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MASTER'S THESIS

BEHAVIORAL MODELING TECHNIQUES FOR POWER AMPLIFIER DIGITAL PRE-DISTORTION

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ABSTRACT

The dramatic increase in the capacity of telecommunication networks has increased the requirements of the devices, one example of which is the continuously widening bandwidth. Using broadband signals requires often high linearity from the transmitter – and especially from the power amplifier at the end of the transmitter chain – but at the same time, it should operate as efficiently as possible. The power amplifier is the most power consuming component in the transmitter and inherently nonlinear, so its linearization is an essential part of the overall system performance. Of the current linearization techniques, digital pre-distortion has established itself as the most common tool for providing better linearity and efficiency in a power amplifier and transmitter.

In this thesis, the performance of power amplifier models used in digital pre-distortion was investigated and their differences compared to the more complex reference model used in the actual base station product. The aim of this thesis was to create a behavioral model that corresponds the physical component as accurately as the reference model. This behavioral model could be used for example to design and optimize a power amplifier and linearization algorithm without the need for the secret model for the product. This, in its turn, would result in more efficient work with third parties such as component vendors and reduce the linearization time.

The performance parameters of the behavioral models were introduced at the beginning of the thesis. These were also used in later parts to analyse the measurement results. Power amplifier linearization measurements were performed under laboratory conditions on a MATLAB® test bench. From the results, it was found that the use of a simple memoryless behavioral model is not enough to describe the physical nonlinear component with sufficient accuracy. The results also showed that the complexity of the model reduces its accuracy if the model coefficients are not correctly positioned. In this thesis, we succeeded in creating a memory model that describes the reference model sufficiently accurately on several meters, taking into account also the memory effects of the power amplifier. This thesis thus provides a good basis for further development of the actual modeling tool for product projects.

Keywords: power amplifier, modeling, linearization, digital predistortion, memory effect

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TIIVISTELMÄ

Tietoliikenneverkkojen kapasiteetin räjähdysmäinen kasvu on lisännyt laitteiden vaatimuksia, joista yhtenä esimerkkinä on jatkuvasti suureneva kaistanleveys. Laajakaistaiset signaalit vaativat usein lähettimeltä – ja etenkin lähettimen loppupäässä olevalta tehovahvistimelta – korkeaa lineaarisuutta, mutta samalla sen on toimittava mahdollisimman tehokkaasti. Tehovahvistin on lähettimen eniten tehoa kuluttava komponentti ja luonnostaan epälineaarinen, joten sen linearisointi on oleellinen osa koko systeemin suorituskykyä. Nykyisistä linearisointitekniikoista digitaalinen esisärötys on vakiinnuttanut paikkansa yleisimpänä työkaluna paremman lineaarisuuden ja tehokkuuden saavuttamiseksi tehovahvistimessa.

Tässä diplomityössä tutkittiin digitaalisessa esisärötyksessä käytettävien käyttäytymistason tehovahvistinmallien suorituskykyjä ja niiden eroja varsinaisessa tukiasematuotteessa käytettävään, monimutkaisempaan referenssimalliin verrattuna. Työn tavoitteena oli luoda käyttäytymismalli, jolla voidaan kuvata fyysistä komponenttia yhtä tarkasti kuin referenssimallilla. Mallia voitaisiin käyttää esimerkiksi uuden tehovahvistimen suunnittelussa ilman, että kaupalliseen tuotteeseen tulevaa, salaista referenssimallia on tarve käyttää. Näin voitaisiin tehostaa työskentelyä ulkopuolisten tahojen, kuten komponenttitoimittajien kanssa ja vähentää linearisointiin käytettävää aikaa.

Työn alussa esiteltiin käyttäytymismallien suorituskykyparametrit, joita käytettiin mittaustulosten analysointiin. Tehovahvistimien linearisointimittaukset suoritettiin laboratorio-olosuhteissa MATLAB®-testipenkissä. Mittauksissa todettiin, että yksinkertainen, muistiton käyttäytymismalli ei riitä kuvaamaan fyysistä komponenttia riittävän tarkasti. Tuloksista pääteltiin myös, että liian kompleksinen malli heikentää sen tarkkuutta. Työssä onnistuttiin luomaan muistillinen käyttäytymismalli, joka kuvaa referenssimallia riittävän tarkasti usealla eri mittarilla tarkastellen – huomioiden osaltaan myös tehovahvistimen muistiefektejä. Tämä opinnäytetyö tarjoaa siis hyvän pohjan varsinaisen mallinnustyökalun jatkokehitykselle tuoteprojekteihin.

Avainsanat: tehovahvistin, mallintaminen, linearisointi, digitaalinen esisärötys, muistiefekti

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FOREWORD

This Master's thesis and its research was done at Nokia Networks and Solutions in Oulu. The purpose was to investigate different power amplifier modeling structures and their performance in modeling nonlinear phenomena of power amplifiers.

I want to thank the people in Nokia for all the help and innovative ideas, but also for challenging me on this topic. Special thanks to Technical Advisor of this thesis, D.Sc. (Tech) Tero Kangasvieri for proposing me this topic and encouraging my work. Also, many thanks to M.Sc. (Tech) Henri Hyyryläinen for insightful comments and for supporting me with practical issues.

I am also grateful to Prof. Timo Rahkonen for supervising my thesis and for expert and realistic feedback and D.Sc. (Tech) Janne Aikio for being a second examiner.

I would like to express my main thanks to my future wife Iina for all the support and patience and pushing me forward. Also, great thanks to my parents and siblings for encouraging attitude towards study and life.

I want to thank my awesome friends for all the things we have done during our studies. Those times are now over, but not forgotten.

Oulu, April 8th, 2020

Riku Karppinen

LIST OF ABBREVIATIONS AND SYMBOLS

2G	2nd generation cellular network
5G NR	5th generation (New Radio) technology developed by 3GPP
3GPP	3rd Generation Partnership Project
ACP	adjacent channel power
ACPR	adjacent channel power ratio (in dBc)
ACLR	adjacent channel leakage ratio
ADC	analog-to-digital converter
AGC	automatic gain control
AM/AM	the amplitude modulation to amplitude modulation
AM/PM	the amplitude modulation to phase modulation
BB	baseband
CDMA	code division multiple access
CFR	crest factor reduction
CW	continuous wave signal
DAC	digital-to- analog converter
DC	direct current
DLA	direct learning architecture
DPD	digital pre-distortion
DSP	digital signal processing
EVM	error vector magnitude
GaN	gallium nitride
GMP	generalized memory polynomial
GMP2	memoryless model, based on generalized memory polynomial
GMP3	model with short memory, based on generalized memory polynomial
GMP5	model with longer memory, based on generalized memory polynomial
I	in-phase component of complex envelope
ILA	indirect learning architecture
IM	intermodulation
IM3H	third order intermodulation distortion, higher
IM3L	third order intermodulation distortion, lower
IM5H	fifth order intermodulation distortion, higher
IM5L	fifth order intermodulation distortion, lower
IMD	intermodulation distortion
LDMOS	laterally diffused metal oxide semiconductor
LTE	long Term Evolution, 4th generation technology developed by 3GPP
LUT	look-up table
MSE	mean squared error
NMSE	normalized mean squared error
OFDM	orthogonal frequency division modulation
OPEX	operating expenditure
PA	power amplifier
PAE	power added efficiency
PAPR	peak-to-average power ratio
PD	pre-distorter
PDF	probability density function
PM/AM	the phase modulation to amplitude modulation

PM/PM	the phase modulation to phase modulation
PSD	Power Spectral Density
Q	quadrature component of complex envelope
QAM	quadrature Amplitude Modulation
QPSK	quadrature phase shift keying
RF	radio frequency
A	forward amplifier gain
a_n	basis function parameters, complex coefficients
a_{nm}	(generalized) memory polynomial model coefficients
b_{nmk}	(generalized) memory polynomial model coefficients
c_{nmk}	(generalized) memory polynomial model coefficients
dB	decibels
dBm	decibels with reference to one milliwatt (mW)
dBc	decibels relative to carrier power
f_n	sum of basis functions
G	normalization gain
h_p	Volterra kernel
k	discrete time value
m	index of “power” delay in generalized memory polynomial model
M	memory depth of model
mW	milliwatt
MHz	megahertz
n	index of sample delay in generalized memory polynomial model
N	number of (time) samples, nonlinearity order of model
$P_{avg,W}$	average power in watts
P_{adj}	adjacent channel power level
P_{dc}	DC power level
P_{in}	input power level
$P_{max,W}$	maximum power in watts
P_{out}	output power level
P_{ref}	reference channel power level
S_r	vector of the demodulated constellation point
$S_{r,n}$	vector of the reference constellation point
v_{in}	input voltage
v_{out}	output voltage
W	watt
x_I	in-phase component of complex envelope
x_Q	quadrature component of complex envelope
y	output signal
$\hat{y}$	output signal estimate
$\theta(t)$	time varying phase
β	feedback circuit gain
ω	frequency component

1 INTRODUCTION

1.1 Need for linear transmitters

During the last decades, the amount of data transferred on data channels has increased significantly due to the internet and wireless networks. In the recent years, ever larger and larger amounts of this data are transferred over wireless channels, such as mobile networks, which makes the limited wireless frequency spectrum more and more congested. One of the most essential components in a wireless transmitter is the power amplifier (PA). It amplifies the signal to a high enough power level to compensate the attenuation caused by the path loss of the channel. However, the PAs are inherently nonlinear components that cause most of the distortion in the transmitter. It is a bottleneck of transmitter as far as cost, power consumption, system performance, and most importantly, reliability are concerned.[1]

The highly nonlinear PA causes not only in-band distortion, but also out-of-band distortion by spectral regrowth, which, in its turn, causes interference and degrades the performance of other wireless devices. The accepted distortion levels of some standards are specified by communications agencies, such as 3^{rd} Generation Partnership Project (3GPP). The easiest, but not the most efficient way, to avoid these nonlinear distortive effects is by backing off the PA to its linear region. Especially modern wireless systems that employ multicarrier schemes, such as orthogonal frequency division multiplexing (OFDM), produce high peak-to-average power ratio (PAPR) signals. The high PAPR requires large back-off to avoid nonlinear distortion. Thus, backing off the PA causes a dilemma: linearity versus efficiency. Poor efficiency increases the heat dissipation, which in turn demands a higher capacity cooling system and consumes even more power. The power consumption is a hot potato also from the carbon footprint point of view. According to [2], the Base Stations are consuming almost 60% of whole Cellular network power consumption. This means that the CO_2 emissions are also remarkable high, and these could be decreased with better linearization techniques. In this way, engineering is in a key role limiting the greenhouse gas emissions. [3], [4]

In addition to harmful spectral and energy emissions, the transmitter nonlinearity is also a remarkable financial issue. Continuously growing number of base sites and greater bandwidth demands mean more operating expenditure (OPEX) costs to network operators. Thus, better linearization reduces OPEX and carbon emissions for wireless networks, so its impact extends all the way to product marketing, especially at this time of green trend. [3], [2]

1.2 PA linearization

There are several linearization techniques for PAs, such as feedback and feedforward linearization techniques and nowadays considered the most effective one, pre-distortion. A pre-distorter is a generic special case of open-loop linearization techniques and this thesis is also focusing on digital pre-distortion (DPD) linearization, which is an essential method to enable the transmitter to meet the linearity specifications. Compared to closed-loop systems, pre-distorters' disadvantage is reduced precision, but the key advantages are the much wider bandwidth, cheaper price and flexibility with components. [1]

In most narrowband systems, such as 2G, memoryless nonlinear model is adequate for PA characterization. For wider bandwidth systems, the nonlinear behaviour of the PA gets frequency-dependent, which is called memory effects. Thus, nonlinear models with memory are capable to capture the frequency-dependency of broadband systems. There are a variety of nonlinear models with memory for the pre-distortion design and most of these are based on

Volterra models or polynomial models. There is also a number of papers that focus on performance of different PA models, such as [5]. [6]

1.3 Thesis goals and structure

The main reason and motivation for this thesis was to improve the power amplifier design process. The PA design process will be more and more important from the system performance, power consumption and time-to-market perspective. If this thesis could improve even the first stages of the PA design process, it would offer a significant financial savings. And, if the research could provide information on nonlinearities' "root-causes", it would also be very useful for linearization algorithm design and optimizing. In general, this thesis aims to improve the knowledge about linearization and modeling of power amplifiers. These techniques can then be used to design and improve the linearization algorithms, such as digital pre-distortion.

The first final target of this thesis was to create a behavioral power amplifier model to be able to find the most optimal PA component out of multiple choices for existing DPD algorithm. The first step here was to find a proper model structure that represents the amplifier as accurately as the reference model. What kind of model is the most accurate and why? As presented in Figure 1, we could choose the best PA component for existing DPD algorithm and thus optimize the performance of the end-product.

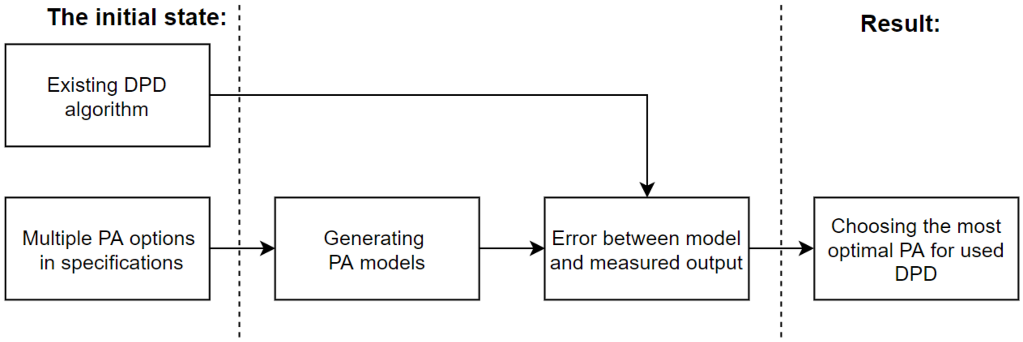


Figure 1. The flow of the first target.

Another, and more challenging target of this thesis was to search the most important products of nonlinearities: What causes them and is there some correlation between nonlinearities and model coefficients? If we were able to identify the causes of nonlinearity, we could shorten the pre-distortion algorithm design time and make it more efficient. The flow to the second target is presented in Figure 2.

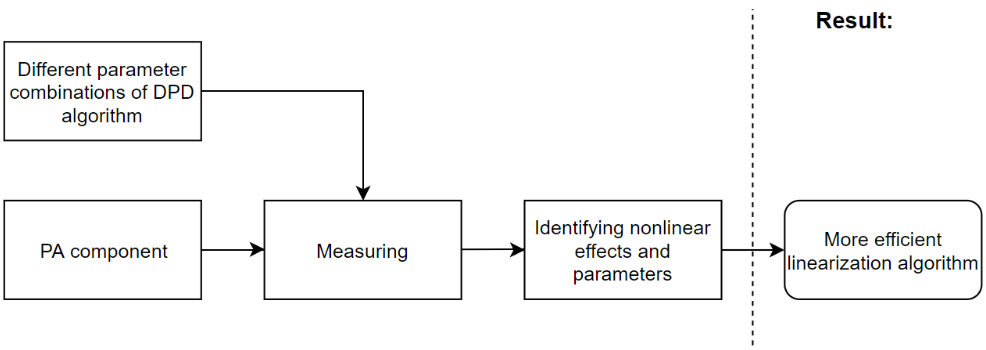


Figure 2. The flow of the second target.

The thesis is organized as follows: In Chapter 2, the transmitter's main requirements and figures-of-merit are introduced. After that, Chapter 3 introduces the power amplifier with main characteristics and memory effects. Chapter 4 represents the general linearization techniques and continues more deeply with digital pre-distortion. The power amplifier models and modeling techniques with performance and error metrics are discussed in Chapter 5. The measurement system is introduced and analysed in Chapter 6 and experimental results after that in Chapter 7. Finally, in Chapter 8, is the discussion and ideas for the future work.

2 RF TRANSMITTER

Wireless systems have taken a major role in today's society and our everyday lives. The requirements and demands on transmitters have increased and meeting the technical needs is getting very difficult. Wireless transmitters that are designed for modern communication systems are expected to handle wideband signals with amplitude and phase modulation with three major performance metrics: power efficiency – to minimize operating costs and environmental impact, linearity – to preserve the quality of signal and avoid losses and bandwidth – to accommodate higher data rates. [7]

The function of a transmitter is to transform the message to transmission signal which is transmitted through the radio channel to the receiving side. The transmitter processes the signal to create a suitable input meeting the channel characteristics, such as different mediums. The transmission consists of many unwanted effects on the signal such as signal power attenuation that makes the detection more difficult. The channel may also introduce some undesired signals from natural resources (solar radiation) or from other transmitters. Former type of undesired signals is called "noise" and latter type of signals are "interference". After the signal has reached the receiver, it will be filtered, demodulated and decoded to recover the original input signals. In Figure 3, is presented a block diagram of simplified transmitter architecture. [8]

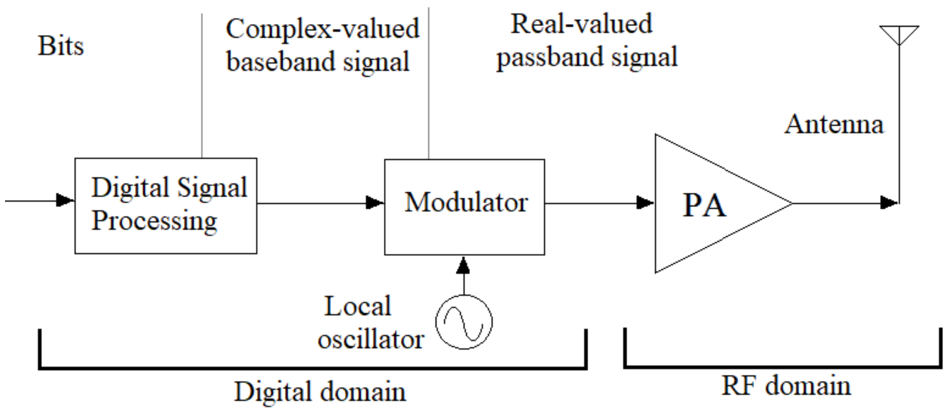


Figure 3. Block diagram of simplified transmitter architecture.

2.1 Wireless transmitter phenomena

In the following discussion, will be analyzed the main concepts and phenomena that must be considered to deliver strong RF power while taking care of sufficiently linear characteristics of the overall transmitting chain.

2.1.1 Transmitter distortion impacts on performance

The nonlinearity of transmitter depends on the input power level. Thus, phase or frequency modulated signals with constant envelope aren't suffering from transmitter's nonlinearity. However, majority of modern communication systems are using compact complex modulation schemes such as quadrature amplitude modulations (e.g. 16QAM, 64QAM) and advanced multiplexing techniques, such as orthogonal frequency division multiplexing (OFDM). These result in amplitude modulated signals with strong envelope fluctuations.

Increasing capacity makes also the amplitude variations of signal higher, which is critical, especially in nonlinear devices. [7], [8], [15]

Amplitude modulated signals are characterized with peak-to-average-power (PAPR), which is given by:

$$PAPR_{dB} = 10 \times log_{10}\left(\frac{P_{max,W}}{P_{avg,W}}\right) = P_{max,dBm} - P_{avg,dBm}, \quad (1)$$

where $PAPR_{dB}$ indicates the signal PAPR expressed in dB. $P_{max,W}$ and $P_{avg,W}$ are the maximum and average powers of signal in watts and in later part in dBm, respectively. Typical PAPR values vary between 10-13 dB and these can be reduced using crest factor reduction (CFR) technique, discussed in 4.2.1. To linearly amplify signals with high PAPR, one must make sure that the maximum peak power of the input signal to be amplified stays within the linear region of PA. If the maximum peak power is not within the linear region, part of the signal will be clipped, which in turn impacts on power efficiency of the system. [7], [8], [15]

2.1.2 Input-Output Power Characteristics and 1 dB Compression point

Output power versus input power is a commonly used way to characterize the transfer function of amplifiers. P_{out} vs. P_{in} characterizes the relation between input power of device under test (DUT) at the fundamental frequency to its output power at the same frequency. When the amplifier is driven in the nonlinear region, a gain compression appears in the higher power values and it increases until it reaches the saturation power. P_{out} vs. P_{in} characteristics are presented in Figure 4 with the 1 dB compression point. [7]

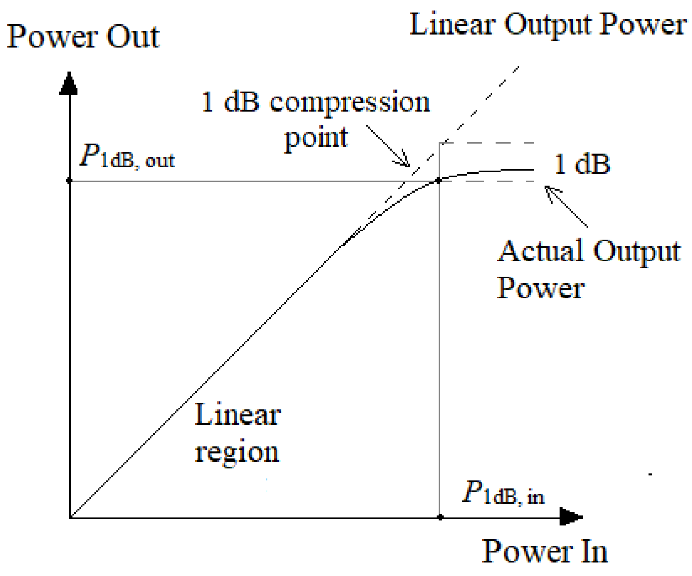


Figure 4. Pout vs. Pin graph.

The 1 dB compression point is a commonly used factor to characterize the power capabilities of a power amplifier along with the linearity. In the P_{out} vs. P_{in} characterization, the 1 dB compression point is the point, where the actual output power is 1 dB lower than linear line (the value that output power would have been if the amplifier was linear). [7]

However, modern systems with high PAPR signals are demanding so high linearity that amplifiers operating close to 1 dB compression point, are already highly nonlinear. Thus, modern amplifiers are backed-off well below a 1 dB compression point. [9]

2.1.3 Intermodulation distortion and spectral regrowth

Intermodulation distortion (IMD) is an amplifier specification that quantifies the non-harmonic frequencies added to an input signal. It occurs in a non-linear amplifier device when two (or more) signals are mixed. Each of these tones interacts with each other causing altered amplitudes in the frequency formation that the original signal didn't present. The new combinations of the input signals are called intermodulation products and they are undesired components in an amplifier passband, because they will lead to signal distortion. [10]

One of the most used method to model system nonlinearity is the polynomial modelling, which is based on polynomial coefficients of the input signal(s) and can be written with:

$$y = a_0 + a_1 * x + a_2 * x^2 + a_3 * x^3, \tag{2}$$

where a_0-a_n are the complex coefficients from the narrowband approximation. Polynomial modeling eases the computational complexity, but its drawback is that it is only affected by the input amplitude and not by the signal bandwidth. [11]

If we consider a narrowband, two-tone input voltage with two closely spaced frequencies ω_1 and ω_2:

$$v_i = V_0(\cos \omega_1 t + \cos \omega_2 t), \tag{3}$$

we get the output spectrum harmonics in the form of

$$m\omega_1 + n\omega_2 \,, \tag{4}$$

where m and n = ±0, ±1, ±2, … These combinations are called intermodulation products. Figure 5 shows a typical spectrum of the second and third order intermodulation products based on above frequencies. As we can see, some of the nonlinear components are closer to the input signals and thus impossible to get rid of by filtering. [10]

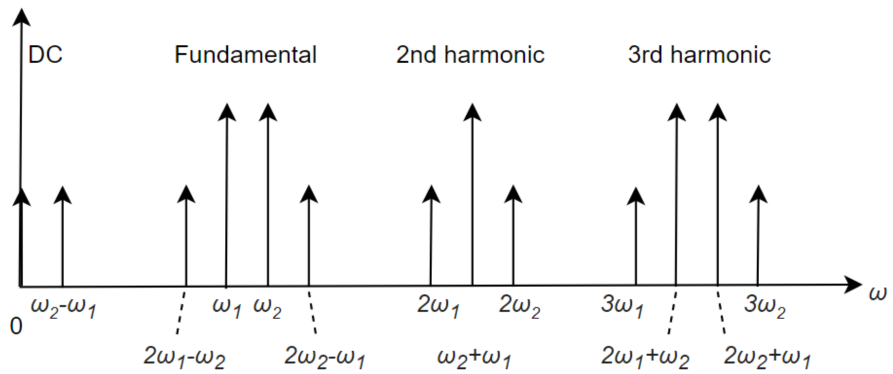


Figure 5. Output spectrum of two-tone intermodulation products.

To illustrate out-of-band distortion, let's consider a band limited signal. The output spectrum is the sum of the linear component and intermodulation distortion products, as presented in Figure 6 below. The band-limited, linear component remains in the allocated channel, whereas the distortion spreads into the adjacent channels. This phenomenon is also referred to spectral regrowth, which is one of the key concerns of Power Amplifier. [12]

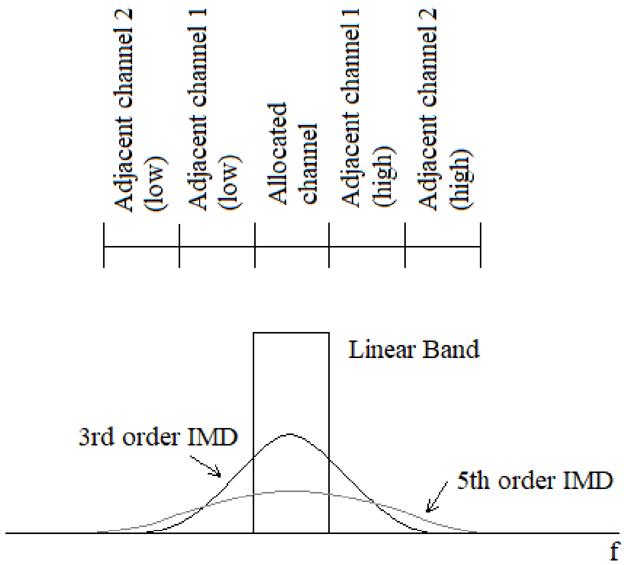


Figure 6. Spectral regrowth with third- and fifth-order intermodulation distortion and adjacent channels.

2.2 Requirements and figures of merit

In the next section, we go through the main transmitter specifications that are mostly related to nonlinearity of transmitter. Some of these parameters will be used in later Chapters to evaluate the measurement results and the quality of linearization.

2.2.1 ACPR

Adjacent Channel Power Ratio (ACPR) or Adjacent Channel Leakage Ratio (ACLR) is a frequency domain measure that is used to quantify the nonlinearity of PAs driven by modulated signals. It defines the filtered ratio of the mean power in the allocated channel (P_{ref}) to the filtered mean power in the adjacent radio channel (P_{adj}). It is a critical parameter of transmitter linearity, so it needs to be minimized and controlled. Each wireless standard, such as 3GPP, has specified the ACLR threshold for base stations. ACPR is visualized in Figure 7, where the black graph is the input signal and the grey one is the output of the power amplifier. [7], [8]

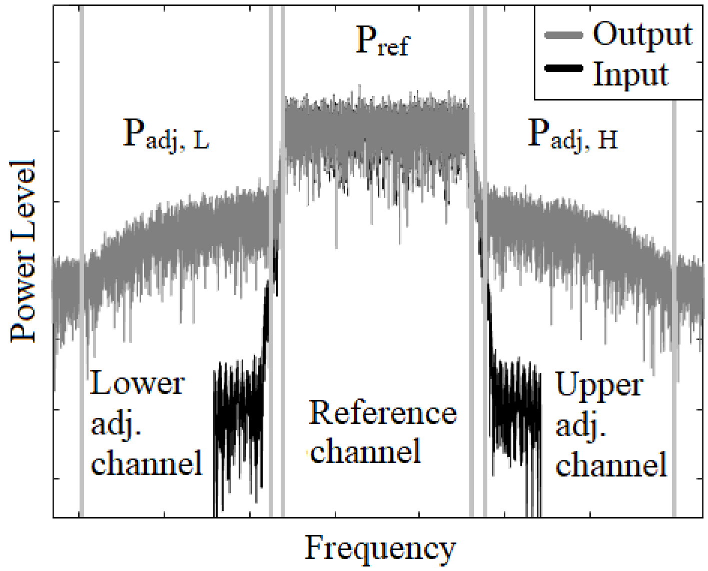


Figure 7. ACLR visualization with spectrum.

2.2.2 Error Vector Magnitude

RF transmitters' and PAs' nonlinear distortions can be also quantified with the error vector magnitude (EVM). It is a measure in the constellation domain that evaluates the deviation between the reference constellation point and the actual constellation point. Transmitter distortion can exist in three different forms: amplitude distortion (a), phase distortion (b) and amplitude and phase distortion (c), which are illustrated in Figure 8 with Quadrature phase shift keying (QPSK) modulation. [7]

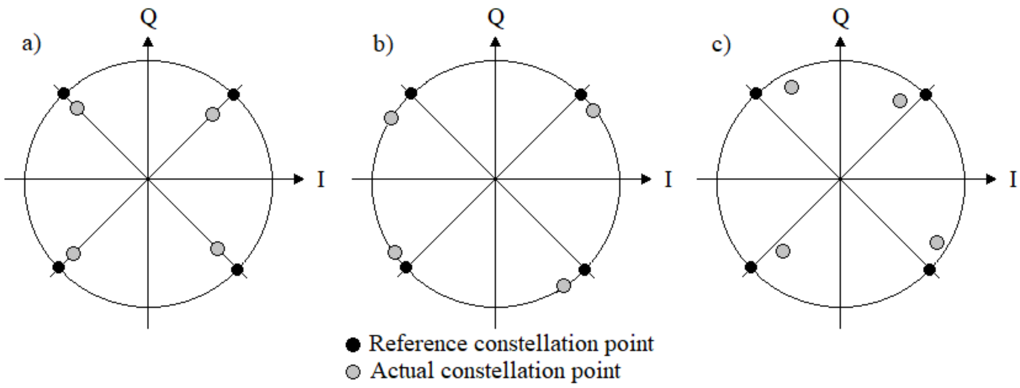


Figure 8. Effects of amplitude and phase distortion visualized with QPSK modulation. a) amplitude distortion b) phase distortion c) amplitude and phase distortion.

The error vector refers to the deviation between the vector of the actual constellation point (S_n) and the vector of the reference constellation point ($S_{r,n}$). Thus, the EVM refers to the magnitude of the error vector, as presented in Figure 9.

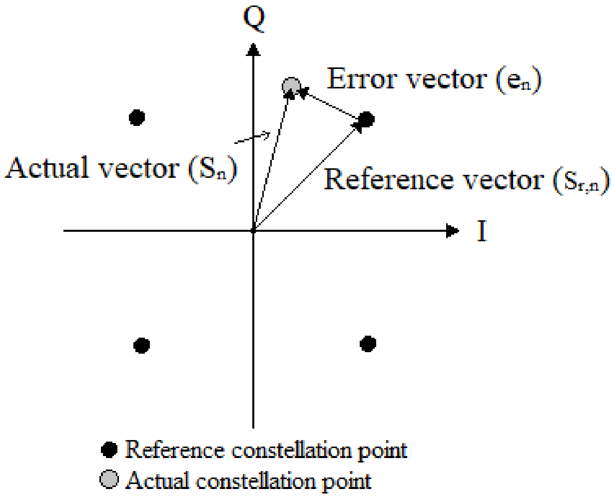


Figure 9. Error vector magnitude products.

Each communication standard specifies the EVM threshold and the values are typically expressed in percentage. The calculation is according to:

$$EVM(\%) = \sqrt{\frac{\frac{1}{N}\sum_{i=1}^{N}|s_i - s_{r,i}|^2}{\frac{1}{N}\sum_{i=1}^{N}|s_{r,i}|^2}}, \tag{5}$$

where N is the number of samples in the waveform. [7]

3 POWER AMPLIFIER THEORY

Power Amplifier is one of the most power demanding components in a wireless transmitter and it has a key role in the whole system's functionality and specifications. In fact, the PA is the limiting factor for many – if not all – transmitter specifications and it is often contradicting the overall transmitter architecture. The purpose of PA is to boost the modulated signal to power level so that the receiver can reach the signal at a suitable level to allow detection. In wireless radio communication, it is often appropriate to transmit the signal as efficiently as possible to achieve minimum power dissipation, but at the same time, keep the signal distortion small. These two features are though inversely proportional and contradict each other, thus leading to a trade-off between the PA efficiency and linearity. [13]

This thesis focuses on power amplifier and it is well known that RF PA used in a radio transmitter is inherently nonlinear. PA is supposed to operate near saturation for maximum efficiency, but near saturation it causes intermodulation products that interfere with adjacent channels. To reduce distortion and ensuring that signal peaks don't exceed the saturation point, PA output power is commonly "backed-off". In older narrowband telecommunication systems, such as GSM/EDGE, this has not been a critical concern, because the peak-to-average power ratio of modulation has been only a few dB leading to acceptable reduction in efficiency. However, such as 3GPP LTE (Long Term Evolution) signals' PAPRs exhibit in excess of 10 dB, so the back-off could remarkably degrease the PA efficiency. Backing off amplifiers that operates with wideband waveforms may turn the process highly inefficient leading typically efficiencies of less than 10%, which is not acceptable. [8]

The efficiency is defined as the ratio between the generated RF power and the drawn dc power. If we want to use PA with high efficiency, the bad linearity is causing problems with regulations. Indeed, the linear and efficient PA is one of the most problematic design tasks in modern radio telecommunication systems. [9]

3.1 Performance metrics

In the RF power amplifier design, it is useful to understand the definition and significance of the most important figures of merit. The power levels in PAs are generally described in dBm, which refers to the decibel representation of power referenced to 1 milliwatt (mW). [14]

An important figure of merit for the power amplifier is the efficiency, which tells how much energy is converted to power and how much wasted to heat. The better the efficiency, the less the amplifier heats up and more energy can be used to wanted processes. Particularly on mobile devices, it is important to take into consideration to extend the battery life. To take the substantial input drive into account, power-added efficiency (PAE) is used, which is defined as,

$$PAE = \frac{P_{out} - P_{in}}{P_{dc}}, \tag{6}$$

where P_{out} and P_{in} are the RF power levels of output and input and P_{dc} is the consumption of the DC power. [14], [19]

Another remarkable figure of merit of PA is its linearity. Linearity can be characterized with adjacent channel leakage ratio (ACLR), which describes the out-of-band distortion and error vector magnitude (EVM), which describes the in-band distortion. Both were discussed in Chapter 2.2. and they will be used in later Chapters defining the linearization quality of measured amplifiers. Real power amplifiers contain various nonlinear mechanisms interacting with each other. Nonlinear responses are acting inputs to other nonlinearities and thus capable of generating new nonlinear responses. [8], [11]

3.2 Memory effects

Memory effects is a term that is used to describe the influence of the history of the signal on its present values. The memory effects are a result of energy storing components, such as inductors and capacitors, in the system and are causing the dynamic behaviour of the system. Although the memory effects may not decrease the linearity of the amplifier dramatically, it can reduce the performance of the used linearization method remarkably, thus weakening the trade-off between efficiency and linearity. [11]

In a nonlinear system, such as a power amplifier, the previous samples of the signal influence the output. The number of samples that affect the output is known as the memory depth of the PA. Memory within a power amplifier can be modelled with a filter in front of and after a memoryless PA block with a feedback around it, as presented in Figure 10. [12]

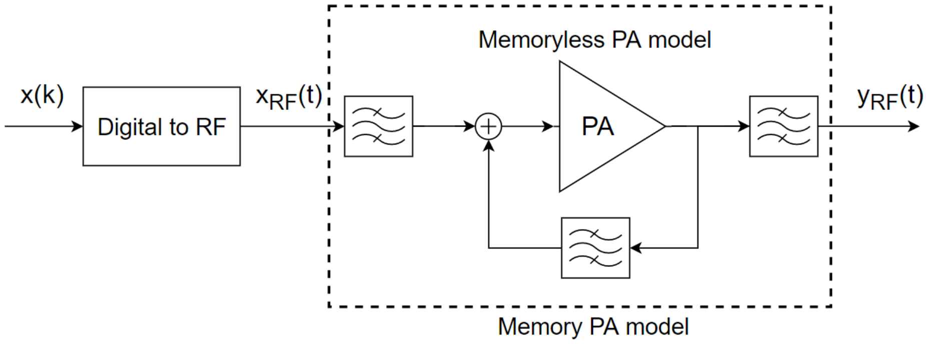


Figure 10. Power Amplifier memory model.

Memory effects can be divided into short-term and long-term memory effects. Short-term effects are roughly in the same scale than the period of the RF carrier frequency and they consist, e.g. of matching network nonidealities and device capacitances. Long-term memory effects exist in much a longer scale than the RF carrier frequency and the causes are, e.g. thermal effects, charge trapping or bias circuit effects. In Figure 11, is presented a simplified power amplifier structure with the sources of memory effects. [12]

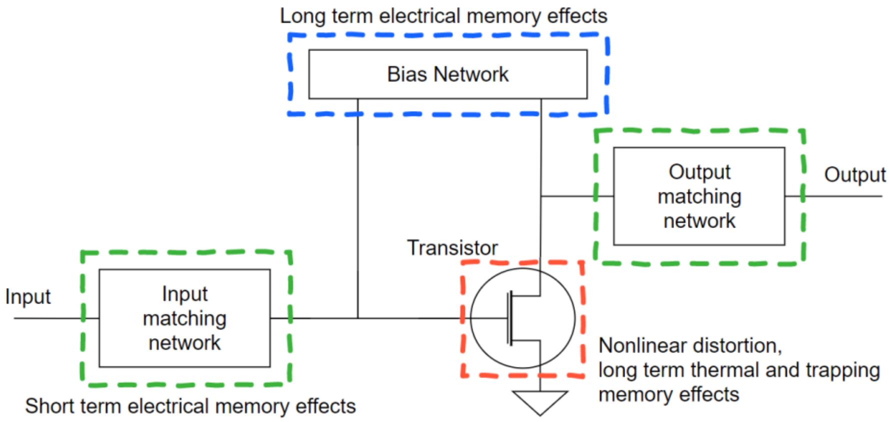


Figure 11. Simplified power amplifier architecture.

Semiconductor materials are not ideal, and especially with modern, in high frequency amplifier technologies, widely used gallium nitride (GaN) will cause trapping effects which is in a key role in the design of the whole wireless system. Also, many PA circuits include control features, such as automatic gain control (AGC). These control circuits improve the performance of a raw amplifier, but they can also cause memory effects that are difficult to correct. These, memory-based differences between different PA technologies will be presented in experimental results in Chapter 7. [12], [15]

3.2.1 Electrical and electrothermal memory effects

When we want to research the causes of memory effects, it is important to find the differences between real power amplifier output and memoryless model. The differences can be divided into electrical and electrothermal memory effects. The main origins of electrical memory effects are the variations in envelope, fundamental or second harmonic impedance at various modulation frequencies. The major cause of electrical memory is the envelope impedances, because the envelope frequency varies from the DC to the maximum modulation frequency (can be even a few megahertz). [16]

As the name indicates, the thermal memory effects are caused by the electrothermal coupling in the power transistor. Power dissipation caused temperature variations are defined with thermal impedance of the material. In the active devices, thermal impedance is a wide range of time constant distributed low-pass filter, which means that thermal changes of power dissipation don't occur instantaneously. A more detailed discussion about memory effects sources can be found in [16]. [7]

3.3 AM/AM and AM/PM characteristics

P_{out} vs. P_{in} discussed in Chapter 2 is a basic way to characterize PAs or transmitters, but in many cases, more comprehensive representations are needed, including the amplitude as well as phase information. In general, a dynamic nonlinear transmitter can be described completely using four characteristics: The amplitude modulation to amplitude modulation (AM/AM), the amplitude modulation to phase modulation (AM/PM), the phase modulation to amplitude modulation (PM/AM) and the phase modulation to phase modulation (PM/PM). PAs are mainly described by AM/AM and AM/PM characteristics, because their distortions are amplitude dependent and phase modulated signals. Conversely, PM/AM and PM/PM distortions are mainly due to the gain and phase imbalances in the frequency up-conversion stage and transmitter's non-flat frequency response over the input signal's bandwidth. So far, these two characteristics haven't been considered in behavioural modeling. With multi-band power amplifier systems, with large bandwidths, it is more likely to suffer from a non-flat frequency response of the PA. Thus, the contribution of the PM/AM and PM/PM is getting more significant and their role in the behavioral models and pre-distorters will be remarkable. [7]

In Figures 12 and 13, are presented AM/AM and AM/PM diagrams of two different PAs, which are linearized with memoryless and memory models. Average power is marked with grey line. The graphs on the left (a) are GaN and on the right (b) LDMOS technology. Even raw AM/AM and AM/PM diagrams (red ones) are much worse for LDMOS, a memoryless model can improve the linearity remarkably. For GaN, a memoryless model can improve only the gain expansion, but the dispersion of the graph is still very high, which indicates the including memory effects. [7]

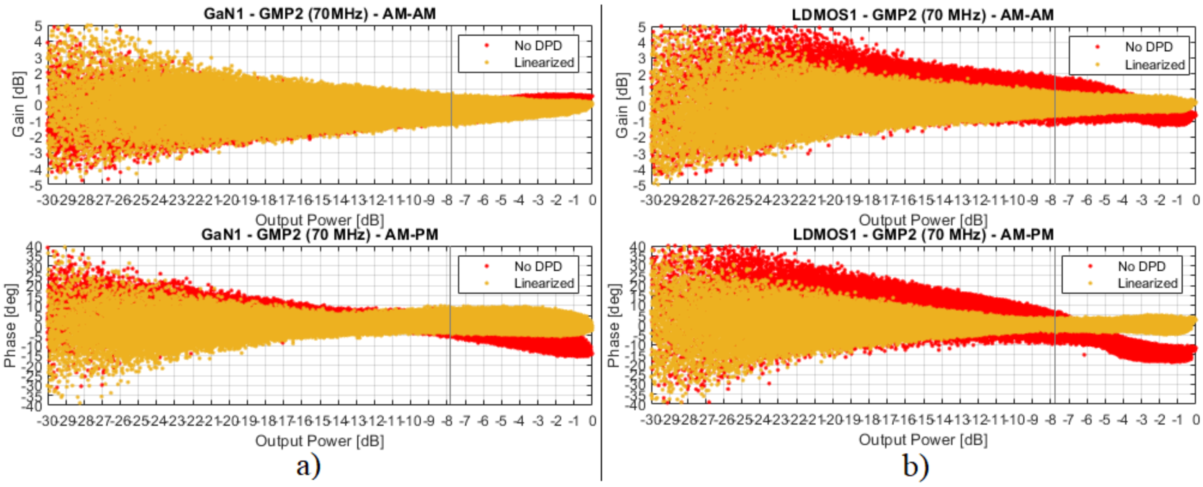


Figure 12. AM/AM and AM/PM with memoryless model, a) GaN and b) LDMOS.

In Figure 13, is presented linearization results with a memory model. This model can improve not only compression and expansion, but also memory effects better, which can be seen by lower dispersion compared to results obtained with the memoryless model.

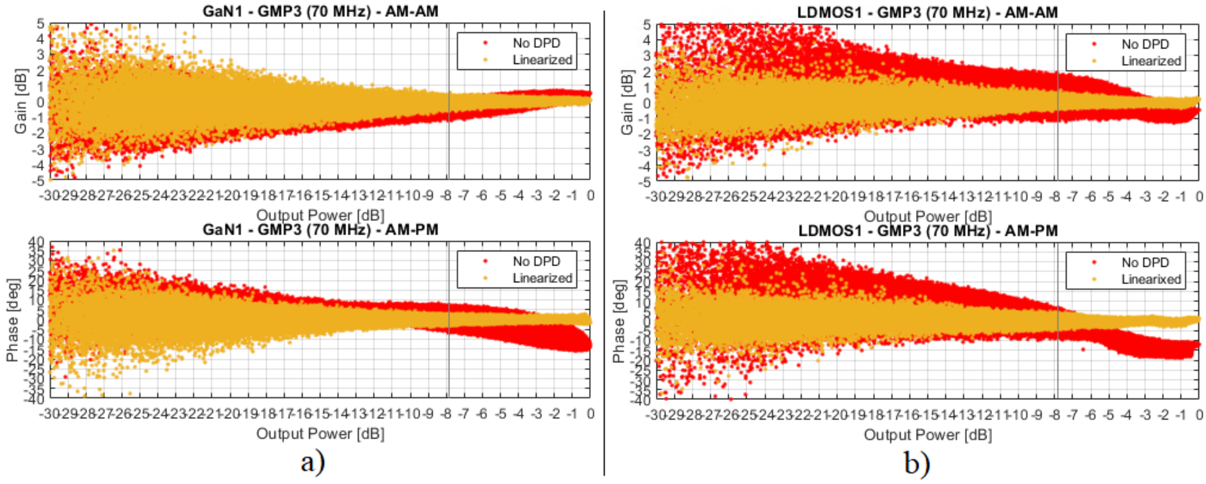


Figure 13. AM/AM and AM/PM with memory model, a) GaN and b) LDMOS.

4 DIGITAL PRE-DISTORTION

As stated in earlier Chapters, the main challenge in wireless transmitters is the power efficiency with high linearity demand. It is known that the power amplifier is one of the most power consuming devices in telecommunication and thus its linearization is in a key role to enhance the power efficiency of a transmitter [8]. This Chapter introduces the basic linearization methods of power amplifier also a widely used method of modern telecommunication systems, digital pre-distortion (DPD) is introduced more details as well.

4.1 Linearization techniques of PA

Basic power amplifier linearization techniques are introduced shortly in this part. They all work with the similar concept using the amplitude and phase of the input RF envelope as a base with which to compare the output and so generate appropriate corrections. The key issue of the linearization is that it does not increase the inherent power capability of the amplifier, but it modifies its power saturation characteristics “harder”, as shown in Figure 14.

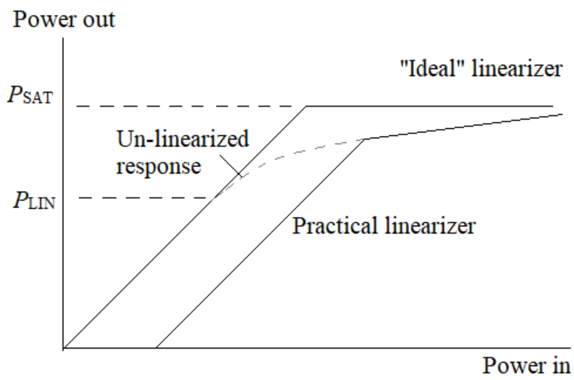


Figure 14. Basic action of PA amplitude linearization.

Especially designing of RF PA linearization techniques still largely focus on the fundamental concept of feedback, because its implementation at RF frequencies suffer from stability and time causality difficulties. Next, the main linearization methods will be introduced shortly. [1]

4.1.1 Feedback Linearization

The classical feedback amplifier schematic is presented in Figure 15. The basic idea of this method is to sample the signal in the output and then apply an attenuated version of sampled signal at the input, in opposite phase with the original signal. The composite gain of an amplifier is given by:

$$\frac{v_{out}}{v_{in}} = \frac{A}{1 + \beta A}, \tag{7}$$

where A refers to forward amplifier gain and β to feedback path gain. [12]

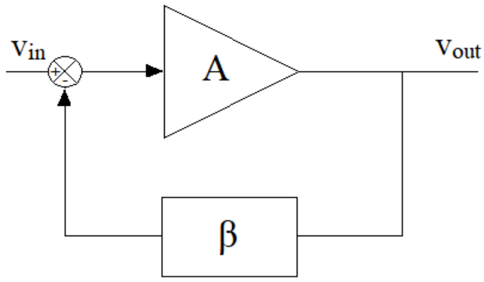


Figure 15. Simplified schematic of the feedback principle.

This simple technique is popular, especially in low-frequency circuits, where the time delay of the loop is short enough. The improvement of the feedback linearization is proportional to the loop gain, which is low at RF and therefore the potential benefits are only modest. The presence of parasitic capacitance and inductance can also introduce another unwanted feedback path to the system causing more complex analysis and in the worst case an unwanted oscillation. [12]

4.1.2 Feedforward Linearization

A feedforward linearization method is commonly used in wideband amplifiers. It uses a similar concept as feedback except that the correction is applied to the output instead the input of the amplifier. This removes the causality conflict of direct feedback, and in this way, it offers the benefits of feedback without instability problems and bandwidth limitations. The concerns of the feedforward method are the additional amplifier (error amplifier) whose own distortion properties set the upper limit on the overall correction and efficiency. The feedforward linearization schematic is presented in Figure 16. [1], [9], [12]

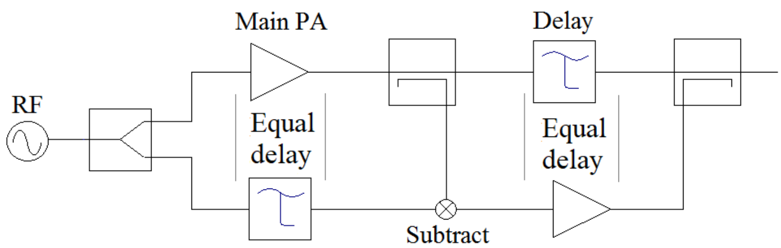


Figure 16. Simplified schematic of the feedforward principle.

4.1.3 Pre-distortion

Unlike previously described methods, in pre-distortion, we add distortion components to the signal input of the PA. This way, we cancel the inherent nonlinearity of the PA seeking for the linear replica of the original input signal. As presented in Figure 17, the pre-distorter can be thought of as a component straight in front of the power amplifier transforming the input signal into the new, distorted signal. [12]

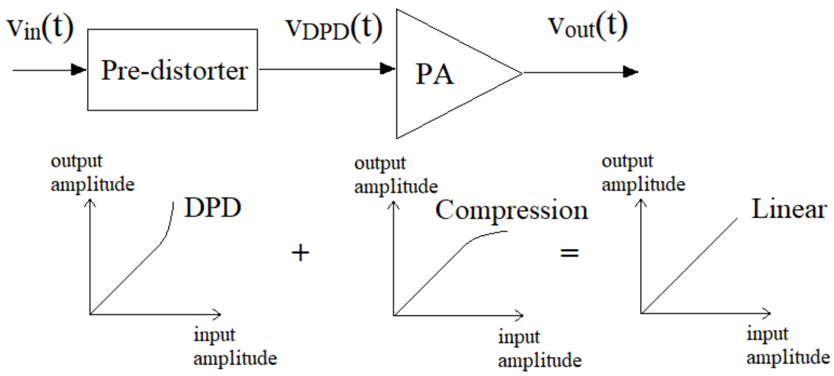


Figure 17. A sketch of pre-distorter and PA arrangement with AM-AM responses.

Predistortion requires a quite slow feedback to adapt the predistortion function. It is a wideband linearization method with a low hardware complexity and good power efficiency. For these reasons, it is one of the most popular linearization methods in modern wireless systems and chosen as the linearization method of study in this thesis as well. [12], [9]

4.2 The Digital Pre-distortion system

The digital pre-distortion is the most potential linearization method to reduce the size and cost of device. In the digital pre-distortion, a power amplifier's distortion function is used in a pre-distorter as an inverse to compensate the nonlinearities caused by the power amplifier. As presented in Figure 18, the gain of the PA is linear in the small signal region and tends to diverge from the straight line when the input power level increases. To compensate this gain compression, a linearization block (pre-distorter) can be inserted in the signal path in front of the PA to make a gain inversion of the amplifier. The combination of these two nonlinear systems in cascade creates a linear output. [8]

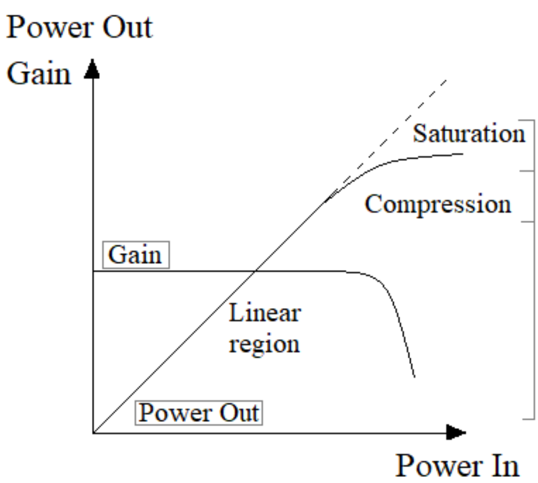


Figure 18. The output power and gain compression of PA.

By using digital pre-distortion, the linear range of the PA can be extended, and PA can be operated at a higher input power level to produce higher output power without distortion. This leads to higher power efficiency, which is one of the main issues in PA concerns [8].

With DPD, it is already possible to achieve efficiencies in the range of 8%-10%, whereas with conventional power amplifiers, efficiencies are in the range of 3%-5% only [5].

4.2.1 Crest factor reduction

Crest factor is another way to describe the amplitude distribution between the peak amplitude and the root mean square (RMS) value levels, which was already mentioned in Chapter 2. In wideband systems where the crest factor of transmit signals are often very high, it is recommendable to compress the signal peaks to a satisfactory level before the digital pre-distortion. This increases the power efficiency, because the PA can be operated with a higher average power. [8]

DPD extends the power amplifier's linear range of saturation, but the transmission signal peak value is still limiting the maximum delivered power of PA. Thus, wideband systems, that are operating with signals with high PAPR, crest factor reduction (CFR) techniques can be used to enhance the power efficiency and those have become more general in the last few years. [8]

4.2.2 Concerns

A couple of basic issues that can weaken the DPD system performance are discussed shortly next. First, it is important to compensate the time delay between the signal that appears first on a transmitter and when the replica appears to the output, as presented in Figure 19. The data captures from the feedback loop must be time-aligned with the original input signal as well. Second, the data capture size should be large enough to avoid the input signal statistics variations between captures. [8]

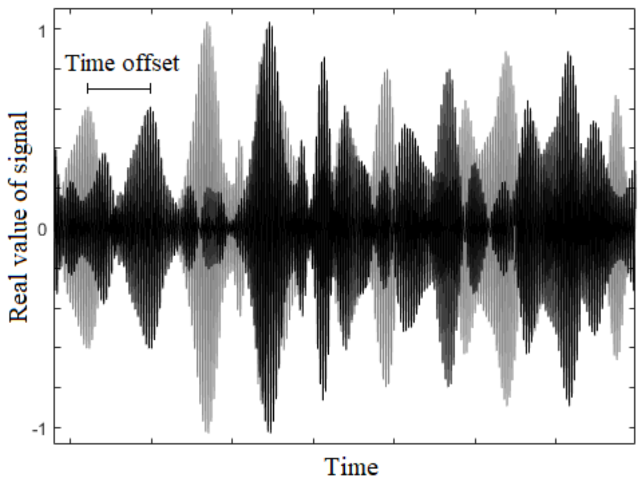


Figure 19. Offset between signal and delayed signal.

5 PA MODELS AND MODELING

For any system, a model describes the relationship between the input and output signals. So, in general, it is a mathematical abstraction of the input-output relationship. In this thesis, the system means a power amplifier, but it can be also refer to a transistor or the whole transmitter, for examples. Even if the physics of the system is known well, the model is never an exact replica of the physical component. The usefulness of the model is based on how much insight it provides us, when solving the larger problems of the system design. [12]

The power amplifier can be modelled with a circuit model, where the circuit elements and their values are extracted from the measured data, so that the simulation of the model mimics the measured data. A circuit-level model provides excessive details and thus is consuming a lot of time and resources. Otherwise, if the model is based on data without direct circuit representation, it is called a behavioral model, which represents the input-output relationship of the system that we want to model. In this Chapter, we go through behavioral PA models. [8], [12]

5.1 Model building

The behavioural models of power amplifiers at system level are defined as single-input single-output (SISO) systems. The behavioral model extraction for DPD linearization is implemented by complex envelope signal observations using an amplitude and phase modulated bandpass signal. The complex envelope can be defined as:

$$x(t) = A(t)e^{j\theta(t)} = A(t)\cos\big(\theta(t)\big) + jA(t)\sin\big(\theta(t)\big) = x_I(t) + jx_Q(t), \qquad (8)$$

where $A(t)$ and $\theta(t)$ are the time-varying amplitude and phase, and respectively, $x_I(t)$ and $x_Q(t)$ are the in-phase (I) and quadrature (Q) components of complex envelope. [8]

If we want to extract the PA behavioral models that allow us to design the DPD at baseband, it is necessary to have the input and output discrete complex envelope signals. Thus, we can express the complex envelope, from (8) in a discrete form:

$$x(k) = x(t)|_{t=kT_s} = x_I(kT_S) + jx_Q(kT_S) = x_I(k) + jx_Q(k). \qquad (9)$$

Here, the baseband signal is a sequence of ideal pulses appearing at discrete times (k = 1,2,3,…).[8]

5.1.1 Basis functions

The solution for power amplifier output can be written in the form of the sum of basis functions. These basis functions form fundamental solutions to the system whose output can be written:

$$y(t) = \sum_{n=0}^{N} a_n f_n\big(u(t)\big), \qquad (10)$$

where $y(t)$ refers to the output and $f_n(x)$ the sum of basis functions. The most common basis functions for linear systems are trigonometric, $sin(\omega t)$ and $cos(\omega t)$. [12]

The formalism of linear basis functions can be extended to nonlinear systems by using nonlinear basis functions, where the nonlinearity is confined to the function $f(x)$ and the solution is "linear in the parameters a_n". This means that even a nonlinear model can be extracted with a wide array of linear solution techniques, such as least squares that will be discussed next. [12]

5.1.2 Least Squares Algorithm

When we have chosen the model structure, but not yet the parameters, we can collect measured data over many time samples, N. We can use this data to choose the optimal parameters, θ, that give us the closest estimation of the calculated value of the output, $\hat{y}$ to the measured data y using the measured regression vector data $\phi(t)$. Model configurations are introduced in Section 5.3.2. [12]

5.1.3 Error measures

The least squares estimation is a simple and widely used technique for estimating the model parameters based on a given set of data through minimizing the difference between the actual, measured output data and calculated values over the whole data set. A relevant thing to know about the quality of our estimation is the error between our estimate, the model and the measured data. [12]

5.1.3.1 Mean Squared Error

One commonly used error measure is the mean squared error (MSE), which comes directly from the previously defined least squares technique. Simplified, The MSE calculates the difference between the measured data (y) and the estimate ($\hat{y}$) as follows:

$$MSE = \frac{1}{N}\sum_{t=1}^{N}\left(\hat{y}(t) - y(t)\right)^2. \tag{11}$$

The MSE is usually normalized to measured data yielding to the Normalized mean squared error (NMSE):

$$NMSE = 10log_{10}\left(\frac{\sum_{t=1}^{N}\left(\hat{y}(t) - y(t)\right)^2}{\sum_{t=1}^{N} y(t)^2}\right), \tag{12}$$

which is often expressed in decibels. The problem of the NMSE is that it is calculated in the time domain so the error in different bands is blended. In many cases, in-band and out-of-band errors would be useful to know separately. However, NMSE is dominated by the higher power in-band error, so it is suitable for this thesis purpose, because we want to evaluate model accuracy just in-band frequency. [7], [12], [17]

5.2 Behavioral modeling

With a behavioral model or black-box-model, we want to model the nonlinear dynamical behaviour of power amplifier, which is usually operating close to saturation and so very nonlinear. The dynamical effects are caused by reactances in transistors themselves, matching networks and in charging storages of the bias networks. So, basically, we want to build a nonlinear dynamical model of power amplifier based on the knowledge of its input and output signals. [12]

The key advantage of behavioral modeling is that it doesn't require deep knowledge of the circuit functionality and physics. As visualized in Figure 20, it simplifies the circuit modeling based on mathematical formulation related to input and output of the device. So, the performance of behavioral modeling is influenced by two key factors: the observation (input and output signals) and the formulation (the choice of a suitable mathematical relation).

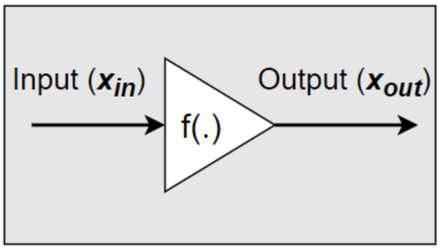


Figure 20. Black-box modeling.

A behavioural model's accuracy is highly sensitive to the adopted model structure and the parameter extraction process. Thus, it is very important to pay attention to used model structure in linearization methods and this is also one of the key issues in the later measurement analyzing parts. [8], [12]

In digital pre-distortion systems, the behavioral modeling is crucial to predict the nonlinearity of the power amplifier and the transmitter in general; therefore pre-distortion can be considered also as a behavioral modeling problem. When designing a digital pre-distortion at baseband, it is important to take account of a couple of key issues: The behavioral model's capability to meet the accuracy requirements and its efficient implementation in FPGAs without an excessive computational cost. [8]

5.3 DPD models

Multiple DPD models have been proposed in recent years, many of which are implemented in the digital baseband domain, shown in Figure 21. Next, we will discuss memoryless and systems with memory, and the main differences based on implementation of predistortion architectures and models.

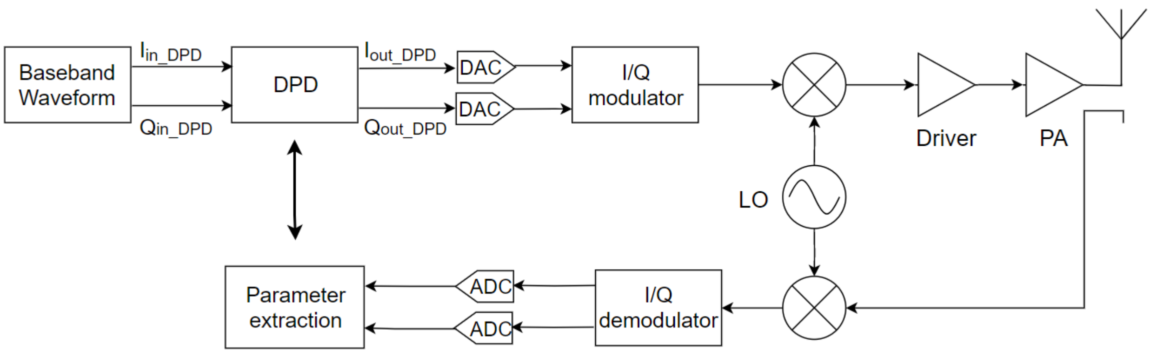


Figure 21. Block diagram of DPD.

5.3.1 Memoryless nonlinear models

In narrowband systems, static nonlinearities are the main cause of distortions. For compensating these distortions, only memoryless DPDs are needed. Let's go shortly through look-up tables (LUT) and polynomial functions.

5.3.1.1 Look-up table

A widely used look-up table (LUT) based DPD is a simple and relatively easily implemented technique. In this technique, the pre-distortion data or coefficients are stored in a table, which is used in processing the transmitted signals and then fed them to the amplifier. There are two main methods of look-up table indexing: direct mapping and complex gain indexing. So, a LUT-based DPD is simple, but while wireless systems are migrating to wideband operations and bandwidth is increasing dramatically, LUT-requiring memory capacity increases the system complexity remarkably. [8]

5.3.1.2 Polynomial functions

In an analytical function based DPD, PA characteristics are represented with mathematical equations. Each value of the pre-distorted output is calculated with a small number of pre-defined parameters, when needed. This avoids storing all possible values and requires less memory than LUT-based methods and makes this a more suitable one for wider band applications. However, the polynomial model is not considering the bandwidth or frequency of the input signal, for which reason it is called narrowband modelling. [8]

5.3.2 Memory nonlinear models

As wireless communication evolves towards broadband services, power amplifiers may exhibit frequency-dependent behaviour, which is also known as memory effects. In order to develop the full potential of DPD, memory effects must be considered, which will be even more important as the bandwidth increases. [5]

5.3.2.1 Volterra series

The Volterra series is the most complete model for non-linear behaviour. It can be used to characterize accurately a dynamic nonlinear system, including linearity and various types of memory effects. Unlike traditional models, such as Taylor series, the Volterra series provides the ability to capture the memory effects of the system and so it is considered as the most complete model to taking account of linearity and memory effects [7]. However, the number of coefficients increase exponentially with the degrees of nonlinearity and memory, thus, in practice, the usage of Volterra series model is very limited. [12]

In Volterra series models, the output signal is related to input signal as follows:

$$y(n) = \sum_{n=1}^{N} \sum_{m_1=0}^{M} \cdots \sum_{m_n=0}^{M} h_n(m_1, \dots, m_n) \prod_{j=1}^{n} x(n-m_j), \quad (13)$$

where $x(n)$ and $y(n)$ represent the input and output, $h_n(m_1,\dots,m_p)$ are called the Volterra kernels, N is the nonlinearity order of the model and M is the memory depth. In real applications, N and M are truncated to finite values to limit the number of the coefficients. [7], [8]

5.3.2.2 Memory polynomial

After Volterra Series, we consider some simpler memory structures. One of the simplest pruned Volterra model is the memory polynomial model. It can be described as a reduction of the Volterra model to only include "diagonal" terms and it can be written as

$$y_{MP}(t) = \sum_{n=1}^{N} \sum_{m=0}^{M} a_{nm} u(t-\tau_m)|u(t-\tau_m)|^{n-1}, \tag{14}$$

where a_{nm} represents the coefficients of the model, τ is the time delay and N and M are the nonlinearity order and memory depth. A memory polynomial (MP) model consists of a delay line and polynomial function, as shown in Figure 22. The number of "taps" in the delay line is defined by the memory depth of the model. [12]

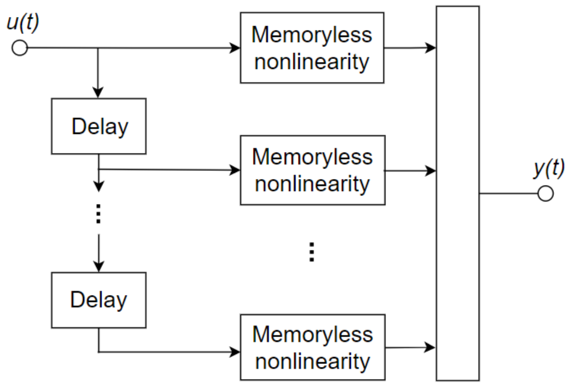


Figure 22. Block diagram of memory polynomial.

In Figure 23, is visualized the difference between two previous models, Volterra, whose performance is high, but also complexity and Memory Polynomial, which is simple, but its performance is poor, especially in wideband applications. The optimal model is somewhere between these two and one of suitable implementations would be the Generalized Memory Polynomial model, which is introduced next. [7]

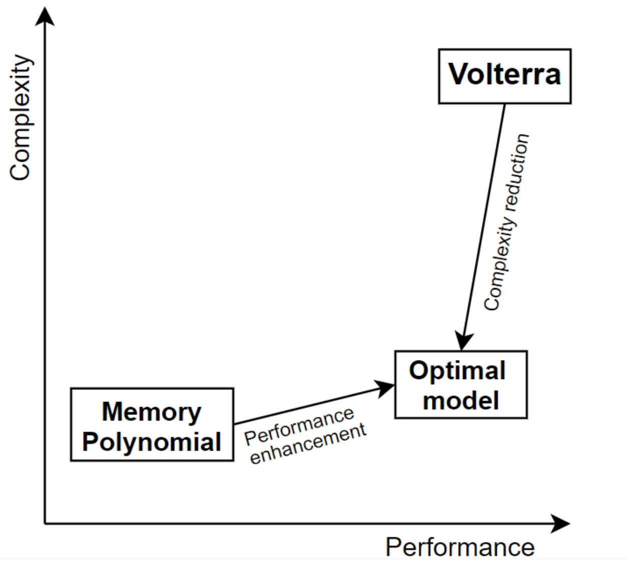


Figure 23. Volterra model and Memory Polynomial model comparison.

5.3.2.3 Generalized memory polynomial

In addition to memory polynomial model, Generalized memory polynomial model (GMP) includes leading and lagging terms (both negative and positive cross-term time shifts), so it allows an additional delay to be included in polynomial expressions. It is built by adding some upper and lower diagonal terms to the basic memory polynomial main diagonal and it can be written as

$$y_{GMP}(t) = \sum_{n=1}^{N}\sum_{m=0}^{M} a_{nm}u(t-\tau_m)|u(t-\tau_m)|^{n-1} + \sum_{n=1}^{N}\sum_{m=0}^{M}\sum_{k=1}^{K} b_{nmk}u(t-\tau_m)|u(t-\tau_m-\tau_k)|^{n-1}, + \sum_{n=1}^{N}\sum_{m=0}^{M}\sum_{k=1}^{K} c_{nmk}u(t-\tau_m)|u(t-\tau_m+\tau_k)|^{n-1} \quad (15)$$

where *u(t)* indicates the input and *a*, *b* and *c* refer to the coefficients of the model. [5], [12]

5.3.2.4 Wiener, Hammerstein and Wiener-Hammerstein models

Wiener, Hammerstein and Wiener-Hammerstein models, which are the special cases of Volterra model, each formulation based on Equation 13. All these models are based on separating the memory and memoryless parts of the nonlinearity, which is done by dividing the system to filter part (linear and dynamic) and memoryless part (static nonlinearity), as presented in Figure 24, a so called three-box model. [5]

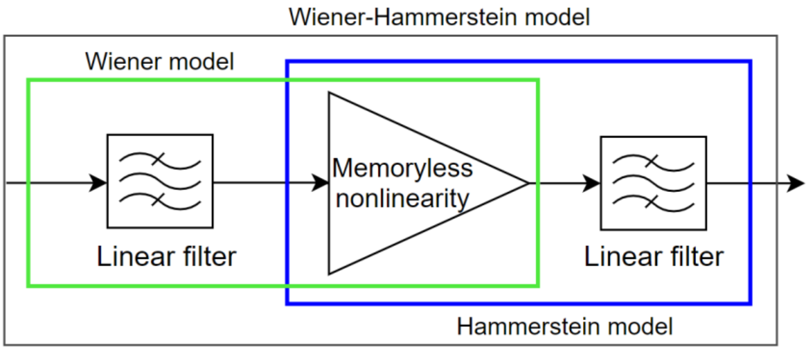


Figure 24. Three-box model.

The Wiener model consists of a linear filter followed by the memoryless nonlinearity. The Hammerstein model consists of the same blocks in opposite order, and because it is linear in parameters, it is more straightforward to identify. The last one, Wiener-Hammerstein model, consists of linear filters in both sides of memoryless nonlinearity. With these models, we can simplify the Volterra model significantly and instead of several cross-product terms, these models require only the filter parameters and the memoryless structure parameters. [5], [19]

5.4 Model extraction in Adaptive DPD

In digital pre-distortion systems, the effectiveness is based on how well the pre-distortion model is matched to the nonlinear characteristics of the DUT. Because the nonlinearity varies with time due to aging or drifts, it is necessary to update the pre-distortion function continuously, adaptively. An adaptive linearization model can be extracted with either closed or open loop configuration. [7]

With open loop configuration, it is possible to identify the amplifier's model first, and then build the DPD function inverting this model. Another way is to calculate the post-inverse of the amplifier and use it directly. These two variants, indirect and direct learning architectures, are presented in Figure 25. [7], [12]

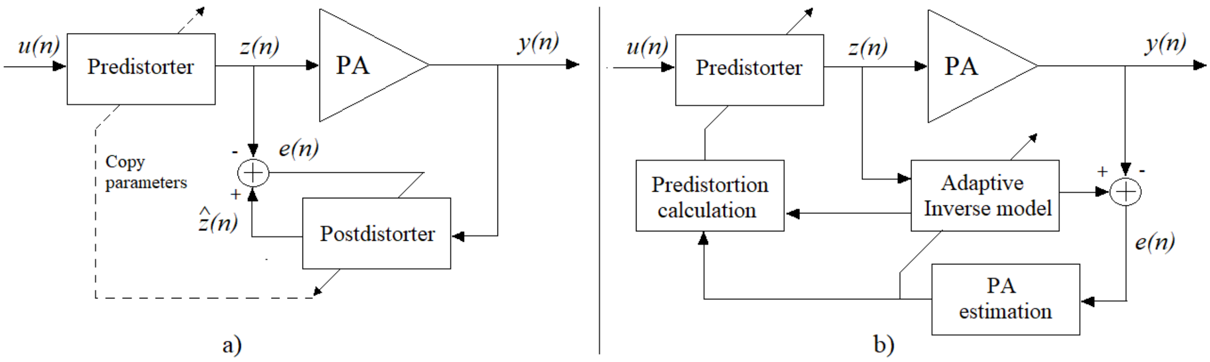


Figure 25. Block diagram of the a) indirect and b) direct learning architectures.

In this thesis' linearization measurements, the indirect learning architecture (ILA) was used. ILA is the most common digital pre-distortion identification technique [23]. It is computationally simpler, but its performance is a bit poorer than that of direct learning architecture (DLA). More specific comparison can be found in [20].

6 MEASUREMENTS

6.1 Measurement System Description

Next, will be introduced the main issues to focus on in measurements and data capturing. Measurement system and used devices will be also discussed in this part. In Figure 26, is presented the main points that must be considered during the DPD measurement.

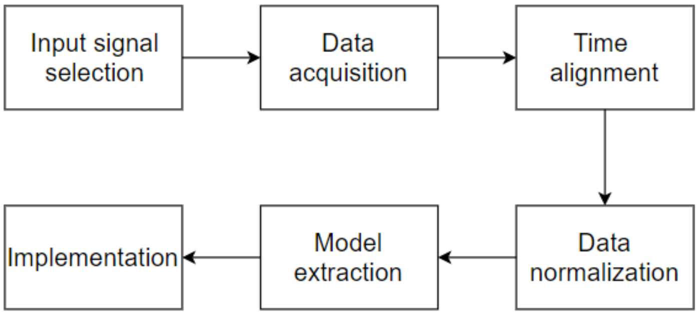


Figure 26. DPD measurement system characterization.

6.1.1 Test signals: Continuous Waves and Modulated Signals

Power amplifier characterization can be done with a variety of test signals. The simplest case are the continuous wave test signals that can be used during the PA design process. CW signal can be defined by its frequency and power level. Thus, if we want to characterize the power dependent nonlinear behaviour of PA, we must sweep the power level of the continuous wave signal. Continuous wave signal doesn't have an inherent bandwidth, so it doesn't provide any accurate insight into DUT's dynamic behaviour, either. Using a two-tone test signal, we get richer spectral content (inherent bandwidth) and this way we can characterize the DUT dynamic behaviour. The spacing between these two tones can be used to investigate the memory effects exhibited by the DUT. [7]

After development of measurement instruments, it has been possible to characterize the power amplifiers' nonlinear behaviour using modulated signals. A modulated signal achieves a more accurate model, but it also requires more complicated identification techniques than using continuous wave or multi-tone characterization. In [7], it was also proven that power amplifier behaviour is strongly affected by the statistical characteristics of the signal. Thus, reaching a better model accuracy, it is recommendable to use a modulated signal with similar statistical characteristics that will be used for the power amplifier. [7]

In measurements done in this thesis, we used two LTE (Long-Term Evolution) modulated test signals with different bandwidths: two 5 MHz carriers with 60 MHz and 70 MHz spacing to investigate model accuracy with different bandwidths. In addition to signal statistical characteristics, two main parameters of modulated test signals are the bandwidth and average power that will be discussed later in this section. [7]

6.1.2 Time alignment and Data normalization

Another key issue when capturing data samples is the time alignment of the original and measured signals. This was already shortly discussed in Section 4.2.2 and visualized in Figure 19. To ensure system performance and accurate model, it is necessary to align signals carefully before the DPD model can be extracted. One simple approach to align signals is to use cross-correlation and interpolation. [8]

In addition to time alignment of signals, it is necessary to normalize the power level of signals that are used to model extraction. In Figure 27, is visualized the situation where the gain with the DPD is higher than the original gain. If we want to use the parameters directly in the DPD, the model extraction data must be scaled to the same power level. [8]

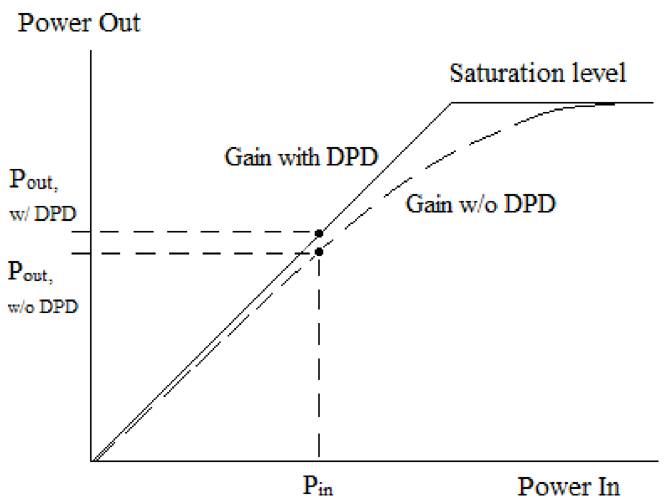


Figure 27. Need for power level normalizing with and without DPD.

6.1.3 Model extraction

In the measurements done in this thesis, the DPD function was implemented with an indirect learning architecture. First, the PA-model function was calculated from the input and output signals of the PA and after that the DPD function was built by inverting the model.

In the early part of the measurements, it was important to find a proper model structure to be able to model the power amplifier with enough precision. In this case, we shortlisted three arbitrarily named GMP-based models, whose memory coefficients are presented in Figure 28. Generalized memory polynomial theory was discussed in Section 5.3 and these models are based on that.

Figure 28. Memory coefficients of arbitrarily named GMP models a) without memory, b) with short memory and c) with longer memory.

Memory coefficients of these models were adjusted with two parameters, where horizontal axis, *n* indicates advancing (negative) or delaying (positive) the signal sample, and vertical axis, *m* indicates advancing or delaying the power, respectively [21]. Below the coefficient is the number of how many degrees it can process – specified in more detail in Table 1 is in next Chapter.

The simplest of these models is memoryless GMP2, whose all six coefficients are in "real-time. The second model is GMP3, which contains in addition to the previous, memory terms in four different locations. Diagonal coefficients' degree is six and others' degree is two, so the total number of coefficients is 20. The most complex model is the GMP5, which contains even more memory coefficients and its total number of coefficients is 48.

6.1.4 Measurement system

Figure 30 shows a simplified visualization of the testbed used in laboratory measurements. Here, the modulated test-signal is first downloaded as complex I and Q signals to the signal generator (R&S SMW 200A). The signal generator up-converts the signal and feeds it to the pre-amplifier, which increases the power level and passes signal to the power amplifier, our device under test. Output of the amplifier is attenuated and downconverted in the spectrum analyzer.

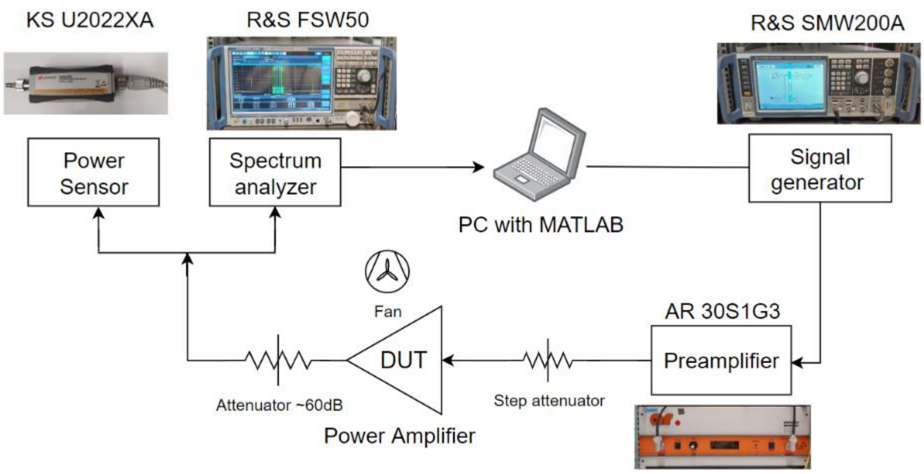


Figure 29. Diagram of measurement set-up.

6.1.5 Device Under Test

The experiments were done with Doherty amplifiers operated at 2.6 GHz with an output power of 46-47 dBm. Doherty is the ruling power amplifier architecture in use of wireless base stations today. Its advantage is the high efficiency even in backed-off from the peak power. The basic structure of the Doherty PA is presented in Figure 30 below. In a Doherty amplifier, the Peaking amplifier is switched on only at high power levels. [12]

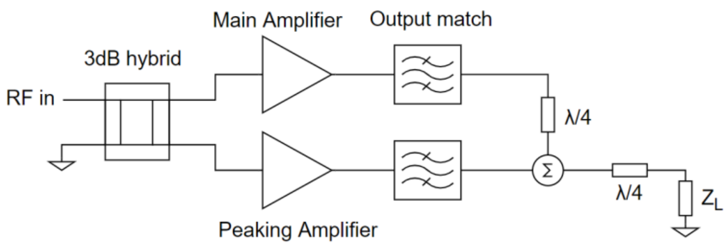


Figure 30. Doherty PA schematic.

7 EXPERIMENTAL RESULTS

In this Chapter, the measurement results will be introduced: Three chosen PA models were compared to one reference model in the light of earlier introduced performance parameters. Following Figures give information how well each of the models performs in power amplifier linearization. Experimental results were measured after 0 to 4 iterations, where iteration 0 indicates raw input signal without DPD and 4 refers to fully linearized.

We were measuring PAs of two different technologies: GaN (gallium nitride) and LDMOS laterally diffused metal-oxide semiconductor) to investigate if there occur differences between these technologies. All these PA variants (two of both) were measured in all models to investigate how much each of those variated between PAs. The parameters of these arbitrarily named models can be seen in Table 1. The target of this part was to find the GMP model which was as close as possible to the linearization performance of the reference model, which is used in real-life applications. The reference model is not GMP-based, so the coefficients are not comparable. [12]

Table 1. Parameters of used models

Model	Nbr. of Coeffs.	Degree	Iter-ations
GMP2	6	1-6	5
GMP3	20	1-3/1-6	5
GMP5	48	1-3/1-6	5
Reference	x	x	5

7.1 Power spectra of Feedbacks

Next, will be introduced Power Spectral Density (PSD) plots measured after every iteration from one GaN PA's output. PSD presents the normalized power content of the spectrum in the frequency domain [22]. This same measurement was done to all PAs and the results were similar except that the performance of memoryless model GMP2 was better with LDMOS, which will be seen in later Figures.

With following PSD Figures, we can visualize multiple important factors, such as ACP, IM3 and IM5 products, which were defined earlier as the most important nonlinearity figures of merit. We can also see how the number of iterations is affecting each model. Same measurements were done also with an even wider bandwidth, and the result were similar than presented in figures 31-34.

7.1.1 GMP2 - Memoryless model

In Figure 31, we see the simplest, memoryless GMP2 model's power spectrum. With this model, it is worthless to iterate the linearization more than once, because it gets to its best performance at once. The zoomed Figure shows that ACP is very poor with GMP2.

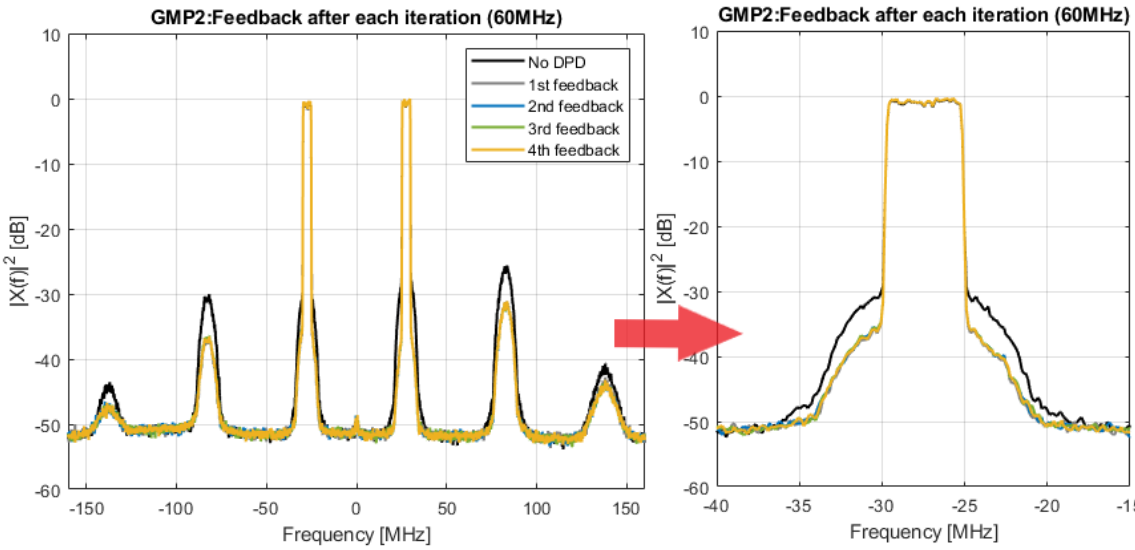


Figure 31. PSD captured with memoryless GMP2 model (GaN).

7.1.2 GMP3 – Model with shorter memory

Using the second model, GMP3, the linearity is greatly improved, as shown in Figure 32. Especially the IM3 level is remarkably lower than in the previous Figure. The IM5 level of lower frequency is also decreasing after every iteration, but the higher IM5 level stays high because of model limitation. The most significant improvement compared to memoryless model is the ACP level, which apparently requires memory features from the model. This Figure also shows an improvement in results as the iterations progress; some models require more iterations to achieve the best result.

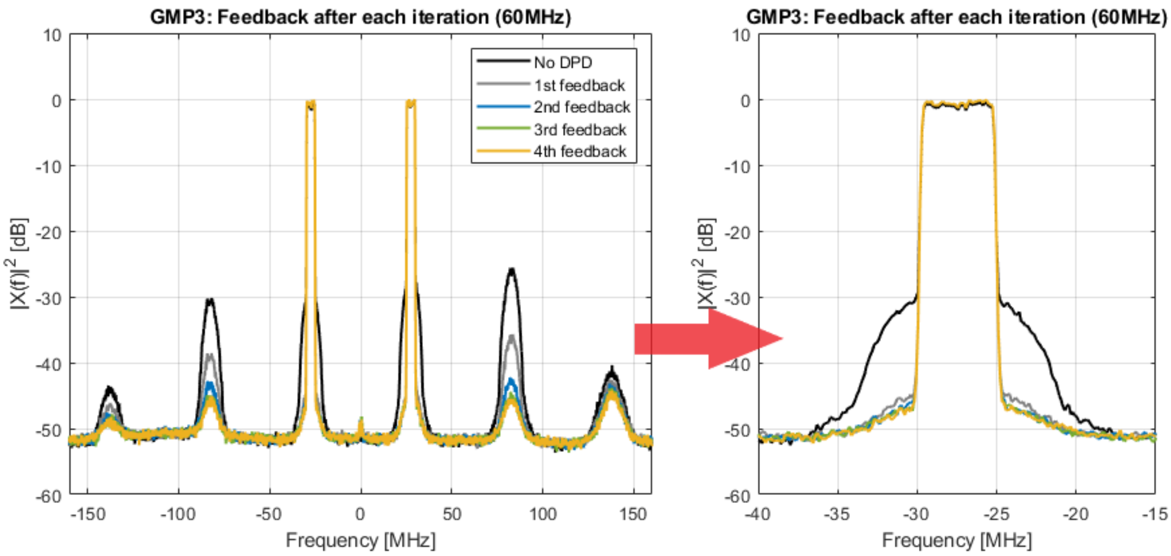


Figure 32. PSD captured with GMP3 model (GaN).

7.1.3 GMP5 - Model with longer memory

After adding more coefficients to the model, we get even better performance for IM3 and ACP levels, as presented in Figure 33. However, IM5 level is higher than with a shorter memory model GMP3 – and even more annoying is to see that IM5 level increases as the iteration progress.

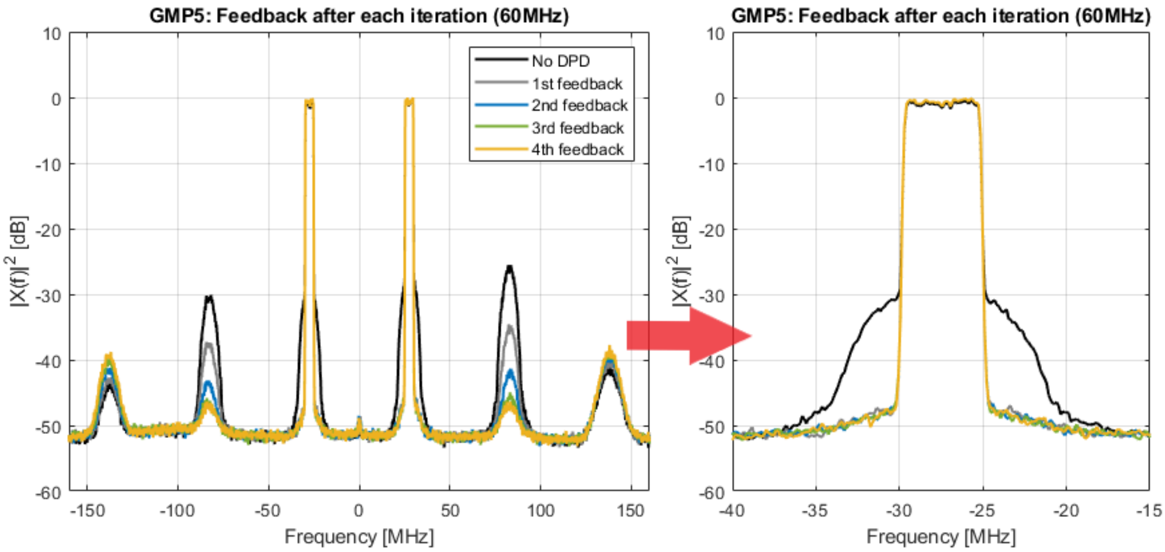


Figure 33. PSD captured with GMP5 model (GaN).

7.1.4 Reference model – This is how it should work

In Figure 34, it can be seen how well the Reference model linearized the PA: ACP is very flat straight after the first iteration and IM3 improving well.

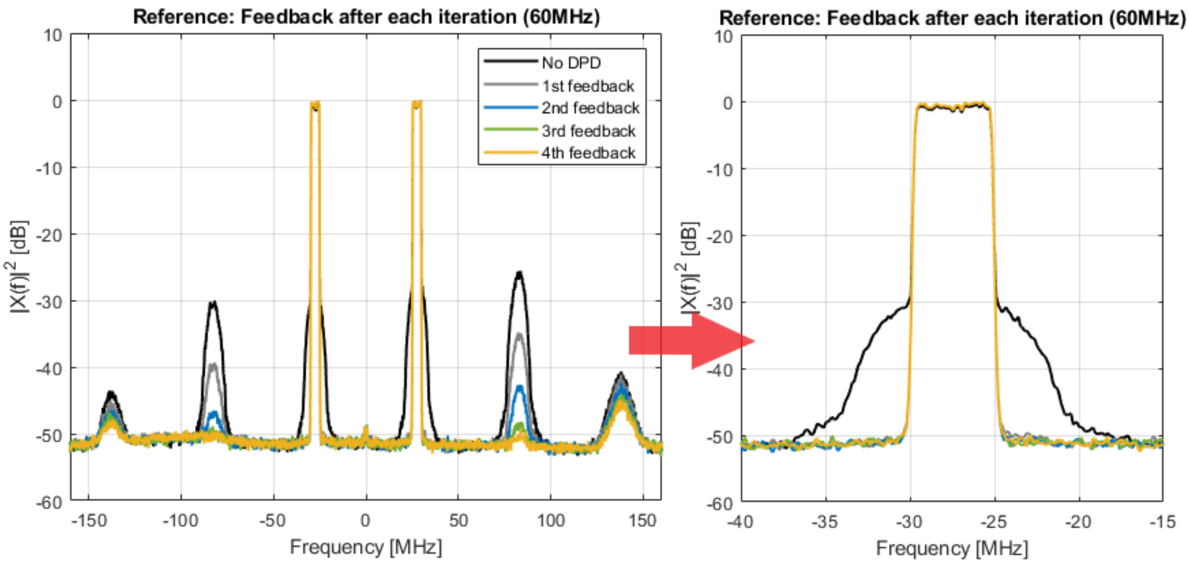


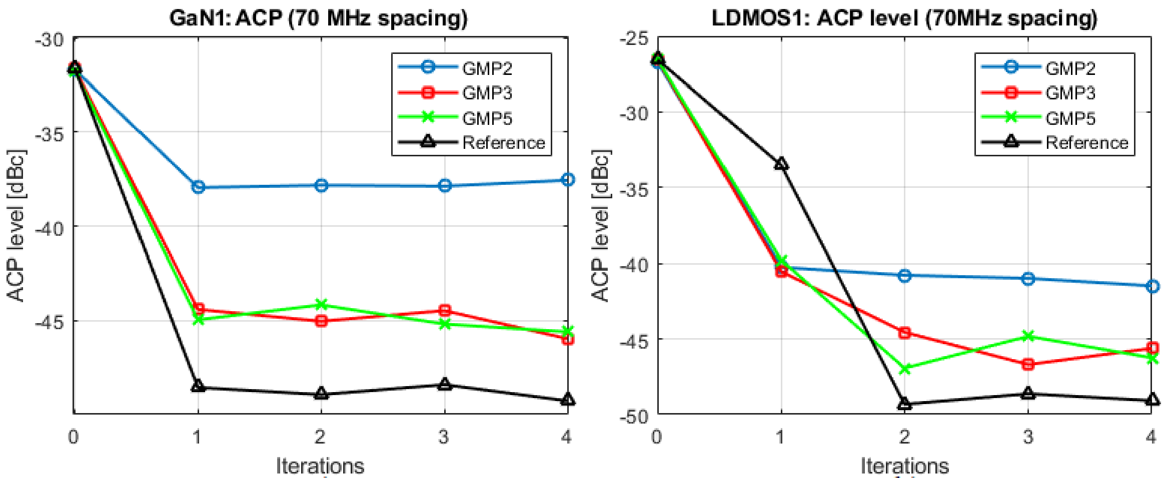
Figure 34. PSD captured with reference model (GaN).

7.2 ACPR

Adjacent channel power indicates the power leakage to the adjacent frequency channel. In the Power Amplifier linearization, it is one of the most important figures of merit. A high ACP value indicates more leakage of power, which in its turn decreases the efficiency. [14]

In the following Figure, it is presented the ACP development of two measured PAs with a different technology. The ACP after each iteration was measured from the lower and higher frequency bands and the worse one was considered.

In Figure 35, one thing to note is that, with GaN technology, ACP value is not improving at all even if there are multiple iterations done. With LDMOS, the ACP value is improving quite much during the first iterations.



a) b)

Figure 35. ACP variation after each iteration for two different technology a) GaN and b) LDMOS power amplifiers.

The next Figure 36 is very similar to the previous one, but the final ACP values of all measured Pas are compared there, with two different bandwidth signals. PAs 1 and 2 are GaN and 3 and 4 LDMOS technology.

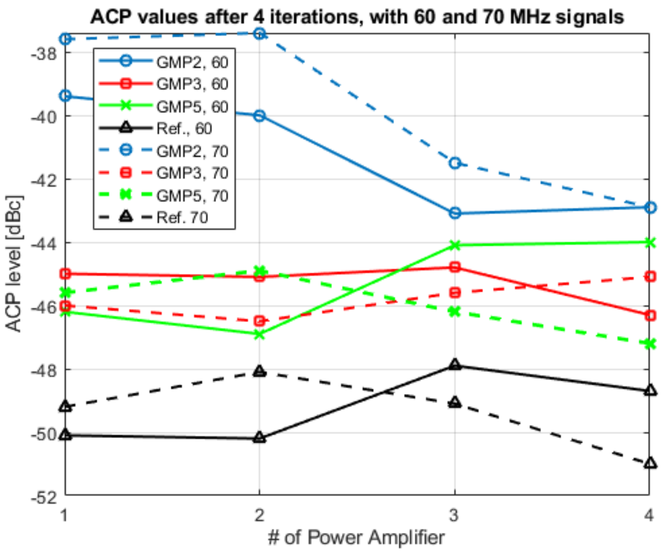


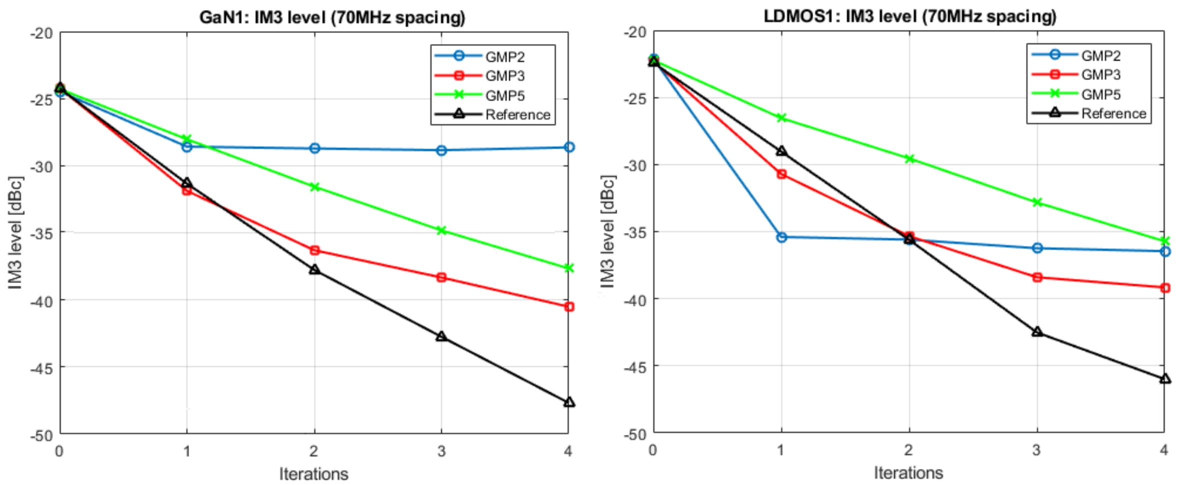
Figure 36. ACPR for all PAs with two bandwidths, 1 and 2 are GaN, 3 and 4 are LDMOS.

The reference model result is around 5 dB better than results with memory-GMP models. Noteworthy is also that the ACP value of memoryless model (GMP2) is almost 4 dB weaker with GaN than LDMOS. The reason may be that GaN linearization requires memory more than LDMOS.

It is also interesting to note that 60 MHz and 70 MHz spaced signal graphs of GMP5 and reference model are crossing between GaN and LDMOS. Because the ACP of 70 MHz signal is lower at LDMOS than GaN, it would suggest that GaN causes more memory effects, which can be seen only with the two most complex memory models. However, all these graphs are arbitrary, making it difficult to draw clear conclusions for the ACP.

7.3 IM3 and IM5

If linearizability of digital pre-distortion is poor, intermodulation product's level stays high. Thus, IM3 and IM5 levels are important figures of merit. In Figure 37, is presented the IM3 levels after each iteration for GaN and LDMOS amplifiers.



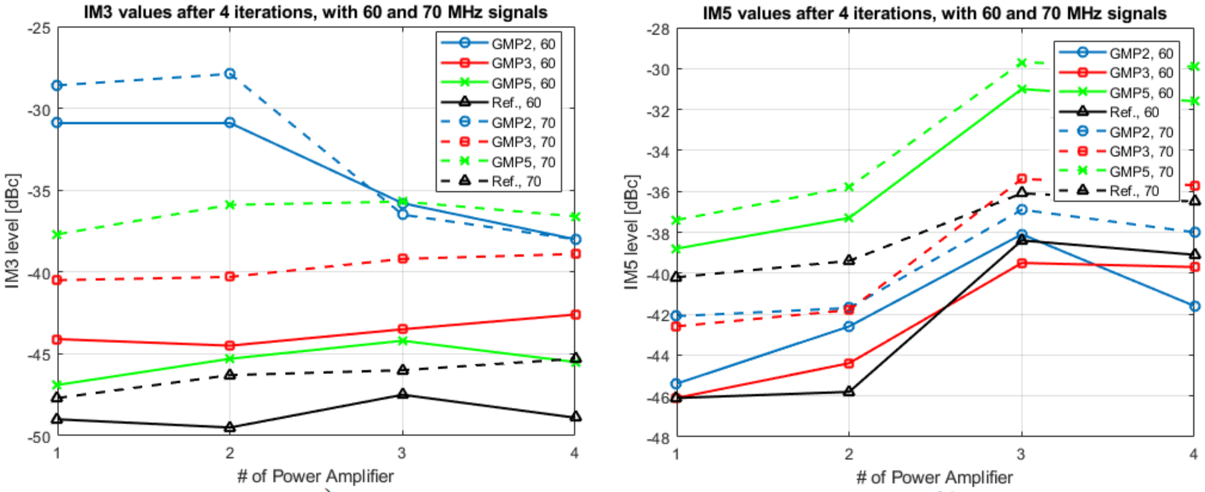
a) b)

Figure 37. IM3 levels after each iteration of a) GaN b) LDMOS power amplifiers.

From these Figures, we see that the IM3 level of memoryless GMP2 model (drawn in blue) is 8 dB worse with GaN than with LDMOS technology. In the LDMOS case, memoryless model performance is rather good after first iterations, but as the iterations progress, it no longer improves. The GMP3 model drawn in red, follows the reference model (black plot) well on both technologies until the difference increases after the third iteration. Here, the number of iterations could have been somewhat bigger, making the differences more visible.

The reason why the reference model stands out from the other models may be that its ability to minimize the error around the carriers is better than that of other models. When it corrects errors close to carrier frequencies faster, it can also put effort to better accuracy at IM3 frequencies. This can be seen as smoothing the IM3 plots of other models, which also have a weaker ACPR level.

In Figure 38, is presented the final IM3 and in IM5 values of all measured PAs with 60 and 70 MHz spacing test signals. IM3 values are staying stabile (within 2 dB) for all PAs, except for the memoryless model, GMP2 suffers from variation between GaN and LDMOS technologies (#1-2 and #3-4).



a) b)

Figure 38. IM3 (a) and IM5 (b) levels after five iterations for all measured PAs using both 60 and 70 MHz spaced test signals, 1 and 2 are GaN, 3 and 4 are LDMOS.

In Figure 38 b), IM5 levels are 5-10 dB lower with GaN than LDMOS. The longer memory GMP5 model is the worst in IM5 comparison, but the shorter memory GMP3 model better than the reference model. Therefore, we can note that useless memory coefficients are causing harm instead of good.

An important issue concerning IM3 and IM5 products is the symmetry of the lower and upper frequency products. As we saw in PSD Figures in Section 7.1, in all cases, the upper frequency IM levels are a few decibels higher than the lower frequency ones. This asymmetry is a result from the AM-AM and AM-PM conversion superposition, which means that the amplifier suffers from nonlinearity of both mentioned forms. This can be seen also in Tables in Section 7.5. A more detailed discussion can be found from the source below. [3]

7.4 Estimation error

An important issue in DPD is the estimation accuracy of the linearization algorithm. The idea is to improve the estimation accuracy after each iteration. When we want to investigate the model accuracy, we calculate the residual error between the input and pre-distorted output of each model. In Figure 40, we see the Normalized means squared error results between used models for all measured PAs. Results in Figure 39 have been measured with 70 MHz spacing signal, but the same measurements were also made with 60 MHz spacing. Both results were similar, but a wider bandwidth caused 1-2 dB larger error.

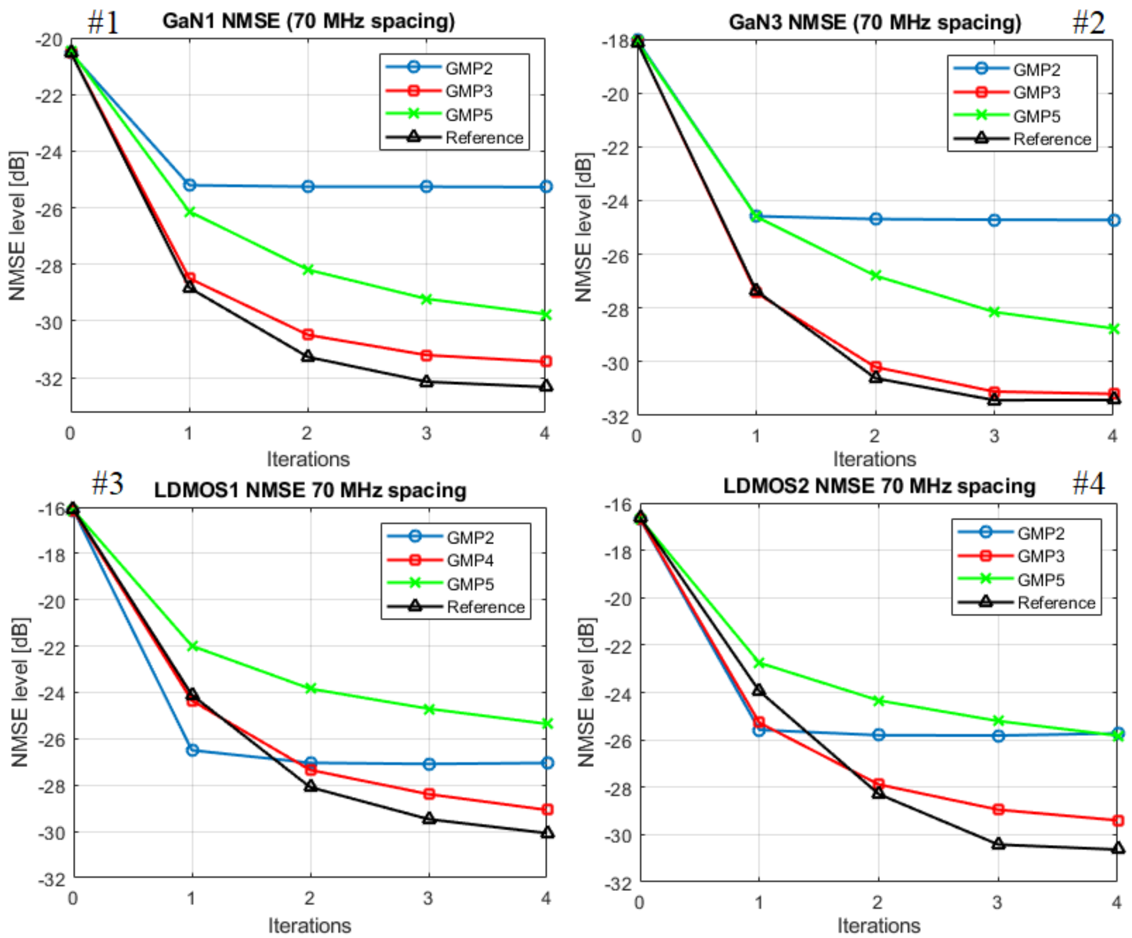


Figure 39. NMSE for all PAs, 1 and 2 are GaN, 3 and 4 are LDMOS.

There are also some differences between GaN and LDMOS technologies. Two top Figures, #1 and #2, are GaN technology and the bottom ones are LDMOS. If we compare the memoryless model (GMP2) performance between all PAs, we see that its performance is a few decibels better in LDMOS. The reason can be that GaN is a more sensitive technology for memory effects than LDMOS and thus the memoryless model's performance is weaker.

The difference between memory-GMP-models (GMP3 and GMP5) remains stable for each PA. It was assumed that a model with more memory coefficients would cause smaller error. However, with the shorter memory model, GMP3, the NMSE was at least 4 dB smaller than a longer memory model, GMP5. One reason for this is that the selected coefficients are not positioned correctly, so they cannot model the PA well. If the coefficients are not needed for modeling, they collect noise and only degrade the performance.

7.5 Summary of the results

In Tables 2-5 below, is presented a summary of PAs #1 (GaN) and #3 (LDMOS) results with 60 MHz and 70 MHz spaced test signals. From these results, the asymmetry between lower and upper frequencies and variations between two technologies and bandwidths can be seen. A wider bandwidth causes a small decreasing in results.

All in all, created models seem to follow the reference model's results reasonably well within these metrics, which can be considered an achievement.

Table 2. Experimental results of linearized PA #1 (GaN) with 60 MHz test signal

Model	**NMSE**	**ACP** [dBc]		**IM3** [dBc]		**IM5** [dBc]	
	[dB]	Low	High	Low	High	Low	High
GMP2	-26.9	-40.4	-39.4	-36.0	-30.9	-46.2	-45.4
GMP3	-32.3	-49.3	-45.0	-44.1	-46.5	-47.4	-46.1
GMP5	-30.9	-49.0	-46.2	-46.9	-47.5	-38.8	-39.4
Reference	-32.7	-50.1	-51.3	-49.3	-49.0	-48.4	-46.1

Table 3. Experimental results of linearized PA #3 (LDMOS) with 60 MHz test signal

Model	**NMSE**	**ACP** [dBc]		**IM3** [dBc]		**IM5** [dBc]	
	[dB]	Low	High	Low	High	Low	High
GMP2	-27.6	-44.3	-43.1	-41.1	-35.8	-44.2	-38.1
GMP3	-30.7	-47.7	-44.8	-45.5	-43.5	-46.5	-39.5
GMP5	-27.0	-47.8	-44.0	-47.2	-44.2	-35.7	-31.0
Reference	-30.1	-49.6	-47.9	-48.0	-47.5	-41.7	-38.4

Table 4. Experimental results of linearized PA #1 (GaN) with 70 MHz test signal

Model	**NMSE**	**ACP** [dBc]		**IM3** [dBc]		**IM5** [dBc]	
	[dB]	Low	High	Low	High	Low	High
GMP2	-25.5	-37.6	-39.3	-35.3	-28.6	-46.5	-42.1
GMP3	-31.4	-46.0	-46.0	-43.1	-40.5	-46.1	-42.6
GMP5	-29.8	-45.6	-45.9	-40.1	-37.7	-39.3	-37.4
Reference	-32.3	-49.2	-50.8	-50.3	-47.7	-43.2	-40.2

Table 5. Experimental results of linearized PA #3 (LDMOS) with 70 MHz test signal

Model	**NMSE**	**ACP** [dBc]		**IM3** [dBc]		**IM5** [dBc]	
	[dB]	Low	High	Low	High	Low	High
GMP2	-27.0	-41.9	-41.5	-38.5	-36.5	-43.3	-36.9
GMP3	-29.1	-46.7	-45.6	-40.6	-39.2	-42.9	-35.4
GMP5	-25.4	-48.4	-46.2	-39.7	-35.7	-36.2	-29.7
Reference	-30.1	-49.8	-49.1	-46.0	-46.2	-39.5	-36.1

The plan was to verify the created model with several more amplifiers, which, however, proved impossible on schedule so the verification process is discussed in future work section in the next Chapter.

8 DISCUSSION

The aim of this thesis was to create a power amplifier behavioral model to find the optimal PA component to match the existing DPD algorithm of Nokia. The model was created using generalized memory polynomial (GMP) based PA models and comparing them with the existing reference model. Initially, several variations of GMP model structure were used with different configurations: first, the memoryless model, which was complicated step by step. After few complex but poor models, it was simplified a lot, which turned out to be the most optimal one.

Based on the experimental results, it was proved that a memory model represents a physical nonlinear component, such as a power amplifier, much better than a memoryless polynomial model. The difference between them increases even more as the model coefficients are updated adaptively as the number of iteration increases. On the one hand, a memoryless behavioral model is capable of counteracting the static nonlinear behaviour, but, on the other hand, the model should also be able to find the dynamic nonlinear behaviour. Therefore, it is important that the model has memory if it is used in broadband applications, where the nonlinearity is a bigger problem.

However, it was also showed that an overly complex behavioral model is not good if the coefficients are not correctly positioned, which was learned the hard way in the early stages of model development. Useless coefficients collect noise, degrading model accuracy and consume capacity for no reason. This issue becomes relevant when the performance of devices needs to be fully optimized. To answer the question “which is the best structure of the model?”, it is essential to remember that the key target of digital pre-distortion is to meet the specification of used modulation format. There is no prize even if the ACPR wins the specification by 15 dB. In practice, it is important to determine the DPD structure so that it can be extended if the original system does not meet the specification.

Based on the results presented in Chapter 7, it can be said that the first target – accurate behavioral model – was achieved. If the results are evaluated with the parameters presented, such as ACPR, IM3 and NMSE, the created model was even better than expected. In some cases, such as IM3 comparison, the number of iterations should have been somewhat higher, which would have shown the progress of results better. For the number of iterations used, the created model worked well. However, the thesis also had another final goal: Finding the main causes of nonlinearity and correlation with DPD model parameters. This goal proved to be as challenging as expected in this time limit – creating a new PA model is a very demanding, specialist work that requires persistent work on that subject.

What is the new value that this tool creates to a company? If the “reference product” is not possible – or allowed – to use, these created models can be used for many purposes. The experimental results proved that models fulfil the measured reference specification. By using these models, there are at least two ways to improve the current way of working: First, when working with other organizations, such as component vendors, own secret products may not be usable. In such a situation, it is useful to have a matching model that can be used as a measure of own product. Therefore, the amplifier can already be optimized close to its final linearization algorithm and save time from later work, which can also be called “Shift Left”. This is an important improvement. Another use case is the design and testing of the pre-distortion algorithm. By using differently parameterized models than those in actual product, linearization may be more realistic, and linearization weaknesses will be more visible.

The topic of this thesis was broad and somewhat challenging, but also instructive and rewarding. In this project, power amplifier measurements were done multiple times which was very time-consuming, but it gave also good touch in PA measurements in general. Analysing results with MATLAB gave good knowledge on signal processing tools, which may be useful also in other tasks in the future.

8.1 Future work

As mentioned in Chapter 7, the PA model created in this thesis was still planned to be tested with several power amplifiers more. Even the experimental results were already measured with four power amplifiers, a larger set in verification would ensure the accuracy. The plan was to measure 5-10 amplifiers with the product's official linearization algorithm in another, calibrated test bench. Comparing them with the results linearized with the model developed in this thesis (GMP3) would give a realistic estimate of the model's performance and provide a better starting point for further development of the tool. The GMP3 model reliability was proved in this thesis at least at some level, but more careful evaluation is necessary in the future. The output power level variation between measured amplifiers could cause small errors between results, which must be removed from future measurements. Also, current measurement devices and set-up caused a quite high noise level, which limited the usage of some results. Especially comparing the AM/AM and AM/PM characteristics in the future, noise floor must be as low as possible. However, these factors do not degrade the result presented in this thesis but are mainly considerations for the future.

When there was discussion about this project, there occurred plenty of ideas in which direction this should be taken. Most of these ideas could not be implemented in this thesis, so a few proposals for the future steps are introduced next. First, piloting this behavioral model to product projects. As mentioned earlier, a modeling tool based on this thesis could be used in collaboration between different parties, such as amplifier design with the manufacturer. This kind of co-modeling tool is another campaign, but it has potential that should definitely be exploited.

Secondly, this modeling tool could be used improving the linearization algorithm design. A more realistic testing on the linearization algorithm could be implemented with a PA model different from DPD. If the PA model criteria are the same as the DPD model, it is obvious that the adaptation is successful. So, the power amplifier and digital pre-distortion algorithm should be developed together already at an earlier stage.

Third, a generated power amplifier model would be interesting to integrate into simulation environment, such as Simulink®. However, simulating a power amplifier is challenging because it is a nonlinear component and its modeling is difficult. But as a concept, all the things that could be done before producing the actual component should be investigated.

9 SUMMARY

Transmitters in modern telecommunication systems are expected to handle amplitude and phase modulated signals with consistently higher bandwidths, which tightens the whole system specifications. A power amplifier is one of the most difficult problems to solve requiring good efficiency versus higher linearity. Power amplifier linearization is not straightforward, but it can decrease power dissipation remarkably. In this thesis, the goal was to create a behavioral PA model to improve the power amplifier design and linearization process. An improved PA modeling process could achieve better linearizability, shorter time to market and remarkable cost saving.

In this thesis, a comprehensive overview of power amplifiers, their linearization and especially digital pre-distortion techniques was given. In the beginning, for gaining a better understanding of the whole system, the RF transmitter's main requirements and phenomena were introduced with the most important figures of merit. After the transmitter, a bit more specific area, Power amplifier theory, was discussed. PA is one of the key components in characterizing the entire transmission system and the most energy consuming component, so the theory behind it must be well known. Memory effects were also introduced with the power amplifier. Modern, wideband systems are sensitive to memory effects, which will be an even more important issue in future systems.

The theory section continued with the most common linearization techniques of power amplifiers. One of the most common linearization methods used in modern wireless systems, and also in this thesis, digital pre-distortion, was discussed in more detail. Finally, in the theory section, the power amplifier behavioral modeling and metrics were introduced, which will be significant in the future system modeling. Different DPD models, both memoryless and memory nonlinear models and modeling error measures, such as mean squared error, were also introduced here.

After theory introduction, the measurement system was presented. Several Doherty power amplifiers were measured and linearized with three different PA model configurations and the results were compared to the reference model. Measurements were done with two signals with different bandwidths: 2x5 MHz LTE signal with 60 MHz and 70 MHz spacings. By measuring multiple amplifiers with two different bandwidths, we were able to draw better and more reliable conclusions from the results.

The analysis section focused on the comparison of PA models: which of the models was closest to the reference model and how big the differences are between the models? As expected, the results confirmed that models with memory have better performance than memoryless models. A memoryless model was able to correct the static nonlinearities, but its correction was quite limited. The model with shorter memory (less memory coefficients) turned out to be the best option, which was a bit of surprising. The reason was probably that the memory coefficients must be positioned correctly in order to be useful – if the coefficients are in the wrong position, they only collect noise and interfere with linearization. And, it is also essential to remember that the key target of digital pre-distortion is to meet the specification and not so much to break records. Therefore, the main conclusion of results of this thesis is to avoid too complex behavioral models. Simple is beautiful.

10 REFERENCES

[1] Cripps, S. (1999) RF Power Amplifiers for Wireless Communications. Artech House Inc.

[2] Han, T. & al. (2011) Green radio: Radio Techniques to Enable Energy-Efficient Wireless Networks. IEEE Communication Magazine May, 46 – 50 pp.

[3] Kenington P. (2000) High-Linearity RF Amplifier Design. Artech House Inc.

[4] Cheong M. (2013) Development of digital predistorters for broadband power amplifiers in OFDM systems using the simplicial canonical piecewise linear function. Doctoral Dissertation. Aalto University, Department of Signal Processing and Acoustic, Helsinki.

[5] Morgan D. & al. (2006) A Generalized Memory Polynomial Model for Digital Predistortion of RF Power Amplifiers. IEEE Transactions on Signal Processing, Vol. 54, No. 10, 3852 – 3860 pp.

[6] Ding L. & al. (2004) A Robust Digital Baseband Predistorter Constructed Using Memory Polynomials. IEEE Transactions on Communications, Vol. 52, No. 1, 159 – 165 pp.

[7] Ghannouchi F., Hammi O. & Helaoui M. (2015) Behavioral Modeling and Predistortion of Wideband Wireless Transmitters. John Wiley & Sons Ltd

[8] Edited by Luo F., (2011) Digital Front-End in Wireless Communications and Broadcasting - Circuits and Signal Processing. Cambridge University Press

[9] Vuolevi J. & Rahkonen T. (2003) Distortion in RF Power Amplifiers. Artech House.

[10] Pozar D. (2012) Microwave Engineering 4th edition. John Wiley & Sons, Inc.

[11] Vuolevi J. (2001) Analysis, measurement and cancellation of the bandwidth and amplitude dependence of intermodulation distortion in RF power amplifiers. Doctoral Dissertation. University of Oulu, Department of Electrical Engineering, Oulu.

[12] Wood, J. (2014) Behavioral Modeling and Linearization of RF Power Amplifiers. Artech House.

[13] Luzzatto A. & Shirazi G. (2007) Wireless Transceiver Design: Mastering the Design of Modern Wireless Equipment and Systems. John Wiley & Sons Ltd.

[14] Raghavan, A., Srirattana N. & Laskar J. (2008) Modeling and Design Techniques for RF Power Amplifiers. John Wiley & Sons Ltd.

[15] Tehrani A. (2012) Behavioral modeling of wireless transmitters for distortion mitigation. Doctoral Dissertation. Chalmers University of Technology, Department of Signals and Systems, Gothenburg.

[16] Vuolevi J, Rahkonen T. & Manninen J. (2001) Measurement Technique for Characterizing Memory Effects in RF Power Amplifiers. IEEE Transactions on Microwave Theory and Techniques Vol. 49, No. 8, 1383 – 1389 pp.

[17] Wisell D. (2007) Measurement Techniques for Characterization of Power Amplifiers. Doctoral Dissertation. Kungliga Tekniska Högskolan, School of Electrical Engineering, Stockholm.

[18] Complex Bandpass Filter Design with MATLAB (read 10.1.2020) URL: https://se.mathworks.com/help/dsp/examples/complex-bandpass-filter-design.html

[19] Teikari I. (2008) Digital predistortion linearization methods for RF power amplifier. Doctoral Dissertation, Helsinki University of Technology, Department of Micro and Nanosciences, Helsinki.

[20] Paaso H. & Mämmelä A. (2008) Comparison of Direct Learning and Indirect Learning Predistortion Architectures. In: IEEE International Symposium on Wireless Communication Systems, October 21 – 24, Reykjavik, Iceland.

[21] Confidential Document 1, Nokia.

[22] What is Power Spectral Density (PSD)? (read 9.2.2020) URL: https://community.sw.siemens.com/s/article/what-is-a-power-spectral-density-psd

[23] A new variant of the indirect learning architecture for the linearization of power amplifiers, In: 10^{th} European Microwave Integrated Circuits Conference (EuMIC), September 7 – 8, Paris, France.

[24] Cao, H. (2011) Linearization of High Efficiency Transmitters for Wireless Communications. Doctoral Dissertation, Chalmers University of Technology, Department of Microtechnology and Nanoscience, Gothenburg.

[25] Wisell, D., Isaksson M. & Keskitalo N. (2007) A General Evaluation Criteria for Behavioral Power Amplifier Modeling. In: 69^{th} ARFTG Conference, June 8, Honolulu, USA.