Square Error
RLS	Recursive Least Square
RRF	Root-raised Cosine Filter
$SFDR$	Spurious-free Dynamic Range
T_{amb}	Ambient Temperature
TDD	Time Division Duplexing
$UMTS$	Universal Mobile Telephone System
VSA	Vector Signal Analyzer
$WCDMA$	Wideband Code Division Multiple Access
$WiMAX$	Worldwide Interoperability for Microwave Access
Z_{th}	Thermal Impedance

CHAPTER 1

INTRODUCTION

As engineers in the fields of signal processing and digital front-end wireless communication and circuit design, by demonstrating and using the theory and taking it into account,in order to achieve ideal design methodology with the systematic presentation of different algorithms and implementation.Design trade-offs and comparison between simulation and experimental parts will be investigated. LTE (Long Term Evolution) is the current element in the development chain of digital cellular communication systems with following key design targets such as: Significantly higher peak data rates than older standards (e.g. 100 Mbps in 20 MHz bandwidth Downlink and 50 Mbps in 20 MHz bandwidth Uplink), Scalable bandwidth for more spectrum flexibility for the interval from 1.25 MHz, 1.6, 2.5, 5, 10, 15, 20 MHz. Other benefits of using LTE-DL modulated signal like: MIMO (Multiple-Input Multiple-Output), Low latency (round trip delay $<$ 10 ms), Packet oriented data transmission (all IP network), High UE (User Equipment) mobility conditions: Up to 350 or even 500 km/h are convinced engineers to use them for the improvement of nonlinear high frequency power amplifiers with memory effects in the wireless communication systems.

1.1 Background

With the rapid demand for the worldwide deployment of wireless communication infrastructure and increasing the number of users of digital processing technology, the drawbacks and problems occur in the way of digital front-end in transmitters and receivers of wireless communication should be compensated. Nowadays, by increasing the number of the users beside limited radio frequency spectrum, new modulation techniques like wideband code division multiple access (WCDMA), orthogonal frequency division multiplexing (OFDM) and long term evolution (LTE) are used in order to overcome this limitation and get more efficient radio frequency spectrum.As a matter of fact, by increasing the numbers and demands of the users, logically more efficient bandwidth and frequency spectrum is required.So Some diversity techniques have been applied in third generation (3G) [1]. Currently, it still uses in LTE so far. As more detailed explanation, long term evolution (LTE) is a next generation mobile communication system, as a project of the 3rd Generation Partnership Project (3GPP) [2]. Both LTE and WiMAX support frequency division duplexing (FDD) and time division duplexing (TDD) modes, and have more deployment flexibility than previous 3G systems by using scalable channel bandwidths with different numbers of subcarriers, keeping frequency spacing between subcarriers constant. Orthogonal frequency division multiplexing (OFDM) with cyclic prefix (CP) is used in the downlink of LTE systems and both the uplink and the downlink of WiMAX systems rather than signal carrier modulation schemes in traditional cellular systems. These two standards have set specific requirements in the terms of the power spectrum density (PSD) of the signal for the control of in-band and out-of-band spectrum regrowth. As a result, it is very important to know the relationship between the spectrum regrowth and nonlinear parameters of the system power amplifier.

The OFDM modulation scheme is the superposition of a high number of modulated subchannel signals, base on multiple access technique, usually has some drawbacks like: high peak to average power ratio (PAPR) which causes more power consumption and also inefficiency of the system plus nonlinearity of power amplifier (PA) in transmitter which is not desired in the wireless communication. Therefore, in order to design a system to work with high efficiency and make it cost efficient, then prolong battery life by decreasing power consumption, overcome to the nonlinearity problems is essential. The main source of nonlinearity in communication systems is power amplifier, which this nonlinearity causes two types of distortions: out of band distortion that generates spectral regrowth and in-band distortion respectively. These drawbacks cause the adjacent channel interference (ACI) which effects on reduction in adjacent channel power ratio (ACPR) and increase in bit error rate (BER).Hence, to improve the effects of the nonlinearity and increase the efficiency of amplifier in wireless RF front-end communications system, Some linearization techniques should be applied.

1.2 Problem Statement

In the modern wireless broadband front-end communication systems, the modulated signals contain high peak to average power ratio which caused by big fluctuations as consequence of high spectral efficiency in the envelopes of such signals like: WCDMA, OFDM, WIMAX, LTE. As one of the solutions to avoid and reduce the PAPR, power amplifier needs to be back-off far from its saturation point and work in its linear domain, but this solution results in very low efficiency around less than 10% [3] and 90% of the DC power gets wasted and turns into heat. This means loss of amplifier's gain and shortens in battery life. Indeed, there is always a trade-off between the linearity and efficiency.This leads to one of the main issues related to choose suitable PA in various fundamental amplifier classes (A-F) in order to perceive the design challenge with respect and compromise to these two characteristics. High PAPR, affect the wireless systems to operate with high power-added efficiency (PAE), while the HF power amplifier is operated nearby the saturation point and then resulted in in-band and out-of-band distortions known as nonlinearities.
However, the amplifier is designed to have optimum results in terms of high efficiency and high output power in 1 dB compression point, besides considering the proper return loss and heat dissipation. As a matter of fact, high-efficient amplifier design is relied on burdening the PA characteristics into the band-pass region and also biasing the PA dynamically versus the input signal to attain high

peak powers.
As a result, these elements cause nonlinearity in power amplifier in terms of memory effects in which change the characteristics of the power amplifier, especially dynamic AM-AM (Amplitude Modulation to Amplitude Modulation) and AM-PM (Amplitude Modulation to Phase Modulation). Therefore, as the main contribution of this thesis, it is critical to apply some techniques in order to avoid out-of-band distortions which figure as spectral regrowth that cause increment in ACLR. These techniques can be applied with respect to high efficient operations aimed to compensate the dynamic distortions as memory effect of nonlinear power amplifiers.

1.3 Objectives of the Study

The objectives of this study are:

1. To simulate and analyze the memory polynomial digital predistortion technique for compensation of the nonlinearity in the high frequency power amplifiers

2. To test and evaluate the performance of the memory polynomial DPD, when applied to the commercial PA with a real-time 5 MHz LTE input signal.

1.4 Scope of the Thesis

The main solutions to overcome the problems caused by nonlinearity of the PAs, can be counted into two main aspects:
1: Power Amplifier Linearization, which enables the amplifier to be driven nearby the saturation point.
2: Signal Preconditioning, which deducts PAPR without significant signal distortion.

The digital predistortion technique is discussed to be used in this thesis as the aim of compensating the PA nonlinearities with memory effects.
Therefore, in theoretical part, the mathematical equations required for the memory polynomial DPD are explained in order to represent the adaptive predistortion technique, as the aim of compensating the dynamic distortions in terms of memory effects used in simulation part. Then, in the simulation part, it can be seen that the computational complexity of the system will be increased for the higher orders of the polynomial, due to the difficulties in extracting the coefficients in this case, while the bandwidth is constrained and number of iterations or the amount of memory length are increased. In the experimental setup, Agilent equipment are taken into account to make a simple test bench for generating the modern modulated LTE downlink 5 MHz signal as the input and export the characteristics information of the ZVE-8G+ power amplifier as a real PA with memory in the arbitrary I/Q waveform format, for the simulation part in MATLAB software.

At the end, final results of the simulations are discussed with PSD, ACLR, EVM metrics. Also, the effects of the increasing amplitude and decreasing voltage of the back-off point (IBO) are studied. DPD performance for different PAs with different amount of the memory based on the parameter which is named Memory Effects Modeling Ratio (MEMR), is investigated.

1.5 Thesis Organisation

This thesis contains relevant information about amplifier linearization, from the fundamentals to the simulation of the memory polynomial digital predistortion. Hence, this thesis is structured by:
In chapter 1, problem statement and scope and aims and objectives of the this are explained briefly.
In chapter 2, a good literature is presented to cover the topics of power amplifier characterization setup and effects of PA behavioral nonlinearity and then, the power amplifier memory effects and power amplifier modeling, are described in detailed. At the end of this chapter, different PA linearization techniques are investigated to answer that why DPD algorithm is required to be taken into account for PA nonlinearites.
In chapter 3, the proposed memory polynomial DPD is illustrated along the mathematical equations used to apply in Matlab code. Then, the Agilent signal generator and analyzer are introduced.
In chapter 4, the proposed method is analyzed with different metrics by using Matalb software for different input signals such as OFDM, LTE with different bandwidths which are generated by Agilent equipment in the real time.
In chapter 5, conclusion is resulted from the whole content of the PA nonlinearity which is discussed in this thesis and finally, the suggestion for the future works is mentioned.

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