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ENHANCED MEMORY POLYNOMIAL WITH REDUCED COMPLEXITY IN DIGITAL PRE-DISTORTION FOR WIRELESS POWER AMPLIFIER

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ENHANCED MEMORY POLYNOMIAL WITH REDUCED COMPLEXITY IN DIGITAL PRE-DISTORTION FOR WIRELESS POWER AMPLIFIER

By

CHOO HONG NING

Thesis Submitted to the School of Graduate Studies,
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For the betterment of humanity

Abstract of thesis presented to the Senate of Universiti Putra Malaysia
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ENHANCED MEMORY POLYNOMIAL WITH REDUCED COMPLEXITY IN DIGITAL PRE-DISTORTION FOR WIRELESS POWER AMPLIFIER

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Power Amplifier (PA) is one of the prominent devices in a communications system. Ideally, the PA linearly amplifies signals, but exhibits non-linearity when operates in the actual world, where PA output power deviates away from the ideal linear region. The non-linearity of the PA has result in various undesired effects include amplitude and phase distortion which contributes to Adjacent Channel Interference (ACI) that degrades the signal quality at the receiver side. Inevitable increasing bandwidth and transmission speed causes memory effects in the PA. Memory effects causes scattering of the PA output signal and increases overhead processing requirements at the receiver side to decode/rectify deteriorated signal quality. PA linearization is therefore required to neutralize the non-linearity effects on the system. Among various linearization methods, Digital Pre-distortion (DPD) stands out due to its balanced advantages and trade-offs in terms of implementation simplicity, supported bandwidth, efficiency, flexibility and cost. DPD models the PA, pre-distorts the input signal with an inversed function of the PA, and further feeds the pre-distorted input signal into the PA. The Memory Polynomial method (MP) by (Ding, 2004), a simplified derivative of the Volterra Series is capable of modeling the PA with Memory Effects with reduced complexity. This project presents the MP with Binomial Reduction method (MPB) which is an optimized MP with reduced addition and multiplication operations. Referring to Computational Complexity Reduction Ratio (CCRR) by (Hou, 2011), Multiplication Operations Reduction Ratio (MORR) and Addition Operations Reduction Ratio (AORR) are derived to showcase the reduction percentage of addition/multiplication operations in MPB against the method to be compared. Comparing to MP, MPB is capable of achieving similar Adjacent Channel Power Reduction (ACPR) Ratio performance, amplitude and phase distortion reduction, memory effects elimination, improvements in Normalized Mean Square Error (NMSE) of 36.5dB, 86.43% AORR and 50% MORR. MPB is also compared with one of the recent derivatives of MP, the Augmented Complexity Reduced General MP (ACR-GMP) by (Liu, 2014) with 56.76% MORR, 84.38% AORR and 92.36dB of NMSE improvement. The method is simulated in *MATLAB* by *Mathworks* using a modeled ZVE-8G PA and fed with sampled 4G (LTE) signals.

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PENAMBAH-BAIKAN MEMORI POLINOMIAL DENGAN PENGURANGAN KOMPLEKSITI DALAM PRA-DISTORSI DIGITAL UNTUK KOMUNIKASI TANPA-WAYAR

Oleh

CHOO HONG NING

Februari 2017

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Amplifier Kuasa atau *Power Amplifier* (PA) merupakan salah satu peranti utama dalam sistem komunikasi. Dalam situasi ideal, PA memperbesarkan signal secara linear, tetapi gagal mengekalkan lineariti apabila beroperasi dalam dunia sebenar, di mana kuasa output PA melencong dari rantau linear yang ideal. Ketidak-linearan PA telah menyebabkan pelbagai kesan yang tidak diingini, seperti distorsi amplitud dan distorsi fasa, yang menyumbang kepada Gangguan Saluran Bersebelahan, atau *Adjacent Channel Intereference* (ACI), menyebabkan pemburukan kualiti signal di bahagian penerima. Jalur lebar atau *bandwidth* yang semakin meningkat dengan kelajuan penghantaran signal yang semakin bertambah tinggi menyumbang kepada Kesan Memori, atau *Memory Effects* dalam PA. Kesan Memori menyebabkan penyerakan signal di bahagian output PA, seterusnya meningkatkan keperluan pemprosessan di bahagian penerima bagi dekod/memperbetulkan kualiti signal yang sudah menurun. Oleh yang demikian, pelinearan PA amat diperlukan bagi meneutralkan kesan ketidak-linearan ke atas sistem. Antara pelbagai kaedah pelinearan, Pra-distorsi Digital atau *Digital Pre-distortion (*DPD) telah berjaya menarik perhatian atas kelebihan-kelebihan seperti kemudahan implimentasi, jalur lebar yang disokong, kecekapan, fleksibiliti, dan kos. DPD memodelkan PA, memproseskan signal di input menggunakan fungsi PA yang songsang, dan seterusnya menyalurkan signal yang telah diproses ke dalam PA. Kaedah Memori Polinomial (MP), merupakan terbitan Siri Volterra yang telah dipermudahkan yang mampu mengambil kira Kesan Memori PA dengan kerumitan yang dikurangkan. Projek ini membentangkan Kaedah Memori Polinomial dengan Pengurangan Binomial (MPB) yang merupakan MP yang dioptimumkan melalui pengurangan operasi tambahan dan pendaraban. Dengan merujuk kepada Nisbah Pengurangan Kompleksiti Pengiraan, atau *Computational Complexity Reduction Ratio* (CCRR) daripada (Hou, 2011), Nisbah Pengurangan Operasi Pendaraban, atau *Multiplication Operations Reduction Ratio* (MORR) dan Nisbah Pengurangan Operasi Tambahan, atau *Addition Operations Reduction Ratio* (AORR) telah diperolehi bagi menunjukkan peratus pengurangan operasi tambahan/pendaraban MPB dengan kaedah yang dibandingkan

Berbanding dengan MP, MPB mampu mencapai prestasi yang hampir sama bagi Nisbah Pengurangan Kuasa Rangkaian Bersebelahan atau *Adjacent Channel Power Reduction* (ACPR), pengurangan distorsi amplitud/fasa, penghapusan Kesan Memori, dan juga penambah-baikan dalam Penormalan Min Ralat Persegi atau *Normalized Mean Square Error* (NMSE) sebanyak 36.5dB, 86.43% AORR, dan 50% MORR. MPB juga dibandingkan dengan salah satu derivatif MP yang terkini, Augmentasi Memori Polinomial Umum dengan Pengurangan Kompleksiti, atau *Augmented Complexity Reduced General MP* (ACR-GMP) daripada (Liu, 2014). Pengurangan sebanyak 56.76% dalam operasi pendaraban, 84.38% dalam pengurangan penggunaan operasi tambahan, dan 92.36dB penamabah-baikan NMSE telah dicapai. Kaedah ini disimulasi dalam *MATLAB* daripada *Mathworks*, menggunakan PA *ZVE-8G* yang dimodelkan dan disalurkan dengan signal 4G (LTE) disampel.

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I certify that a Thesis Examination Committee has met on 20 February 2017 to conduct the final examination of Choo Hong Ning on his thesis entitled "Enhanced Memory Polynomial with Reduced Complexity in Digital Pre-Distortion for Wireless Power Amplifier" 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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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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Name of Member of Supervisory Committee:	Dr. Pooria Varahram		

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LIST OF ABBREVIATIONS

3G	3rd-Generation Mobile Communication Networks
4G	4th-Generation Mobile Communication Networks
ACI	Adjacent Channel Interference
ACPR	Adjacent Channel Power Ratio
ACLR	Adjacent Channel Leakage Ratio
ADC	Analog to Digital Converter
AM / AM	Output Amplitude against Input Amplitude
AM / PM	Output and Input Phase Difference against Input Amplitude
AORR	Addition Operations Reduction Ratio
CCRR	Computational Complexity Reduction Ratio
DAC	Digital to Analog Converter
DPD	Digital Pre-distortion
EVM	Error Vector Magnitude
FPGA	Field Programmable Gate Array
LINC	Linear amplification with Nonlinear Components
LTE	Long-term Evolution
LUT	Look-up Table
MORR	Multiplications Operations Reduction Ratio

OFDM	Orthogonal Frequency Division Multiplexing
PA	Power Amplifier
PAE	Power Added Efficiency
PAG	Pre-Amplifier Gain
PAPR	Peak to Average Power Ratios

CHAPTER 1

INTRODUCTION

1.1 Background

The Power Amplifier (PA) is one of the most significant electrical components in a transmitter of a communications system. Ideally, the output power of the PA behaves linearly when its input power increases. However, the PA exhibits non-linearity, when operated in real-world scenarios. When the input power of the PA is increased to a certain limit which is unique to each class of PA, the output power measured will lost its linearity with reference to the PA input power. The PA output power slowly converges to the maximum power, despite the increase in PA input power. The PA has now entered into its saturation region, where several undesired outcomes are observed due to the non-linearity of the PA.

The non-linearity of the PA has triggered several issues that concerns researchers and communication engineers. First, the decrease in power efficiency of the PA is obvious, as the PA output no longer increases linearly with the PA input power. Consequently, more power is needed to drive the PA to produce the signal at the desired output power level. This PA inefficiency increases operating cost for communication service providers, which in turn adds cost to the users. Besides inefficiency, the PA non-linearity also leads to Adjacent Channel Interference (ACI), which causes the signal to suffer high possibility of corruption in intelligence, where the unwanted rise of energy at the sidebands of the signal interferes with the neighboring signals during transmission. ACI heavily jeopardizes the quality of communication and introduces extra cost to the system for interference elimination. Maintaining the linearity of the PA is therefore plausible to retain the efficiency which results in cost saving, higher profit margin, and further leads to a more competitive industry that benefits the end users.

Linearizing the PA has always been a tradeoff between the linearization performance, with factors such as ease of implementation, gate counts, memory requirement, complexity of the algorithm, and bandwidth supported. The Digital Pre-distortion (DPD) method stands out from the rest of the linearization methods due to its balanced overall strengths and weaknesses. DPD generally involves pre-processing the input signal at the baseband before passing the signal to the PA. The DPD block functions as an inverse of the PA's model in terms of non-linearity, where the convergence happens at the input power instead. The multiplications of the two systems are expected to result in a final PA output that has improvement in linearity compared to the un-predistorted PA. The next challenge that is worth exploring shall be the DPD method that is suitable to be used, with considerations in communication technology requirement and the effects onto the PA due to high frequency modulations.

In comparison with operating in lower frequencies, the PA possesses more challenges to be solved when it operates in higher frequency applications. Due to rapid changes in signal during high frequency transmission, the components of the PA experiences fluctuations in heat and electrical features. These factors observed from 3rd Generation/ 4th Generation Network's (3G/4G) high frequency transmission, contributes to the formation of the Memory Effects. PA exhibits Memory Effects when the output power no longer stays within the expected region, but shows frequent glitches at the output. When graphed in terms of output power vs. input power, the PA output signal scatters across the expected operating region, introduces extra challenge to the PA linearization due the additional unpredictability of the system. The direct solution to counter the Memory Effects will be the backing-off the PA to operate only in its non-saturating region, a.k.a. linear region to avoid the peaks in signals. This results in a limitation to PA performance because operating only in the linear region is inefficient. To proper linearize the PA that operates at higher frequencies, the DPD method needs more considerations and accuracy in modeling, which results in a more complex system, if compared to the PA at lower frequency applications that is memoryless.

In conjunction with today's direction in communication technology advancement, this project focuses on the DPD implementation in 3G/4G where high frequency transmission is inevitable. The pre-distortion algorithm of the DPD block will need to take into considerations in handling Memory Effects, therefore resulting in a relatively advance formula compared to the memoryless DPD implementation. Modeling the PA is evidently a challenging but important task, because the DPD relies heavily on the PA model where it is used to obtain the inversed model. Derived from the Taylor Series, the Volterra series have been traditionally used to model non-linear systems. Moving forward, the Memory Polynomial (MP) PA modeling is widely used in today's pre-distortion academia research, due to its reduced complexity compared with the Volterra Series. MP PA modeling is capable of achieving acceptable difference in measured and calculated PA performance, with significantly lesser PA coefficients that defines the order of non-linearity and Memory Effects. The MP pre-distortion algorithm which is similar to the MP PA modeling, has been widely implemented and tested in 3G/4G applications, with noticeable contributions towards a better algorithm with lesser coefficients, simpler implementation, and better performance.

1.2 Problem Statement

MP is one of the most commonly used DPD methods in PA linearization, especially for latest systems with high transmission rate which results in Memory Effects. However, when compared to memoryless linearizing methods, the MP method possesses several drawbacks such as increased complexity in design implementation, and also a higher number of operations required. The increase in resources results in extra cost for the communication industry as technologies move into higher data transmission speed to support more users. Therefore, it is evidently beneficial for an improved system in terms of operation resources, while capable of achieving comparable linearization performances with the MP method.

1.3 Objective

The objective is to develop a DPD algorithm where:

a) The predistorted PA output signal has similar linearization performance compared with MP in terms of amplitude and phase distortion reduction, indicated via the AM/AM, AM/PM and Adjacent Channel Power Ratio (ACPR) graphs.

b) The predistorted PA output signal has lesser error deviation against the ideal PA output, indicated via the Normalized Mean Square Error (NMSE) performance metric, as compared with the MP and one of the recent method derivations of MP, the Augmented Complexity Reduced Generalized MP (ACR-GMP) by (Liu, 2014).

c) The improved DPD algorithm has improvement in operational resource optimization by having reductions in number of multiplication and addition operations used, when compared with MP and one of the recent method derivations of MP, the ACR-GMP. The operations comparison is to be done using the Multiplication Operations Reduction Ratio (MORR) and Addition Operations Reduction Ratio (AORR), derived from Computational Complexity Reduction Ratio (CCRR) by (Hou, 2011).

1.4 Related Work

The linearization of PA has been carried out by various researchers, using different methods. DPD has a leading advantage against the other linearization methods, with a balanced trade-offs between metrics such as efficiency, cost, flexibility, and bandwidth. In ensuring the maximum performance of the DPD, modelling of the PA plays a significant role, as the DPD acts as an inversed of the PA function. Volterra series is used to model the non-linearity of the PA, but with disadvantages in high number of coefficients, which results in high complexity. In order to improve the Volterra Series modelling, several derivatives of simpler approach are developed. The Wiener Model, the Hammerstein Model, and the Hybrid Wiener-Hammerstein Model are examples of simpler representations of the Volterra Series, with different arrangements of Linear Time Invariant (LTI) block and Non-linearity Block. The MP, which utilizes only the diagonal kernels of the Volterra Series is one of the most successfully reduced version of the infamous series (Ghannouchi, 2009; Gotthans, 2013). MP is capable in achieving huge reductions in number of coefficients which results in reduced complexity. This method is then heavily used by researchers in DPD implementation across modern telecommunication systems. Although capable of compensating signal distortion caused by Memory Effects present in high speed transmissions in 3G/4G technology, MP is still relatively having a higher complexity compared to memory-less DPD methods. Numerous efforts have been conducted to simplify MP. It could be

categorized to 4 directions: Augmentation, Branch Pruning, Basis Function Extension, and Basis Function Reduction

1.5 Research Scope

Figure 1.1 shows the research scope of this thesis project.

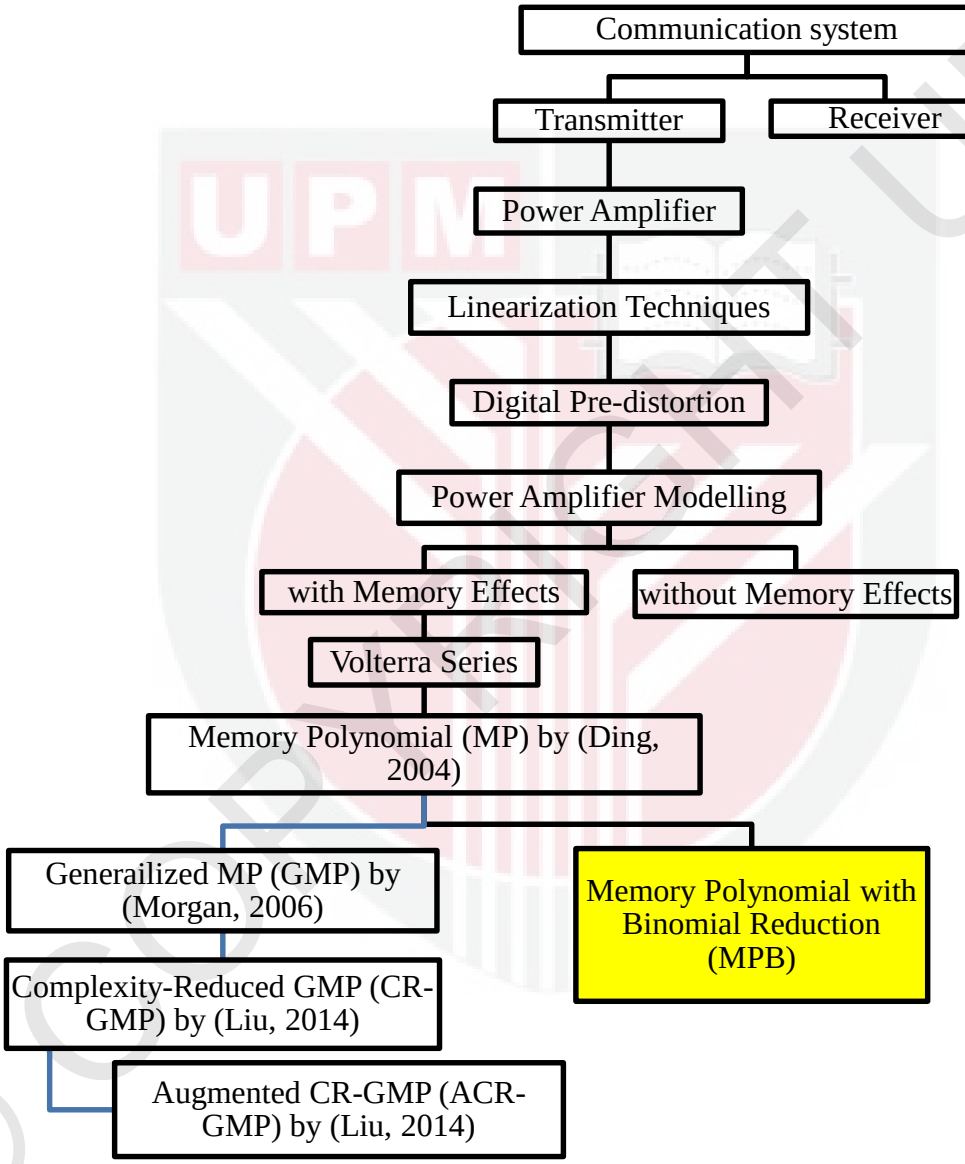

Figure 1.1: Research Scope Structure

The research is performed at the transmitter side of a communication systems, with focus on one of the most vital components in the system, the PA. Various linearization methods are used to compensate signal distortion due to the non-linearity of the PA, where DPD has championed among linearization methods. DPD is an inversed function of the PA, which makes modeling the PA the next challenge, with consideration of Memory Effects that exists in today's high bandwidth transmission technology. Volterra Series is capable of modeling the PA together with Memory Effects, but has high complexity due to the exponentially increased coefficients. The MP model is an simplified Volterra Series, which is widely used by researchers in the field. MP is further optimized in this thesis project, by binomially reduce the basis function of the respective model, resulting in the MP with Binomial Reduction (MPB) model.

To justify the strength of MPB, the model is simulated in *MATLAB* by *Mathworks* with a modeled ZVE-8G PA and fed with sampled 4G (LTE) signals. The output signals are then compared with a simulated MP model in terms of NMSE to check for improvement in error deviation from the ideal output. Besides that, MPB is also compared with MP using the derived MORR and AORR from CCRR (Hou, 2011) to check for percentage of reductions in multiplication/addition operations usage. Furthermore, ACPR, AM/AM and AM/PM is also used to verify the ability of MPB against MP to cope with amplitude/phase distortion and Memory Effects.

MPB is also compared with a simulated recent derivative of MP, the ACR-GMP by (Liu, 2014) in terms of NMSE, AORR and MORR.

1.6 Thesis Contribution

The project presents a novel Binomially Reduced Optimized MP Method. The optimization in resources is capable of contributing towards a more energy efficient system, which is beneficial to energy conservation. A more efficient system results in lower cost, which is also a key triggering point for better revenues. A cost effective solution, results in a cheaper solution for the users, which is a win-win situation that is healthy for the industry as a whole.

The discussion of materials related to DPD in PA Linearization, serves as a reference point for prospective researchers to commence work in the respective field. The novel classification of MP improvement directions, paves the road for future improvements by researchers.

1.7 Thesis Organization

The thesis is comprised of 5 chapters.

The first chapter, **Introduction,** gives an overview of the whole project. The chapter starts with the background description, problem statement, objective, related works, research scope and contribution, thesis contribution, and thesis organization.

The second chapter, **Literature Review,** presents the readings involved to support the project research effort. Compiled research findings include PA, PA linearization, DPD, DPD Learning Architecture, MP, and Improvement Directions of MP.

The third chapter, **Methodology**, shows the binomial reduction process in simplifying the MP Method. The simulation components are presented, together with the performance comparison metrics. The system architecture is presented as well, together with explanations and derivation steps of the related performance comparison metrics.

Chapter four, **Results and Discussion**, displays prove of workability of the developed MPB method. The optimization results are shown, with the respective performance comparison metrics of NMSE, MORR, AORR ACPR, AM/AM and AM/PM by having MP as a reference point. MPB is also compared with ACR-GMP in terms of NMSE improvement, MORR and AORR.

The last chapter, chapter five, **Conclusion**, concludes the MPB method on its significance in resource optimization with improvements in linearization performance when compared to MP and ACR-GMP.

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