OULUN YLIOPISTO

FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING

DEGREE PROGRAMME IN ELECTRONICS AND COMMUNICATIONS ENGINEERING

MASTER'S THESIS

PASSIVE INTERMODULATION TESTER CHARACTERISTICS

Author	Veli Kuronen
Supervisor	Timo Rahkonen
Second Examiner	Janne Aikio
Technical Advisor	Timo Tarvainen

March 2020

Kuronen V. (2020) Passive intermodulation tester characteristics. University of Oulu, Faculty of Information Technology and Electrical Engineering, Degree Programme in Electronics and Communications Engineering. Master's Thesis, 59 p.

ABSTRACT

Passive intermodulation (PIM) is a severe issue for base transceiver stations. It can cause issues to the receiver of the device or to nearby devices if power levels are high enough. In the past, there have been many studies on the PIM, mostly concerning on modelling and mitigation of PIM. In this thesis, 3rd and 5th order forward PIM levels are measured and analysed from base station filters to determine if they are good enough for receiving of low-level signals. Also, used PIM test setup is simulated with modified component parameters for finding output third order intercept point (OIP3) threshold values of each component for which the setup still provides accurate enough results. Also, noise level calculations and cost estimation of typical PIM test setup is presented.

PIM products were measured with accurate test setups that had residual PIM levels clearly below measured levels. As PIM performance often varies with time all measurements were repeated several times. The best unit out of all 10 measured devices under test (DUTs) had 100 % pass rate and less than 2.5 dB standard deviation. Results were also more than 8.5 dB over the limit in average. All the results were calculated from all measurement samples of DUTs. There were 4 – 16 of measurements per DUT. The worst unit had 25 % pass rate and PIM results that were below limit in average. PIM results suggest that high standard deviation is linked to failed results, usually. Two additional DUTs was tested for finding if the source was electro-thermal nonlinearity. The results suggest that it might have been the source, but due to low quantity of measurements, waterproof conclusion can't be made.

There are many limiting factors in testing of PIM. First of all, the test results must be clearly above noise floor in order to see the real PIM products. Also, the test setup must have its residual intermodulation at least 10 dB below the measured PIM of DUT. Then, the measured results are considered to be accurate enough. That's why the components of the setup have to be low-PIM. For these reasons, test setup simulations were done with AWR simulation tool in order to find the threshold values on which the setup still provides reliable test results for each test setup components. It was found out that the combiner should have the highest OIP3 value, of at least 61.3 dBm when ≈ 40 dB notch filter was used before DUT at the measured 3rd order PIM frequency. Without notch, OIP3 should be at least 73.7 dBm. Therefore, notch filter lowered the need of OIP3 by 12.4 dB. Signal generators, power amplifiers and circulators of the setup were limited by their 1 dB compression point.

As a conclusion, this thesis work was successful since the limitations of the setup were found by simulations and calculations. Also, testing and analyzing of PIM products was performed successfully with low residual levels. The theory, calculations and simulations presented in this thesis can be used in acquisition of PIM test setup components. Also, the simulation model can be modified for simulating the PIM impact of any components in the test setup.

Key words: passive intermodulation, non-linear, residual intermodulation, low-PIM, test setup simulation.

Kuronen V. (2020) Passiivisen keskinäismodulaatiotesterin piirteet. Oulun yliopisto, tieto- ja sähkötekniikan tiedekunta, elektroniikan ja tietoliikennetekniikan tutkinto-ohjelma. Diplomityö, 59 s.

TIIVISTELMÄ

Passiivinen keskinäismodulaatio (PIM) on vakava häiriö tukiasemille. Kun signaalien teho on tarpeeksi suuri, voi PIM aiheuttaa suuria ongelmia laitteen vastaanottamiskykyyn tai muihin lähellä oleviin laitteisiin. PIM:n mallinnusta ja heikennystä on tutkittu paljon menneisyydessä. Tässä diplomityössä 3:n ja 5:n asteen suoraan etenevän (eng. forward) PIM:n tasoja mitataan ja analysoidaan tukiasemien suodattimista, jotta voidaan päättää onko ne hyviä pienitehoisten signaalien vastaanottamiseen. Lisäksi käytettyä PIM-testijärjestelmää simuloidaan muuntamalla testijärjestelmän komponenttien parametrejä siten, että löydettäisiin jokaisen komponentin kolmannen asteen leikkauspisteen (OIP3) raja-arvot, jolla testijärjestelmä toimii taaten tarpeeksi tarkkoja tuloksia. Tavanomaisen PIM-testijärjeslmän kohinatason laskuja ja kustannusarvio on myös esitetty.

PIM-tuotokset mitattiin tarkoilla testijärjestelmillä, joiden residuaaliset PIM-tasot olivat selvästi alle tutkittavasta laitteesta (DUT) mitattavia tasoja. Parhaalla yksiköllä 10:stä mitatusta oli 100 %:n läpäisytaso sekä alle 2,5 dB:n keskihajonta. Lisäksi, tulokset olivat keskimäärin 8,5 dB parempia kuin läpäisyraja. Kaikki tulokset on laskettu DUT:en kaikista mittausnäytteestä, joita oli 4 – 16 per DUT. Huonoimalla yksikkö oli 25 %:n läpäisytaso ja sen tulokset olivat keskimäärin alle läpäisyrajan. PIM-tulokset viittaavat siihen, että suuri keskihajonta on yleensä yhteydessä huonoihin tuloksiin. Kaksi ylimääräistä yksikköä testattiin, jotta tiedettäisiin olisiko PIM:n lähteenä sähkö-terminen epälineaarisuus. Tulokset viittaavat, että se voisi olla PIM:n lähde, mutta pienestä testimäärästä johtuen vedenpitävää johtopäätöstä ei voida tehdä.

PIM:n testauksessa on monia rajoittavia tekijöitä. Ensinnäkin, testitulosten pitää olla selvästi yli kohinatason, jotta ne erottuvat nähtäviksi. Myös testijärjestelmän residuaalisen keskinäismodulaatio pitää olla vähintään 10 dB:ä matalemmalla tasolla kuin testattavan yksikön PIM. Siten mitatut tulokset mielletään tarpeeksi tarkoiksi. Sen takia testijärjestelmän osien pitää olla pienitasoisia PIM-teholtaan. Näiden syiden takia, testijärjestelmän simulointeja tehtiin AWR-simulointityökalun avulla, jotta löydettäisiin raja-arvot mittajärjestelmän eri osille, millä mittajärjestelmä tuottaa luotettavia tuloksia. Selvitettiin, että kaikista osista yhdyssuodattimella (eng. combiner) pitäisi olla suurin kolmannen asteen leikkauspiste (OIP3), vähintään 61.3 dB noin 40 dB:n kaistanestosuodattimen, joka tulee ennen DUT:a mitattavalle PIM-taajuudelle, kanssa ja vähintään 73.7 dB ilman kaistanestosuodatinta. Täten suodatin laski OIP3:n tarvetta 12.4 dB. 1 dB kompressiopisteet rajoittivat OIP3-raja-arvoja signaaligeneraattoreilla, tehovahvistimilla ja sirkulaattoreilla.

Kaikkiaan työ oli onnistunut, sillä testijärjestelmän rajoitukset löydettiin simulointien ja laskutoimitusten avulla. Lisäksi mittaukset ja PIM-tulosten analysointi tehtiin onnistuneesti pienillä residuaalisilla tasoilla. Tämän diplomityön teoriaa, laskutoimituksia ja simulaatioita voidaan käyttää PIM-testijärjestelmän komponenttien hankintaan. Lisäksi, simulaatiomallia voidaan muokata siten, että minkä tahansa komponentin vaikutusta PIM-häiriöihin voidaan simuloida sen avulla.

Avainsanat: passiivinen keskinäismodulaatio, epälineaarinen, residuaalinen keskinäismodulaatio, pienitasoinen PIM, testijärjestelmän simulointi.

TABLE OF CONTENTS

PREFACE

This work was made at Flex Oulu Design Center. The purpose of this thesis was to measure different filter modules of base stations and analyze the results. Also, the restrictions of the PIM testing setup were studied with the help of AWR simulations.

I would like to thank my technical adviser Timo Tarvainen for the idea of this thesis and the guidance throughout the writing process. Thanks to supervisor Timo Rahkonen for all the guiding and correction propositions. Also, thanks to second examiner Janne Aikio.

Finally, I would like to thank my family, girlfriend and friends for all the support and motivation during the writing of this thesis.

Oulu, March 31, 2020

Veli Kuronen

LIST OF ABBREVIATIONS AND SYMBOLS

a_n	Taylor coefficient
A	Amplitude
B	Bandwidth
C	Capacitance
d	Distance of an object from antenna
D	Longest dimension of the antenna
f	Frequency
$f_{1,2}$	Frequency of carrier signal
f_{IM}	Intermodulation frequency
F	Noise factor
G_p	Power gain
I_D	Diode current
I_s	Saturation current
k	Boltzmann's constant
K_i'	Zero location
m, n, N	Positive integer number
No	Noise floor
NF	Noise figure
t	Time
P	Power
P_{dis}	Dissipated electrical power
P_{DC}	Direct current power
$P_{I@O}$	Fundamental input tone power at output
P_{IM3}	3rd order intermodulation power
P_{loss}	Total loss power
q	Charge of an electron
R	Resistance
R_{th}	Thermal resistance
T	Temperature
T_{sweep}	Sweep time
T_a	Ambient temperature
V_D	Diode voltage
V_t	Threshold voltage of diode
V_T	Thermal voltage
x_n	Test result
x_a	Average test result

4G	Fourth generation
5G	Fifth generation
BTS	Base transceiver station
CA	Carrier aggregation
CDMA	Code division multiple access
CW	Continuous wave
DAS	Distributed antenna system
DANL	Displayed average noise level
DC	Direct current
DSP	Digital signal processing
DTP	Distance-to-PIM
DUT	Device under test
ET-PIM	Electro-thermal passive intermodulation
FDD	Frequency division duplex
I-V	Current-voltage
IEC	International Electrotechnical Commission
IIP3	Input third order intercept point
IP3	Third order intercept point
IM	Intermodulation
IM2	2rd order intermodulation
IM3	3rd order intermodulation
IM5	5rd order intermodulation
IP3	Third order intercept point
LNA	Low-noise amplifier
LTE	Long term evolution
MIM	Metal-insulator-metal
MM	Metal-to-metal
OFDM	Orthogonal frequency-division multiplexing
OIP2	Output second order intercept point
OIP3	Output third order intercept point
P1dB	1 dB compression point
PIM	Passive intermodulation
PIM3	3rd order passive intermodulation
PIM5	5rd order passive intermodulation
PIMC	Passive intermodulation cancellation
RBW	Resolution bandwidth
RC	Resistor-capacitor
RF	Radio frequency
RX	Receive
SA	Signal analyzer
TCR	Temperature coefficient of resistance
TX	Transmission

Δ	A change of quantity
Σ	Sum
θ	Phase
λ	Wavelength
σ	Standard deviation
σ_i	Pole location
τ_n	Delay of stimuli
ω_c	Angular frequency of carrier signal

1 INTRODUCTION

Passive intermodulation (PIM) is a severe issue in modern transceiver systems that operate with high powers. PIM causes elevated noise floors which weakens the sensitivity level of the receiver. Therefore, receiving of low power signals becomes much harder or sometimes even impossible. PIM is considered as a highly sensitive interference and it may have multiple sources at the same time. PIM is generated when two or more high power carrier signals are mixed in a non-linear passive component like circulator or isolator or in multiple components. The most usual PIM sources are the connectors in the signal path. Usually, the most harmful components are the 3rd order PIM products since they are the most powerful PIM components that can't be filtered out if they are produced on RX frequency band of the device. Disadvantages of PIM can be dropped calls, connection losses and degrading data rates. Therefore, PIM related problems must be considered already in the designing phase. One way of preventing high level PIM is to avoid high current densities in signal paths.

Testing of PIM has become a standard test of linearity of RF-devices like base stations. PIM has been tested with various test setups that have some limitations. Usually, most of those limitations are due to very low power level of PIM products. Noise floor and residual PIM levels of the setups must be very low in order to measure the PIM products that DUT produces itself. Residual PIM level of the test setup must be at least 10 dB below of the measured PIM of the DUT according to IEC62037 standard. [30] These restrictions mean that the test setup must have highly linear components and a receiver that can detect PIM products from the noise floor.

This thesis focuses on testing and analyzing of PIM results from different DUTs. Also, simulation model for PIM testing is done to determine the reliability of the test results. Additionally, components of the test setup are simulated with different parameter values in order to find threshold values on which the test setup still works properly for each component of the setup. Also, noise considerations of the setup are presented.

In this thesis, Chapter 2 deals with the theory of intermodulation. It examines the mechanism of how the intermodulation (IM) products are developed in nonlinear components. Additionally, it deals with the power levels of IM products. Chapter 3 concentrates on the sources, types and harmful effects of passive intermodulation PIM. Chapter 4 deals with the test setups and their limitations. Also, it presents the measurement results and analysis of them. Additionally, noise considerations and cost estimations are included. Chapter 5 focuses on the test setup modelling with AWR simulation tool. Also, simulation results and analysis are presented. Discussion of the work is presented in the Chapter 6. And lastly, Chapter 7 summarizes this thesis by stating the objectives and reviewing the most important test and simulation results.

2 THEORY OF INTERMODULATION

This Chapter describes the basics of intermodulation (IM) theory. Intermodulation products, power levels and disadvantages of IM are discussed.

2.1 Nonlinear systems

Intermodulation is a type of amplitude modulation where two or more fundamental frequency signals mixes into many more frequency components if the system has nonlinearity. Many problems like unwanted modification to gain and signal shapes can occur. Thus, linearity is usually desired. A system that is nonlinear does not comply with superposition principle. It means that the output signal of two or more input signals is not the sum of each individual outputs of each input signals. As an example of this nonlinearity, as stated in [1], the power gain (G_p) of transmitter power amplifier (PA) is:

$$G_p = 1 + \frac{P_{DC} - P_{diss}}{P_{in}} \quad (1)$$

where P_{DC} is the direct current (DC) power of the power supply, P_{diss} is the total loss power and P_{in} is the input power. As seen from Equation (1), it is impossible for the amplifier to keep the same gain as the input power increases because the power supply has a limited power it can deliver to the amplifier. Also, insertion losses are not likely the same with all different input powers because of the heat dissipation for example. Therefore, as the input power increases, the output power will stop increasing at some point. The amplifier has clearly nonlinear behavior that can be seen from the Figure 1 (red line), where the power transfer characteristics is seen. The amplifier would be completely linear if the output power would increase with the same rate as the input like the ideal straight (blue) line in the Figure 1. [1]

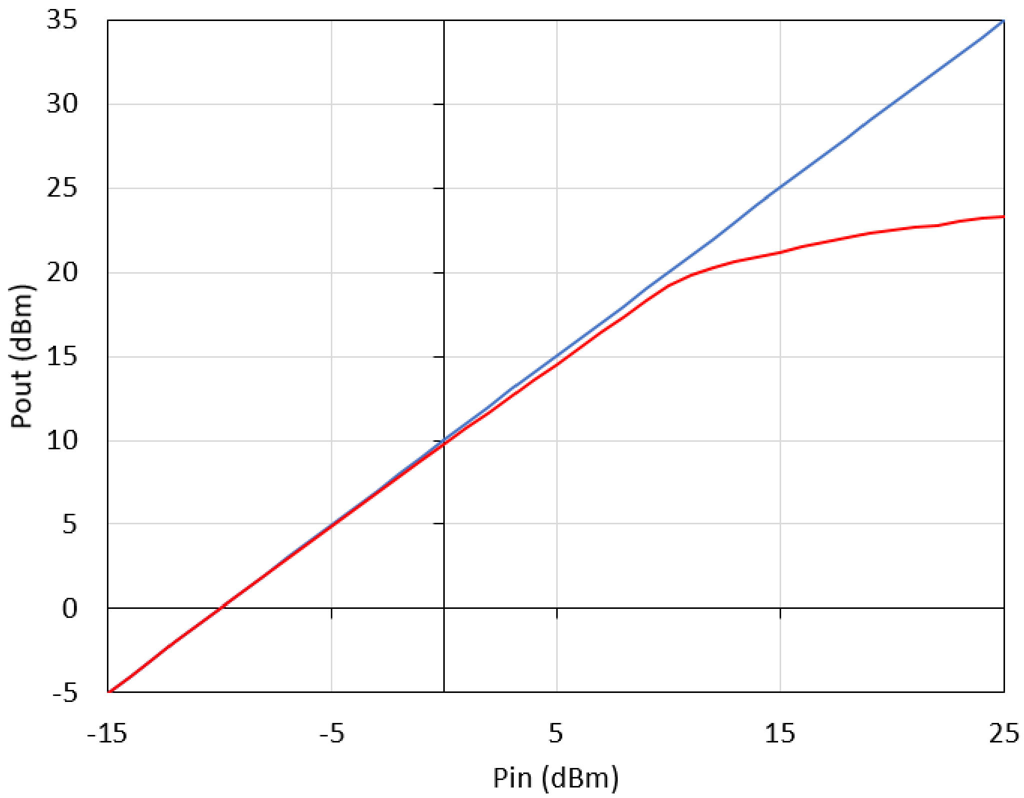

Figure. 1. Ideal (blue) and typical (red) power transfer characteristics of an amplifier. [1]

Usually, in wireless environment stimulus inputs are sinusoids, that are amplitude and phase modulated by baseband signals, in form of Equation (2), [1]

$$x(t) = A(t)\cos\,[\omega_c t + \theta(t)] \qquad (2)$$

where amplitude $A(t)$ and phase $\theta(t)$ are functions of time t and ω_c is the angular frequency of the carrier signal. The response of this stimuli, restricting it to maximum of third degree, can be expressed as Taylor series:

$$y(t) = a_1 x(t-\tau_1) + a_2 x(t-\tau_2)^2 + a_3 x(t-\tau_3)^3 \qquad (3)$$

In Equation (3), a_n are Taylor coefficients and τ_n represent delays of stimuli with n being positive integer number. Thus, with the knowledge of Equation (2), response of the system would be like Equation (4):

$$\begin{aligned} y(t) = {} & a_1 A(t-\tau_1)\cos[\omega_c t + \theta(t-\tau_1) - \phi_1] \\ & + a_2 A(t-\tau_2)^2 \cos[\omega_c t + \theta(t-\tau_2) - \phi_2]^2 \\ & + a_3 A(t-\tau_3)^3 \cos[\omega_c t + \theta(t-\tau_3) - \phi_3]^3 \end{aligned} \qquad (4)$$

In Equation (4), $\phi_1 = \omega_c\tau_1$, $\phi_2 = \omega c\tau_2$ and $\phi_3 = \omega_c\tau_3$. In wireless systems, amplitude and phase modulating signals are slowly varying compared to sinusoidal carrier signal. If the time delays of the system are comparable to the carrier period, they are insignificant, and Equation (4) can be expressed like Equation (5):

$$y(t) = a_1 A(t) \cos[\omega_c t + \theta(t) - \phi_1] + a_2 A(t)^2 \cos[\omega_c t + \theta(t) - \phi_2]^2 + a_3 A(t)^3 \cos[\omega_c t + \theta(t) - \phi_3]^3 \quad (5)$$

Using trigonometric Equation (6) [6]:

$$\cos(\alpha)\cos(\beta) = \frac{1}{2}\cos(\alpha - \beta) + \frac{1}{2}\cos(\alpha + \beta) = \frac{1}{2}[cos(\alpha - \beta) + \cos(\alpha + \beta)] \quad (6)$$

Equation (7) can be written:

$$= a_1 A(t)\cos[\omega_c t + \theta(t) - \phi_1] + \frac{1}{2} a_2 A(t)^2 + \frac{1}{2} a_2 A(t)^2 \cos[2\omega_c t + 2\theta(t) - 2\phi_2] + \frac{3}{4} a_3 A(t)^3 \cos[\omega_c t + \theta(t) - \phi_3] + \frac{1}{4} a_3 A(t)^3 \cos[3\omega_c t + 3\theta(t) - 3\phi_1] \quad (7)$$

As seen from Equation (7), the nonlinear output response has frequency components at its linear response frequency as well as near DC ($0\omega_c$) and harmonic frequencies ($2\omega_c$ and $3\omega_c$). Therefore, nonlinear systems can modify the frequency spectrum by eliminating and generating new frequency components. This phenomenon is called spectral regrowth. [1]

2.2 Nonlinearity in time

In the previous Chapter 2.1, nonlinearity was handled as a function of the frequency. However, in the time domain, nonlinear component or device can modify the output spectrum also. It can cause the original sinusoidal signal to be cut down in the highest parts of the signal like in Figure 2. Also, the linear response of the signal is presented as a reference. [15]

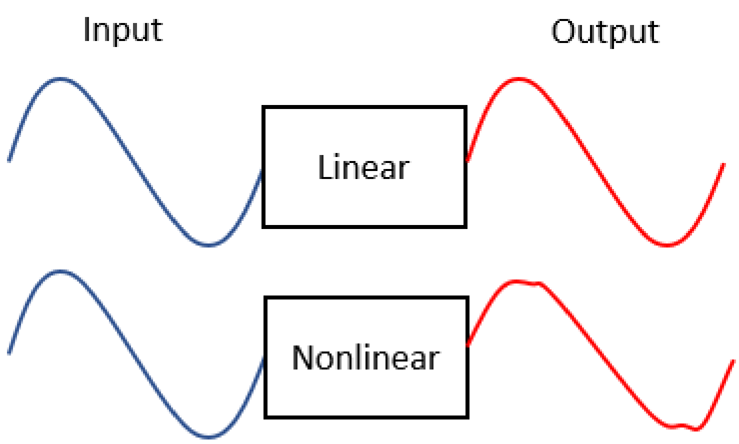

Figure 2. Linear and nonlinear response to a sinusoidal input signal. [15]

When the output of the system is nonlinear in the time domain, the energy of the one frequency is spread around a lot of frequencies. Those are the wanted output frequency and the harmonic frequencies in this case with one input signal. Completely linear output signal would have all of its energy at the same frequency as the input signal. [15]

2.3 Products of intermodulation

In a situation with two carrier signals, the frequency spectrum will be more crowded compared to the situation with one carrier, which are presented in Chapter 2.1, because more frequency components will be generated in the intermodulation mixing process. With two amplitude modulated carriers, the input signal is like Equation (8):

$$x(t) = A_1(t)\cos(\omega_{c1}t) + A_2(t)\cos(\omega_{c2}t) \tag{8}$$

where ω_{c1} is the angular frequency of the first carrier and ω_{c2} is the angular frequency of the second frequency. Using the same amplitude for both signals ($A_1(t) = A_2(t)$), the response of the signal using Taylor series for the first four terms is like Equation (9):

$$\begin{aligned} y(t) = a_0 &+ a_1A_1(t)(\cos(\omega_{c1}t) + \cos(\omega_{c2}t)) \\ &+ a_2{A_1}^2(t)(\cos(\omega_{c1}t) + \cos(\omega_{c2}t))^2 \\ &+ a_3{A_1}^3(t)(\cos(\omega_{c1}t) + \cos(\omega_{c2}t))^3 \end{aligned} \tag{9}$$

Using trigonometric Equations (6), (10) and (11) [6]:

$$cos^2(\alpha) = \frac{1}{2}[1 + \cos(2\alpha)] \tag{10}$$

$$cos^3(\alpha) = \frac{1}{4}[3\cos(\alpha) + \cos(3\alpha)] \tag{11}$$

Equation (9) can be written as:

$$\begin{aligned} y(t) = a_0 &+ a_1A_1(t)\cos(\omega_{c1}t) + a_1A_1(t)\cos(\omega_{c2}t) \\ &+ a_2{A_1}^2(t)\left[1 + \frac{1}{2}\cos(2\omega_{c1}t) + \frac{1}{2}\cos(2\omega_{c2}t) \right. \\ &\left. + \cos(\omega_{c1}t - \omega_{c2}t) + \cos(\omega_{c1}t + \omega_{c2}t)\right] \\ &+ a_3{A_1}^3(t)\left[\frac{3}{4}cos(\omega_{c1}t) + \frac{1}{4}cos(3\omega_{c1}t) + \frac{3}{4}cos(\omega_{c2}t) \right. \\ &\left. + \frac{1}{4}cos(3\omega_{c2}t)\right] + a_3{A_1}^3(t)[\frac{3}{2}\cos(\omega_{c1}t) \\ &+ \frac{3}{2}\cos(\omega_{c2}t) + \frac{3}{4}\cos(2\omega_{c1} + \omega_{c2})\,t + \frac{3}{4}\cos(2\omega_{c1} - \omega_{c2})\,t \\ &+ \frac{3}{4}\cos(2\omega_{c2} + \omega_{c1})\,t + \frac{3}{4}\cos(2\omega_{c2} - \omega_{c1})\,t] \end{aligned} \tag{12}$$

As seen from Equation (12), the output spectrum is formed from DC components, fundamental carrier frequency components (at frequencies ω_{c1} and ω_{c2}), harmonic frequency components (at frequencies $n \cdot \omega_{c1}$ and $l \cdot \omega_{c2}$ n and m being integer numbers) and intermodulation (IM) products (at frequencies that are form of $n \cdot \omega_{c1} + m \cdot \omega_{c2}$). The order of the intermodulation is determined as $|n| + |m|$. Therefore, due to the restriction of using only the first four terms of Taylor development, Equation (12) has only 2nd and 3rd order intermodulation products. Usually, the 3rd order products are the most important products to analyze and the Equation (12) would be a lot longer with additional terms. That's why the Taylor series is limited to the first four terms. [7]

Equations (13) and (14) present the frequency components that are formed due to the intermodulation distortion:

$$f_{IM} = nf_1 - mf_2 \tag{13}$$

$$f_{IM} = nf_2 - mf_1 \tag{14}$$

where f_1 and f_2 are the fundamental carrier frequency components.

Usually, the fundamental carrier frequencies are relatively close to each other compared to their harmonic and second order intermodulation frequencies. As a result, those unwanted frequency components can be easily filtered out by passband filter that rejects those out-of-band frequencies. Filtering out these frequency components will mitigate the interference caused by those products. In addition to the 2nd order products, usually all even order IM products are further away from the original carrier frequencies. Also, 3rd order components at frequencies $2\omega_{c1}+\omega_{c2}$ and $2\omega_{c2}+\omega_{c1}$ are relatively far from the wanted signal frequencies and can be filtered out. However, often the most harmful components from the Equation (12) are the difference 3rd order intermodulation terms at frequencies $2\omega_{c1}-\omega_{c2}$ and $2\omega_{c2}-\omega_{c1}$ which can be close to the fundamental frequencies. These frequencies cannot be filtered out if they are located in the passband of the receiver. [7]

In Figure 3, a typical output spectrum of the 2nd and 3rd order harmonic and intermodulation products with infinitely small signal bandwidths is presented. For clarification, intermodulation frequencies are marked below angular frequency axis and fundamental input frequencies and harmonic frequencies above their arrows. [7]

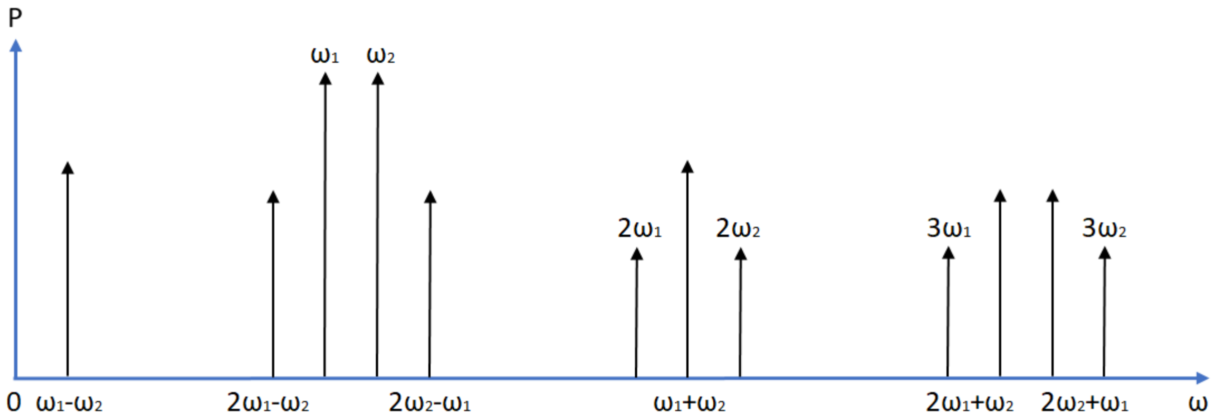

Figure 3. Output frequency spectrum with 2nd and 3rd order harmonic and intermodulation products of a nonlinear device. [7]

2.3.1 Intermodulation amplitude example

According to Equation (12), output amplitude of the frequency component "ω_{c1}" is $a_1 \cdot A + 9/4 \cdot a_3 \cdot A^3$ and amplitude of component "$2\omega_{c1} - \omega_{c2}$" is $3/4 \cdot a_3 \cdot A^3$. Voltage amplitude V_{pk} can be calculated using Equation (15) [46]:

$$V_{pk} = \sqrt{2 \cdot P \cdot R} \tag{15}$$

where P is power, and R is resistance. With traditional $R = 50\ \Omega$ and input power 43 dBm (20 W), $V_{pk} = A \approx 44.7$ V. As an example, when 3rd order intermodulation (IM3) level is -107 dBm ($\approx$ 20 fW) which is a threshold level for low-PIM [12], $V_{pk} \approx 1.41\ \mu$V. These mean that a_3 would be $\approx 21.1 \cdot 10^{-12}$. Since the intermodulation product is very low power compared to the input power, also Taylor coefficient a_3 is numerically small. The output power level of fundamental frequency ω_{c1} would be close to 20 W because a_1 is usually close to 1 and the term $9/4 \cdot a_3 \cdot A^3 \approx 4.23\ \mu$V is very small compared to 44.7 V and doesn't have much effect on the output level. Therefore, $a_1 \cdot A$ is a dominant term in the Equation (12).

2.3.2 Harmful effect of intermodulation

As a base transceiver station (BTS) example, in the LTE frequency band 8, the uplink RX-band is from 880 MHz to 915 MHz while the downlink TX-band is from 925 MHz to 960 MHz. When two transmitter carriers are located at the frequencies 930 MHz and 955 MHz, with using the Equations (13) and (14), the 2nd order IM products will be in the frequencies of 25 MHz, 1860 MHz, 1885 MHz and 1910 MHz. Those frequencies are far from the RX-band so the filtering will prevent the interference impact from those components.

More problematic are the IM3 products that will be at the frequencies 905 MHz and 980 MHz, like in Figure 4. In this case, the 905 MHz IM product will be in the uplink band and affect the receiver. The other, 980 MHz component can cause problems with other systems operating in that frequency. Also, there is one 5th order product (IM5) which will be at the frequency of 880 MHz. The upper half of that IM product in the frequency spectrum will be in the uplink frequency band causing additional harm to the receiving of signals. Therefore, typically the odd 3rd and 5th order intermodulation signals are the strongest frequency components that cause interference. [2, 3, 4]

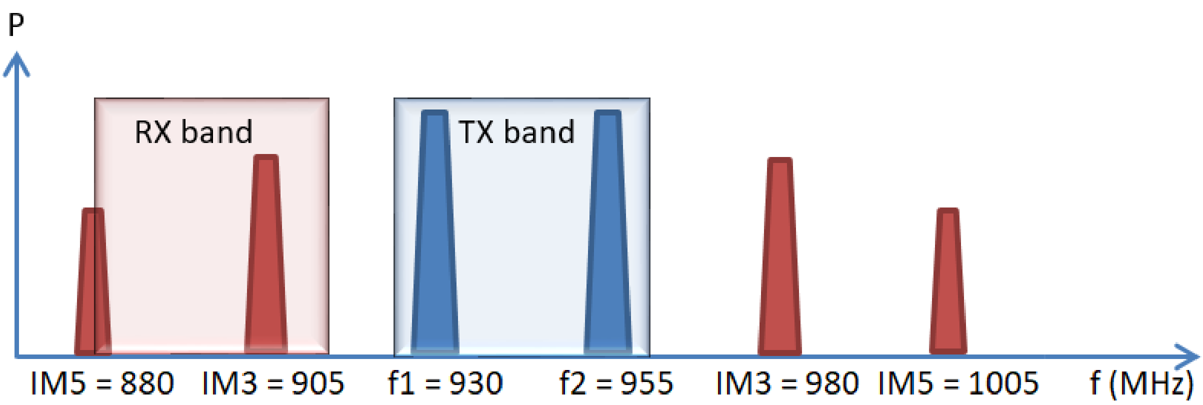

Figure 4. 3rd and 5th order intermodulation products fall to the RX band. [3]

2.4 Power levels of intermodulation

IM power levels are normally low and may fall below the thermal noise level with low power devices. But for example, in base stations where power requirements of the carriers are high, IM powers are significant and can't be ignored in the designing phase.

When defining the IM power levels it's useful to define the harmonics first. Harmonic signals are located at the multiples of the fundamental signal in the frequency spectrum. These signals can be expressed as a sum of each harmonic components as in Equation (16):

$$V_{out} = a_1 A cos(\omega t) + a_2 A^2 \cos(2\omega t) + a_3 A^3 \cos(3\omega t) + \cdots \tag{16}$$

Where a_1, a_2 and a_3 are transfer functions for fundamental, second and third harmonic signals respectively and A is the amplitude of input signal. The first term is the fundamental signal, the second term is the second harmonic and so on. Mathematically, the exponent of the harmonic product defines the order. Also, the rate of amplitude change follows the power-law. For example, the second harmonic is a function of input signal A squared. Therefore, the amplitude of the second order harmonic product will change squared to the change of the input signal (doubled in dB scale). And the third order harmonic will change cubed to the change of input signal (three times in dBs). Thus, the change increases as the order of the harmonic component increases. For example, if the input signal was increased so that the fundamental output was 3 dB higher, in theory the amplitude of the second order harmonic would have increased 6 dB and the third order harmonic 9 dB like in Figure 5. [5]

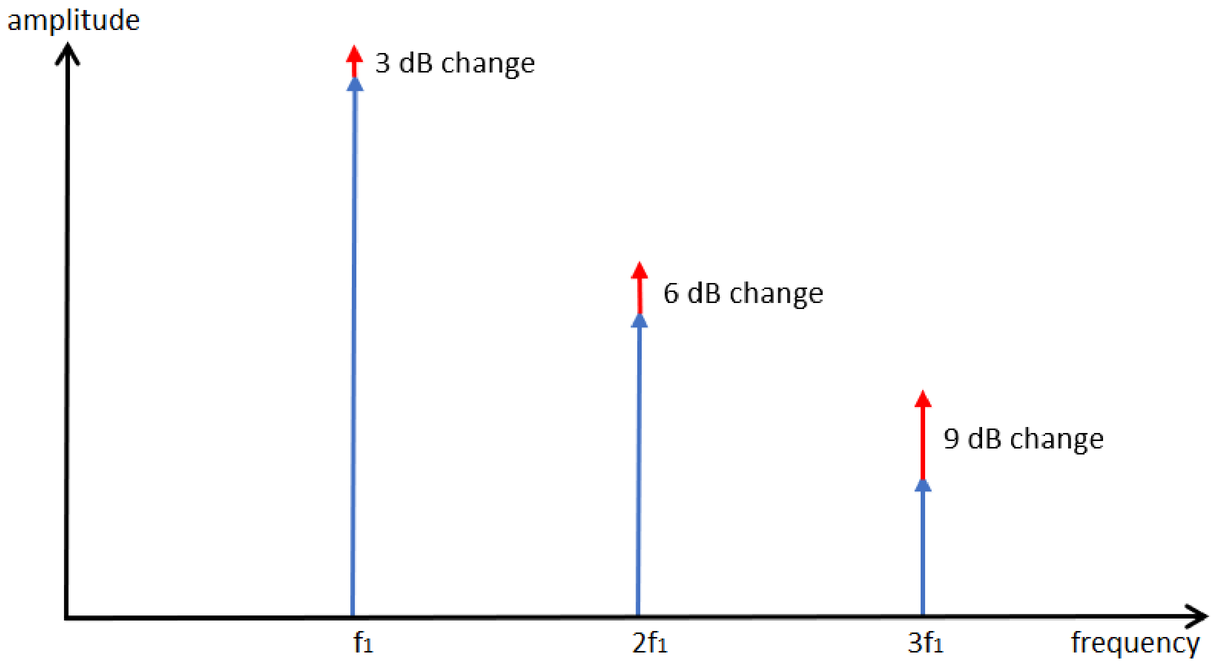

Figure 5. Level change effects on the amplitude of harmonic components. [5]

The above principle of power level change holds true with intermodulation products also. The change for the 2nd order intermodulation (IM2) products will be twice the rate in dBs and for the third order IMs three times the rate in dBs compared to the change of the fundamental input frequency signal level. Although, the power change rate for IM3 is higher than for IM2, with typical 43 dB input power level, IM2 levels are usually highest IM levels of any device.

In theory, for example with IM3, 3 dB/dB IM vs. power rate would mean that with some input power level, IM3 level would be higher than the wanted output signal level. The point where the power of the fundamental signal is the same as the power of IM3 product is called third order intercept point (IP3). IP3 is referred to the output third order intercept point (OIP3) or input third order intercept point (IIP3). IIP3 can be converted to OIP3 by adding the gain of the device. The higher value of IP3 means that the device is more linear because IM3 level reaches the fundamental value later. However, with real devices, IP3 is never reached since the compression effects starts at some level of power reducing both fundamental and 3rd order intermodulation output power like in Figure 6. Dashed lines that continue from the linear lines represent the theoretic response of the fundamental signal, the second order IM product and the third order IM product. [8] IIP3 levels for high-quality switches are +70 dBm and for duplexers +80 dBm. [26] IM3 power levels of a device or component can be calculated from dBm value of IP3 using Equation (17):

$$P_{IM3}(dBm) = 3 \cdot P_{I@O} - 2 \cdot IP3 \tag{17}$$

where $P_{I@O}$ presents the fundamental tone power at output in dBm. The value of $P_{I@O}$ is approximately the input tone power minus losses in the signal path. [41]

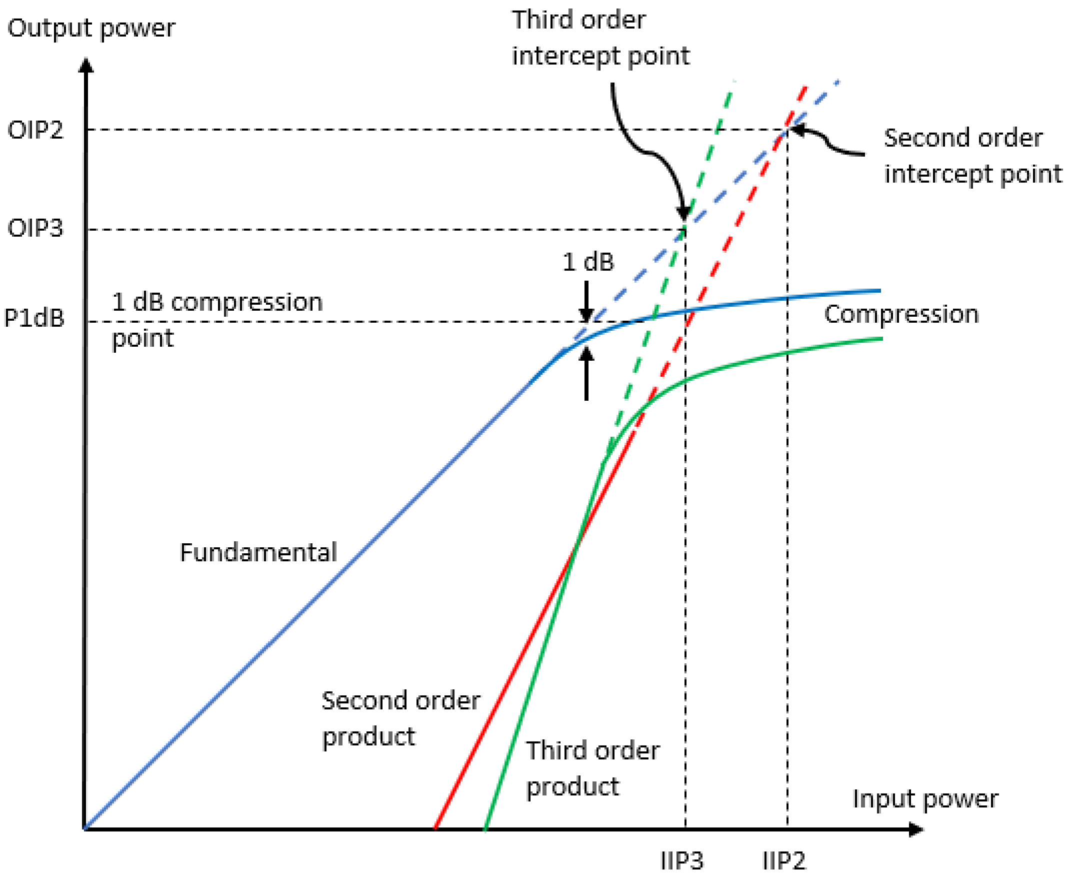

Figure 6. Second and third order input and output intercept points and 1 dB compression point in power graph. [8]

Additionally, Figure 6 shows 1 dB compression point (P1dB) which is the output power level at where the output level has decreased 1 dB from the constant linear response. P1dB is considered as the point where the compression starts, and devices are considered as nonlinear. [8]

2.4.1 Power levels with more than two input carriers

With three carriers the highest IM3 level generated in frequency $f_1+f_2-f_3$ is theoretically 6 dB higher than IM3 level with 2 carriers in frequency $2f_1-f_2$. However, this 6 dB difference is only a theoretical value that holds true when the slope of IM is 3 dB/dB like in Figure 7. In real life situation, measurements and simulations in [11] have shown that type $2f_1-f_2$ IM levels with 2-carriers and 8-carriers varies as a function of slope of IM. Typically, if the slope is less than 3 dB/dB, type $2f_1-f_2$ IM level is lower with 8-carrier configuration. And if the slope is more than 3 dB/dB, the IM level is higher with 8-carriers. [11]

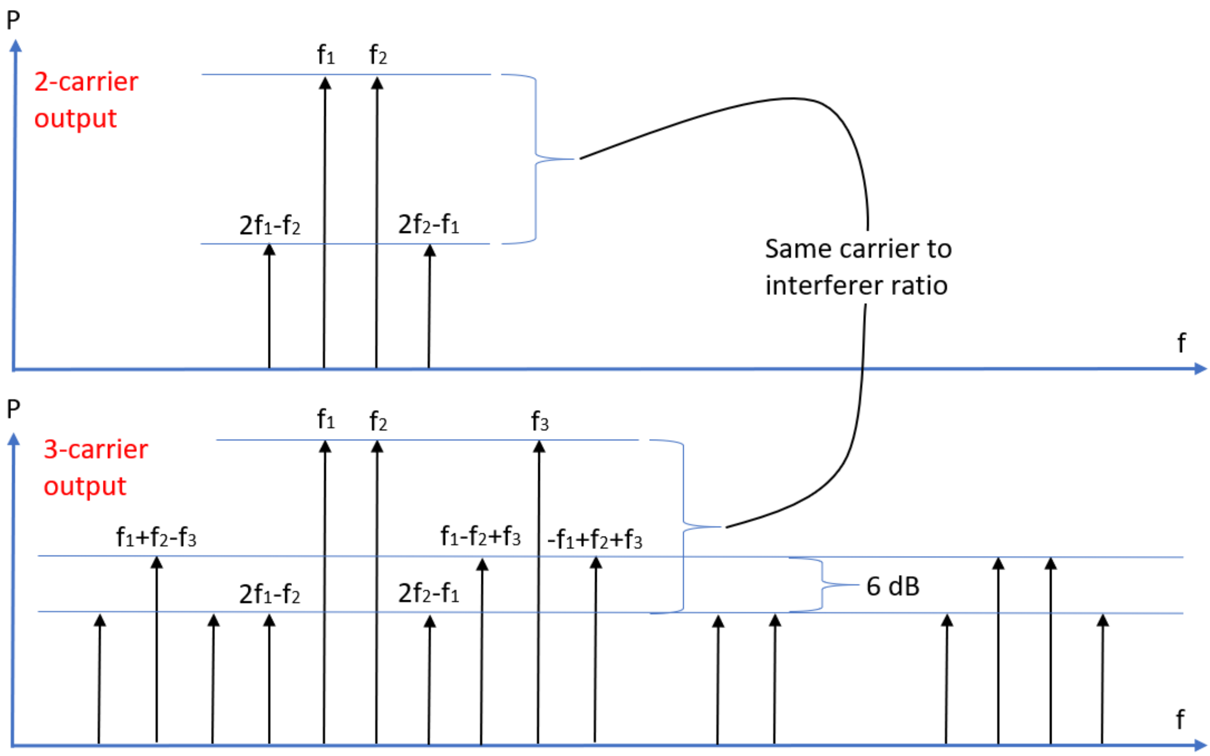

Figure 7. Theoretic 3rd order intermodulation products with 2-carrier and 3-carrier configurations. [11]

3 CHARASTERISTICS OF PASSIVE INTERMODULATION

As communication system development continues, the need of more and more power in the transmission and sensitivity in the receiving becomes relevant. If any interference is present in the receive band, the lowest received signal will be higher compared to situation with no interference. Therefore, the systems are required to be highly linearized. Usually, the active components cause non-linearity in the systems, but these products can be usually linearized to make the signal linear. However, the intermodulation products generated by passive devices or components can't be filtered out with the same way making it harder to remove these signals from causing problems in the receiver (RX). Passive components like resistors, inductors, capacitors, circulators and isolators don't need any electric power to operate. The phenomenon that is caused by these nonlinear passive components is called passive intermodulation (PIM). It is considered as a severe issue for networks. PIM can cause interference that can reduce the sensitivity of the receiver because the PIM products raise the noise level of the receiver. This increased noise level results in reduced signal-to-noise ratio (SNR), degraded channel capacity and receiver desensitization. Therefore, receiver could be unable to receive weak signals that would be received without PIM due to high sensitivity demands of the devices. [2]

Nowadays, PIM testing is becoming more and more important since duplex transmissions and collocated transmitters and receivers are more common in the frequency division duplex (FDD) systems. Also, many new technologies are developed to have multi-carrier and multi-band activity which may produce PIM over a wide range of spectrum. Additionally, new digital modulation schemes like code division multiple access (CDMA) and orthogonal frequency-division multiplexing (OFDM) increase the peak power of communication systems which increases PIM as well making it even more severe issue. [2, 3]

Passive intermodulation distortion occurs when two or multiple high-power RF signals are mixed in a nonlinear component, the same way as any intermodulation presented in Chapter 2 occurs. New frequency components are formed to the frequencies accordingly to the Equations (13) and (14). [2]

3.1 Power levels of passive intermodulation

Typically, due to the random characteristic and small breakdowns of nonlinear junctions third order PIM levels are increased by 2.2 dB – 2.8 dB, instead of the theoretic 3 dB, for an increase of 1 dB in power. Also, the high return loss values at harmonic frequencies and extreme slope variations on the hysteresis curves of ferrite devices affects on the PIM vs. power rate. In addition, in presence of multiple PIM sources, some sources are dominant with low input power levels and others with higher power levels because of impedance changes of PIM sources with different power levels. [9] Because of this large variation, it's not possible to precisely predict the power level of other PIM levels if one PIM level is known. [5]

For example, in [10] PIM levels of different devices was measured with varying test powers. It was concluded that for measured line sweep cable the PIM vs. power rate was 2.86 dB/dB, for jumper cable 3.42 dB/dB and for coupler 2.32 dB/dB. However, with input power levels from 34 dB up to 46 dB with measurement steps of 1 dB, the line sweep cable had the highest 3rd order passive intermodulation (PIM3) level and therefore, the poorest linearity. But with high enough input power, the jumper cable would have been the most nonlinear component since it's PIM3 level rises with the steepest slope compared to the input power.

3.2 Sources of passive intermodulation

The sources of passive intermodulation are the weak nonlinearities of different materials and contacts. Typically, the source components are connectors, antennas, multiplexers, phase-shifters, cables and contacts between two different metals. Usually, PIM problems are caused by corrosion, cold solder joints and poor torqueing or otherwise weak contacts between metals in the signal path. Therefore, every point of interface is a possible cause of PIM. Also, PIM has time-dependent properties because the nonlinearities depend on the age of the components, temperature and humidity. Therefore, PIM is harder to predict in the ever-changing environment. [2]

3.2.1 Current density

PIM is caused usually by high current density. Current density is defined as the current per unit area in the connectors (A/m^2). Coaxial connectors which are generally used in high frequency transmitting has the highest current density levels near the surface of the conductor and is significantly less in the center of the conductor due to the skin effect like in Figure 8.

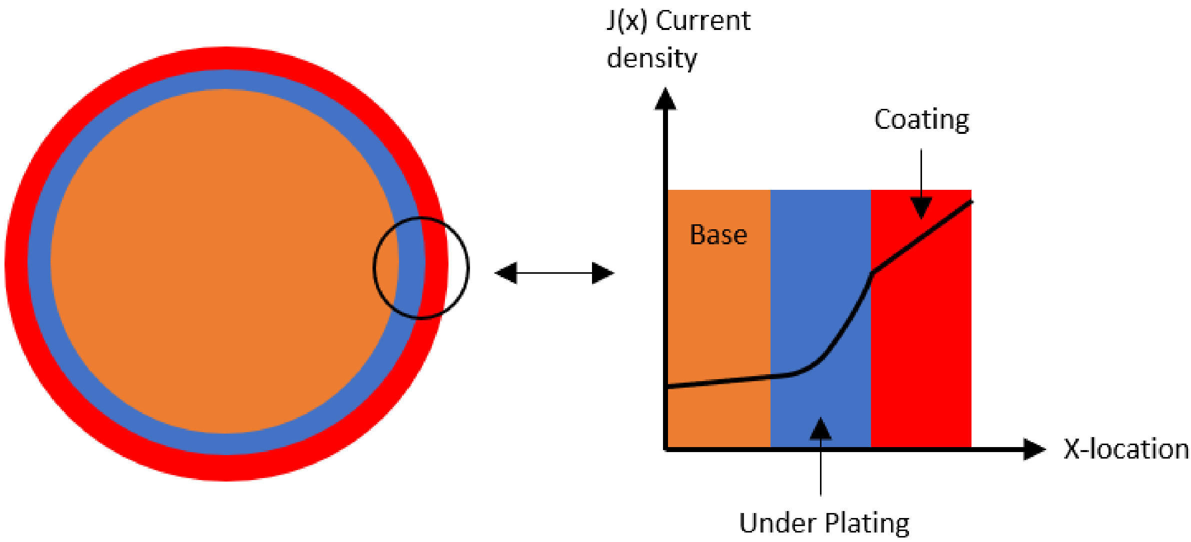

Figure 8. Inner conductor cross section and the current density distribution of a coaxial connector.

Also, the base material differs from the coating material and thus the current density also differs, and the current density profile becomes discontinuous. Additionally, the surface current density increases as the frequency increases due to the same skin effect. However, increasing the coating thickness up to the skin depth of the material decreases the surface current density. But if the thickness surpasses the skin depth, the surface current density increases since then even more current travels in the surface of the connector. [12]

Also, the permeability of the base connector material is a factor of the current density. If the permeability is increased, the skin depth of that material decreases which increases the current density of the outer boundary of that material. However, the current density of the whole base material decreases because the current decreases. This results as an increase of the current and the current density in the coating material. Though, the change in the current of the layers in a recent study of coaxial connectors [12] is only less than 1 % with base metal permeabilities from 1.01 to 1.5. In the study, ternary alloy was used as coating material and silver as underplating material. [12]

After all, the high coating thickness and conductivity decrease the produced PIM level. Due to the high conductivity, metals like silver are widely used in the low-PIM conductors. Silver has higher conductivity than for example gold. Therefore, more current flows through the coating material silver than if it's gold. Usually, the more current in the coating material results in reduced PIM powers because the current flowing through the PIM-wise less good base material (iron content of the material) is reduced. Additionally, silver has low surface resistivity compared to gold due to higher conductivity. [12]

Also, with noncoated materials, it's possible to get acceptable PIM values. In [12], measured PIM3 levels were lower than -107 dBm which is considered as low-PIM when input signals were 43 dBm. Though, corrosion and fretting can easily have unwanted effects on the connector. Additionally, unstable contact will lower the high-frequency performance. Since, using coating is recommended. [12]

3.2.2 Contact sources

Different contacts in the signal path are the usual causes of PIM. Contact sources concerning PIM is said to be metal-to-metal (MM) contacts, metal-insulator-metal (MIM) contacts, tunneling and fritting. MM and MIM contacts are not ideal in the microscopic perspective. There is always some roughness in the contacts which separates the junction into contact and noncontact areas like in Figure 9. The real contacts between metals is called a-spots which are a series of contact areas in on macroscopic contact. Surface geometry, metal hardness and the pressure of the contact are affecting the size and number of these spots. Roughness can have effect on the elevation of current density levels and thus elevation of the PIM levels. Also, metal surfaces have some native oxide or sulfide cover layer. Addition to metal roughness, the a-spots are even smaller because of that dielectric layer. [2, 13]

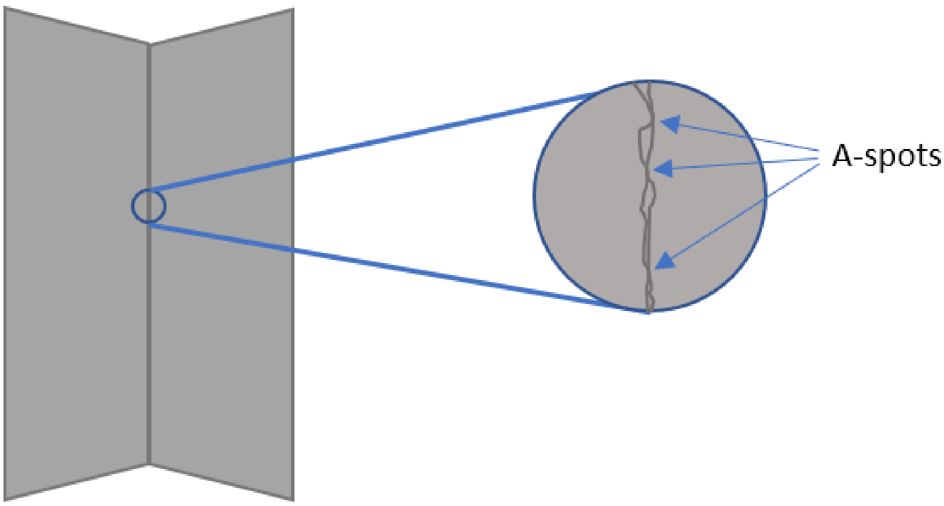

Figure 9. Zoomed contact surface of metals. [2]

Most metals are usually surrounded by a thin oxide layer like in MIM contacts causing potential barrier between connectors. Electrons which don't have enough energy to overcome the barrier can tunnel through the barrier with some finite probability. It also generates current which is by nature nonlinear. However, this tunneling effect is measurable for thin films that are less than 100 Angstroms width. In addition, there is Schottky effect where electrons are injected over the barrier. This also increases the nonlinear current flow. [2, 14]

Fritting happens when small voltages cause breakdown across thick contamination. A-fritting creates new contact spots and B-fritting expands already existing spots. Fritting occurs as broadband interference every 2-3 seconds which elevates the caused PIM. Also, microscopic arcing can occur in contacts where contaminations are present. [2]

3.2.3 Materials causing high passive intermodulation levels

Ferromagnetic materials like nickel, iron, cobalt and metal alloys can cause very high levels of passive intermodulation and the use of these should be avoided in RF-components. Ferromagnetic materials have parallel alignment of magnetic moments which causes a large magnetization. Nonlinear response is caused by this hysteresis effect of magnetization and demagnetization. [16]

Ferrimagnetic materials, also called ferrites are iron-oxide based materials that have proper magnetic and dielectric properties are used in RF-components like circulators, resonators and isolators can also contribute on producing PIM. Ferrites have nonequal magnetic moments of its sublattices and therefore ferrites can have the same hysteresis behavior as ferromagnetic materials. However, devices that have ferrimagnetic materials are usually optimized PIM wise. In the past, PIM testing was mostly detection of cracked ferrite components in RF-components like isolators and circulators. [2, 16]

Due to the proper selection of materials in the RF devices, contaminants like dirt, dust, moisture and oxides on electrically conducting surfaces are usual causes of PIM. These materials can get to the connectors in the manufacturing phase creating nonlinear junctions between the metals in the signal path. [2]

3.2.4 Electro-thermal nonlinearity

Some PIM sources is said to be caused by nonlinearity of current-voltage (I-V curve) dependence. But the actual PIM causing source in high dynamic range devices is usually electro-thermal nonlinearity. The interaction between thermal and electrical signals happens when the modulated RF signal has baseband components at low frequencies and the signal periods are comparable to device’s thermal time constants. Significant self-heating occurs when high power levels are driven to resistive materials. The heat generation and thus the resulting interference depends on current density. Also, that resistance varies in time due to the thermal transients and therefore, time varying PIM is generated. Circuits work on voltages and currents while heat transfer works on power. This coupling of different order processes leads to memory effect as long tail transients. [17]

Like in Figure 10, thermal responses act like low-pass filter but the filter slope is less than 20 dB per decade which is a normal response of a single pole filter. In the study [17], the slope of the electro-thermally induced intermodulation products was around 10 dB/decade. It’s that due to multiple evenly distributed time constants in output. Thus, poles and zeros form approximately that approximately 10 dB/decade response. Less frequent intervals of time constants would lead to a different slope value.

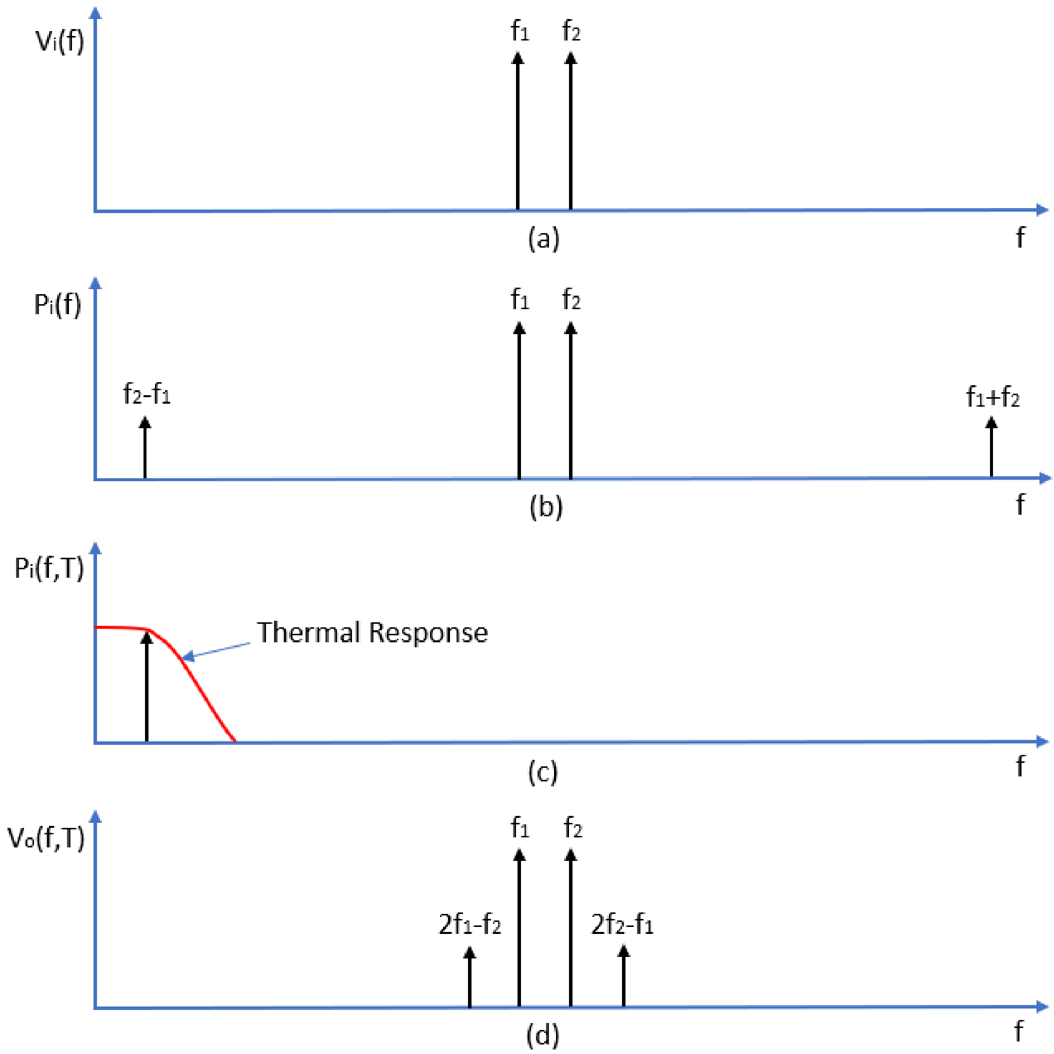

Figure 10. Formation of electro-thermally induced passive intermodulation.

In the Figure 10(a) is the presentation of the input voltages of the two tones. The instantaneous power from the two-tone excitation varies periodically at the spacing frequency of the two tones. It has sum and difference terms like in Figure 10(b) which shows the input power spectrum. Figure 10(c) shows that the frequency products in the baseband frequencies can interact with the slow thermal response if the two tones are close enough. The results of this mixing are shown in voltage output spectrum of Figure 10(d) where 3rd order intermodulation products are present.

Characteristic of the electro-thermal nonlinearity is that the thermal resistance is dependent on the carrier frequency separation (Δf). And, the induced electro-thermal PIM (ET-PIM) is dependent on $1/\Delta f$. Therefore, ET-PIM is identifiable from other initial sources. ET-PIM is strongly related to device temperature coefficient of resistance (TCR). TCR means a change in resistance of any substance per change of degree of temperature. [19] Therefore, low TCR components have usually higher linearity and therefore lower and better PIM levels. [17, 18]

3.3 Types of passive intermodulation

Passive intermodulation is classified to three different types which are design PIM, assembly PIM and rusty bolt PIM. These are covered in detail in the next three Subchapters. [3]

3.3.1 Design PIM

Design PIM is concerning the tradeoffs between low levels of PIM and low cost, small size of the system and high-performance options. Therefore, components like switches, circulators and duplexers with acceptable levels of PIM are usually selected. The components with the best PIM characteristics are usually too expensive for the devices. The effect of design PIM is even more significant in small cell radio designs. [3]

Material choices affect the PIM a lot, also. Ferromagnetic materials such as nickel and steel do have nonlinear characteristics due to the nonlinear current to voltage (I-V) ratio and hysteresis effect. Better choices for current path are materials like brass and copper which are accepted as linear materials. Tests have proven that for example nickel plate under gold on the center contact will increase the PIM results up to 50 dB. Also, stainless steel can raise PIM level 10 to 20 dB. Also, use of identical metals as much as possible is recommended because the contacts between same metals are more linear than with two different metals. [20]

Plating of current path materials is also crucial. Skin effect restricts the current densities to reside only at the surface of the conductors. When the thickness of plating is sufficient enough, the current travels mostly within the plating material. In usual RF connector types like Type N and Din 7/16, the plating material is silver because of its high conductive nature that reduces contact junction resistance substantially. Din 7/16 connectors are also very robust and large with a large contact area and mating force which result in a low resistance of the contact. [20]

3.3.2 Assembly PIM

Assembly PIM refers the problems system ageing, whether effects and wrong installation of system setup such as too loose or too tight torqueing of connectors. Assembly PIM occurs mostly in cables, connectors and waveguides. [3]

Assembly PIM problems can occur if the cable is flexed too much or exorbitant vibration or wind is targeted at cable. Also, dirty connectors can lead to PIM. Therefore, covering of all kinds of connectors and using of robust enough cables is important. [3]

Assembly PIM is not as stable as design PIM because the amplitude variations can be over 100 dB and PIM may exist with only few conditions. Due to the variating nature, single sweeps are not enough to capture the issue. Therefore, larger inspections are needed to capture the PIM. [3]

3.3.3 Rusty bolt PIM

PIM is considered rusty bolt PIM or PIM beyond the antenna if the PIM effect happens after the antenna. This type of PIM occurs when signals are reflected back to the device from usually rusty objects like poles and fences with IM products like in Figure 11. The intermodulation occurs the same way as in wired path IM like when junction of two different metals is in the current path. Rusty bolt PIM can be cancelled or lowered by assembling the system in a safe position from the potential PIM sources. Sometimes the cancellation challenge is more difficult because vibration, mechanical movement of device, wind and other weather conditions can modulate the PIM contribution. [3]

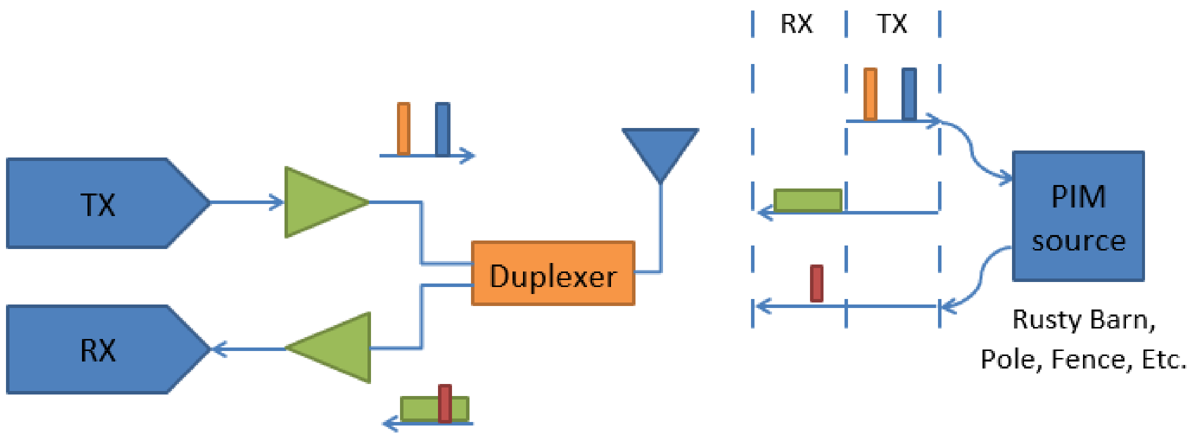

Figure 11. Rusty bolt PIM. [3]

Rusty bolt PIM sources can be detected with antenna positioning. When the antenna is positioned towards the PIM source, the PIM level is higher than when the antenna points to some other direction. Other way to find out the PIM source is to use time delay estimation. [3]

In the near field, the radiation patterns aren't formed completely. Metal objects in the near field ($d < 2D^2/\lambda$) and especially in the reactive near field ($d < 0.62(D^3/\lambda)^{1/2}$) should be avoided, because of the high PIM generation in the near field. [22] Here, λ is the wavelength of the operation, D is the longest dimension of the antenna and d is the distance of the object from the antenna. Also, polarization of the feed lines can affect the PIM results. Basically, the closer the PIM causing materials are, more PIM it will generate. [21]

In the street configurations, distributed antenna systems (DAS) that have quasi-omni antennas are popular because of the nulls in the azimuth pattern in the directions that have metal poles etc. Those elements are the usual cause of high PIM. Also, this type of antenna configuration doesn't have a lot of impact on the site coverage due to the nulls because of the large scattering in the street environment. [21]

3.4 Variation of passive intermodulation in time

Passive intermodulation is also a measure that varies in time. Two different types of PIM generation have been found. One of them is a broadband burst type PIM that appears in about 1 second (sometimes 2-3 second) bursts. Typically, this type of PIM occurs in periodic breakdowns in mechanical functions with high power levels. [23]

The other type is related to the heating of conductors and interfaces. Due to that, contact integrity and therefore PIM levels can change with time. It has been studied that when poorly constructed cable assembly is PIM tested, first the PIM level might be good but after a while it can be degrade a lot due to the heating. Also, the opposite effect has been found. Sometimes a bad PIM performance can turn into a good one because heat causes mechanical interfaces to expand and compress which lowers the PIM power levels. Also, different weather circumstances effect on the change of PIM levels with time. Wind, sunshine and rains produce mechanical stress and heating effects of interfaces. For example, sun could heat up the connectors and depending on the quality of the assemblies and RF components, PIM level could either rise or fall. Therefore, the PIM levels can vary in different times of the day in the field use of the devices. [23]

3.5 Disadvantages of passive intermodulation

PIM shows usually as high noise floors and receive noise floor diversity imbalance which occurs with cells that have two receive paths. The other has higher noise floor than the other. [2] These can result in dropped calls, connection losses and degrading data rates. This means that the whole quality of the connections is suffering. It's approximated that 5-10 percent of all base station problems are caused by PIM. [24]

These issues are costly to the operators since they can't charge users for the data that wasn't used due to connection breaks. Also, PIM causes indirect issues, like operator's brand degrading which can attract customers to use other operators. Nowadays, it's very common and easy for customers to hop between different operators. Therefore, the most cost-efficient way is to design the products to be low PIM and make the assemblies properly. [24]

3.6 Prevention of passive intermodulation

Nowadays, due to dense use of frequency bands, PIM issues are harder to be prevented by locating the receiver band far from the transmitter band. Therefore, there must be other ways to prevent high PIM levels. A few examples of this are proper cleaning, covering of different ports and cancellation of PIM. These and all other commonly used ways to prevent PIM are discussed more in detail in the Subchapters below. Also, material selection (like not using ferromagnetic materials) is crucial in the designing phase of low-PIM devices, which is dealt more in depth in the earlier Chapter 2.7.1.

3.6.1 Procedures for low passive intermodulation

Most of the time, PIM is generated in the interfaces and contacts. Therefore, good ways to achieve low-PIM are periodical maintenance and cleaning which prevent the contaminants from the contacts. Also, proper torqueing should be done to ensure that the real contact areas are sufficient in size, and the couplings are not too loose or too tight. If connector is torqued too tight, it could be damaged and if too loose, contact areas might be too small. Also, connecting and disconnecting the same junction many times can induce PIM related issues. However, component manufacturers provide mating cycle quantities that the connectors work properly. Proper soldering and using enough conductive glue are other ways to prevent PIM issues. [2, 25]

Another style is to design separate antennas and low loss transmission lines for transmission and receiving. However, it's a costly way of designing base stations. Also, the sizes of the devices would be greater. Therefore, it is not that commonly used. [25]

3.6.2 Passive intermodulation cancellation

Obvious way to avoid PIM is to reduce transmit power to a low level but nowadays it's difficult because of the ever-growing need of more power. Also, the required sensitivities of the receivers are only getting lower which are harder and harder to reach. Therefore, there must be ways to reduce the effects of PIM. Even if the PIM causing components are highly linear, the distortion power can be high enough to desensitize the receiver. Also, isolation and shielding are good ways to lower the PIM levels but costly and space consuming.

In the recent studies [26, 27] one of the best ways to reduce PIM is the digital cancellation of PIM (PIMC). Digital cancellation is also more cost efficient than isolation and shielding. One way to cancel PIM digitally is to suppress the frequency-selective PIM with time delay differences between the transmit signals. The parameter estimation of this method is very complex. Also, power amplifier (PA) nonlinearities and memory effects have to be considered to make the method work more reliable. In study [27], memory effect was also considered in the cancellation. The method in the study showed to suppress PIM in both RX main and RX diversity branches significantly. With diversity RX branch, PIM was coupled over the air. In both branches, it was concluded that the memory effect had some effect (1.3 dBm in main branch and 0.3 dBm in diversity branch main antenna being 5 cm away from the diversity antenna). As a result, PIM cancellation can loosen the linearity requirements of the components and enable more efficient usage of frequency bands. [26, 27]

In addition to memory effects, PAs can induce nonlinearity to the carriers on its own before combining, which leads to the spectral regrowth and can cause PIM. Therefore, it can have additional effect on the cancellation of PIM. In recent studies like [27], it's usual that PAs are assumed to be linearized properly through digital pre-distortion and therefore the effect is not considered. [27]

3.7 Modelling of passive intermodulation

3.7.1 Diode model

Practical and simple PIM model is a diode-like model. Diode is a simple semiconductor that has a pn-junction. Diode has nonlinear current-voltage (I-V) relation. Current and voltage aren't directly proportional to each other and that's why diode is considered as a nonlinear component. The diode current has that nonlinear I-V relation [28]:

$$I_D = I_S\left(e^{\frac{V_D}{V_T}} - 1\right) = I_S\left(e^{\frac{qV_D}{kT}} - 1\right) \tag{18}$$

where I_s is saturation current, V_D is diode voltage, $V_T = kT/q$ is thermal voltage, q is charge of an electron, k is Boltzmann's constant and T is temperature in Kelvin. As seen from Equation (18), diode current and voltage vary as a function of temperature. [28]

Diode models the basic junctions and connectors that cause PIM. Diode model with two diodes is an accurate model for odd order intermodulation products. This type of simple diode model is presented in Figure 12. Other diode starts to conduct after voltage rises over V_t threshold and as it keeps rising, diode current rises significantly and nonlinearly. This nonlinear current-voltage characteristic can be modified with the selection of different semiconductor materials and doping. [29]

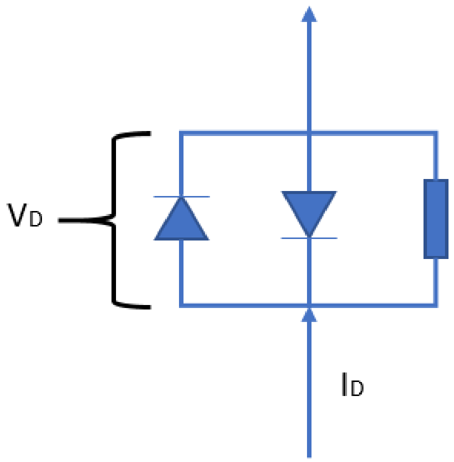

Figure 12. Diode model for passive intermodulation modelling. [29]

This kind of model works only for odd-order intermodulation products since using Taylor series to the transfer function of the model presented in Figure 12 would lead to Equation (19):

$$I_D = I_S \frac{e^{\frac{V_D}{V_T}} - e^{-\frac{V_D}{V_T}}}{2} = I_S \sinh\left(\frac{V_D}{V_T}\right) = I_S\left(\frac{V_D}{V_T} + \frac{1}{6}\left(\frac{V_D}{V_T}\right)^3 + \frac{1}{120}\left(\frac{V_D}{V_T}\right)^5 + \frac{1}{5040}\left(\frac{V_D}{V_T}\right)^7 \ldots\right) \tag{19}$$

In the Taylor series expansion, even order terms are multiplied by sinh(0) = 0 and odd order terms are multiplied by sinh's derivative cosh terms like cosh(0) = 1. Thus, only odd terms are present in Equation (19). [29]

3.7.2 Electro-thermal model

As stated in Chapter 2.7.4, if there exist baseband components within the thermal time constant, electro-thermal PIM is caused by coupling between electrical and thermal domains. A basic compact thermal model, resistor-capacitor (RC) filter model, is used for determining temperatures of different components. However, this compact model is not able to show the thermal time constant correctly since the model has only one time constant. More accurate model is presented in Figure 13. It is an approximate Foster expansion model. [40]

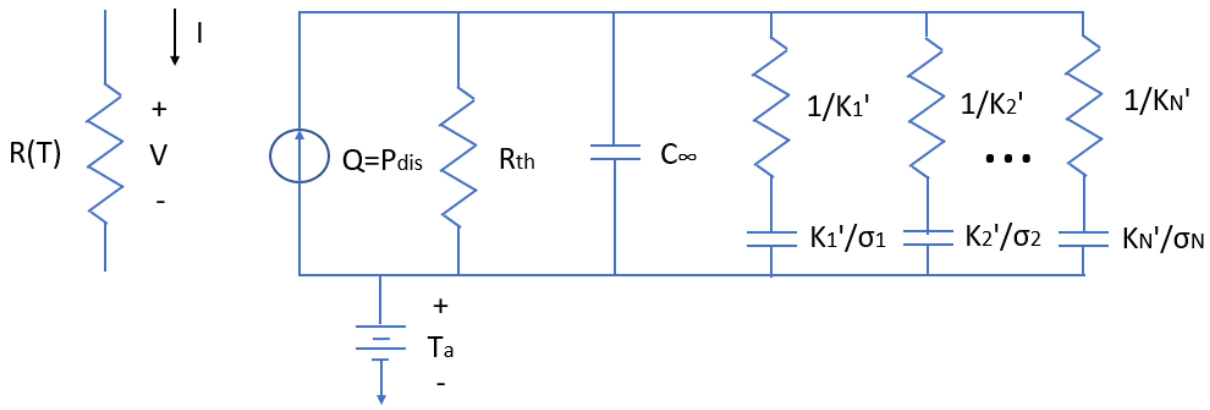

Figure 13. $(N+1)^{th}$ order compact foster electro-thermal model. [40]

In Figure 13, R_{th} is the thermal resistance and the thermal capacity is formed from a stability capacitor C_∞ and N times RC branches. K_i' are the zero locations and σ_i are the pole locations. P_{dis} is the dissipated electrical power in the element and T_a, the ambient temperature is included as a voltage source. The accuracy of this model depends on the order of the approximation. More on this model can be found in [40].

4 TESTING OF PASSIVE INTERMODULATION

Nowadays, PIM testing is an important measure of linearity of the system since power and sensitivity requirement are ever-growing in the industry. Accurate testing of PIM is difficult due to the very low levels of PIM. Usually, testing requires high dynamic range over 110 dB. Also, the components in the PIM analyzers must be ultra-low PIM because the residual PIM must be 10 dB below the measurement range of the analyzer. Only then, the measurement results represent mostly the PIM of the DUT and not the PIM of the measurement device. Currently, modern PIM analyzers use high-end digital signal processing (DSP) technology with ultra-low PIM components to make sure that the residual PIM specifications won't exceed. [30]

Usually, PIM related problems are shown up right after the installation of the system, after long period of aging or when new carriers are introduced to old systems. Therefore, PIM testing is a crucial measure of linearity of any given time of the system’s life span. [2]

In this Chapter, typically used test setups, testing methods and limitations of the testing is discussed. Also, test results of 10 different DUTs are presented and compared with each other.

4.1 Passive intermodulation testing methods

Usually, PIM levels are measured with two-tone reflected PIM test like in the PIM specific International Electrotechnical Commission (IEC) 62037-1:2012 standard. Testing is done with high input power, in mobile communication systems typically with two 43 dBm (20 W) input signals. PIM products are measured as scalar measurements of the power levels of PIM signals in the receiver (RX) band. As mentioned in the Chapter 2.4, the third order PIM product is often the most powerful PIM product with 2x20 W power but sometimes it doesn’t fall straight in the receiver band due to the mixing of discrete fundamental signal frequencies. Therefore, sometimes the measured PIM products are 5^{th}, 7^{th}, 9^{th} or even higher order IMs. With 43 dBm testing power, higher order of PIM means lower PIM power levels. As a result, it’s easier to stay in the acceptance limits of PIM. These levels are extremely low, in the range of -100 to -120 dBm with two 43 dBm input signals. PIM levels are expressed usually in decibels to carrier (dBc) units. -110 dBm PIM level with two 43 dBm fundamental signals would mean -153 dBc PIM. Usually, tones are continuous wave (CW) signals in PIM testing. [31]

4.1.1 Passive intermodulation standards

Currently, the only international standards for PIM testing is the IEC62037 standards published 2012 by The International Electrotechnical Commission which helps component manufacturers to compare the linearity of the RF-devices. These include standards for general methods, coaxial cable assemblies, connectors, coaxial cables, filters and antennas. [2] Also, IEC has formed a technical committee (TC46/WG6) to work towards a new PIM measurement standard. The future standard will include test methods and relevant limits for PIM in the RF and microwave frequencies for many passive components like connectors and cables. The TC46/WG6 will work with other committees (TC 102 and SC 48B) for matters relevant to antennas and connectors. [32] The first release of that standard is coming soon. More information on the standard is released in [33].

4.1.2 Typical measurement procedures

The most usual PIM testing procedure is the reverse (sometimes called as reflective) PIM test. For example, the commercial field use testers are often reverse type ones. Like in Figure 14, two signals are amplified by power amplifiers (PAs) and the high-power signals are combined together by hybrid combiner. Between combiner and the PAs can be circulators which protect against the reflections. After that, the signal goes to the duplexer which allows only the TX band frequencies from the output of the combiner and filters all other frequency components effectively because duplexer has a bandpass filter for TX frequencies. As an example, as seen from the specifications [42], low-PIM duplexer in band 5 attenuates frequencies in the RX band at least 50 dB. Transmitted frequencies are then applied to the device under test (DUT). PIM signals in the RX band are returned to the receiving measuring device like spectrum analyzer (SA) through the duplexer and low noise amplifier (LNA). Measuring device will show the PIM frequencies and their power levels. In the precise measurements, cable loads can be used as loads. Also, using notch filter at carrier frequencies before LNA can be used to improve the dynamic range of the measurement if it's needed.

Reverse PIM testing may have challenges cause the test results might be affected by the antenna cables for example. Testing can be inaccurate because of the adding and canceling of reverse waves. Therefore, the testing is best to do the way that the other frequency is swept over the frequencies. In that way the PIM product is also swept across the RX band. As a result, partial error signal cancelation can be avoided from the measurement result. Therefore, it's important to sweep the other frequency which shows the real PIM performance. [2]

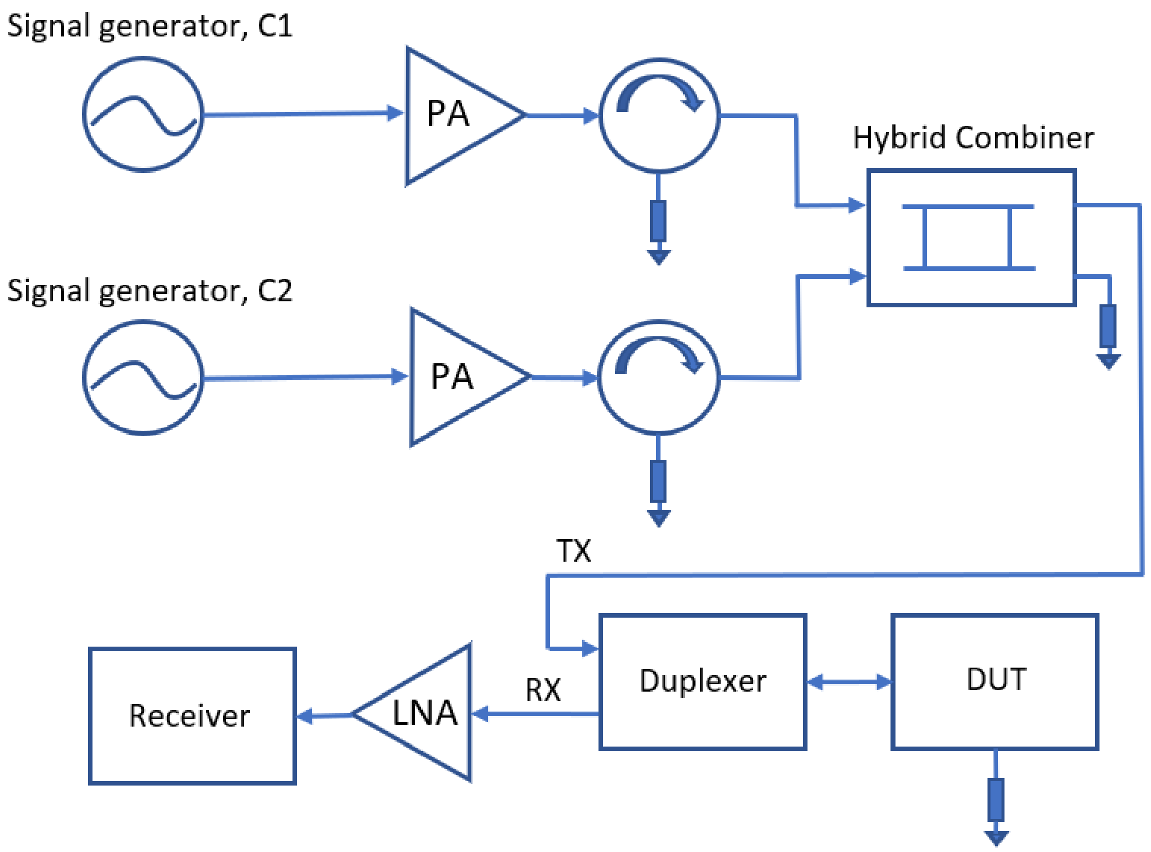

Figure 14. Typical reverse PIM measurement block diagram. [37]

Another type of PIM testing is called the forward PIM testing. Forward PIM testing requires additional duplexer or triplexer on the output of the DUT compared to Figure 14. That duplexer separates high power signals from the PIM signal. Other way to measure forward PIM is to use external antenna for measuring propagated signals. However, forward testing is not that used method for radio transmitters like base stations because it's not so practical in real life configurations. Also, the reverse test setup is simpler due to the need of only one duplexer. [2, 37]

It is important to remember that line sweeping is different than PIM testing because it cannot detect PIM levels while it measures signal losses and reflections in a system over the band. On the other hand, PIM testing cannot measure the losses and reflections. [34]

Typically, commercial PIM analyzers that have the same components like in Figure 14 are narrowband, but PIM sensitivities are very good and low. Those sensitivity levels can be better than -170 dBc. However, usually PIM analyzers are expensive and are only for PIM measurements. Using setup like in Figure 14 is more cost efficient since the measurement components and devices can be used for other testing as well. [35]

4.1.3 Used measurement setup

Measurements of passive intermodulation were executed using forward PIM measurement test setup which is shown in Figure 15. In this thesis, measured DUT was only a filter module of a whole base station product. Since DUTs were base station filter modules, diplexers were not needed, and the forward measurement setup was the most logical and easiest way of measuring PIM response. Measuring filter PIM levels is a good indicator of PIM levels of the whole device since the filter is usually the dominant source of PIM in a BTS. Therefore, usually only the filter is measured PIM-wise from the whole BTS in the field.

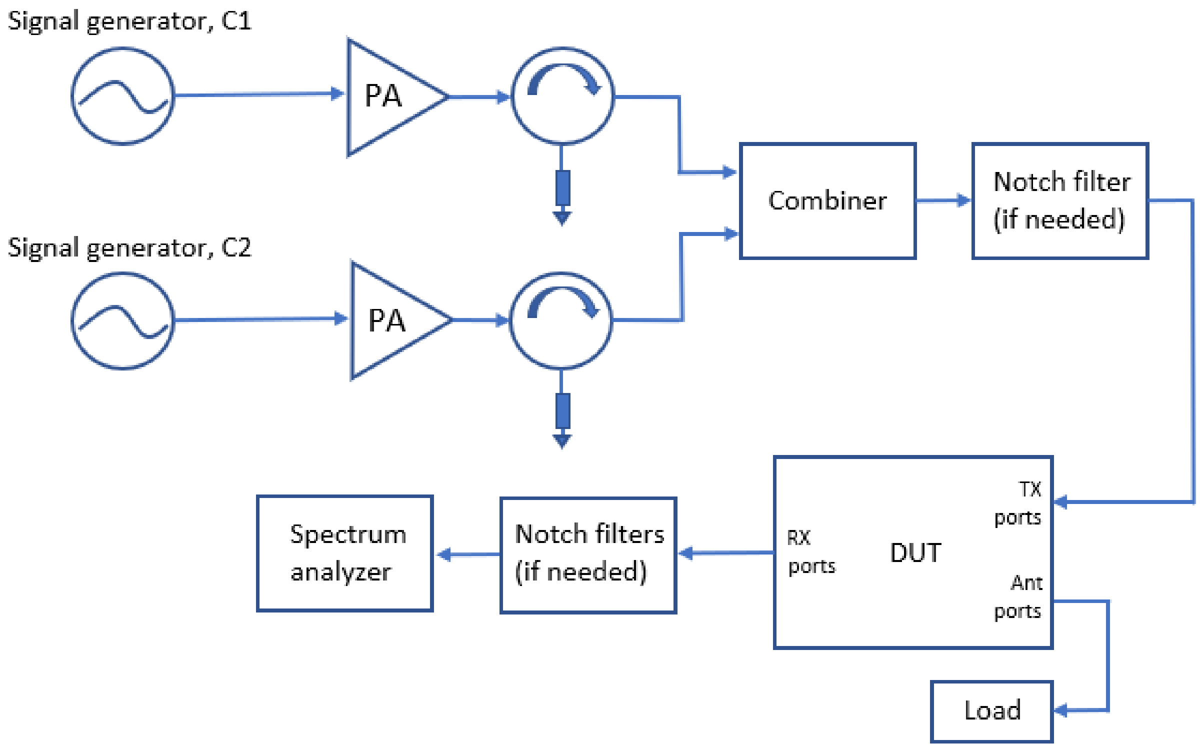

Figure 15. Forward passive intermodulation test setup for filters.

The test setup in the Figure 15 has similarities to the test setup in the Figure 14. However, in forward PIM testing the signal goes through the DUT to the spectrum analyzer while in reflective PIM testing presented in Figure 14, the test signal is reflected from the DUT to the spectrum analyzer with the help of duplexer or triplexer. In this forward test setup, the first notch filter can be used to filter out intermodulation products (for example IM3 or the most powerful IM tones that are at the combiner output at RX-band) that PA units might generate by themselves. The second notch filters before SA for fundamental signal frequencies can be used to if SA generates too high IM level by itself. Also, LNA before spectrum analyzer can be used if dynamic range of SA is limiting the measurement. Offset level of the SA can be set to the same level as the loss between RX port and SA is.

4.1.4 Distance-to-PIM

Distance-to-PIM (DTP) is a measure of internal (e.g. feed system) and external passive intermodulation sources. PIM can be caused beyond to actual system like in rusty bolt PIM where the transmitted signals are reflected back to system from unclean or rusty poles and fences causing raised noise level. PIM problems were used to be eliminated with the movement of low PIM terminations in the feed line until the PIM level was within the required specification. This procedure was time consuming and the good connections in the feed line were opened possibly causing additional problems like damage to the connections or contamination. Nowadays, with modern DTP it’s possible to measure the distance from where the actual PIM source is located. For example, Anritsu PIM Master has a feature which allows two traces overlaying with each other. This way it’s easy to decide whether the PIM source is inside a feed system or antenna or beyond the antenna. With being many times faster, DTP is also more cost efficient than the old procedures. [36]

4.2 Challenges in passive intermodulation testing

Passive intermodulation products are very low power level frequency components. Also, the transmission signals have very high power compared to the unwanted PIM signals and are relatively close to the PIM frequencies. Therefore, PIM testing setup needs to have high dynamic range for reliable results. This means that the noise level must be very low in order to observe the PIM products. Also, the measuring setups or analyzers needs to have very high-quality parts (high IP3 values of the components) and materials because the overall PIM effect of the measuring test setups needs to be very low. Generally, it’s said that the residual PIM level must be at least 10 dB lower than the measured PIM of the DUT. [10, 30]

Most of the commercial PIM analyzers are inherently narrowband which means that one PIM analyzer suits only for measuring PIM products from devices that work at same frequency band. However, the analyzers have usually very low residual PIM level and therefore they can be used to accurately measure the PIM products. [29]

4.2.1 Noise levels in passive intermodulation testing

Due to the very low levels of PIM signals, noise floor must be very low. Only then the PIM products become visible on the screen of the receiver of the test setup. The noise floor (or noise output) of the receiver can be calculated using Equation (20) [42]:

$$N_o(dBm) = 10 \cdot \log_{10}\left(\frac{k \cdot T}{1 \cdot 10^{-3}}\right) + 10 \cdot \log_{10}(BW) + NF_{Total} \tag{20}$$

where k is Boltzmann constant, T is temperature is Kelvin's, BW is receiver's noise bandwidth and NF_{Total} is the total noise figure of the setup. $k \approx 1.38 \cdot 10^{-23}\ m^2kgs^{-2}K^{-1}$ and $T \approx 295$ K since the testing is usually executed in the room temperature. [42] With those numerical values, the first term of the Equation (20) is approximately -174 dBm. It is the thermal noise floor of the receiver and BW and NF_{Total} terms are only going to raise the output noise floor accordingly to the parameters value of the setup components. In the most PIM setups, the receiver is spectrum analyzer. In that case, the BW is the resolution bandwidth (RBW) of the SA. RBW defines the resolution of SA, the passband bandwidth of the intermediate frequency (IF) filter of SA. Ideally, it's as narrowband as possible to ensure that observed frequency components are separated from each other by SA. Too high RBW would lead to blending of adjacent frequency components into wideband signal component seen from the screen of SA. In the most of the modern SAs', RBW can be adjusted down to 1 Hz which adds 0 dB to the Equation (20). However, every decade of increased RBW will increase the noise floor by 10 dB. Therefore, RBW must be very low in order to see the low-level signals.

Downside of the narrow bandwidth RBW is high sweep time of SA. With traditional swept type spectrum analyzers, the sweep time can be calculated with Equation (21) [43]:

$$T_{sweep} = k \cdot \frac{\Delta f}{B^2} \tag{21}$$

where k is correction factor for the settling of the resolution filter, Δf is the frequency range (= span) in the screen of SA and B is the narrower bandwidth from RBW and video bandwidth (VBW). Usually, k is from 1 to 3 and B = RBW in the PIM measurements. According to the Equation (21), with the values k = 1, span = 10 kHz and RBW = 10 Hz, the sweep time would be 100 s. With RBW = 100 Hz, T_{sweep} would be 1 s. Therefore, every increased decade of RBW will reduce the sweep time to the 1/100th part with the cost of 10 dB increased noise floor. However, modern wideband spectrum analyzer, that use fully digital IF processing and a fast Fourier transformation (FFT) analysis, execute the same measurements by at least 10 times faster. Thus, the modern analyzers are recommended for PIM measurements although they are more expensive than the traditional swept type analyzers. [43]

NF_{Total} is the third term of Equation (20) and it will raise the noise floor by some measure. Total noise factor and total noise figure can be calculated with Equations (22) and (23) respectively [45]:

$$F_{Total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 \cdot G_2} + \cdots \tag{22}$$

$$NF_{Total} = 10 \cdot \log_{10}(F_{Total}) \tag{23}$$

Where F_{Total} is the total noise factor, F_i is noise factor of a single component and G_i is the gain of a single component while i is positive integer number. As seen from the Equation (22), the first stages with the noise factors F_1 and F_2 are the most crucial components. Every time the gain is significant, the noise from the following components are divided by it. In the PIM test setups, like in Figures 14 and 15, noise factors from PAs are the most important, since every component after PAs will be divided by the gain of the PAs. Also, it should be noted that there are two paths of noise before combiner. However, total noise level before the combiner is not doubled compared to the situation with one path since combiners have insertion losses. With 3 dB insertion loss of combiner, the noise floor would be raised approximately the amount of noise in the combiner. Usually, manufacturers denote noise by noise figure in the component specifications. Therefore, Equation (23) can be used to transform noise figures of single components of a setup to noise factor and then the total effect on noise can be calculated. However, in the typical PIM test setups there are duplexers or triplexers that filter out the noise that is mostly generated in signal generators and PAs from the RX band effectively. Also, DUT filters that are measured in this thesis have high TX-port to RX-port (TX-RX) isolation of around 100 dB in the RX band. As a result, higher noise floors in the TX-ports doesn't affect the measurements executed from the RX-ports much. More on this topic in the Chapter 4.5.

After adjusting RBW as low level as possible and using low noise components, noise floor can also be decreased by using noise cancellation function that is in the modern SAs. It may increase the SNR up to 10 dB. The third way of lowering noise level is using SA's internal pre-amplifier which is usually an option in modern SAs. It's recommended to be used if the power levels to be measured are very low level because pre-amplifier is a nonlinear component which generates IM signals by itself and may have an impact on the measured PIM level. [44]

An important SA parameter is displayed average noise level (DANL). It is the thermal noise floor of the SA. Therefore, DANL defines the minimum signal level that can be observed amongst noise from the screen of SA. DANL ranges from -115 to -170 dBm with typical analyzers depending on the whether the preamplifier is used or not. [43]

4.3 Advantages of high-power testing

Due to strict requirements of fourth generation (4G) and fifth generation (5G) systems, higher linearity is demanded in the wireless industry. In Anritsu PIM Test Power Level application note [10] the study on 46 dBm (40 W) PIM test power shows that the accuracy of PIM testing is increased compared to standardized (IEC62037) 43 dBm (20 W) power. The reason behind this is that the difference between the actual PIM signal level and residual PIM level of the instrument is higher if the test power is higher. The result of high difference is low measurement error as seen in Figure 16. In the Figure 16, blue line shows how much higher and orange line how much lower can the measured PIM result be than the actual PIM of DUT. For example, with 20 dB difference between measured PIM and PIM of the measurement system, error is lower than 1 dB. But with 5 dB difference, error can be over 7 dB.

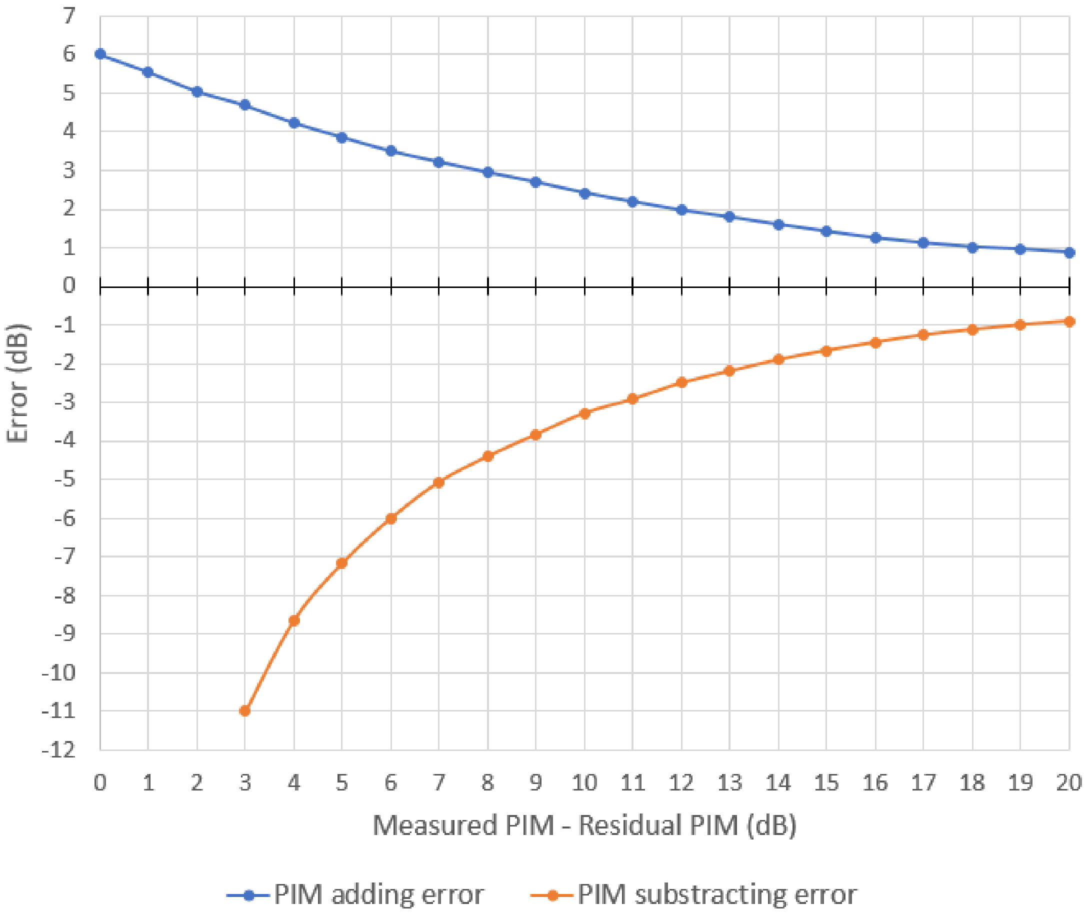

Figure 16. Standard IEC 62037 PIM measurement error curves. [10]

The IEC specification states that residual instrument PIM should be at least 10 dB lower than the measured PIM signal level. Looking at the Figure 16, measurement error in the IEC specification can be approximately +2.4 dB to -3.3 dB. In study [10], the difference for coupler with 37 dBm (5 W) test power was 8.0 dB, with 43 dBm (20 W) 14.8 dB and with 46 dBm (40 W) 22.9 dB. With 37 dBm the IEC62037 standard requirements aren’t met. Also, other measured items had more difference with more test power. This empirical study shows that usually the measurement accuracy is higher with higher testing power. However, this may not be true with all testing instruments because the test equipment could have more residual PIM and it could increase more with increasing test power. [10]

In addition, more stringent measurements can be done with 46 dBm test power since the residual PIM might not increase much in comparison to situation with 43 dBm test power. As a result, the PIM measurement could have almost plus 3 dBs of dynamic range. [10]

Also, with combination of internal (such as a feed system) and external PIM sources the PIM slope (PIM level vs. test power) can be inconstant. The measurement of distance-to-PIM (DTP) must be performed to unveil the sources of PIM. The increased test power (up to 46 dBm) can help to reveal this situation because different source can be dominant cause of PIM with lower test powers and the other with higher test powers. With some test power, two different sources could have similar magnitudes and the PIM level could be lower compared to the PIM level with slightly lower test power. But, when the power is increased to a certain level, the external source becomes more and more dominant and the change rate of PIM level vs. test power could be over 6 dB/dB. Usually, as mentioned previously, the rate of PIM slope is in average 2.2 –

2.8 dB/dB and with one PIM source almost constant with the normal power levels used in the industry. [10]

4.4 Test results

In Figure 17, PIM test results from 10 different filters are presented as average results from limit. Measurement was made with the setup presented in Figure 15. Measured DUTs had four to six antenna pipes and that same amount of RX and TX ports. The used testing powers of fundamental frequencies in the TX port of the DUTs were either 43 dBm or 46 dBm. For confidential reasons, DUTs can’t be named after their real product codes in this thesis. Also, used frequencies and exact test results can’t be revealed. Measurement results weren’t limited by residual effects of the test setup.

A couple of measurements were unstable and varied significantly when DUT was knocked or sometimes when air was blown to it. Some measurements varied even without affecting the measurement purposefully. Unstableness of these measurements is caused by the sensitiveness to any contaminant in the filter. For example, fine metallic leftover from the tuning of filters can be a factor for elevation of PIM interference. Tuning session of a filter can take over six hours to do and thus a lot of sources for PIM is generated just by it. However, the contaminants are mostly removed from the filter by vacuuming the filter while the filter is being vibrated and turned to varying directions. Therefore, most of the measurements were stable.

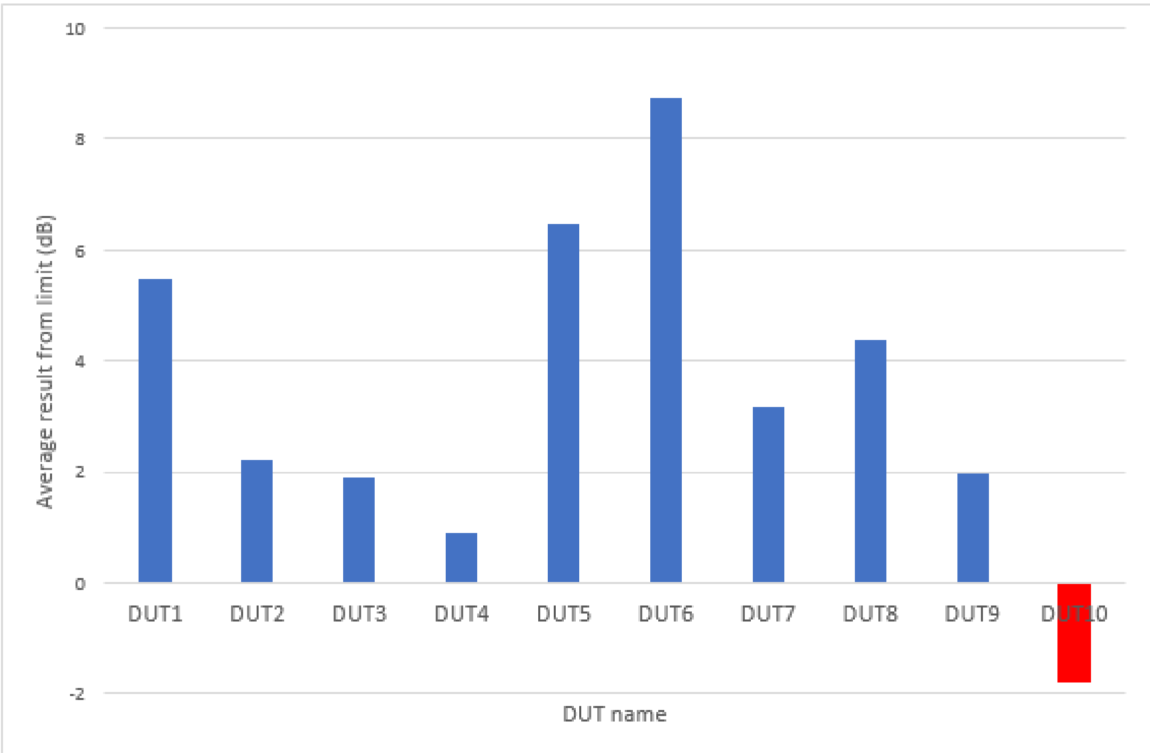

Figure 17. Passive intermodulation average results from limits for 10 different filters.

Test results in Figure 17 consist of PIM3 and PIM5 measurement of the filters. PIM5 acceptance limits are typically around 9 dB less than PIM3 limits with industry typical 43 dBm powers. Measurements are also fixed in frequencies due to the time limits and testing specifications of different measurements. As an exception, results from two additional DUTs which aren’t shown in this Thesis was measured with two different frequency spacings. Thus, the results can be lightly compared to the theory of electro-thermal nonlinearity. More on that in the Chapter 4.4.1.

As seen from the Figure 17, nine out of ten DUTs had better results in average than the limit. DUT6 had especially good results compared to the limit, almost 9 dB better than the limit. DUT10 was the worst unit and the results were almost 2 dB worse than the limit in average. However, the measurement uncertainty was 2 dB in all measurements. Thus, the results might be pass in average if there would be an ideal setup with no measurement uncertainty. In any case, the measurement results were mainly good and met the requirements. Usually, the earlier product versions of DUTs could have worse performance. It means that the PIM results might also be worse with these versions. After the first versions, the DUTs are being modified with better designs and the measurement results are also better. The first versions with a bit worse designs are one of the main reasons for failed PIM measurements. Other usual PIM causes are any contaminants in the structures of filters that might be able modify the test results. Those contaminants might be hard to remove.

Table 1 presents pass rates of the PIM measurements. There were 4 to 16 measurements for each DUTs.

Table 1. Pass rates of PIM measurements of DUT filters.

DUT	DUT1	DUT2	DUT3	DUT4	DUT5	DUT6	DUT7	DUT8	DUT9	DUT 10
Pass rate	4/4	4/4	4/4	12/16	13/16	12/12	8/12	9/12	6/12	3/12

Figure 18 shows histogram presentations of the pass rates.

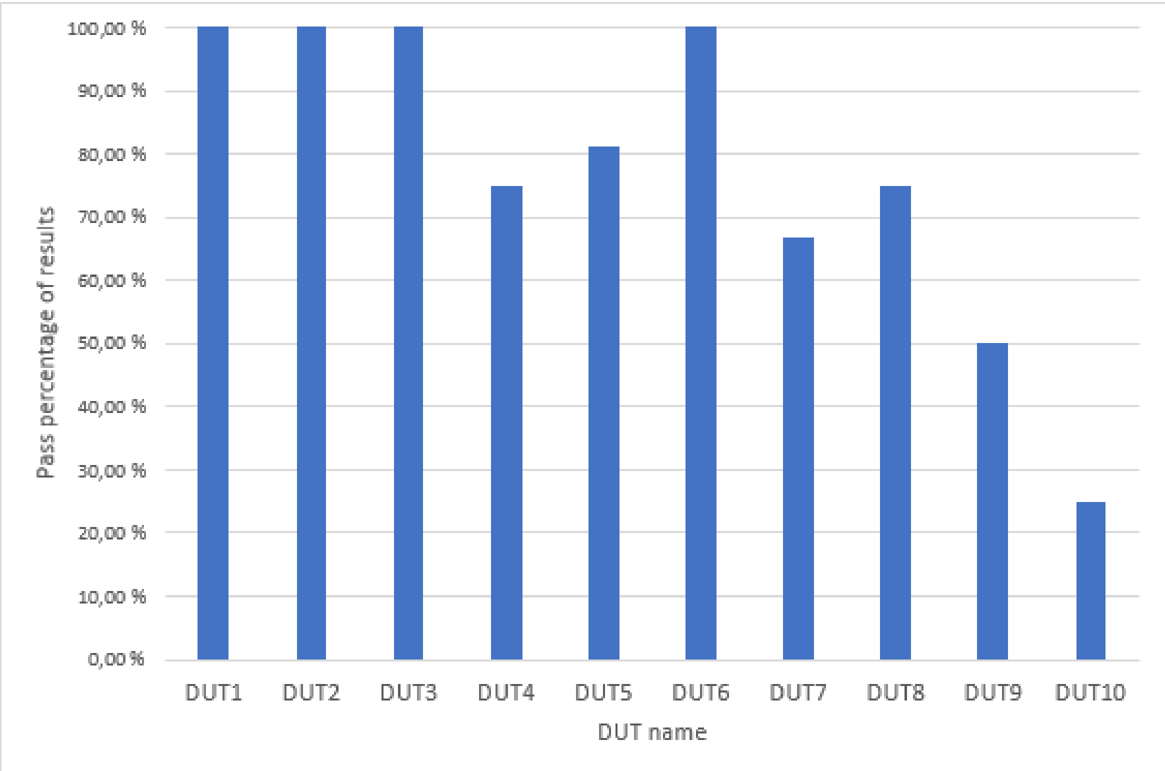

Figure 18. Pass percentage of the passive intermodulation test results.

It can be observed from the Figure 18 that four out of ten DUTs had pass results in all PIM tests. Also, most of the DUTs had majority results that were passes. Still, the goal is always to have pass rates of 100 % every time. As seen from the Figure 18, DUT10 has the worst pass rate of below 30 % and it can be said that the DUT is not capable of being a part of a high-quality base station with so poor PIM results. DUT6 which had the best average results, has also 100 % pass rate. Therefore, it was the best DUT PIM-wise.

Standard deviation from the measured test results is presented in Figure 19. It was calculated using Equation (24) [38]:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - x_a)^2}{n}} \qquad (24)$$

where x_1, x_2, …, x_n are the test results and x_a is the average of those results. Standard deviation is a measure of how close the results are from the mean value in average. Therefore, low standard deviation tells that the results doesn't vary from each other a lot which is preferable quality-wise. High standard deviations suggest that some measurements were significantly better than others. Usually, that is the case when some of the measurement results were clearly below and some clearly above the measurement limit. Therefore, high standard deviation is linked to failed results with relatively small number of measurements from one DUT in PIM testing. This sort of conclusion can be also seen from Figure 19.

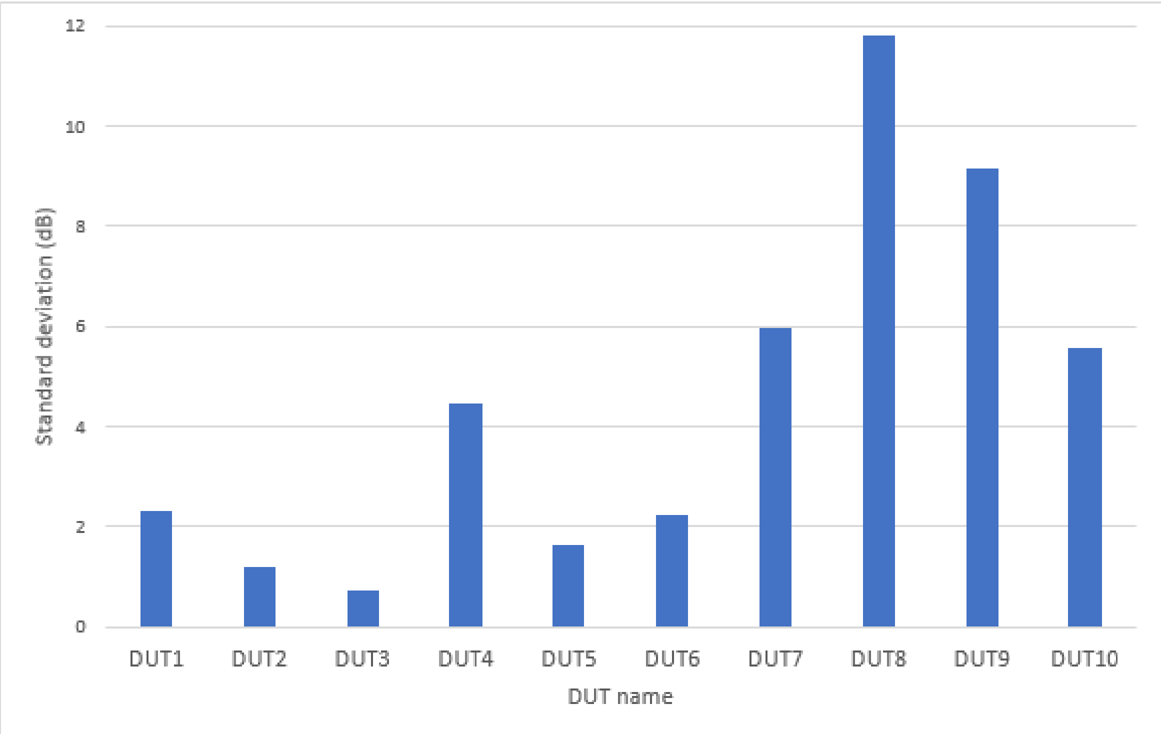

Figure 19. Standard deviation of passive intermodulation measurements.

In figure 19, DUTs 1, 2, 3, 5 and 6 had the lowest standard deviation results. All of those results were below 2.5 dB. If those results are compared to the pass percentage results of Figure 18, the same DUTs had also the highest pass rates of measurements. Also, the worst filter, DUT10 had quite high standard deviation of nearly 6 dB. Still, DUT8 had the highest standard deviation of almost 12 dB.

4.4.1 Test results vs. electro-thermal nonlinearity

Two additional filters had two different tone spacing testing configurations. The other was organized to produce the IM frequency approximately to the middle of the RX band and the other to near the edge of the RX band. One high-power tone frequency was fixed, and the other tone was moved 10 MHz in the spectrum between the measurements. The theory in chapter 3.2.4 [17] says that electro-thermal PIM level increases by 10 dB if the frequency spacing of the two fundamental tones is decreased by one decade. Therefore, if the tones are closer together, PIM levels should be higher if electro-thermal nonlinearity is the dominant source of PIM.

The PIM measurement results with the narrower frequency spacing value were clearly (= over 2 dB) higher level than with the broader spacing most of the time. Some of the measurements with the narrow spacing were actually lower level. Still, most measurements suggest that narrower spacing might have an effect on the results. The spacing frequencies was around 10 MHz and around 20 MHz. In linear scale, it means that the spacing is doubled, approximately. In logarithmic scale, doubling in linear scale means an increase of around 3 dB. With the PIM slope of 10 dB/decreased decade, 3 dB increase of spacing would lead to 3 dB decrease of PIM level. While the results were mostly 2 – 4 dB better with broader spacing, it can be said that electro-thermal nonlinearity might be the source for the difference. However, the quantity of these measurements was small and indisputable conclusions can't be made from these measurements. For the research purposes of electro-thermal PIM, it would have been great to measure more different frequency configurations from all the DUTs but due to the time limits, it wasn't possible.

4.5 Noise considerations of the setup

Noise of the test setup can be calculated using Equations (20), (22) and (23). The total noise figure for an example test setup is seen from the Table 2. Also, it describes the noise figures and gains of individual parts of one test setup. Output noise level of one commercial signal generator [47] is ≈ -130 dBm with 3 dB input CW power and 10 Hz bandwidth. In table 2, DUT is assumed to have 100 dB TX-RX isolation in the RX band. Noise floor of SA is -130 dBm. Because of the filtering of DUT and notch, mostly spectrum analyzer is limiting the noise floor of the setup.

Table 2. Noise and gain parameters of passive intermodulation test setup.

Part	Output Carrier Power (dBm)	Noise Figure (dB)	Gain at RX band (dB)	Total Gain at RX band (dB)	Total Noise Figure (dB)	Output Noise level at RX band (dBm)
Signal Generator	3	0	0	0	0	-130
Power Amplifier	47.45	6	44.45	44.45	6	-79.55
Circulator	47	6	-0.45	44	6.00	-80.00

Combiner	44	Noise doubled	-3	41	9.00	-80.00
Notch filter	43	1	-40	1	9.00	-120.00
DUT (filter)	-57	1	-100	-99	9.11	-219.89
Spectrum Analyzer	-57	-	-	-99	9.11	-130.00

In Table 2, total noise figure after combiner is around 3 dB higher than before the combiner because two sources that are considered here as identical are being combined. As a result of this combining, the noise is doubled which means + 3 dB in logarithmic scale. However, with 3 dB combiner loss, the noise level stays the same, approximately.

In addition, Table 2 doesn't deal with the losses and noise from cables and adapters because different setups need different amount of those components. Usually, the overall cable and adapter losses are around 1 dB to 3 dB in typical test setups. Low-PIM cables and adapters have PIM3 values from -150 to -168 dBc. [51, 52] Thus, these components might have a little impact on the measurement results. Especially the cable between DUT and spectrum analyzer must be low-PIM.

Noise floor of SA is marked as DANL in the specification sheets. DANL of one basic [48] spectrum analyzer is -130 dBm with 10 Hz RBW and 1 Hz VBW with preamplifier OFF and -148 dBm with preamplifier ON at 1 GHz environment. With more advanced SA [49], noise floor is -155 dBm with preamplifier OFF and -165 dBm preamplifier ON with 1 Hz RBW which means that the noise floor is around 10 dB higher with 10 Hz RBW at 1 GHz environment.

Since the isolation of the DUT filters are high, the noise floor is mostly determined by the RBW of SA. Thus, for the basic SA [48] with 10 Hz RBW like in Table 2, the noise floor is around -130 dBm. The modern high-quality PIM testers have around the same -130 dBm receiver noise floor. [50] As a result, down to -173 dBc PIM measurement results can be achieved with 43 dBm input levels. Additionally, components like notch filter and LNA that might be needed after DUT and before SA can raise the noise floor of the RX band.

Anyhow, it's important to wait at least couple of sweeps to get the highest PIM response when measuring high order PIMs. The measurements are very slow since RBW must be very low in order to get the noise floor down and IM signals visible. Usually, when measuring PIM3, RBW can be higher, 100 Hz or sometimes even 1 kHz. However, when measuring higher order terms, it must be very low, usually 10 Hz.

Spectrum analyzer is not damaged in the measurements since also TX-band in the RX-port is filtered by a high isolation. Calculation in Table 2, filtering is 100 dB since output carrier power after DUT is 100 dB lowered. Same 100 dB filtering is used in simulation in Chapter 5 as well. With 100 dB carrier filtering, TX components are only around -57 dBm. For example, one basic spectrum analyzer [48] can take up to 37 dBm (≈ 5 W) of continuous input power maximum of 3 minutes at a time without any damage to the analyzer.

4.6 Cost estimation of passive intermodulation test setups

Usually, PIM testing equipment and analyzers are usually quite expensive. Therefore, as an example, test setup components from one setup are shown in Table 3. [49, 53, 55, 57] This setup costs around 60 000 €. Table 3 consist of components presented in Figure 15. However, due to confidentiality, the same components aren't used in testing in this thesis.

Table 3. Measurement components of one example PIM test setup.

Device	Device model	Quantity
CW Signal Generator	Rigol DSG815	2
Power Amplifier	Product PA	2
Circulator	JCC0700T1000NMNFNF (as an example)	2
Combiner	Creowave product specific	1
Notch Filter	WTRCTW8	1
Cable Load	-	1
Cables and Adapters	Multiple different	-
Spectrum Analyzer	Keysight PXA	1

Usually, companies that work in the RF-field have already some signal generators and might have spectrum analyzers and other equipment like low-PIM cables and adapters available to use for PIM measurements. Thus, the overall investment might be much lower. Also, testing devices noted in Table 3 can be used for other base station testing. However, usually signal generators are much more expensive than Rigol DSG815, but PIM testing is often done with only CW signals and more complex generator is not needed. However, Rigol DSG815 reaches only up to 1.5 GHz. [57] If higher than 1.5 GHz frequency products is to be measured, other SGs must be used. In addition to Table 3, it should be noted that if test setup like in Figure 14 is used, also frequency dependant duplexer must be in the setup. Cost estimate of one duplexer is around 5 000 € - 10 000 €.

Other type of PIM testing is executed with PIM analyzer where only DUT has to be connected to the analyzer and that analyzer takes care of the rest of the measurement. The analyzers can measure down to -130 dBm PIM products with traditional 2 x 43 dBm input power. However, the price of PIM analyzers is high. Some of the analyzers might be cheaper than the test setup with signal generators and spectrum analyzer but PIM analyzers are usually only for specific frequency bands. One example of these kind of analyzers are the iBA B-series analyzers which costs 26 900 $. [39, 56] Although these analyzers are more convenient to use, they are usually for specific products only since they are so narrowband. Thus, built test setups might be a better choice overall.

5 TEST SETUP SIMULATIONS

As mentioned in the Chapter 4, PIM test setups must have at least 10 dB lower PIM power level than the measured PIM level. Thus, in linear scale, the measured PIM has to be at least 10 times higher than the IM generated by the measurement setup in the same frequency. The lower the residual PIM levels of the test setups are, more accurate are the measured PIM levels which means that it's best to have the test setup with the least residual PIM. Figure 16 showed the maximum errors of the measurements with varying measured to residual PIM values. With 10 dB difference, measurement errors are maximum of +2.4 dB to -3.3 dB.

In this Chapter, the test setup in Figure 15 is simulated with varying component parameters. The goal is to find the threshold values on which the setup works reliable for each setup components. Test setup simulations are done with AWR simulator tool. All of the simulations are done with "RF budget only" noise modelling of components. With that setting, the noise floor drops to very low level and the analysis of low-level PIM products is possible. All the simulations are done in 1 GHz environment with tone frequencies 0.95 GHz and 1.05 GHz. PIM3 that generates at frequency 0.85 GHz is considered to be on the RX band. Due to the confidentiality of Chapter 4's test results, real frequency bands of were not used.

5.1 Simulation of DUT

First, one DUT with parameters shown in Table 4 is simulated using linear signal generator for two 43 dBm tones like in Figure 20. The same simulation for PIM3 products can be done with component that has 118.5 dBm IP3 since 118.5 dBm leads to -108 dBm PIM3 according to Equation (17) if DUT is considered lossless.

Table 4. DUT simulation parameters.

FREQ=0.95G						
FREQB=1.05G						
PIn(,dBm)	POut(Mag,dBm)	POut(Phs,deg)	IM_2_1(Mag,dBm)	IM_1_2(Mag,dBm)	IM_3_2(Mag,dBm)	IM_2_3(Mag,dBm)
43	43	180	-108	-108	-117	-117

In Table 4, in addition to PIM3 and PIM5 value, power input PIn(dBm) and power output POut(dBm) and output phase POut(deg) values were given. Also, carrier frequencies FREQ and FREQB were noted.

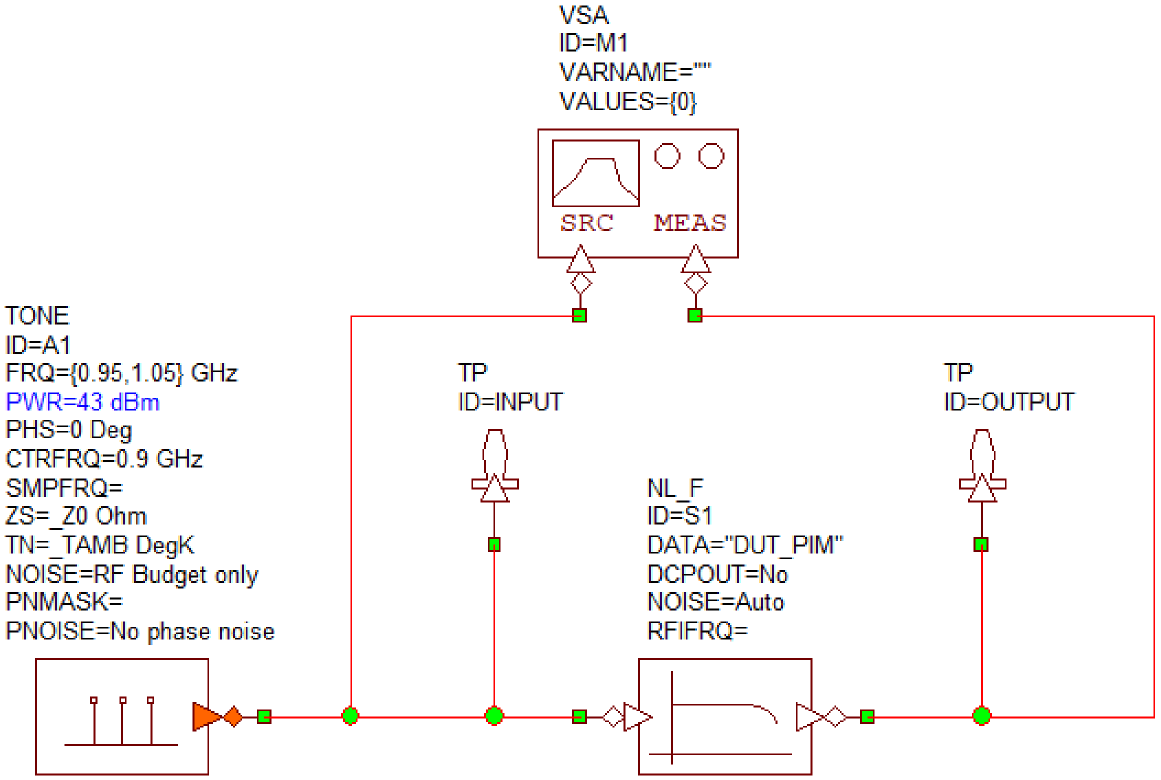

Figure 20. Simulation system of nonlinear DUT in linear environment.

As expected, the simulation leads to output spectrum shown in Figure 21 where PIM3s are -108 dBm and PIM5s are -117 dBm. PIM3 and PIM5 frequencies are calculated using Equations (13) and (14). PIM3s are located at frequencies 0.85 GHz and 1.15 GHz and PIM5s at frequencies 0.75 GHz and 1.25 GHz. This is the ideal nonlinear output that is not interfered by any measurement device or component.

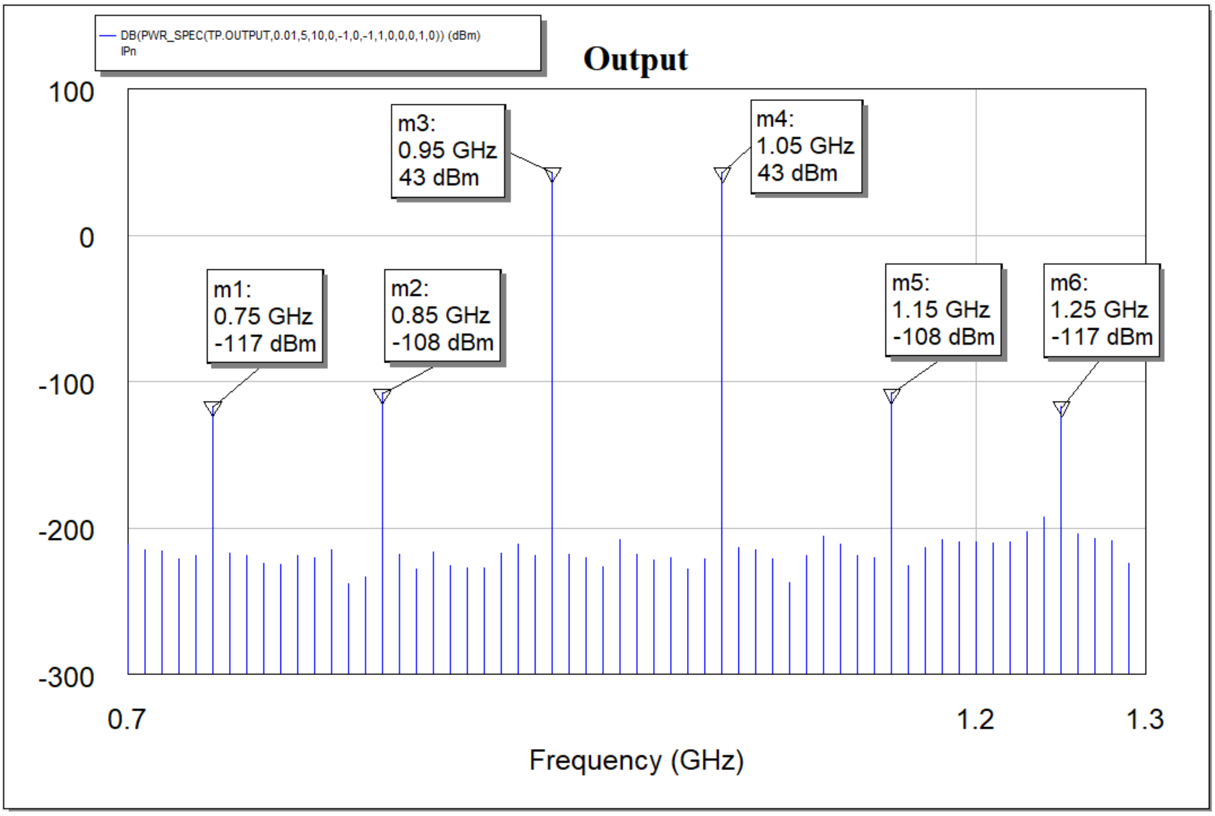

Figure 21. Output frequency spectrum of DUT.

5.2 Simulation of passive intermodulation test setup

In Chapter 5.1, it was proven that a simple DUT simulation model works in the AWR environment. This Chapter focuses on the simulations of the whole test setup. The test setup is shown in Appendix 1 since it's too large to be shown as a Figure. It has the same components as shown in the Figure 15. In simulations in this Chapter, DUT also has TX-RX isolation parameter of 100 dB which means that power levels from TX-ports to RX-ports are attenuated by 100 dB at RX band frequencies.

At first, PIM test setup was simulated with typical setup parameters shown in Table 5. [47, 53, 54] Signal generator OIP parameter is presented as output second order intercept point (OIP2) instead of OIP3 in Table 5. Sometimes, manufacturers note PIM related values by PIM3 power levels or PIM relative to carrier (dBc) values. OIP3 values are calculated from PIM3 values using Equation (17).

Table 5. Typical test setup parameters.

Part	Gain (dB)	P1dB (dBm)	OIP3 (dBm)	Noise
Signal Generator	-	-	(35 dBm OIP2)	RF budget
Power Amplifier	44.59	63	73	RF budget
Circulator	-0.45	65.5	75.5	RF budget
Combiner	-3	109.5	119.5	RF budget
Notch	-1 (~40 dB loss in RX band)	-	-	RF budget

Filter DUT	-1 to Ant port (100 dB TX-RX isolation)	-	118.5	RF budget

Figure 22 shows the frequency spectrum after notch filter. Notch has been tuned to lower IM3 frequency. As seen from the Figure 22, carrier power is right around 43 dBm which is specified to be the power level before DUT in the test specifications. Gain of the both power amplifiers are modified in a way that 43 dBm carrier power is achieved to the TX-port of DUT. All the insertion losses have to be compensated by the gains of PAs. Also, offset level of the SA can be set to the same level as the loss between RX-port and SA is. Therefore, the losses can be compensated both ways, before and after DUT.

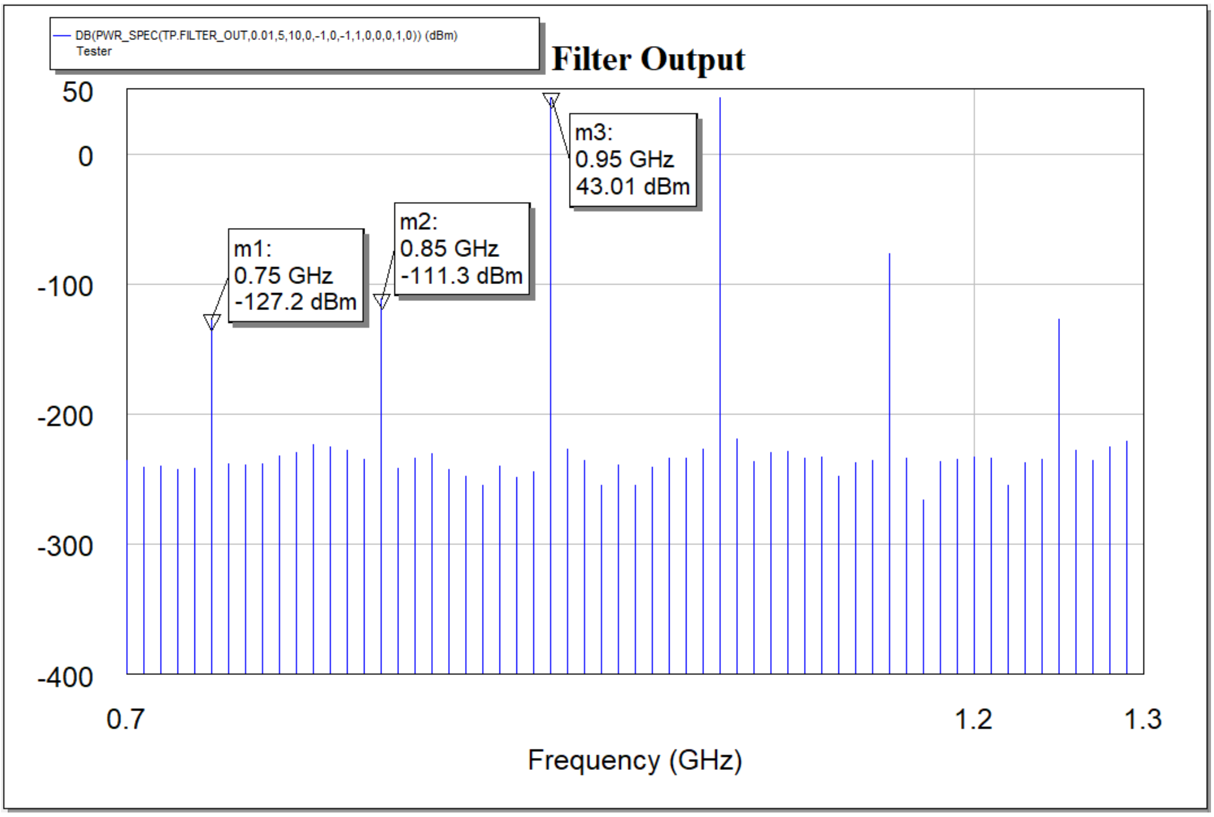

Figure 22. Frequency spectrum after notch filter.

Figure 22 shows that PIM3 power level at 0.85 GHz is around -111 dBm which already quite low. Since DUT's TX isolation on RX-port, from which the measurements are done, is around 100 dB, residual PIM effects of the setup before DUT go below noise level. Thus, only the PIM level that is being measured is significant. After DUT, the simulated frequency spectrum is shown in Figure 23. PIM3 at 0.85 GHz has a power level of -107.7 dBm which is close to DUT's PIM3 parameter that is -108 dBm. Also, the simulated power level of PIM5 is only 0.3 dB higher than given PIM5 parameter value of DUT.

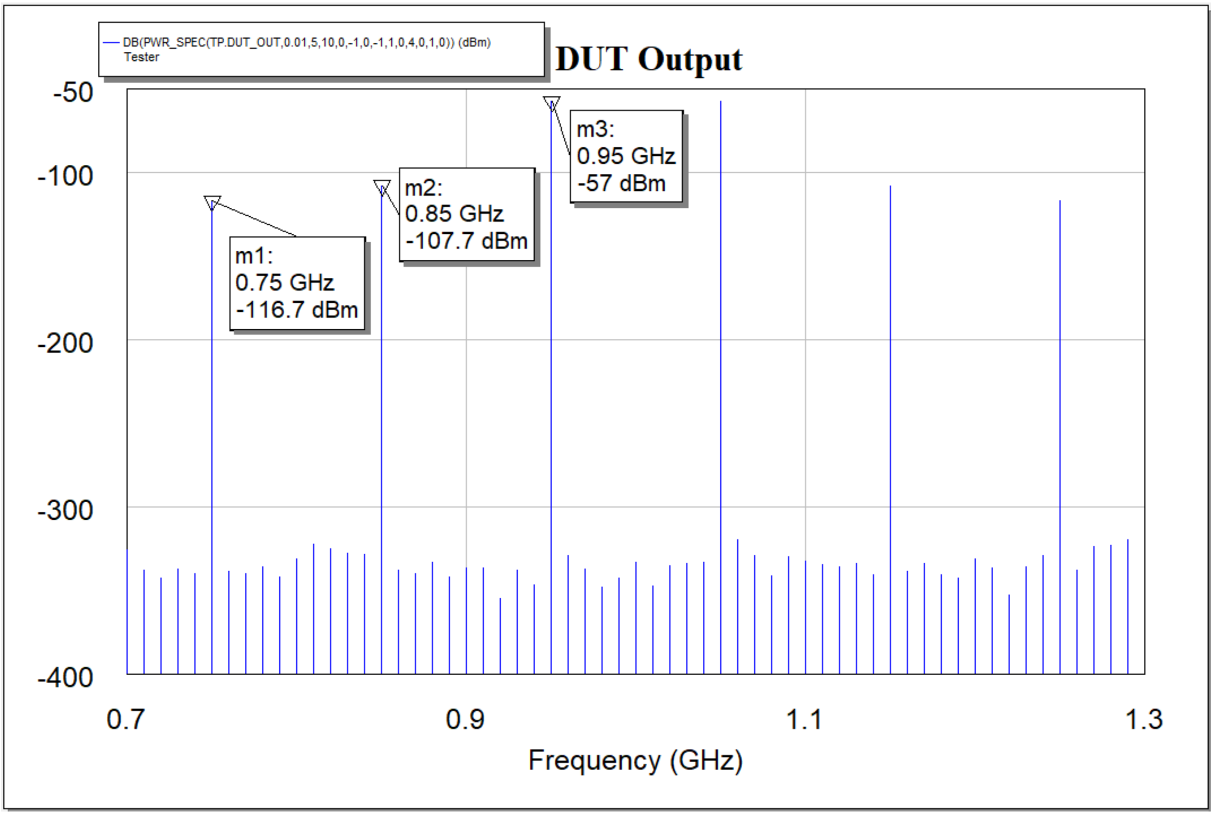

Figure 23. Output spectrum of DUT.

Because the carrier power is also attenuated in the DUT filter, low-PIM components like adapters and cables, that are after DUT in the signal path, don't have much impact on the simulation result, since their PIM rating is at least -150 dBc.

The test setup in this thesis benefited from the high TX-RX isolation value of the DUT filter. Other test setups like shown in Figure 14 have one or multiple duplexers or triplexers. Those duplex filters also filter power levels of RX band the same way as DUT filters do in this thesis. As a conclusion, components like signal generators, PAs, circulators and combiners before DUT in the signal path doesn't have to be as good as stated in Table 5 PIM-wise.

5.3 Threshold values for simulation components

Test setup shown in Appendix 1 can be modified. Components can be added or removed and the effect on the PIM levels can be compared then. Also, simulation thresholds can be found by simulating the same setup with lowered IP3 values of each component. Residual PIM of the setup has to be 10 dB below the measured PIM as stated in Chapter 4.2. [30] That is the limit which can't be exceeded in order to have reliable measurement results. Also, setup components should not be driven to compression. P1dB level is assumed to be 10 dB lower than OIP3 level and about 20 dB lower than OIP2 with every component. Component OIP3 threshold values of setup were simulated by modifying only one component at a time and leaving all parameters of other components as they are presented in Table 5. The results are presented with and without notch filter in Table 6. These threshold OIP3 values are simulated with insertion loss values presented in Table 5.

Table 6. OIP3 threshold values of the test setup components.

Part	Gain of PA (dB)	OIP3 (dBm) threshold value with notch	Gain of PA (dB) without notch	OIP3 (dBm) threshold value without notch
Default	44.59	-	-	-
Signal Generator	44.59	22.7 (OIP2)	44.59	22.7 (OIP2)
Power Amplifier	45.45	57.6	44.45	56.6
Circulator	45.40	57.5	44.40	56.5
Combiner	45.08	61.3	43.6	73.7

P1dB values of signal generators, power amplifiers and circulators calculated from OIP2 and OIP3 values from Table 6 are just around the same as the power level of the carriers. This means that these components are almost driven to compression. If P1dB is crossed, components are considered as nonlinear. It can be said that compressions limit these components in PIM testing. However, this is not the case with combiner since with the OIP3 values presented in Table 6, PIM3 power level before DUT is already very high, -18 dBm. With 100 dB TX-RX isolation of DUT, it means that the residual PIM of the test setup is -118 dBm. This is the limitation of residual PIM, if measured PIM3 is -108 dBm. However, in real life situation, OIP3 value of combiner should be at least 10 dB higher than shown in Table 6. Then PIM3 levels down to -128 dBm can be measured because PIM3 level before DUT filter is around -38 dBm with 43 dBm carrier power like in Figure 24. As a result, residual PIM would be around -138 dBm. That simulation result presented in Figure 24 contains frequency spectrum simulated without notch filter and with 83.7 dBm combiner OIP3.

As seen from Table 6, using notch filter, OIP3 of combiner could be significantly lower than without using notch filter in the test setup. Difference of combiner OIP3 is around 12.4 dB. Due to the high TX-RX isolation of DUT filter, notch filter doesn’t have much effect on OIP3 values of other components since those components are limited by their P1dB values. While using notch, OIP3 of SGs, PAs and circulators must be only 1 dB higher since insertion loss of notch is 1 dB in the simulations.

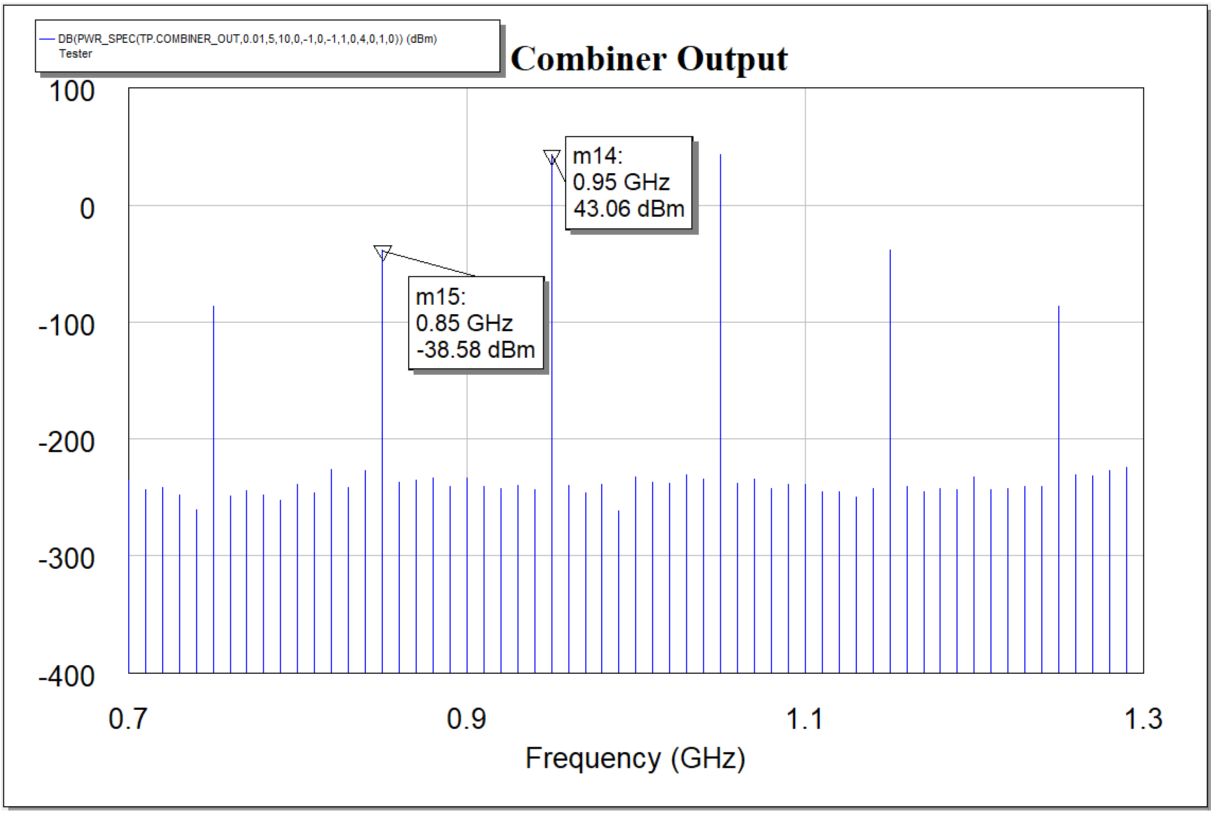

Figure 24. Combiner output spectrum with 83.7 dBm OIP3.

Spectrum analyzer, the receiver of the test setup, is also one component that might limit PIM testing. It can produce IM products on its own especially if its preamplifier is used. In that case another notch filter can be used to lower IM levels by filtering fundamental carrier signal frequencies. Therefore, higher level IMs can’t be generated. However, usually the limitation that spectrum analyzer causes in PIM testing is the noise floor which is depending mostly on RBW of the SA. Noise level simulations with the test setup shown Appendix 1 were not possible with AWR tool since the simulations would have been really slow due to very low level of noise. Therefore, only the noise calculations presented in Chapter 4.5 can be used to determine the limitation of noise in the setup.

6 DISCUSSION

The aim of this thesis was to analyze the measured test results with the help of theory and measurements. Also, PIM tester simulations were executed in order to research tester's characteristics and its limitations. This work was considered as success since the testing was done with good accuracy and the limitations of the test setup were found. These results can be used when a company is making considering purchasing or changing PIM test setup components. Additionally, the work of this thesis enabled a change to modify the simulation model for examining the PIM effect of certain component in the PIM setup. Also, testing results showed some typical characteristics from the measured DUTs.

For the purposes of this thesis, 12 filter units of base stations was measured altogether. The measurements were made using 2 x 43 dBm or 2 x 46 dBm input tone power from the RX ports of the filters. The results from 10 of these DUTs were presented. Four out of 10 DUTs was considered to be good because the results were 100 % pass with those units. Pass rates are calculated from the amount of measurement samples which was 4 - 16. Six DUTs were fails since the pass rates weren't 100 %. One DUT even had the average results which were below limit. Usually, the failing units had also high standard deviations which is expected because some of the results were poor and some good.

Two additional DUTs was measured and compared with two different frequency spacing values. In average, results showed that electro-thermal nonlinearity might have been the dominant source of PIM since the difference in PIM3 power levels was around 2-3 dB higher with 10 MHz frequency tone spacing compared to 20 MHz spacing. Since steep filters have high quality factors, either voltage or current has high gain. Therefore, hotspots for electro-thermally induced PIM can be found. If measurements were done with very closely spacing carriers, also notch for residual IM3 products before DUT could cause problems since it would filter TX carrier power close to that IM3 frequency. However, that is not problem with real life base stations. Usually, base stations have at least 5 MHz frequency spacing between TX and RX bands. Therefore, the tone spacing, that will form IM3 product at RX-band, must be at least 5 MHz, also.

Simulations of PIM test setup was executed for finding the limitations of the setup. It was found out that combiner of the setup must have the highest OIP3 value, 61.3 dBm, of all the components in the setup. Also, notch filter before DUT at measured IM frequency was proven to mitigate the need of high OIP3 value of combiner by 12.4 dB. 1 dB compression point was considered as the limitation for signal generators, power amplifiers and circulators. Additionally, noise floor was the most limiting factor for spectrum analyzers since the detection of low-level signal depends on it and the residual PIM of analyzers is usually low.

This thesis work taught a lot from the subject of passive intermodulation, its testing procedures and limitations. Using of AWR simulation tool was a good choice to simulate the impact of intermodulation. It's easy to use and the possibility to use noise parameter "RF budget only" enabled the opportunity to analyze very low-level intermodulation products from the noise floor because the noise level was so low level.

The work gave also some new ideas on future studies about PIM. One possibility could be to sweep one fundamental frequency in a two-tone test. Therefore, more test results in different RX frequencies would have been obtained with varying frequency spacing values. That way it would be easier to compare the measurement results to the theory of electro-thermal nonlinearity. Additionally, it would have shown the worst cases for each DUTs since in this thesis the measured test results might not be measured with the worst-case tone frequencies. Also, the use of different test powers might have shown effects of multiple PIM sources.

With more profound measurements, in the future it would be interesting to measure the PIM from the whole base station and compare those results with the filter unit results. That way it could be defined if the dominant PIM source was the filter or something else in the base station.

7 SUMMARY

The aim of this work was to find the theoretical boundaries of PIM testing with the help of theory, measurements and simulations. At first, the theory of intermodulation was presented with the ways to calculate intermodulation products and to analyze the power levels. Then, more specific introduction to PIM sources, types, disadvantages and modelling was presented in order to have wider understating of the PIM issue. Also, typical testing procedures of PIM was presented with the layout of the used test setup. Additionally, the difficulties and limitations of testing was discussed and calculated.

Testing was made with reliable low-PIM test setup consisted of quality components in the room temperature. The results from 10 different unit was presented in this thesis. Due to the confidentiality, the results were presented only as average from limit, pass percentage and standard deviation of the results. As a conclusion, four of those DUTs were really good since they had 100 % pass rate with good results. Pass rates are calculated from measurement samples that were 4 – 16. The same DUTs had good average from limit results and had fairly low standard deviation. The best unit had results better than 8.5 dB over the limit in average. It also had 100 % pass rate and less than 2.5 dB standard deviation. The failed six units didn't have 100 % pass rates and are considered as failed units. The worst unit PIM-wise had the results that were about 1.8 dB worse than the limit in average and pass rate was only 25 %. Also, the standard deviation was high, around 5.6 dB.

Measurements from the two additional DUTs showed that electro-thermal nonlinearity might have been the dominant source of PIM in the measurements. Those measurements showed around 2-3 dB increase of power levels in average while frequency spacing values are decreased from 20 MHz to 10 MHz which suits the theory.

PIM test setup was simulated with differing OIP3 values of each setup component. It was discovered that the combiner was the most critical component PIM-wise. It was simulated that OIP3 of combiner needs to be at least 61.3 dBm in a setup that contains notch filter before DUT at measured IM frequency if PIM levels down to -108 dBm is being measured. Without notch, OIP3 should be at least 73.7 dBm. However, in real life configurations, OIP3 of combiner should be around 10 dB higher (83.7 dBm without notch) in order to measure down to -128 dBm. For signal generators, power amplifiers and circulators, 1 dB compression point was considered to be the limitation since it was reached before PIM3 rose to a high level. In addition, the most limiting factor for usual spectrum analyzers is the receiver noise floor.

Finally, the success of this work was discussed, and the test results and simulation results were presented. Also, some new ideas on the future studies was presented including measurements with varying frequencies and input power levels.

8 REFERENCES

[1] Pedro J. C., Carvalho N. B. (2003) Intermodulation Distortion in Microwave and Wireless Circuits. Boston: Artech House (p. 4-13)

[2] Anritsu, Passive Intermodulation (PIM) (read: 29.10.2020) URL: https://www.anritsu.com/en-US/test-measurement/technologies/pim

[3] Kearney F., Chen S. (2007) Passive Intermodulation (PIM) Effects in Base Stations: Understanding the Challenges and Solutions (read: 29.10.2019) URL: https://www.analog.com/en/analog-dialogue/articles/passive-intermodulation-effects-in-base-stations-understanding-the-challenges-and-solutions.html

[4] Niviuk, LTE frequency band (read: 30.10.2020) URL: http://niviuk.free.fr/lte_band.php

[5] Intermodulation Measurements (read: 1.11.2019) URL: https://www.electrotest.co.nz/site/etl/Papers/Intermod_Measurements.pdf

[6] Trigonometric Identities (read: 7.11.2019) URL: https://www.math.uci.edu/~aaronc8/trig-ids.pdf

[7] Pozar D. M. (2012) Microwave Engineering, 4th ed. John Wiley Sons Inc. (p. 513-515)

[8] RF Wireless World, IIP3 vs OIP3 | difference between IIP3 and OIP3 (read: 20.11.2019) URL: https://www.rfwireless-world.com/Terminology/IIP3-vs-OIP3.html

[9] Kaelus, Does PIM Vary with Power Level? (read 20.11.2019) URL: https://www.kaelus.com/en/resource-center/faqs#collapse24k

[10] Anritsu (2017) PIM Test Power Level (read: 6.11.2019) URL: http://dl.cdn-anritsu.com/en-us/test-measurement/files/Application-Notes/Application-Note/11410-01008A.pdf

[11] Jacques Sombrin, Geoffroy Soubercaze-Pun, Isabelle Albert (2014) Relaxation of the multicarrier passive intermodulation specifications of antennas. *IEEE The 8th European Conference on Antennas and Propagation (EuCAP) 2014*

[12] Qiuyan Jin, Jinchen Gao, George T. Flowers, Yongle Wu, Gang Xie, Lingyu Bi (2019) Modeling of Passive Intermodulation in Connectors With Coating Material and Iron Content in Base Brass. *IEEE Transactions on Microwave Theory and Techniques (Volume: 67, Issue: 4) April 2019*

[13] Carlos Vicente, Hans L. Hartnagel (2005) Passive-intermodulation analysis between rough rectangular waveguide flanges. *IEEE Transactions on Microwave Theory and Techniques (Volume: 53, Issue: 8) August 2005*

[14] Isola-Group, PIM in PCBs: Mechanisms & Mitigation (read: 25.11.2019) URL: https://www.isola-group.com/wp-content/uploads/PIM-in-PCB-Mechanisms-Mitigation.pdf

[15] Kirill Shaposhnikov (2018) How to Perform a Nonlinear Distortion Analysis of a Loudspeaker Driver (read: 15.12.2019) URL: https://www.comsol.com/blogs/how-to-perform-a-nonlinear-distortion-analysis-of-a-loudspeaker-driver/

[16] Istitute for Rock Magnetism, Classes of Magnetic Materials (read: 15.12.2019) URL: http://www.irm.umn.edu/hg2m/hg2m_b/hg2m_b.html#ferromagnetism

[17] Jonathan Wilkerson, Kevin Gard, Alexander Schuchinsky, Michael Steer (2008) Electro-Thermal Theory of Intermodulation Distortion in Lossy Microwave Components. *IEEE Transactions on Microwave Theory and Techniques (Volume: 56, Issue: 12) December 2008*

[18] Michael Steer, Thomas Williamson, Joshua Wetherington, Jonathan Wilkerson, Peter Aan, Alex Schuchinsky (2018) Power and temperature dependence of passive intermodulation distortion. *IEEE 22nd International Microwave and Radar Conference (MIKON) 2018*

[19] Electrical 4 U (2019) Temperature Coefficient of Resistance (read: 8.12.2019) URL: https://www.electrical4u.com/temperature-coefficient-of-resistance/

[20] Weinstein D., Passive Intermodulation Distortion in Connectors, Cable and Cable Assemblies (read: 12.12.2019) URL: https://www.digikey.ca/en/pdf/a/amphenol-rf-division/passive-intermodulation-distortion

[21] Bell T. (2013) Mitigating external sources of Passive Intermodulation (PIM) (read: 13.12.2019) URL: https://dl.cdn-anritsu.com/en-us/test-measurement/files/Technical-Notes/White-Paper/11410-00756A.pdf

[22] Everything RF, Antenna Near Field & Far Field Distance Calculator (read: 15.12.2019) URL: https://www.everythingrf.com/rf-calculators/antenna-near-field-distance-calculator

[23] Kaelus, Does PIM Change with Time? (read: 22.11.2019) URL: https://www.kaelus.com/en/resource-center/faqs#collapse29k

[24] Afzal S., Sonin A. (2014) PIM-tester – worthwhile investment (read: 13.12.2019) URL: http://etn.fi/index.php/tekniset-artikkelit/1759-pim-testeri-kannattava-investointi

[25] Bin Wang, Li Jia Chen, Zhao Wei, Qing Yuan, Jing Hui Qiu (2014) Methods of Low Passive Intermodulation Design. *IEEE Applied Mechanics and Materials 2014, Vol.532, pp.496-499*

[26] Hayg-Taniel Dabag, Hamed Gheidi, Saeed Farsi, Prasad S. Gudem, Peter M. Asbeck (2013) All-digital cancellation technique to mitigate receiver desensitization in uplink carrier aggregation in cellular handsets. *IEEE Transactions on Microwave Theory and Techniques, vol. 61, no. 12, pp. 4754-4765, December 2013*

[27] Muhammad Zeeshan Waheed, Pablo Pascual Campo, Dani Korpi, Adnan Kiayani, Lauri Anttila, Mikko Valkama (2018) Digital Cancellation of Passive Intermodulation in FDD Transceivers. *IEEE 52nd Asilomar Conference on Signals, Systems, and Computers, October 2018*

[28] Purdue University (2018) ECE 255, Diodes and Nonlinear Circuits (read: 4.12.2019) URL: https://engineering.purdue.edu/wcchew/ece255s18/ece%20255%20s18%20latex%20pdf%20files/ece255Lecture_4_Jan18_Diode_Nonlinear_Circuit.pdf

[29] Chen F. (2017) Passive Inter-modulation Cancellation in FDD System. Master's Thesis. Lund University, Department of Electrical and Information Technology, Lund.

[30] Damm W. (2013) About PIM: Forward – Reverse – Residual (read: 12.1.2020) URL: https://awt-global.com/wp3/wirelesspages/wirelesspages1013.pdf

[31] Dmitry S. Kozlov, Alexey P. Shitvov, Alexander G. Schuchinsky, Michael B. Steer (2016) Passive Intermodulation of Analog and Digital Signals on Transmission Lines With Distributed Nonlinearities: Modelling and Characterization. *IEEE Transactions on Microwave Theory And Techniques, vol. 64, no. 5, May 2016*

[32] Kaelus, Are There Measurements Standards for Passive IM? (read: 10.12.2019) URL: https://www.kaelus.com/en/resource-center/faqs#collapse35k

[33] International Electrotechnical Commission, WG 6 Passive Intermodulation Measurement (PIM) (read: 10.12.2019) URL:

https://www.iec.ch/dyn/www/f?p=103:14:5036673123675::::FSP_ORG_ID,FSP_LANG_ID:2248,25

[34] Electronics Notes, PIM Testing & Testers (read: 11.12.2019) URL: https://www.electronics-notes.com/articles/radio/passive-intermodulation-pim/testing-tester.php

[35] Everything RF, PIM Analyzers (read: 11.12.2019) URL: https://www.everythingrf.com/search/pim-analyzers

[36] Anritsu (2015) Using Distance-to-PIM (DTP) and Distance-to-Fault (DTF) trace overlay to speed site repair (read: 10.12.2019) URL: https://dl.cdn-anritsu.com/en-us/test-measurement/files/Application-Notes/Application-Note/11410-00869A.pdf

[37] Andrew J. Christianson, Justin J. Henrie, William J. Chappell (2008) Higher Order Intermodulation Product Measurement of Passive Components. *IEEE Transactions on Microwave Theory and Techniques (Volume: 56 , Issue: 7) July 2008*

[38] Peda Siikalatva, Standard Deviation (read: 8.1.2020) URL: https://peda.net/siikalatva/siikalatvan-lukio/oppiaineet/matematiikka/maa102/mappi2/mappi/kjo:file/download/a4fb66926de912b5d118c533c0e233799f639510/Keskihajonta%20ja%20otoskeskihajonta.pdf

[39] Email conversation with Rikard Wahlström (Microdata) 18.3.2020

[40] Wilkerson J. (2010) Passive Intermodulation Distortion in Radio Frequency Communication Systems. Doctoral Dissertation. North Carolina State University, Raleigh.

[41] RF Cafe, Cascaded 2-Tone, 3rd-Order Intercept Point (IP3) (read: 24.2.2020) URL: https://www.rfcafe.com/references/electrical/ip3.htm

[42] Faison K. (2006) Understanding noise figure in radio receivers (read: 26.2.2020) URL: https://www.eetimes.com/understanding-noise-figures-in-radio-receivers/#

[43] Rohde & Schwarz (2012) Speed considerations for Spurious Level Measurements with Spectrum Analyzers Application Note (read: 26.2.2020) URL: https://scdn.rohde-schwarz.com/ur/pws/dl_downloads/dl_application/application_notes/1ef80/1EF80_1E.pdf

[44] Rohde & Schwarz (2012) Intermodulation Distortion Measurements on Modern Spectrum Analyzers Application Note (read: 26.2.2020) URL: https://cdn.rohde-schwarz.com/pws/dl_downloads/dl_application/application_notes/1ef79/1EF79_1E.pdf

[45] RF Cafe, Cascaded Noise Figure & Noise Temperature (read: 27.2.2020) URL: https://www.rfcafe.com/references/electrical/noise-figure.htm

[46] Signal Processing Stack Exchange (2017) How can I calculate the amplitude of a signal from its power in dBm? (read 3.3.2020) URL: https://dsp.stackexchange.com/questions/36359/how-can-i-calculate-the-amplitude-of-a-signal-from-its-power-in-dbm

[47] Keysight N5194A and N5192A Datasheet (read: 9.3.2020) URL: https://www.keysight.com/de/de/assets/7018-05693/data-sheets/5992-2228.pdf

[48] Keysight N9320B Datasheet (read: 9.3.2020) URL: https://www.keysight.com/de/de/assets/7018-02996/data-sheets/5990-8119.pdf

[49] Keysight N9030A Datasheet (read: 9.3.2020) URL: https://www.keysight.com/de/de/assets/7018-02142/data-sheets/5990-3952.pdf

[50] Kaelus (2017) PIM Test Power Levels For Mobile Communication System (read: 9.3.2020) URL: https://www.kaelus.com/getmedia/4766daf9-2774-46e6-9540-6ef220c2a264/PIM-Test-Power-Levels.pdf.aspx?ext=.pdf

[51] Fairview Microwave, Low PIM RF Cable Assemblies (read: 11.3.2020) URL: https://www.fairviewmicrowave.com/rf-products/low-pim-rf-cable-assemblies.html

[52] Hasco Inc, Low PIM Adapters (read: 11.3.2020) URL: https://www.hasco-inc.com/categories/pim.html

[53] JQL (2015) Circulator JCC0700T1000NMNFNF Datasheet (read: 11.3.2020) URL: http://www.jqlelectronics.com/wp-content/uploads/2015/09/JCC0700T1000NMNFNF.pdf

[54] Innowave RF, Combiner 121-700-2700-2-N Datasheet (read: 11.3.2020) URL: http://www.innowaverf.com/low-pim-2-way-power-combinerdivider.html

[55] Wainwright Filters, Tunable Notch Filter WTRCTW8 Datasheet (read: 11.3.2020) URL: https://www.wainwright-filters.com/standard-filter-pdf/manually-tunable-band-reject-notch-filters/0f9d58ff-4f6c-4eb3-8594-85e7cbc5ca49

[56] Kaelus, Bench PIM Test Equipment (read: 12.3.2020) URL: https://www.kaelus.com/en/test-measurement-solutions/bench-pim-testing/iba-series

[57] TEquipment, Rigol DSG815 9 kHz to 1.5 GHz, RF Signal Generator (read: 22.3.2020) URL: https://www.tequipment.net/Rigol/DSG815/AM/FM-Signal-Generators/

9 APPENDICES

Appendix 1 Passive intermodulation test setup system diagram.

Appendix 1 Passive intermodulation test setup system diagram.