Multi Carrier Analysis of a Satellite Converter Output Amplifier

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Nonlinearity behavior in microwave circuits generates intermodulation products that can interfere with the desired output signals. Linearity requirement of a microwave circuit is often specified by third-order intersect point (IP3) and 1 dB compression point (P1dB). These parameters are determined for an input of one or two signals whereas in reality microwave circuits often have a lot more than two input signals, and therefore it is desired to investigate the nonlinear behavior during a multi carrier case.

In this thesis an investigation of the nonlinear behavior in an output amplifier when exposed to a multi carrier case has been performed. To perform the investigation a simplified simulation model was developed using the computer design software Advanced Design System. Measurements of a satellite converter output amplifier when subjected to multi carrier tests were conducted. This thesis also compares the simulation and measurement results for the multi carrier case.

The figure of merit investigated, C/I, is determined as the relation between the carrier signals and the intermodulation products, and the relation between C/I, output power, IP3 and P1dB was studied for the multi carrier case.

The results showed that C/I is similar for the all investigated multi carrier cases if compared at the same total output power, and C/I is therefore not strongly affected by the number of input signals.

The results also showed that C/I is limited by IP3 at lower output powers, and by P1dB at higher output power. A breakpoint output power was found where C/I was affected by both IP3 and P1dB. The relation between the breakpoint output power, $P_{\text{out}}$, IP3 and P1dB for these measurements is given in the results.

An important lesson from the thesis work is that the phases of the input signals are very significant for the output result of a multi carrier case. Thus when conducting a multi carrier simulation or test it is needed to use a suitable method to sum all contributions to the intermodulation product.
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CHAPTER 1

1 INTRODUCTION

Over fifty years have passed since the first satellite was launched into space. Today satellites are an essential part of our daily lives as they provide us useful tools such as weather reports and television transmissions. In fact, today we take for granted the everyday use of wireless communication such as mobile phones, and there is a fast growing market for wireless communication in space applications.

Microwave radio transmission is commonly used in satellite communication and as the demands of satellite communication increase the demand of microwave circuits increases as well. A big concern when designing microwave circuits is the nonlinear phenomena that occurs, which causes to the communication systems not to operate in reality as they should in theory.

One of the challenges of microwave circuits today is the requirements of multi carrier input response. Nonlinearity characterization of microwave circuits is still done by a one- or two-tone test, whereas in reality the microwave circuits often have many more than two input signals. The aim of this thesis is to investigate the multi carrier case of microwave circuits used for space applications, and more specific, investigate the multi carrier case for converters and receivers developed by RUAG Space.
1.1 RUAG Space

The thesis work was carried out at RUAG Space and its Microwave Electrical Design section. RUAG Space is the largest supplier of space technology in Europe and develops, manufactures, and tests subsystems and equipment for satellites and launch vehicles. The company is located in Switzerland, Sweden and Austria and RUAG Space offers products and services for both institutional and commercial space missions.

The Microwave Electrical Design section is situated in Gothenburg, Sweden, and has supplied microwave communication equipment for telecom and earth observation satellites for more than thirty years.

1.1.1 Converters and Receivers

Frequency converters and receivers for communication payloads are RUAG Space main microwave electronic products. A frequency converter or receiver converts the uplink radio frequency to a satellite by mixing the received frequency signal with generated oscillator frequencies. This generates a new frequency that is used for the downlink signal. RUAG Space converters and receivers are characterized by small size, low noise, high linearity, excellent frequency stability and low spurious levels [1].

RUAG Space converters and receivers have been selected for use on many well-known satellites, such as Eutelsat, Intelsat, ANIK, JCSat, New Skies, BSAT and Amazonas, and has proven to be highly reliable. No operational failure has ever occurred during flight.

Figure 1-1: Converter used in Amazonas 2
1.2 Thesis background

There are several figures of merits for characterization of nonlinear circuits. For example, an amplifier often has the linearity requirements specified as third order output intercept point, OIP3, in dBm. The intercept point is measured using two closely spaced carriers as test signals. The level of unwanted signals at the output is measured relative to the wanted signals, and the corresponding OIP3 level is calculated. The OIP3 level is the most frequently used linearity requirement for RUAG Space Converters. However, due to the fact that the practical use of the converter consists of several input signals, the two carrier case is superseded by a multi carrier case. The multi carrier, also called multitone, case is more difficult to measure and to simulate, and even more so to analyze and therefore it is desirable to investigate how the circuit operates and how the unwanted signals arise during a multi carrier case.

1.2.1 Thesis goal

The task is to investigate simple simulation methods for the multi carrier case and to study the unwanted signals at the output relative to the wanted signals. The task is also to find a relation between these unwanted signals and output power, OIP3 level and other more easily determined and measured parameters, such as the 1 dB compression point.

Another goal with this thesis work is to perform measurements of the multi carrier case at an output amplifier hybrid, and if possible verify the suggested simulation method with the measurements. If possible, the thesis should also suggest design optimizations with respect to OIP3 and 1 dB compression point for the multi carrier cases.
1.2.2 Thesis limitation

Even though there are several electronic steps in a converter that can cause unwanted signals, the thesis will focus on the output amplifier hybrid. Another limitation is that the thesis will only investigate the unwanted signals in-band as the unwanted signals that arise out of band are not of great concern.
2 THEORY

This chapter is intended to give some basic understanding of nonlinear microwave theory. Most of the theory presented here is taken from microwave engineering books [2], [3] and [4]. For more comprehensive knowledge please see the books listed in the references.

2.1 Introduction Nonlinearity

All electronic circuits are nonlinear. The linear assumption that underlies most modern circuit theory is in practice only an approximation. Some circuits, such as frequency multipliers, are exploited for their nonlinearity and would not be possible if nonlinearity did not exist. Other circuits, such as small-signal amplifiers, are only weakly nonlinear and are used in systems as if they were linear. In these circuits, nonlinearity is responsible for phenomena that degrade system performance.
Nonlinear systems are easily explained as systems that are not linear. Linear systems are defined as those for which the superposition principle holds [2]. That is, whose output to a signal composed by the sum of other more elementary signals can be given as the sum of the outputs to these elementary signals when taken individually. In figure 2-1 the output differences between linear and nonlinear behavior is shown, if the input signal is assumed to be a single sinusoidal tone.

Where the input and output frequencies in linear behavior are the same, in the nonlinear behavior the output frequency may shift. With linear behavior the output frequency only undergoes magnitude and phase changes, whereas with nonlinear behavior additional frequencies, such as harmonics and intermodulation products, are created.

In mathematical terms linearity can be stated as [3]

\[ y(t) = F[x(t)] = a \cdot x_1(t) + b \cdot x_2(t) \]  

(2.1)

where \( a \) and \( b \) are arbitrary real constants and if

\[ x(t) = a \cdot x_1(t) + b \cdot x_2(t) \]  

(2.2)

and

\[ y(t) = F[x_1(t) \cdot y_2(t)] F[x_2(t)]. \]  

(2.3)
Any system that does not obey superposition is said to be a nonlinear system. Stated in this way, it seems that nonlinear systems are the exception, whereas they are really the general rule.

Nonlinear circuits are often characterized as either strongly nonlinear or weakly nonlinear. Although these terms have no generally accepted formal definition, a good working definition is that a weakly nonlinear circuit can be described with adequate accuracy by a power series expansion of its nonlinear current-voltage (I/V), charge-voltage (Q/V), or flux-current (Φ/V) characteristic.

2.2 Frequency generation

One of the properties of a nonlinear system is generation of new frequencies and harmonics of the excitation frequencies. For weakly nonlinear circuits, as the ones investigated in this thesis, the frequency generation can be analyzed via relatively straightforward techniques, such as a power series or Volterra series.

The traditional way of showing how new frequencies are generated in nonlinear circuits is to describe the components I/V characteristic via a power series and by assuming a multitone excitation voltage [2]. The current of a nonlinear circuit is given by the expression

\[ I = aV + bV^2 + cV^3 \]  \hspace{1cm} (2.4)

where \( a, b, \) and \( c \) are constant, real coefficients. Assuming that \( V_s \) is a two-tone excitation of the form

\[ V_s = v_s(t) = V_1 \cos(\omega_1 t) + V_2 \cos(\omega_2 t). \]  \hspace{1cm} (2.5)

substituting (2.5) into (2.4) gives, for the first term,

\[ i_s(t) = av_s(t) = aV_1 \cos(\omega_1 t) + av_s(t) = aV_2 \cos(\omega_2 t). \]  \hspace{1cm} (2.6)

After doing the same with the quadratic second term and applying the trigonometric identities one obtain,
\[ i_b(t) = b v_i^2(t) = \]
\[ = \frac{1}{2} b \left\{ V_1^2 + V_2^2 + V_1^2 \cos(2\omega_1 t) + V_2^2 \cos(2\omega_2 t) \right\} + 2 V_1 V_2 \left[ \cos(\omega_1 + \omega_2) t + \cos(\omega_1 - \omega_2) t \right] \]
\[ \text{(2.7)} \]

and the third cubic term gives
\[ i_c(t) = c v_i^3(t) = \]
\[ = \frac{1}{4} c^3 \left\{ V_1^3 \cos(3\omega_1 t) + V_2^3 \cos(3\omega_2 t) \right\} + 3 V_1^2 V_2 \left[ \cos(2\omega_1 + \omega_2) t + \cos(2\omega_1 - \omega_2) t \right] \]
\[ + 3 V_1 V_2^2 \left[ \cos(2\omega_2 + \omega_1) t + \cos(2\omega_2 - \omega_1) t \right] \]
\[ + 3(V_1^3 + 2V_1^2 V_2) \cos(\omega_1 t) + 3(V_2^3 + 2V_1 V_2^2) \cos(\omega_2 t) \}
\[ \text{(2.8)} \]

Equations (2.6)-(2.8) show a remarkable number of new frequency components, each one generating more new frequencies than the previous. If a fourth- or fifth-degree term was included, the number of new frequencies would be even greater.

In this case there are only two frequency components in the input signal, \( \omega_1 \) and \( \omega_2 \). With even more frequency components for \( V_i \) the generation of frequency components would be very large. In order to have a tractable analysis it is necessary to ignore all frequency components beyond some point. The number of components retained would depend upon the strength of the nonlinearity, the magnitude of the excitation voltage and the desired accuracy of the results.

A closer examination of the generated frequencies shows that all occur at a linear combination of the two excitation frequencies,
\[ \omega_{m,n} = m \omega_1 + n \omega_2 \]
\[ \text{(2.9)} \]

where \( m,n = \ldots -3, -2, -1, 0, 1, 2, 3, \ldots \)

\( \omega_{m,n} \) is called a mixing frequency and the current component at that frequency is called a mixing product. The sum of the absolute values of \( m \) and \( n \) is called the order of the mixing products.

Generation of harmonics occurs at \( m \omega_1 \) and \( m \omega_2 \). In many systems the generation of harmonics is not a serious problem because the harmonics are far removed in frequency from the signals of interest and therefore rejected by filters. In other systems harmonics
and other spurious outputs may interfere and must be reduced carefully by filtering or by other means.

When comparing the linear and nonlinear response the first difference is the number of terms present in (2.8) and (2.5). While the linear response to a modulated sinusoid is a similar modulated sinusoid, the nonlinear response includes many other frequencies, usually named as spectral regrowth, beyond that linear component. Hence in contrary to linear systems nonlinear systems can modify spectra, as they eliminate certain spectral components, and generate new ones.

2.3 Nonlinear phenomena

There are several characterization techniques that enable the correct definition of most nonlinear distortion figures. The most relevant methods for this thesis are presented in sections below.

2.3.1 Intermodulation (IM)

All the mixing products that arise as linear combinations of two or more tones are called intermodulation (IM) products [2]. Intermodulation products generated in an amplifier or communication receiver can cause problems, because they represent spurious signals that interfere with, and can be mistaken for, desired signals. Even-order intermodulation products usually occur at frequencies far above or below the signals that generate them and are therefore often of little concern. The intermodulation products of greatest concern are usually the third-order ones that occur at $2f_1-f_2$ and $2f_2-f_1$, because they are the strongest of all odd order products, are close to the signals that generate them, and are difficult to reject by filters.

2.3.2 P1dB

1 dB compression point (P1dB) is a figure of merit for output power. Higher compression point means higher output power. The 1 dB compression point can easily be determined by a one-tone test. Studying the gain of a nonlinear circuit, at some point the gain will be lowered as the input power is increased. The compression point is defined as the output power level at which the actual gain achieved deviates from the small signal gain by 1 dB [4].
All active components have a linear dynamic range. This is the range over which the output power varies linearly with respect to the input power. As the output power increases to near its maximum capability, the device will begin to saturate. The point at which the saturation effects are 1 dB from linear is defined as the 1 dB compression point as shown in figure 2-2.

![Gain plot showing the saturation power and P1dB.](image)

**Figure 2-2: Gain plot showing the saturation power and P1dB.**

### 2.3.3 Two-tone test

A commonly used method of determining the intermodulation properties of a nonlinear circuit is to perform a two-tone test, in which two excitations of equal amplitude and separated slightly in frequency, are applied to the circuit, and the powers of the resulting output intermodulation components are measured [3], [4]. The spectrum in the frequency domain of the two-tone test is shown in figure 2-3.
2.3.4 Third-Order Intercept Point

The third-order intercept point is a fictitious point that is obtained at which the fundamental and third-order distortion output lines are intercepted [3], [4]. The two-tone test enables the definition of this very important figure of merit for characterizing the intermodulation products in nonlinear devices. The third-order intercept point can be shortened to both TOI and IP3. Higher IP3 means better linearity and less distortion. Figure 2-3 illustrates the two-tone IP3 test in the frequency domain. Because the amplifier is not perfectly linear, it produces two third-order intermodulation (IM3) products. To reduce third order distortion products, the IP3 level must be increased.
Line A is the slope line of the output fundamental, desired, power and line B is the slope line of the third-order distortion output. For every dB increase in input power, the third-order products will increase by 3 dB and eventually intersect the slope of the output fundamental. However, due to compression the output fundamental will saturate before intercepting the intermodulation product, leaving a theoretical intersection. This mathematically calculated intersection is the third-order intercept point.

IP3 can be specified referred to the input power, IIP3, and for the output power, OIP3. The equations for IP3 are given below

\[ OIP3 = P_{out} + \frac{dBC}{2} \]  \hspace{1cm} (2.10)

where dBc is the difference in dBm between one of the fundamental output signals and the third-order product seen in figure 2.

\[ IIP3 = OIP3 - Gain \]  \hspace{1cm} (2.11)
2.4 Multitone test

Although one-tone and two-tone techniques still represent the industry standards in intermodulation product characterization, nowadays, engineers seek for alternative test procedures closer to the practical case of the circuits. Today telecommunications signals are usually composed of more than two carriers. Multitone tests have generated numerous figures of merits for characterizing intermodulation products of nonlinear circuits, such as Multitone Intermodulation Ratio and Noise Power Ratio [4].

![Figure 2-5: Output spectra of a multitone test with 12 carriers](image)

One of the ways to measure intermodulation products with a multitone test is by removing one of the carrier signals, creating an empty channel in the middle of the signals. Measuring and comparing the intermodulation product in the empty channel with the carriers gives a figure of merit, C/I, of the intermodulation products in the nonlinear device and will be used in this thesis.

2.4.1 Carrier phases

An important factor when dealing with multitone tests is the phases of the carriers. Suppose that the 12 signals in figure 2-5 were generated in a way that all the carriers are related in phase. Because all the tones are now correlated, there may be time spots where they all attain their highest maximum and other time spots where they may cancel each other. This is illustrated in figure 2-6.
Figure 2-6: Signal summation with different phases

Figure 2-6 shows the result of summing two signals of equal amplitude but at various phase relationships. In (a) the two sine waves are in phase and the sum of the two sine waves has twice the amplitude of the individual sine waves. In (b) the summing of the signals when there is a 90 degree phase difference between them is shown. The resulting sum signal is the result of a point by point addition of the two individual sine waves. (c) shows the two sine waves 180 degrees out of phase. Each point on the sine wave 2 line is
the exact negative of the corresponding point on the sine wave 1 line. Therefore a sum of the two points equals 0 thus the signals have cancelled each other out.

When the two signals have different frequencies the result is more complicated. The new signal is no longer a sinusoid since it does not follow the simple up and down pattern.

![Figure 2-7: Addition of two signals with different frequencies.](image)

When signals are added with both different phases and frequencies the result is even more complicated, as in the realistic case with multitone signals. The intermodulation products that arise from the carriers are therefore difficult to predict.

As the carriers can have numerous different phases and frequencies they will affect the intermodulation products generated. In figure 2-8 two different output spectra of a multitone test are shown.
The high amplitude intermodulation products in figure 2-8 are generated when all input signals have the same phase, and the lower intermodulation products are created when the input signals have a randomly set phase relatively each other. The difference between the intermodulation products depending on the signal phases can be of great influence for the results. It should be said that the practical case is more likely to have randomly phases for all input signals. Thus the method of signal summation during simulations and measurements will be important.

2.4.2 Power and Voltage summation

When working with multitone cases it is often necessary to determine the total power represented by multiple carriers. The difficulty comes from the fact that summing signals is a linear function but signal powers are measured in log values of dBm. The most accurate method of summing the signals consists of converting the signal powers to linear values, usually in milliwatts, summing them, then converting the sum back to dBm. The equation to convert dBm into watt is shown in equation (2.12).
$$dBm = 10 \cdot \log\left(\frac{W}{0.001}\right)$$

$$\Rightarrow W = \left(\log^{-1}\left(\frac{dBm}{10}\right)\right) \cdot 0.001$$

(2.12)

When signal powers are summed, the resulting power is usually the linear sum of the two powers. One can use either voltage summation or power summation when summing signals. Voltage sum is the sum of multiple signal voltages whereas the signal power is a function of the voltage squared. Thus doubling the signal voltage results in 4 times the signal power.

Whether to use power summation or voltage summation during the simulations and measurements is often depending on the simulation software and the limitations of the instruments. It is however important to keep in mind the differences to get an accurate result that reflect the realistic case.
CHAPTER 3

3  METHOD

The first step to investigate how the multitone case affects the linearity in amplifiers is finding a simulation method in Agilent Advanced Design System (ADS) for the multitone case. The equations presented in this section are taken from Agilent design guides for simulations in ADS. For more comprehensive knowledge please see the guides listed in the references [5], [6] and [7].

Measurements of the multitone case were made on an output amplifier hybrid. The simulation and measurements results were also compared. In this section the procedure to finding a simulation method and the measurement method are presented.

3.1  Simulation in ADS

The simulations of nonlinear amplifiers were made in Agilent Advanced Design System (ADS), which is a computer design software for RF, microwave, and high speed digital applications.
3.1.1 Simulation procedure

A circuit was set-up with a power source that could provide multiple tones, a relatively simple system amplifier model and an output port termination. The simple system amplifier model is based on a polynomial model of the magnitude of the output voltage as a function of the input voltage. The order of the polynomial depends on the data entered by the user. The second order intercept point (SOI) was not specified in these simulations thus the magnitude response was modeled using a polynomial of odd orders \[5\],

\[ y = a_1 \cdot x + a_3 \cdot x^3 + a_5 \cdot x^5 + a_7 \cdot x^7 + \ldots \]  

(3.1)

In these simulations three parameters have been specified; the linear gain S21, the 1 dB compression point (GainCompPower) and the third-order intercept point (TOI). The behavior of the amplifier must match these parameters, and is achieved by fitting

\[ y = a_1 \cdot x + a_3 \cdot x^3 + a_5 \cdot x^5. \]  

(3.2)

Three known quantities allow the determination of the three unknown polynomial coefficients. However, a fifth-order term appears and therefore the amplifier will produce fifth-order harmonics. The fifth-order term for the amplifier is necessary to properly model S21, GainCompPower and TOI [5].

The gain of the amplifier (S21) was set to zero dB so the input power would be the same as the output power. The gain in the simulations does not affect the nonlinear phenomena in the model, so there was no need to increase the gain. This can be seen in equation (2.11). When performing the measurements the test device will have gain, and therefore to obtain the same output power the input power will be lowered.

The third intercept point, TOI, was altered between 37 and 40 dBm during the simulations. The gain compression, P1dB, was altered between 23 and 26 dBm. These values were chosen as they are close to the requirement values of the converters. Two different values of IP3 and P1dB give four different comparison cases, which was feasible for the simulation method.

The input signal during the simulations came from a power source that could produce multiple tones, where each tone could have an individual frequency and amplitude. To create intermodulation products in the multitone simulation the spacing between the tones needed to be equal and for the simulations the spacing between the tones was chosen to 25 MHz.
The removed input signal had a frequency of 3.15 GHz, creating an empty channel in the input frequency spectra. If there was no distortion in the circuit, the depth of this channel in the output spectrum would be infinite. The smaller the depth of this channel, the greater the distortion caused by the circuit, hence greater intermodulation products.

When doing a multitone simulation, it is necessary to randomly set the relative phases of the input signals, otherwise they would all add together in phase and produce an unrealistically large input signal. This phase randomization was accomplished by adding a phase term uniformly distributed between \(-\pi\) and \(+\pi\) to each input tone. These random phase terms were generated via a Monte Carlo simulation.

### 3.1.2 Monte Carlo simulation

The Monte Carlo method simply consists of a series of trials. Each trial results from randomly generating yield variable values, in this case the phase term. A large number of trials were required to obtain high confidence and an accurate estimate of yield. The number of trials can be calculated from following formula [6],

$$N = \left(\frac{C_{\alpha}}{\varepsilon}\right)^2 \cdot Y(1-Y), \quad (3.3)$$

Where \(C_{\alpha}\) is the confidence expressed as a number of standard deviations, \(Y\) is the yield level and \(\varepsilon\) is the percent error of the absolute difference between the actual yield, \(Y\), and the yield estimated.

For a 95.4% confidence level, \(C_{\alpha} = 2\), a yield of 80% and an error of 2.5% the number of trials becomes approximately 1000.

A large number of iterations affect the simulation time greatly and therefore it is not desirable to have a too large number of iterations.

Simulating the multitone case in ADS with this method leads to a power summation of the resulting intermodulation product for each phase. It is possible to use a simulation method that presents each contribution to the intermodulation product separately, and use voltage summation to reach the final intermodulation product. However, this method leads to a even greater number of data points, and requires a great amount of computer memory, making the simulations very time consuming, if even possible. Using the Monte Carlo method was the only feasible simulation method due to computer memory limitations. To get a reliable result from the Monte Carlo method a large number of iterations had to be used to get reliable average values of the intermodulation products.
3.1.3 Simulation cases

Four different multi-tone simulations were performed, a 2-tone, 6-tone, 12-tone and an 18-tone simulation. For the 2-tone simulation the spurious signals besides the carrier signal were measured and compared, for the 6-tone, 12-tone and 18-tone simulations one of the carrier signals was removed, creating an empty channel in the middle of the carrier signals. The intermodulation product in this channel was measured and compared to one of the carrier signals. This difference is referred to as C/I. The unit used for C/I is dBC, which the difference in dBm between the carrier and the intermodulation product.

Figure 3-1: Input spectrum for the 2-, 6-, 12- and 18-tone test case

The purpose of the simulations and the measurements was to compare the four different cases at the same total output power. This required different input power for the carriers for the four different cases, as the input power in the simulations is specified by input power in dBm for each tone. To compare the input power of the four cases the input power was converted into voltage using equation (2.12).

To obtain a total input power between 0 and 30 dBm for all four cases they had different start and stop input power. The input power was swept between the start input power and stop input power in steps of 1 dBm.
Table 3-1: Start power/carrier and stop power/carrier for the four multitone cases

<table>
<thead>
<tr>
<th></th>
<th>Start power [dBm]</th>
<th>Stop power [dBm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-tone</td>
<td>-3.01</td>
<td>26.99</td>
</tr>
<tr>
<td>6-tone</td>
<td>-6.99</td>
<td>23.01</td>
</tr>
<tr>
<td>12-tone</td>
<td>-10.43</td>
<td>19.586</td>
</tr>
<tr>
<td>18-tone</td>
<td>-12.3</td>
<td>17.7</td>
</tr>
<tr>
<td>Total power</td>
<td>0</td>
<td>30</td>
</tr>
</tbody>
</table>

### 3.1.4 Harmonic Balance setup

Harmonic balance is a frequency-domain analysis technique for simulating distortion in nonlinear circuits and systems [7]. It is usually the method of choice for simulating analog RF and microwave problems, since these are most naturally handled in the frequency domain. The harmonic balance simulation computes quantities such as third-order intercept points (TOI) and intermodulation distortion components, and is very suitable for the multitone simulation case of intermodulation products and was therefore used in these simulations.

The harmonic balance method is iterative. It is based on the assumption that for a given sinusoidal excitation a steady-state solution exists that can be approximated to satisfactory accuracy by means of a finite Fourier series. The harmonic balance objective is to compute this steady state solution of the nonlinear circuit. In the simulator, the circuit is represented as a system of $N$ nonlinear ordinary differential equations, where $N$ represents the size of the circuit, i.e., the number of nodes and branch currents. The sources and the solution waveforms are approximated by truncated Fourier series.

A circuit with multiple input frequencies will require a multitone simulation. In this case, the steady state solution waveforms are approximated with a multidimensional truncated Fourier series as follows [7]

$$v(t) = \text{Re} \left\{ \sum_{k_1=0}^{K_1} \sum_{k_2=0}^{K_2} \cdots \sum_{k_n=0}^{K_n} V_{k_1,k_2,\ldots,k_n} e^{j2\pi(k_1 f_1 + \ldots + k_n f_n)t} \right\}$$

(3.4)

where $n$ is the number of tones, $f_1, \ldots, f_n$ are the fundamental frequencies of each source, and $K_1, \ldots, K_n$ are the number of harmonics for each tone.
The truncated Fourier series representation of the solution transforms the system of $N$ nonlinear differential equations into a system of $N \times M$ nonlinear algebraic equations in the frequency domain, where $M$ is the total number of frequencies including the fundamentals, their harmonics, and the mixing terms. This system of nonlinear algebraic equations is solved for the Fourier coefficients of the solution via Newton’s method. This method is the outer solver of the harmonic balance simulator. Newton’s method iterates successively from an initial guess to arrive at the solution.

### 3.1.4.1 Frequency, Order and MaxOrder

There are some main parameters to set when doing a harmonic balance simulation, in these multitone cases the main parameters are the frequency, order and maxorder.

The frequency parameter in the harmonic balance controller set the fundamental frequency. When doing a multitone simulation, additional frequencies need to be set on the controller corresponding to the fundamental frequencies of the additional sources, in this case on the power source.

The frequencies of the input source are related harmonics of the frequency parameter on the controller, otherwise the frequencies of the input source does not get in use in computing the steady state solution [7]. In figure 3-2 the circuit for a 6-tone simulation is shown, where one can see that the fundamental frequency is set to 25 MHz and that the input frequencies are spaced 25 MHz apart. The spacing does not affect the results of the simulation as long as it is the same for each input tone.

The order parameter determines the number of harmonics used in the truncated Fourier series representation of the harmonic balance solution. The order needs to be sufficiently large so that the harmonic balance simulator can compute its solution waveforms to an adequate degree of accuracy but using too high of an order is wasteful of memory, file size and simulation time, so it is not efficient to use an order that is too high [7]. One can determine what order is optimum by simulating the circuit with a smaller order then increase the order gradually. When the solution stops changing you have reached the optimum order. The order in the multitone simulations was set to 168 after taking these circuit design advices under consideration.

The max order determines how many mixing products are to be included in a multitone simulation. A mixing term, or mixing product, is a combination of two or more fundamentals or their successive harmonics [7]. Mixing products will occur when there are multiple sources in a circuit. In the simulations the MaxOrder was chosen to 4.
Figure 3-2: The electronic circuit in ADS for a 6-tone simulation with TOI=37 and P1dB=23.

3.1.5 Equations used in ADS

After a simulation the data is stored as multidimensional data, due to swept input power and Monte Carlo iterations. Processing the data with equations in ADS enables to display plots and to analyze information in various ways.

The equations used in ADS are presented in figure 3-3.
All simulation data is stored in voltage, $V_{in}$ and $V_{out}$, hence some calculations to transform the spectrum into dBm was needed. The stored data have three dimensions, the first parameter is the Monte Carlo iterations, the second parameter is the swept input power and the third is the frequencies of the spectrum.

Due to 1000 Monte Carlo iterations a mean value of the carrier signal and the empty channel was needed. The mean values of all Monte Carlo iterations were calculated using the third and fourth equation shown in figure 3-3, leaving just one value for the intermodulation product in the empty channel and one value for the nearest carrier, for each input power. The notch frequency had number 126 and the nearest carrier had number 125. The notation $1::\text{max}(mc\text{Trial})$ means that the first and last Monte Carlo iterations are neglected. This is desirable because for the first and last iteration all variables are set to nominal values. This means that the phases of all the input signals are the same and therefore produce an unrealistic large value of the output voltage.

All simulations were compared at the same output power, so in each case the total output power was compounded. In the example above the equation for $P_{out}$ was applied at the 2-tone case and therefore multiplied with two. For the 6-tone case the output power was multiplied with 5, for the 12-tone case it was multiplied with 11 and for the 18-tone case it was multiplied with 17.

The relation between the carrier and the intermodulation product is given in the last equation, giving the equation for C/I. The relation is defined as

$$C / I = P_{out_{carrier}} - P_{out_{IM}},$$

After running the simulations the values for C/I were exported to MATLAB in vector form to create the graphs.
3.2 Measurements

To investigate and compare the simulation method with the measurement method tests of the multitone case were performed on an amplifier hybrid. This section presents the method of measurements of the multitone cases.

3.2.1 Test object

The test object was an output amplifier hybrid, a C-band IF amplifier (C-IFOP). The output amplifier hybrid is a part of the converter and was chosen for measurements because most of the spurious signals are created in this stage of the converter. The C-band hybrid consists of a wideband amplifier for gain control, a single transistor stage and finally a balanced transistor stage. The C-band IF amplifier operates in a frequency band of 3.4-4.2 GHz and has a gain of approximately 32 dB.

Figure 3-4: Output amplifier hybrid

Figure 3-5: Output amplifier assembly
3.2.2 Instruments used during test

The signal generator used was a SMBV100A from Rhode & Schwarz which was chosen due to its ability to create multiple carriers consisting of up to 32 modulated carriers. The SMBV100A is a vector signal generator and can adjust the carrier spacing within the total available baseband bandwidth of 80 MHz. Each carrier can be separately defined in terms of power, phase and modulation [8].

![Rohde and Schwarz SMBV100A Vector Signal Generator](image)

Other instruments used during the measurements were a PNA-X network analyzer, spectrum analyzer, power supply and a bias box supply.

3.2.3 Characterization of C-band IF amplifier

Before starting the multitone test the amplifier was characterized in terms of IP3 and gain compression. This characterization was performed with a PNA-X network analyzer. The IP3 characterization was performed with two input signals at an input power of -20 dB for each signal. With a gain of approximately 32 the output power of the signals during IP3 characterization was 12 dBm for each carrier, and the total output power 15 dBm. It should be said that IP3 differs when applying different input powers, however it was not feasible to measure the IP3 value for the whole power sweep and a characterization power was chosen with respect to the usual characterization input power of the C-IFOP.

The gain compression was characterized with an input power sweep between -35 and -5 dBm. P1dB was characterized as the output power at which 1 dB compression occurred.

The characterization was performed at three specific frequencies, the lower and upper band side of the C-IFOP and at a frequency in the middle of the band. To be able to vary
IP3 and P1dB of the hybrid three different bias voltages were used. This gave nine different test cases which are presented in table 3-2.

IP3 and compression measurements were performed with a first stage drain current, Id(TGA), of 50mA.

<table>
<thead>
<tr>
<th>Test case number</th>
<th>Center frequency [GHz]</th>
<th>Bias voltage [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test case 1</td>
<td>3.4</td>
<td>4</td>
</tr>
<tr>
<td>Test case 2</td>
<td>3.4</td>
<td>5</td>
</tr>
<tr>
<td>Test case 3</td>
<td>3.4</td>
<td>6</td>
</tr>
<tr>
<td>Test case 4</td>
<td>3.8</td>
<td>4</td>
</tr>
<tr>
<td>Test case 5</td>
<td>3.8</td>
<td>5</td>
</tr>
<tr>
<td>Test case 6</td>
<td>3.8</td>
<td>6</td>
</tr>
<tr>
<td>Test case 7</td>
<td>4.2</td>
<td>4</td>
</tr>
<tr>
<td>Test case 8</td>
<td>4.2</td>
<td>5</td>
</tr>
<tr>
<td>Test case 9</td>
<td>4.2</td>
<td>6</td>
</tr>
</tbody>
</table>

3.2.3.1 Characterization test set-up

Below a block diagram of the characterization of the C-IFOP is shown.

Figure 3-7: Test set-up for the characterization of the C-IFOP
3.2.4 IM products from signal generator

Before measuring intermodulation products from the C-IFOP measurements of the distortion from the signal generator were performed. The signal generator was connected to the spectral analyzer and the spurious signals in the empty channel were measured for all four multitone cases at different input powers. The relation between the carriers and the IM products were measured and then calculated in MATLAB.

![Test set-up for the measurement of the IM products from the signal generator](image)

3.2.5 Multitone tests of C-IFOP

Four different multitone tests were performed, 2-tone, 6-tone, 12-tone and 18-tone. All four cases were tested at three different center frequencies and with three different bias voltages. The vector signal generator was connected to the C-IFOP which was connected to the spectrum analyzer. A 10 dB attenuator was used at the output port of the DUT to ensure that the spectrum analyzer would not go into compression. A measured power loss in the cable of 0.6 dB was also taken into consideration during the measurements.

The spectrum analyzer measured the carriers and spurious signals at the output port of the DUT, so the input power of the carriers was adjusted to match the desired output power. The output power was measured for one carrier, and the total output powers for all carriers were calculated using equation (2.12).

As an example, for the 2-tone case the lowest measured output power for each carrier was -8.5 dBm. Calculations of the total output power for both signals give -5.5 dBm. From the output port to the spectrum analyzer there is a power loss of 10 dBm from the attenuator and a loss of 0.6 dBm from the cables. This gives a total output power of 5.1 dBm. For the 18-tone case the lowest output power measured was -18 dBm. Calculations of the total output power for 17 carriers give $P_{out} = -5.7$ dBm. Subtracting the power loss from the attenuator and the cables gives a total output power of 4.9 dBm.
In table 3-3 the total output power for the four multitone cases are presented after taking the power loss in cables and in the attenuator into consideration. The lowest output power is the start output power of the measurements, and during the measurements the output power was increased in steps of 1 dBm. The highest output power was simple the output power where measurements still was possible. In most of the measurements the DUT had reached its P1dB when measuring the highest output power and was therefore in compression. When analyzing the data collected during the measurements with the highest output powers this should be taken into consideration.

<table>
<thead>
<tr>
<th></th>
<th>Lowest total Pout [dBm]</th>
<th>Highest total Pout [dBm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-tone</td>
<td>5.1</td>
<td>24.1</td>
</tr>
<tr>
<td>6-tone</td>
<td>5.1</td>
<td>24.1</td>
</tr>
<tr>
<td>12-tone</td>
<td>5.0</td>
<td>24.0</td>
</tr>
<tr>
<td>18-tone</td>
<td>4.9</td>
<td>23.9</td>
</tr>
</tbody>
</table>

It should be said that in during these measurements the gain was not considered. The purpose of the measurements was to compare the four cases at the same output power, and therefore the input power was of no interest in these tests. For knowledge, the DUT have a gain of about 32 dB, which can differ slightly depending on bias voltage of the C-IFOP. The input power was set on the signal generator for each input tone.

In table 3-3 one can see that the total output of the four cases differ a bit, this is because of limitations in the spectrum analyzer. The accuracy when measuring a carrier was not as good as desired due to limitations of the test instruments, making it difficult to perform exact measurements. However, these differences were taking into consideration during post processing in MATLAB.
3.2.5.1  Test set-up

Below a block diagram of the multitone tests of the C-IFOP is shown.

![Block diagram of C-IFOP test set-up]

**Figure 3-9: C-IFOP test set-up**

3.2.6  Spacing between carriers

The signal generator created modulated signals. The spacing between all input signals could be chosen as well as individually settings of each frequency. Due to vector modulation of the signals all signals were coherent. This made it impossible having the same spacing between all signals because the same spacing would have created unrealistically large intermodulation products.

To avoid an unrealistically large summation of the modulated carriers the different carriers were given frequencies making the spacing between each carrier different slightly from each other. The chosen frequencies are listed in table 3-4.
To avoid unrealistically large intermodulation products during the simulation the phase terms were set randomly and the simulations were conducted with a large number of iterations. During the test procedure this was not an option due to limitations in the signal generator and lack of time. Having slightly different spacing between the signals lead to various spurious signals in the empty channel which had to be summed before the C/I relation could be calculated.
In table 3-4, 18 different frequencies are listed. All 18 frequencies were used when conducting an 18-tone measurement, but for the other cases the highest and lowest frequencies were eliminated, leaving 12, 6, or 2 carriers.

### 3.2.7 Summation of spurious signals

With different spacing between the input signals, several spurious signals appeared in the empty channel. These spurious signals were the result from several input signals. If the spacing would have been equal all these spurious signals would have appeared at the same frequency, and the power sum of all these spurious signals would have represented the total intermodulation product for each specific input power. However, due to the spacing offset to avoid an unrealistically large summation these spurious signals appeared with spacing between them, which can be seen in figure 3-11.

Each spurious signal could be measured in the spectrum analyzer and summed to a total power representing the intermodulation product. However, this was not feasible for all multitone cases and all input powers due to time limitations during test. To make the measurements more efficient the sum of these spurious signals related to each intermodulation product were presented in the spectrum analyzer using a lower video BW and a higher RBW on the spectrum analyzer. This gave a sum that could represent the power sum of all spurious signals but only required measurements of a single signal.

![Figure 3-11: Different representation of the spurious signals in the spectrum analyzer.](image)

The left figure in figure 3-11 show an example of all separated spurious signals and the right figure show the representing power sum of these spurious signals on the spectrum analyzer when using a high RBW and a lower video BW. The RBW used was 10 kHz and the video BW used was 100 Hz.
Before using this method to measure the intermodulation products from the C-IFOP measurements of the accuracy of the representation of the effect sum were performed. The various spurious signals were measured and the sum was compared with the representation sum. These calculations were made in MATLAB and the results are presented in the next chapter.

3.3 Comparison of the simulation and measurement results

After performing measurements of the C-IFOP new simulations in ADS were made with the measured characterization parameters IP3 and P1dB. This was made to easily compare the data from the measurements with the simulation results. The same simulation method described in section 3.1 was used which made the simulation fairly easy.

3.4 MATLAB

The major part of the post processing of the data was done in MATLAB, both from the simulation and the measurement data. From the simulations in ADS data was exported with the desired C/I in vector form. The scripts written for post processing will not be described in detail due to the fairly simple approach. Most of the post processing in MATLAB was a matter of sorting vectors and plotting graphs. All graphs in the report except the spectrum graphs are plotted in MATLAB.
Chapter 4

4 RESULTS AND DISCUSSION

This chapter presents the results from the simulations and measurements of the multitone case. Additional figures are given in the appendix.

4.1 Simulation results

The simulations were carried out for four multitone test cases, giving four different output spectrums. Figures 4-1 to 4-4 shows the output spectra for the 6-tone case, for 10 Monte Carlo iterations. The spectra only show 10 iterations as an example, as the simulation case consisted of 1000 iterations. The simulations were carried out with a power sweep that gave a total output power of 0 dBm to 30 dBm. The spectra changes for each input power value, as the output power of each carrier increased with 1 dBm for each step. The output power of the intermodulation product increased more rapidly than the carriers, making the difference between the carriers and the intermodulation product smaller as the total output power increased.
Figure 4-1: Output spectra for 6 input signals. The total output power is 5 dBm and the plot show 10 Monte Carlo iterations.

Figure 4-2: Output spectra for 6 input signals. The total output power is 15 dBm and the plot show 10 Monte Carlo iterations.
RESULTS AND DISCUSSION

Figure 4-3: Closer look at the output spectra for 6 input signals. The total output power is 5 dBm and the plot show 10 Monte Carlo iterations.

Figure 4-4: Closer look at the output spectra for 6 input signals. The total output power is 15 dBm and the plot show 10 Monte Carlo iterations.
Figures 4-1 and 4-3 have a total output power of 5 dBm and figures 4-2 and 4-4 have a total output power of 15 dBm. Comparisons of these plots show the increase of the intermodulation products as the total output power is increased. It is also shown that the intermodulation product in the empty channel varies a lot for the 10 different iterations. This show the importance of the phase, as the only changes between the iterations is the phases of the carriers.

The large number of iterations for each input power in the power sweep gave a great number of data points that needed to be processed. Using equations in ADS the mean value of all the Monte Carlo iterations were calculated leaving just one value for the intermodulation product in the empty channel for each input power.

The mean value of the intermodulation product for all input power values were compared to the carrier. This gave the relationship C/I. Figure 4-3 and 4-4 show C/I plotted for the 6-tone test case. To study how the C/I values are affected by IP3 and P1dB separate graphs were created, one that kept IP3 constant at 37 dBm while altering P1dB, and one that kept P1dB constant at 23 dB while altering IP3.

Figure 4-5: C/I for the 6-tone case. P1dB is 23 dBm and IP3 is changed between 37 and 40 dBm.
Figure 4-6: C/I for the 6-tone case. IP3 is 37 dBm and P1dB is changed between 23 and 26 dBm.

Both figure 4-5 and 4-6 show declining slopes. This shows that the difference between the carriers and the intermodulation product diminish as the output power increase. This is an expected result as the intermodulation products increases much faster than the carriers. A higher C/I value means lower spurious signals and thus a more linear amplifier. The main differences between figure 4-5 and 4-6 are the starting values of C/I and the inclination of the slopes. In figure 4-5 the P1dB parameter is kept constant as the IP3 parameter is altered between 37 and 40 dBm. The graph corresponding to the higher value of IP3 has a higher value for C/I at the lower output powers, but the graph shows that at some point, approximately at an output power of 17 dBm, the higher value of IP3 does not increase C/I relative to the lower IP3 parameter.

In figure 4-6 the IP3 parameter is kept constant instead and the P1dB parameter is changed between 23 and 26 dBm. The figure shows a relationship contrary the one in figure 4-5, where the P1dB parameter does not affect the value of C/I at the lower power outputs, but at the higher outputs powers the higher P1dB parameter gives a higher value of C/I. This result correspond to the theory of the 1 dB compression point, as a higher P1dB value means higher output power for the amplifier. As the output power increases to near its maximum capability, the amplifier will begin to saturate making the intermodulation products even higher, thus giving a lower value of C/I.

The same results were given in the 2-, 12- and 18-tone case. The graphs for these cases are shown in the appendix.
To be able to more closely study the affect IP3 and P1dB, plots of the difference in C/I of the two slopes in figure 4-5 and 4-6 were created.

In figure 4-7 the difference in C/I is shown. The solid line shows that for these simulations, if the amplifier is specified with a P1dB of 23 dBm and the IP3 is increased from 37 to 40 dBm, one get a higher C/I at lower output powers. The dotted line curve shows that if the amplifier instead is specified with an IP3 of 37 dBm and P1dB is increased from 23 to 26 dBm the C/I value increases at the higher output powers.

The same method of comparison can be used for the 2-, 12- and 18-tone case. These simulations were also made for a constant IP3 of 40 dBm and a constant P1dB of 26 dBm, which gave two more comparison cases. These cases are showed in the following figures.
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Figure 4-8: Difference in C/I for the 2-, 6-, 12- and 18-tone case. IP3 constant at 37 dBm, P1dB changed between 23 and 26 dBm.

Figure 4-9: Difference in C/I for the 2-, 6-, 12- and 18-tone case. IP3 constant at 40 dBm, P1dB changed between 23 and 26 dBm.
Figures 4-8 and 4-9 show the gain of C/I for all four cases when IP3 is held constant at 37 respective 40 dBm and P1dB is increased from 23 to 26 dBm. The plots show the same tendency for all cases; that increasing P1dB has a greater effect on C/I at higher output powers. The simulations also gives that the 2-tone case is slightly different from the multitone cases, in these plots the increase in P1dB have a greater effect on C/I for other the multitone cases than for the 2-tone case. It is difficult to determine at which output power the increase in P1dB gives a significant improvement of C/I, thus it seems to be depending on the IP3 of the amplifier model. In figure 4-8 one could say that a significant improvement of C/I occurs at an output power of 15 dBm, in figure 4-9 one could say that a significant improvement of C/I occurs at an output power of 10-12 dBm.

Both results show a peak in the C/I difference. In figure 4-8 this peak occurs at an output power of 21-22 dBm for the multitone cases, and at an output value of 24 dBm for the 2-tone case. In figure 4-9 this peak occurs at a lower output power, approximately at 20-21 dBm for the multitone cases and at an output power of 23 dBm for the 2-tone case.

![Figure 4-10: Difference in C/I for the 2-, 6-, 12- and 18-tone case. P1dB constant at 23 dBm, IP3 changed between 37 and 40 dBm.](image-url)
RESULTS AND DISCUSSION

Figure 4-11: Difference in C/I for the 2-, 6-, 12- and 18-tone case. P1dB constant at 26 dBm, IP3 changed between 37 and 40 dBm.

Figures 4-10 and 4-11 show the increase of C/I for all four cases when P1dB is held constant at 23 dBm respective 26 dBm, and IP3 is increased from 37 to 40 dBm. These plots show the same tendency for all four cases, that increasing IP3 has a greater effect on C/I at lower output powers. The simulations also gives that the 2-tone case slightly differ from the multitone cases, in these plots the increase in IP3 has a greater effect on C/I for the 2-tone case than for the multitone cases. This is clearly seen in figure 4-10 where the curve for the 2-tone case is clearly distinguished from the multitone curves. In figure 4-11 the curves are not as steep as in figure 4-10 which indicates that a higher P1dB have an effect on C/I for the lower output powers as well. In figure 4-11 the 2-tone curve is different from the multitone curves although the difference is not as big as in figure 4-10.

It should also be noted that the increase in C/I when increasing IP3 in these simulations does not give as great effect as increasing P1dB. The highest value of the increase in C/I in figure 4-10 and 4-11 is approximately 6 dB whereas in figures 4-8 and 4-9 the highest value is approximately 11 dB.
4.2 Measurements

In this section the results from the test procedure are presented.

4.2.1 Characterization of C-band IF amplifier

With three different bias voltages and three different center frequencies, nine different measurement cases were measured and determined. The IP3 and P1dB could not be chosen as in the simulations described in previous section, as these figures of merit depend on the design and tuning of the C-IFOP. The characterization of the C-IFOP with respect to IP3 and P1dB is given in table 4-1.

<table>
<thead>
<tr>
<th>Test case number</th>
<th>Center frequency [GHz]</th>
<th>Bias voltage [V]</th>
<th>P1dB [dBm]</th>
<th>IP3 [dBm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test case 1</td>
<td>3.4</td>
<td>4</td>
<td>19.5</td>
<td>28.2</td>
</tr>
<tr>
<td>Test case 2</td>
<td>3.4</td>
<td>5</td>
<td>22.0</td>
<td>34.1</td>
</tr>
<tr>
<td>Test case 3</td>
<td>3.4</td>
<td>6</td>
<td>23.7</td>
<td>34.8</td>
</tr>
<tr>
<td>Test case 4</td>
<td>3.8</td>
<td>4</td>
<td>19.4</td>
<td>32.8</td>
</tr>
<tr>
<td>Test case 5</td>
<td>3.8</td>
<td>5</td>
<td>21.8</td>
<td>38.1</td>
</tr>
<tr>
<td>Test case 6</td>
<td>3.8</td>
<td>6</td>
<td>23.5</td>
<td>38.6</td>
</tr>
<tr>
<td>Test case 7</td>
<td>4.2</td>
<td>4</td>
<td>18.9</td>
<td>33.5</td>
</tr>
<tr>
<td>Test case 8</td>
<td>4.2</td>
<td>5</td>
<td>21.1</td>
<td>37.4</td>
</tr>
<tr>
<td>Test case 9</td>
<td>4.2</td>
<td>6</td>
<td>22.7</td>
<td>38.3</td>
</tr>
</tbody>
</table>

4.2.2 IM products from signal generator

The intermodulation products from the signal generator were measured for all four multitone cases with different input powers. Table 4-2 shows C/I for all measurements.
Table 4-2: C/I from signal generator at different input powers at a $f_c$ of 3.8 GHz

<table>
<thead>
<tr>
<th>Input power [dBm]</th>
<th>-20</th>
<th>-15</th>
<th>-10</th>
<th>-5</th>
<th>0</th>
<th>≈ 56 [dBc]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-tone</td>
<td>54.8</td>
<td>56.8</td>
<td>55</td>
<td>56.8</td>
<td>56.3</td>
<td>≈ 56 [dBc]</td>
</tr>
<tr>
<td>6-tone</td>
<td>55.7</td>
<td>59.2</td>
<td>59.2</td>
<td>59.6</td>
<td>60</td>
<td>≈ 59 [dBc]</td>
</tr>
<tr>
<td>12-tone</td>
<td>58.1</td>
<td>59.3</td>
<td>58.8</td>
<td>59.3</td>
<td>58.5</td>
<td>≈ 59 [dBc]</td>
</tr>
<tr>
<td>18-tone</td>
<td>56.8</td>
<td>59.5</td>
<td>59.7</td>
<td>60</td>
<td>59.7</td>
<td>≈ 59 [dBc]</td>
</tr>
</tbody>
</table>

Table 4-2 show that the C/I value can be considered constant for each multitone case, where C/I for the 2-tone case in approximately 56 dBc and C/I for the 6-, 12- and 18-tone cases is approximately 59 dBc. The constant value show that the intermodulation products from the signal generator increases with the same magnitude as the input signals.

### 4.2.3 Summation of spurious signals

The accuracy of the method of using a representing sum as the sum of the spurious signals on the spectrum analyzer was measured for three different input powers, -20, -15 and -10 dBm. First of all the intermodulation products that were created due to different spacing of the carriers, as shown in figure 3-11, were measured one by one. The results of these measurements are given in tables 4-3 to 4-5.

It should be said that these measurements were only performed for the 6-, 12- and 18-tone case as for the 2-tone case the intermodulation product consisted of only one signal and thus did not need a measurement with the representing sum on the spectrum analyzer.

Table 4-3: Measured output power in dBm of all spurious signals for the 6-tone case.

<table>
<thead>
<tr>
<th>Input power [dBm]</th>
<th>-20 [dBm]</th>
<th>-15 [dBm]</th>
<th>-10 [dBm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-59</td>
<td>-67</td>
<td>-77</td>
<td></td>
</tr>
<tr>
<td>-57,5</td>
<td>-65</td>
<td>-68</td>
<td></td>
</tr>
<tr>
<td>-66</td>
<td>-47</td>
<td>-65</td>
<td></td>
</tr>
<tr>
<td>-68</td>
<td>-44</td>
<td>-50</td>
<td></td>
</tr>
<tr>
<td>-70</td>
<td>-40</td>
<td>-43</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>-43</td>
<td>-21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-62</td>
<td>-17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-75</td>
<td>-29</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-26</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-51</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-54</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4-4: Measured output power in dBm of all spurious signals for the 12-tone case.

<table>
<thead>
<tr>
<th>Input power [dBm]</th>
<th>-20 dBm</th>
<th>-15 dBm</th>
<th>-10 dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>-77</td>
<td>-82.7</td>
<td>-84</td>
<td></td>
</tr>
<tr>
<td>-75</td>
<td>-73.2</td>
<td>-82</td>
<td></td>
</tr>
<tr>
<td>-72</td>
<td>-62.3</td>
<td>-79</td>
<td></td>
</tr>
<tr>
<td>-80</td>
<td>-49.5</td>
<td>-68</td>
<td></td>
</tr>
<tr>
<td>-72</td>
<td>-56.8</td>
<td>-62</td>
<td></td>
</tr>
<tr>
<td>-69</td>
<td>-61</td>
<td>-58</td>
<td></td>
</tr>
<tr>
<td>-61</td>
<td>-79</td>
<td>-51</td>
<td></td>
</tr>
<tr>
<td>-69</td>
<td>-24.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-70</td>
<td>-32.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-73</td>
<td>-37.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-56.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-55.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-66</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-78</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-86.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4-5: Measured output power in dBm of all spurious signals for the 18-tone case.

<table>
<thead>
<tr>
<th>Input Power [dBm]</th>
<th>-20 dBm</th>
<th>-15 dBm</th>
<th>-10 dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>-70</td>
<td>-66.5</td>
<td>-68.5</td>
<td></td>
</tr>
<tr>
<td>-68</td>
<td>-48</td>
<td>-73.8</td>
<td></td>
</tr>
<tr>
<td>-65</td>
<td>-50</td>
<td>-56</td>
<td></td>
</tr>
<tr>
<td>-65.5</td>
<td>-48</td>
<td>-50</td>
<td></td>
</tr>
<tr>
<td>-71</td>
<td>-47</td>
<td>-32</td>
<td></td>
</tr>
<tr>
<td>-82</td>
<td>-52</td>
<td>-29</td>
<td></td>
</tr>
<tr>
<td>-74</td>
<td>-70</td>
<td>-27</td>
<td></td>
</tr>
<tr>
<td>-71</td>
<td>-28</td>
<td>-37</td>
<td></td>
</tr>
<tr>
<td>-56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-67</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-76</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Using equation (2.12) the sum of all spurious signals was calculated in MATLAB. The results of these calculations are given in table 4-6.

**Table 4-6: Calculated power sum in dBm of the output of all spurious signals.**

<table>
<thead>
<tr>
<th>Input power</th>
<th>-20 [dBm]</th>
<th>-15 [dBm]</th>
<th>-10 [dBm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-tone</td>
<td>-54.5</td>
<td>-36.8</td>
<td>-15</td>
</tr>
<tr>
<td>12-tone</td>
<td>-59.6</td>
<td>-48.2</td>
<td>-23.9</td>
</tr>
<tr>
<td>18-tone</td>
<td>-60.1</td>
<td>-41.7</td>
<td>-22.5</td>
</tr>
</tbody>
</table>

The values of the measured intermodulation product of the representing power sum in the spectrum analyzer are presented in table 4-7.

**Table 4-7: IM product of the representing sum on the spectrum analyzer.**

<table>
<thead>
<tr>
<th>Input power</th>
<th>-20 [dBm]</th>
<th>-15 [dBm]</th>
<th>-20 [dBm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-tone</td>
<td>-56</td>
<td>-39</td>
<td>-17</td>
</tr>
<tr>
<td>12-tone</td>
<td>-61.7</td>
<td>-50.2</td>
<td>-24.5</td>
</tr>
<tr>
<td>18-tone</td>
<td>-61.3</td>
<td>-43.7</td>
<td>-24.2</td>
</tr>
</tbody>
</table>

Comparison between table 4-5 and 4-6 shows that the values slightly differ. The difference is 1.5-2.2 dBm for each multitone case and input power, where the measurements of the representing power sum in the spectrum analyzer are the higher ones.

The difference of the two different summation methods is distinguishable, but still acceptable for these tests. However, when analyzing the results from the measurements this difference should be taken into consideration.

### 4.2.4 Measurement plots

After performing measurements with the 2-, 6-, 12- and 18-tone tests for all nine characterization cases, C/I for all test cases were plotted in MATLAB. Figure 4-12 show the C/I graphs for the 2-, 6-, 12- and 18-tone cases for 3 different bias voltages at a center frequency of 3.8 GHz and 4.2 GHz.
Figure 4-12: C/I test results for the 2-, 6-, 12- and 18-tone case at a bias voltage of 4V, 5V and 6V. The left plots have a center frequency of 3.8 GHz and the right plots have a center frequency of 4.2 GHz.
In figure 4-12 a reference line is included in each graph. The reference line is the calculated C/I in dBc for the 2-tone case and the specific IP3 value. As IP3 was measured at a total output power of 15 dBm the value of the reference line and the measured 2-tone case should be the same at an output power of 15 dBm. This can be seen in figure 4-12, although the reference line is slightly higher than the measured 2-tone line at an output power of 15 dBm. This can be explained with error in measurements as it was difficult to perform the measurements with a high accurateness.

The dotted horizontal lines show the level of intermodulation products from the signal generator. At the lower output power levels the measured C/I is close to the expected intermodulation products from the signal generator. This makes it difficult to draw any conclusions from this data as the measured data is affected by the intermodulation products from the signal generator.

All four multitone cases have C/I values in the same range, where the difference between the lowest and highest C/I value at any given output power is less than 10 dBc. In other words, C/I in these four test cases are similar and give an indication that C/I is not strongly affected by the number of input signals.

The results from the measurements show that the slopes of the C/I decrease more rapidly at a certain output power value. This output power value varies depending on IP3 and P1dB of the C-IFOP. At the lower output power values C/I is limited by IP3 and by the intermodulation products of the signal generator, creating a curve with less slope. For higher output powers C/I is limited by P1dB, creating a sharper slope. It is desirable to study at which output power C/I is more limited by P1dB than IP3.

As the inserted reference line is referred to the measured IP3 value of the 2-tone case another reference line is inserted in the 2-tone measurements. This reference line is extracted from the 2-tone slope at higher output powers. At a certain output power one gets an intersection between this extracted line and the C/I reference line. This is shown in figure 4-13. Additional C/I plots with two reference lines are given in the appendix.
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Figure 4-13: C/I test results for the 2-, 6-, 12- and 18-tone case including two reference lines. Bias voltage of 5V and 6V. The left plots have a center frequency of 3.8 GHz and the right plots have a center frequency of 4.2 GHz.

The intersection point of the two reference lines can be referred to as the breakpoint output power where the C/I slope of the 2-tone case decrease more rapidly, hence the breakpoint output power at which C/I is limited by both IP3 and P1dB. This breakpoint output power can be expressed in terms of IP3 and P1dB. The equation for IP3 is

\[
IP3 = \frac{C}{2I} + P_{out} - 3
\]  

(4.1)

IP3 is defined for the output power of one carrier, and as P_{out} in these results is the total power of both carriers it is needed to subtract 3 dB from P_{out}. Solving C/I from equation (4.1) gives the equation of the IP3 reference line,
\[ C / I = 2 \cdot (IP3 - P_{\text{out}} + 3) \] (4.2)

Studying the results presented in figure 4-12 one can see that the C/I is approximately 20 dBc at the given P1dB in each graph for. This makes it easier to express the extracted reference line of the 2-tone slope with respect to \( P_{\text{out}} \) and P1dB,

\[ C / I = -(P1dB - P_{\text{out}}) \cdot k + 20 \] (4.3)

Where \( k \) is the inclination of the reference line.

The intersection point is given when equation (4.2) and (4.3) are equal,

\[-(P1dB - P_{\text{out}}) \cdot k + 20 = 2 \cdot (IP3 - P_{\text{out}} + 3) \] (4.4)

Solving \( P_{\text{out}} \) in equation (4.3) gives

\[ P_{\text{out}} = \frac{2 \cdot IP3 + k \cdot P1dB - 14}{2 + k} \] (4.5)

Equation (4.5) depend on the inclination of the 2-tone reference line, and calculations of the inclination of the 2-tone slope reference line of all nine test cases gives that this inclination lies between -6.7 and -4.4. A mean value of this inclination is -5.5, which give

\[ P_{\text{out}} = \frac{-2 \cdot IP3 + 5.5 \cdot P1dB - 14}{3.5} \] (4.6)

Equation (4.6) gives a relation between the breakpoint output power, IP3 and P1dB for these measurements.

To study the effect of IP3 and P1dB on C/I more closely it was desirable to compare data from test cases that had the same fixed IP3 and alternating P1dB, respectively the same fixed P1dB and alternating IP3. This could not be done in the same way as in the simulations as IP3 and P1dB could not be chosen during the measurements. Instead some of the characterization cases shown in table 4-1 that best could fulfill these requirements were chosen.
The comparison cases chosen are listed below.

**Table 4-8: Comparison cases for fixed IP3 and alternating P1dB**

<table>
<thead>
<tr>
<th>Comparison Case</th>
<th>Test Case Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison case 1</td>
<td>Test case 7, P1dB is 18.9 dBm and IP3 is 33.5 dBm. Test case 2, P1dB is 22.0 dBm and IP3 is 34.1 dBm.</td>
</tr>
<tr>
<td>Comparison case 2</td>
<td>Test case 5, P1dB is 21.8 dBm and IP3 is 38.1 dBm. Test case 6, P1dB is 23.5 dBm and IP3 is 38.6 dBm.</td>
</tr>
</tbody>
</table>

**Table 4-9: Comparison cases for fixed P1dB and alternating IP3**

<table>
<thead>
<tr>
<th>Comparison Case</th>
<th>Test Case Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison case 4</td>
<td>Test case 2, P1dB is 22.0 dBm and IP3 is 34.1 dBm. Test case 5, P1dB is 21.8 dBm and IP3 is 38.1 dBm.</td>
</tr>
<tr>
<td>Comparison case 5</td>
<td>Test case 3, P1dB is 23.7 dBm and IP3 is 34.8 dBm. Test case 5, P1dB is 21.8 dBm and IP3 is 38.1 dBm.</td>
</tr>
</tbody>
</table>

After deciding the comparison cases graphs of the differences in C/I were plotted in MATLAB.

![Figure 4-14: Comparison case 1. Difference in C/I for the 2-, 6-, 12- and 18-tone case. IP3 is 33.5-34.1 dBm, P1dB changed between 18.9 and 22.0 dBm.](image)
RESULTS AND DISCUSSION

Figure 4-15: Comparison case 2. Difference in C/I for the 2-, 6-, 12- and 18-tone case. IP3 is 38.1-38.6 dBm, P1dB changed between 21.8 and 23.5 dBm.

Figure 4-16: Comparison case 3. Difference in C/I for the 2-, 6-, 12- and 18-tone case. IP3 is 34.1-34.8 dBm, P1dB changed between 22.0 and 23.7 dBm.
Figure 4-14 to 4-16 all show plots of the increase in C/I when IP3 is held constant and P1dB is changed. All three results show an increase in C/I with the higher P1dB at the higher output powers, which is the same tendency as in the simulation results. The magnitude of the increase in C/I from the measurements vary, the increase in figure 4-15 is higher and start at a lower output power that the increase in figure 4-15 and 4-16. However, the increase of P1dB in figure 4-14 is 3 dB whereas in figure 4-15 and 4-16 the increase of P1dB is only 1.7 dB.

The IP3 in all three cases is kept as constant as possible, however it still differs. This should be taken into consideration when analyzing the results.

In the simulation results the 2-tone case is distinguished from the other cases, but from the test results the 2-tone and 12-tone case follow each other. Comparison with the simulation results indicates that the results from the 12-tone case do not follow the same pattern.

The following plots show the increase in C/I when P1dB is held constant and IP3 is increased.

Figure 4-17: Comparison case 4. Difference in C/I for the 2-, 6-, 12- and 18-tone case. P1dB is 22.0-21.8 dBm, IP3 changed between 34.1 and 38.1 dBm.
Figure 4-18: Comparison case 6. Difference in C/I for the 2-, 6-, 12- and 18-tone case. P1dB is 23.5-23.7 dBm, IP3 changed between 34.8 and 38.6 dBm.

Figure 4-17 to 4-18 show no increase in C/I which is expected due to the intermodulation products from the signal generator. From the simulation results it is expected that these plots should have an increase of C/I at lower output powers and thereafter decrease to about 0 dBm at higher output powers, as in figures 4-10 and 4-11. Due to the fact that the intermodulation products from the signal generator affected the measured result at the lower output powers this tendency can not be seen.
4.3 Comparison of the simulation and measurement results

New simulations with the characterized IP3 and P1dB from the defined test cases were performed to study the accuracy of the simulation method more closely. The results from these simulations were compared with the measurement results and are presented below.

![Graph](image)

Figure 4-19: Test case 2, results from simulations and measurements. P1dB is 22.0 dBm and IP3 is 34.1 dBm.
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Figure 4-20: Test case 3, results from simulations and measurements. P1dB is 23.7 dBm and IP3 is 34.8 dBm.

Figure 4-21: Test case 4, results from simulations and measurements. P1dB is 19.4 dBm and IP3 is 32.8 dBm.
**RESULTS AND DISCUSSION**

Figure 4-22: Test case 6, results from simulations and measurements.
P1dB is 23.5 dBm and IP3 is 38.6 dBm.

Figure 4-23: Test case 7, results from simulations and measurements.
P1dB is 18.9 dBm and IP3 is 33.5 dBm.
Figure 4-19 to 4-23 show the results from measurements of five test cases as well as simulations with the measured IP3 and P1dB for these cases. Studying the graphs gives that the measurement results follow the declination from the simulations. However, there are some differences that should be discussed.

First of all, at the lower output powers the C/I curves of the measurements do not follow the simulated C/I curves. This can be explained by the intermodulation products created by the signal generator. The dotted line in the plots show the C/I of the intermodulation products created from the signal generator for the 6-, 12- and 18-tone case. For the 2-tone case the intermodulation products were a bit lower, about 56 dB.

The most interesting comparison between the measured data and the simulated data is made at the C-IFOP linear region, i.e. in the region were the C-IFOP is not in compression. This region is different for all test cases as the P1dB is different for all test cases, and therefore the C-IFOP goes into compression at different output powers. In the linear region the measured data follows the slopes of the simulations rather good but in the plots the measured graphs have a bump that does not exist in the simulation results. In this bump the measured C/I is higher than the simulated C/I, which means that the intermodulation products measured are lower than the simulated ones.

There is one multitone case that is different from the others, the 12-tone case does not follow the simulated results as closely as the other cases. Even though the measured data for the 12-tone case follow the same tendency as the rest of the multitone cases, the measured values for the 12-tone case are the ones that differ most from the simulated results.

Following figures show a more detailed comparison of the simulation and the measurement results. Figure 4-24 to 4-27 show the simulated and measured values for the test cases 2 and 7 and each plot show one of the four multitone cases.
RESULTS AND DISCUSSION

Figure 4-24: Simulated and measured results for test cases 7 and 2 and a 2-tone input. In test case 7 IP3 is 33.5 dBm and P1dB is 18.9 dBm, and in test case 2 IP3 is 34.1 dBm and P1dB is 22.0 dBm.

Figure 4-25: Simulated and measured results for test cases 7 and 2 and a 6-tone input. In test case 7 IP3 is 33.5 dBm and P1dB is 18.9 dBm, and in test case 2 IP3 is 34.1 dBm and P1dB is 22.0 dBm.
RESULTS AND DISCUSSION

Figure 4-26: Simulated and measured results for test cases 7 and 2 and a 12-tone input.
In test case 7 IP3 is 33.5 dBm and P1dB is 18.9 dBm, and in test case 2
IP3 is 34.1 dBm and P1dB is 22.0 dBm.

Figure 4-27: Simulated and measured results for test cases 7 and 2 and a 18-tone input.
In test case 7 IP3 is 33.5 dBm and P1dB is 18.9 dBm, and in test case 2
IP3 is 34.1 dBm and P1dB is 22.0 dBm.
All four plots show two test cases, where both cases have similar IP3 but a difference in P1dB of 3.1 dB. One can see that the results from the measurements is similar to the results from the simulation, where the largest difference occurs at the lower output powers due to intermodulation products from the signal generator. The curves have similar inclination and the tendency of a greater C/I at the higher output powers when increasing P1dB is shown for both the simulation and measurement results. These results show that a significant improvement of C/I with a higher P1dB occurs at an output power of about 12 dBm and higher.

The biggest difference between the simulated and measured results occurs in the 12-tone case, seen in figure 4-26. Even though the results from the simulations and measurements are similar, the values of C/I are distinguishably higher for the measured results than for the simulated ones.

Following figures show two additional test cases, test cases 5 and 6. Each plot show one of the multitone cases.

Figure 4-28: Simulated and measured results for test cases 5 and 6 and a 2-tone input.
In test case 5 IP3 is 38.1 dBm and P1dB is 21.8 dBm and in test case 6
IP3 is 38.6 dBm and P1dB is 23.5 dBm.
RESULTS AND DISCUSSION

Figure 4-29: Simulated and measured results for test cases 5 and 6 and a 6-tone input. In test case 5 IP3 is 38.1 dBm and P1dB is 21.8 dBm and in test case 6 IP3 is 38.6 dBm and P1dB is 23.5 dBm.

Figure 4-30: Simulated and measured results for test cases 5 and 6 and a 12-tone input. In test case 5 IP3 is 38.1 dBm and P1dB is 21.8 dBm and in test case 6 IP3 is 38.6 dBm and P1dB is 23.5 dBm.
Figure 4-31: Simulated and measured results for test cases 5 and 6 and a 18-tone input.
In test case 5 IP3 is 38.1 dBm and P1dB is 21.8 dBm and in test case 6 IP3 is 38.6 dBm and P1dB is 23.5 dBm.

These four plots also show two test cases, where both cases have similar IP3 but a difference in P1dB. The same tendencies are shown for these cases, that increasing P1dB gives an increase in C/I at the higher output powers. The curves of the measured result follow the simulated result. For these two test cases the results from the 12-tone measurements are also the ones that differ most from the simulation results. In these results a significant improvement of C/I with a higher P1dB occurs at an output power of about 16 dBm and higher.
One of the goals of this thesis was to investigate the multi carrier case and to find a relation between C/I and output power, IP3 and P1dB. Regarding the relation between C/I and output power and P1dB the simulation and measurement results show the same tendency, that P1dB is more important for C/I at higher output powers, as expected. This means that if an amplifier is to be used with a total output power of above 12 dBm, one gets a greater increase in C/I when improving P1dB than improving IP3.

The simulation results show that increasing IP3 improves C/I at the lower output powers. However, this result can not be shown in the measurements due to spurious signals created by the signal generator.

A tendency that is showed in both the simulations and the measurements is that C/I for the different multitone cases are quite similar, if compared at the same total output power. This means that the intermodulation product have a limited increase when increasing the number of input signals. All C/I plots have a range of less than 10 dBc when having the same P1dB and IP3 values, regardless the number of input carriers.
Figures 4-8 to 4-11 show the simulation results of the differences in C/I when having a fixed IP3 and changing P1dB, respectively having a fixed P1dB and changing IP3. Although these results show that P1dB is slightly more important for C/I at the 6-, 12- and 18-tone cases than for the 2-tone case, this could not unambiguously be stated by the measurements due to differences between the simulated and measured data for the 12-tone case. This difference is also very small which makes it difficult to draw any conclusions.

Figure 4-12 shows the test results from six different test cases. These results show that the C/I curves have less inclination until a certain output power, at which the C/I slopes decrease more rapidly. The point at which the slopes decrease more rapidly can be referred to as the breakpoint output power, and by inserting two reference lines a relation between this breakpoint output power, IP3 and P1dB was found. It should be noted that this relation is based on these specific measurements and have therefore limitations. This relation depends on the inclination of the 2-tone reference line, which varies for each of the nine test cases. However, these slopes are between -6.7 and -4.4 and the used mean value in equation (4.6) gives a reasonable relation between $P_{out}$, IP3 and P1dB for these measurements. This equation is determined for the 2-tone case, but as C/I of the multitone cases is similar to the 2-tone case it is possible to use equation (4.6) to get an indication of the relation between $P_{out}$, IP3 and P1dB for the multitone case as well.

When comparing the simulation and measurement results it is seen that the simulation method gives an indication of the real case and the measurements verifies the tendencies shown in the simulation results. However, there are some differences between the measurements and the simulations that need to be taken into consideration.

The test results at the lower output powers could not be compared to the simulation results due to intermodulation products from the signal generator. Although the 12-tone case shows the same tendency as the rest of the multitone cases, these measurements are the ones that differ more from the simulated values.

There could be several explanations for these differences between the simulation and the measurements. Error of measurements or unfortunate phases for the carriers could explain some of the differences. Also, due to different spacing between the inputs signals the sum of all intermodulation products were measured with a representing sum of the spurious signals, which was consistently higher than the calculation of all intermodulation products individually. This could also contribute to the differences between the measured and the simulated values. This shows that the simple simulation method have limitations, although it gives an indication of how the amplifier hybrid would operate when exposed to a multitone case.
An important lesson from these simulations and measurements is that the phases of the input signals are very significant for the output result of a multitone case. It is often hard to predict which phases the different input signals will have and this makes the multitone case difficult to simulate. When doing a multitone test one needs to use a suitable method to sum all contributions to the intermodulation product, otherwise the measurements are conducted for a special case that does not represent the real multitone case. The suitable method to sum varies depending on the multitone test one wants to investigate but typically power summation of all contributions is appropriate.

Another important aspect when performing a multitone test is the instruments used. During these measurements the signal generator created spurious signals that interfered with the results and the modulated signals that the signal generator created had the same phase. To avoid a power summation of the spurious signals with the same phase a method with different spacing was used, which lead to time consuming measurements with a great number of measured data points that had to be handled. This made it difficult to perform accurate measurements and lead to an increased risk of errors during measurement.

Although the measurements verify the tendencies of the simulations, more tests of the multitone case are needed to draw unambiguous conclusions. The simulation method should also be developed with more components and amplifier stages to represent the realistic output amplifier stage.

In this thesis the figure of merit used to explain the nonlinearity of the amplifier model was C/I. For future work other figure of merits should be investigated, as Noise Power Ratio (NPR) or Multitone Intermodulation Ratio (M-IMR). Other test methods that are not as depending on the different phases of the input signal should be investigated as well.
Both the simulation and the test results show that C/I is similar for the four multitone cases, if compared at the same total output power. In other words C/I is not strongly affected by the number of input signals. All C/I plots have a range of less than 10 dBc when having the same P1dB and IP3 values, regardless the number of input carriers.

When simulating and measuring the multitone case, the phases of the input signals are very significant for the output result of a multitone case. When doing a multitone simulation or test one needs to use a suitable method to sum all contributions to the intermodulation product and typically a power summation is used.

The test results showed that C/I was limited by IP3 and intermodulation products from the signal generator at lower output powers, and by P1dB at higher output power. A breakpoint output power was found where C/I was affected by both IP3 and P1dB. The relation between the breakpoint output power $P_{out}$, IP3 and P1dB for these measurements is given according to

$$P_{out} = \frac{2 \cdot IP3 - k \cdot P1dB - 14}{2 - k},$$

(6.1)

where $k$ is the inclination of the 2-tone reference line at higher output power, and the mean value of $k$ in these measurement is -5.5.
7 REFERENCES


8 APPENDIX

In this section additional figures from the simulation and test results are shown.

Figure 8-1: Output spectra for 2 input signals at a total output power of 15 dBm.
Figure 8-2: Output spectra for 12 input signals and 10 Monte Carlo iterations at a total output power of 15 dBm.
Figure 8-3: Output spectra for 18 input signals and 10 Monte Carlo iterations at a total output power of 15 dBm.
Figure 8-4: C/I for the 2-, 12- and 18-tone case. The graphs to the left have P1dB of 23 dBm and IP3 of 37 and 40 dBm. The graphs to the right have P1dB of 23 and 26 dBm and IP3 of 37 dBm.
Figure 8-5: C/I test results for the 2-, 6-, 12- and 18-tone case at a bias voltage of 4V, 5V and 6V and at a center frequency of 3.4 GHz.
Figure 8-6: C/I test results for the 2-, 6-, 12- and 18-tone case including two reference lines.
Figure 8-7: Test case 5, comparison of simulation method and measurements. 
P1dB is 21.8 dBm and IP3 is 38.1 dBm.

Figure 8-8: Test case 8, comparison of simulation method and measurements. 
P1dB is 21.1 dBm and IP3 is 37.4 dBm.
Figure 8-9: Test case 9, comparison of simulation method and measurements. P1dB is 22.7 dBm and IP3 is 38.3 dBm.