UNIVERSITI PUTRA MALAYSIA

# *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**

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**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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For the betterment of humanity

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**February 2017**

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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.

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

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

Oleh

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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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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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# LIST OF ABBREVIATIONS

| | |
|---|---|
| 3G | $3^{rd}$-Generation Mobile Communication Networks |
| 4G | $4^{th}$-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.

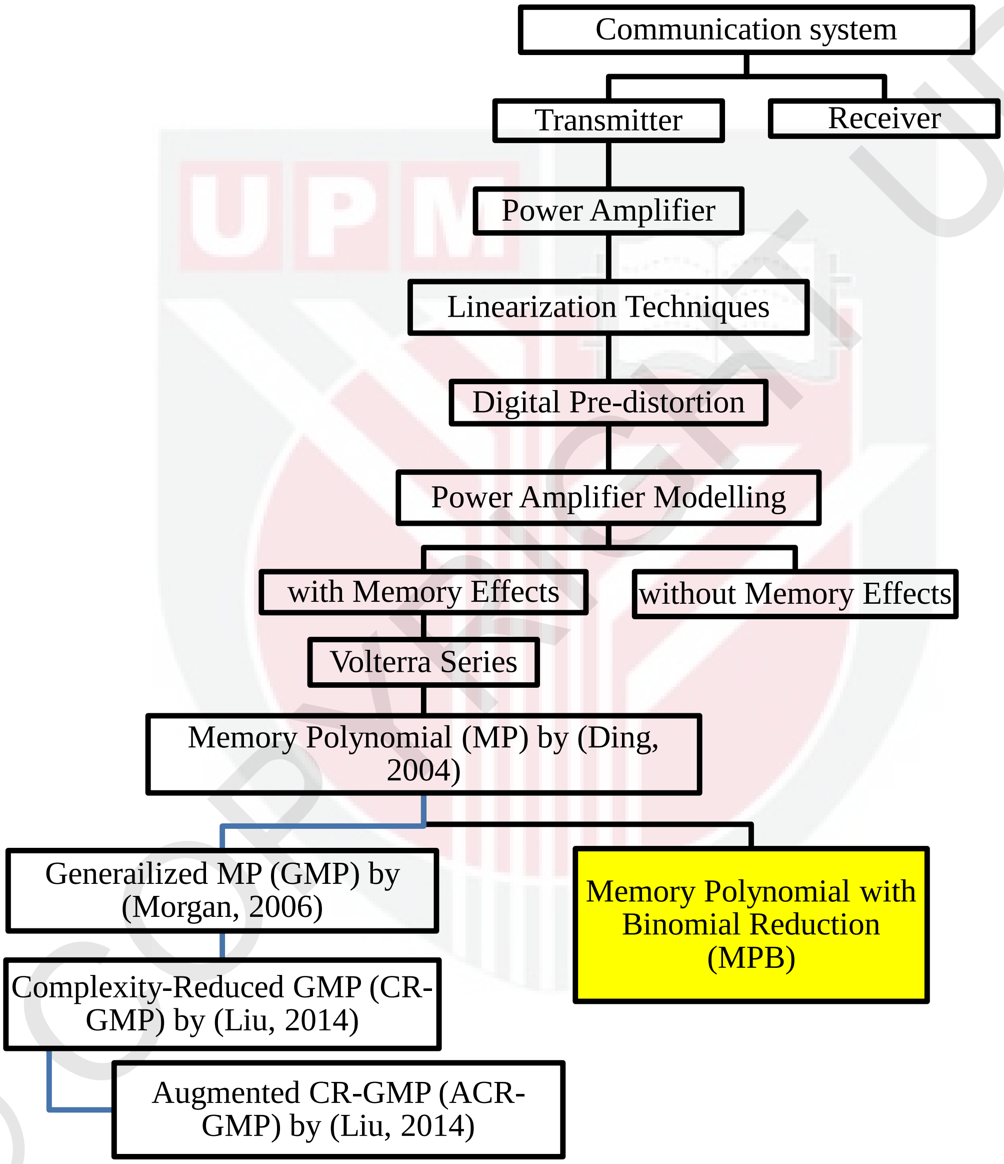


Figure 1.1: Research Scope Structure

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.

# REFERENCES


Braithwaite, R.N., "Wide bandwidth adaptive digital predistortion of power amplifiers using reduced order memory correction", Microwave Symposium Digest, 2008 IEEE MTT-S International, pp. 1517 - 1520, 2008.

Braithwaite, R.N. "Closed-Loop Digital Predistortion (DPD) Using an Observation Path With Limited Bandwidth", Microwave Theory and Techniques, IEEE Transactions on, pp. 726 - 736 Volume: 63, Issue: 2, Feb. 2015.

Cao, G., Xu, T., Liu, T., Ye, Y., Lin, H., Luo, X. and Li L., "Memory polynomial based adaptive predistortion for Radio over Fiber systems", Microwave and Millimeter Wave Technology (ICMMT), 2012 International Conference on, pp. 1 - 4, Volume: 2, 5-8 May 2012.

Chang, S. and Powers, E. J., “A simplified predistorter for compensation of nonlinear distortion in OFDM systems,” in Proc. IEEE Global Telecommun. Conf., vol. 5, pp. 3080–3084, Nov. 2001.

Chen, H-B., Jin, L., Deng, Z-R. and Shen, D., "Simplified parameter-extraction process for digital predistortion based on the indirect learning architecture", Electronics, Communications and Control (ICECC), 2011 International Conference on, pp. 1665 - 1668, 2011.

Chen, H., Li, J., Xu, K., Pei, Y., Dai, Y., Yin, F. and Lin, J., "Experimental study on multi-dimensional digital predistortion for multi-band externally-modulated radio-over-fiber systems", Microwave Symposium (IMS), 2014 IEEE MTT-S International, pp. 1 - 4, 2014

Chen, W. H., Zhang, S. L., Liu, Y. J., Ghannouchi, F.M., Feng, Z. H., and Liu, Y. A., "Efficient Pruning Technique of Memory Polynomial Models Suitable for PA Behavioral Modeling and Digital Predistortion," *Microwave Theory and Techniques, IEEE Transactions on*, On page(s): 2290 - 2299 Volume: 62, Issue: 10, Oct. 2014.

Choi, S., Jeong, E-R. and Lee, Y.H., "A Direct Learning Structure for Adaptive Polynomial-Based Predistortion for Power Amplifier Linearization", Vehicular Technology Conference, 2007. VTC2007-Spring. IEEE 65th, pp. 1791 - 1795, 2007.

Choi, S.,Jeong, E-R. and Lee, Y. H., "Adaptive Predistortion With Direct Learning Based on Piecewise Linear Approximation of Amplifier Nonlinearity", Selected

Topics in Signal Processing, IEEE Journal of, pp. 397 - 404 Volume: 3, Issue: 3, June 2009.

Cripps, S. C., *Advanced Techniques in RF Power Amplifier Design*. Artech House, 2002.

Cripps, Steve. *RF power amplifiers for wireless communications*. Artech House, 2006.

Ding, L., Zhou, G. T., Morgan, D. R., Ma, Z. X., Kenney, J. S., Kim, J., and Giardina, C. R., "A robust digital baseband predistorter constructed using memory polynomials," *IEEE Transactions on Communications*, vol. 52, pp.159–165, Jan. 2004.

Ding, L., "Digital predistortion of power amplifiers for wireless applications," PhD diss., *Georgia Institute of Technology*, 2004.

Ding, L. and Zhou, G.T., "Effects of even-order nonlinear terms on power amplifier modeling and predistortion linearization", Vehicular Technology, IEEE Transactions on, pp. 156 - 162 Volume: 53, Issue: 1, Jan. 2004.

Eun, C. and Powers, E. J., "A predistorter design for a memory-less nonlinearity preceded by a dynamic linear system," in Proc. IEEE Global Telecommun. Conf., vol. 1, pp. 152–156, Nov. 1995.

Frenzel, L., "What's The Difference Between The Third-Order Intercept And The 1-dB Compression Points?" Electronic Design, http://electronicdesign.com/what-s-difference-between/what-s-difference-between-third-order-intercept-and-1-db-compression-point, 2013

Ghannouchi, F. M., and Hammi, O., "Behavioral modeling and predistortion," *IEEE Microwave Mag*., vol. 10, no. 7, pp. 52–64, Dec. 2009.

Gotthans, T., Baudoin, G., and Mbaye, A., "Comparison of modeling techniques for power amplifiers", *Radioelektronika (RADIOELEKTRONIKA), 2013 23rd International Conference,* pp. 232 – 235, 2013.

Gotthans, T., Baudoin, G., and Mbaye, A., "Optimal order estimation for modeling and predistortion of power amplifiers", Microwaves, Communications, Antennas and Electronics Systems (COMCAS), 2013 IEEE International Conference on, pp. 1 – 4, 2013.

Graboski, J. and Davis, R. C., “An experimental M-QAM modem using amplifier linearization and baseband equalization techniques,” in Proc. IEEE Nat. Telecommun. Conf., pp. E3.2.1–E3.2.6, Nov. 1982.

Hekkala, A., Lasanen, M., Vieira, L.C., Gomes, N.J. and Nkansah, A., "Architectures for Joint Compensation of RoF and PA with Nonideal Feedback", Vehicular Technology Conference (VTC 2010-Spring), 2010 IEEE 71st, pp. 1 - 5, 2010.

Hekkala, A., Hiivala, M., Lasanen, M., Perttu, J., Vieira, L.C., Gomes, N.J. and Nkansah, A., "Predistortion of Radio Over Fiber Links: Algorithms, Implementation, and Measurements", Circuits and Systems I: Regular Papers, IEEE Transactions on, pp. 664 - 672 Volume: 59, Issue: 3, March 2012.

Hou, J., Ge, J., Li, J., "Peak-to-Average Power Ratio Reduction of OFDM Signals Using PTS Scheme With Low Computational Complexity," IEEE Transactions on Broadcasting, Volume.57, Issue.1, pp.143, 2011, ISSN: 00189316, 2011.

Jantunen, P., "Modelling of nonlinear power amplifiers for wireless communications." Master Thesis. *http://www. researchgate.net/publication/224263342_Nonlinear_RF_power_amplifier_behavioural_analysis_of _wireless_OFDM_systems* , 2004.

Karam, G. and Sari, H., “A data predistortion technique with memory for QAM radio systems,” IEEE Trans. Commun., vol. 39, pp. 336–344, Feb. 1991.

Karam, G. and Sari, H., “Data predistortion techniques using intersymbol interpolation,” IEEE Trans. Commun., vol. 38, pp. 1716–1723, Oct. 1990.

Liu, Y. J., Zhou, J., Chen, W., et al., “A robust augmented complexity reduced generalized memory polynomial for wideband RF power amplifiers,” IEEE Trans. Ind. Electron., vol. 61, no. 5, pp. 2389-2401, May. 2014.

MATLAB, http://www.mathworks.com/products/matlab/, 2015

McKinley, M. D., Remley, K. A., Mylinski, M., Kenney, J. S., Schreurs, D., and Nauwelaers, B., “EVM Calculation for Broadband Modulated Signals,” Technical Report, Work of United States Government, 2005.

Mini-Circuits, ZVE-8G specifications sheet, www.minicircuits.com/pdfs/ZVE-8G.pdf, 2011.

Morgan, D. R., Ma, Z., Kim, J., Zierdt, M. G., and Pastalan, J., "A generalized memory polynomial model for digital predistortion of RF power amplifiers", *IEEE Trans. Signal Process.*, vol. 54, no. 10, pp.3852 -3860 2006.

Ni, Y., Zhou, J., Zhang, L., Zhou, F. and Zhai, J., "A 6.15GHz balanced linear power amplifier with digital predistortion linearization", Microwave and Millimeter Wave Technology (ICMMT), 2012 International Conference on, pp. 1 - 4, Volume: 1, 5-8 May 2012.

Ni, C., Jiang, T., Meng, D. and Huang B.,"Weighted distortion-to-signal ratio based PTS scheme in nonlinear distorted OFDM systems", Communications in China (ICCC), 2014 IEEE/CIC International Conference on, pp. 349 - 353, 2014

Parta, H., Ercegovac, M. D., and Pamarti, S., "RF digital predistorter implementation using polynomial optimization," *Circuits and Systems (MWSCAS), 2014 IEEE 57th International Midwest Symposium on,* pp. 981 – 984, 2014.

Pham, D.-K.G., Gagnon, G., Gagnon, F., Desgreys, P. and Loumeau, P., "A subsampled adaptive subband digital predistortion algorithm", New Circuits and Systems Conference (NEWCAS), 2014 IEEE 12th International, pp. 25 - 28, 2014.

Pinal P. L. G., “Multi Look-Up Table Digital Predistortion for RF Power Amplifier Linearization”, Department of Signal Theory and Communications, Universitat Politecnica de Catalunya, Barcelona, December 2007.

Qian H., Huang, H. and Yao S.,"A General Adaptive Digital Predistortion Architecture for Stand-Alone RF Power Amplifiers", Broadcasting, IEEE Transactions on, pp. 528 - 538 Volume: 59, Issue: 3, Sept. 2013.

Quaglia, R., Camarchia, V., Pirola, M., Moreno Rubio, J.J. and Ghione, G., "Linear GaN MMIC Combined Power Amplifiers for 7-GHz Microwave Backhaul", Microwave Theory and Techniques, IEEE Transactions on, pp. 2700 - 2710 Volume: 62, Issue: 11, Nov. 2014.

Quaglia, R., Tao J. and Camarchia, V., "Frequency extension of system level characterization and predistortion setup for on-wafer microwave power amplifiers", European Microwave Integrated Circuit Conference (EuMIC), pp. 488 - 491, 2014.

Raich, R. and Zhou, G. T., “On the modeling of memory nonlinear effects of power amplifiers for communication applications,” *IEEE Digital Signal Processing Workshop Proc.*, Oct. 2002.

Raich, R., Qian, H., and Zhou, G., “Orthogonal polynomials for power amplifier modeling and predistorter design,” *IEEE Trans. Veh. Technol.*, vol. 53, no. 5, pp. 1468 – 1479, 2004.

Saleh, A. A. M. and Salz, J., “Adaptive linearization of power amplifiers in digital radio systems,” Bell Syst. Technical J., vol. 62, pp. 1019–1033, Apr. 1983.

Shang, H., Li, Z., Bao, Y. and Gui, T., "Compensation for nonlinear distortion of optical OFDM signals induced by electro-absorption modulated lasers with digital predistortion", Optical Communications and Networks (ICOCN), 2012 11th International Conference on, pp. 1 - 4, 2012.

Suryasarman, P. and Springer, A., "Adaptive digital pre-distortion for multiple antenna transmitters", Global Conference on Signal and Information Processing (GlobalSIP), 2013 IEEE, pp. 1146 - 1149, 2013.

Tafuri, F. F., Guaragnella, C., Fiore, M., and Larsen, T., "Linearization of RF power amplifiers using an enhanced memory polynomial predistorter," NORCHIP, pp.1 – 4, 2012.

Tehrani A. S., Cao H., Afsardoost S., Eriksson T., Isaksson M., and Fager C., “A comparative analysis of the complexity/accuracy tradeoff in power amplifier behavioral models,” *IEEE Trans. Microw. Theory Tech*., vol. 58, no. 6, pp. 1510–1520, Jun. 2010.

Vieira, L.C., Gomes, N.J., Nkansah, A. and van Dijk, F., "Study of complex-envelope behavioral models for radio-over-fiber link nonlinearities", Global Communications Conference (GLOBECOM), 2012 IEEE, pp. 3098 - 3103, 2012.

Vieira, L.C. and Gomes, N.J., "Baseband behavioral modeling of OFDM-Radio over fiber link distortion", Microwave Photonics (MWP), 2012 International Topical Meeting on, pp. 188 - 191, 2012.

Wood, J., Lefevre, M. and Runton, D. ,"Application of an Envelope-Domain Time-Series Model of an RF Power Amplifier to the Development of a Digital Pre-Distorter System", Microwave Symposium Digest, 2006. IEEE MTT-S International, pp. 856 - 859, 2006.

Yu, X.,"Digital predistortion using feedback signal with incomplete spectral information", Microwave Conference Proceedings (APMC), 2012 Asia-Pacific, pp. 950 - 952, 2012.

Yu, X., and Jiang, H., "Digital Predistortion Using Adaptive Basis Functions", *Circuits and Systems I: Regular Papers, IEEE Transactions on*, pp. 3317 - 3327 Volume: 60, Issue: 12, Dec. 2013.

Yu, C. and Zhu A.,"Single feedback loop-based digital predistortion for linearizing concurrent multi-band transmitters", Microwave Symposium (IMS), 2014 IEEE MTT-S International, pp. 1 - 3, 2014.

Xilinx, Xilinx Digital Pre-Distortion (DPD) Reference Design, Digital Pre-Distortion, 2009.

Zhang, S.,Su, G., Chen, Z. and Chen W.,"Extraction of wideband behavioral model of power amplifier with multi groups of narrow band signals", Wireless Symposium (IWS), 2014 IEEE International, pp. 1 - 4, 2014.