COMPARISON OF RADIO FREQUENCY POWER AMPLIFIER CLASSES FOR OFDM COMMUNICATIONS

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Trabalho final de graduação submetido ao Departamento de Engenharia Elétrica da Faculdade de Tecnologia da Universidade de Brasília, como parte dos requisitos necessários para a obtenção do grau de Engenheiro Eletricista.

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"*It is our choices that show what we truly are, far more than our abilities*"
J.K. Rowling

Acknowledgments

I would like to thank my advisor, Professor Daniel Café for all the guidance, teaching and advices that gave me academic and personal growth. Thank you so much. I would also like to thank Professors João Luiz de Carvalho and Professor João Paulo Leite, that helped me with the theme definition and great sources for reference.

I would also like to thank my friends, that gave me the strength I needed to conclude not only this work, but many other college ones. Special thanks to Bianca Fonseca, Amanda Pimenta and Leonardo Pereira.

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Chapter 1 - Introduction and context

1.1 Motivation

Communication systems have been evolving quickly throughout the years. The amount of users in these systems continuously grows, and among with it, the demand for higher speed and better performance also grows. Along the years, different modulation schemes and channel access techniques were developed in order to meet these requirements, and communication protocols were created to organize and set the working rules for this technology that since its beginning hasn't stop evolving.

In order to implement all these different communication schemes, it is necessary to develop the hardware that will process the signals (radio waves) that carry the desired message. Hardware for signal processing is present in both ends of a communication link, or hop: transmitter and receiver. The picture below shows a generic form for a RF communication link:

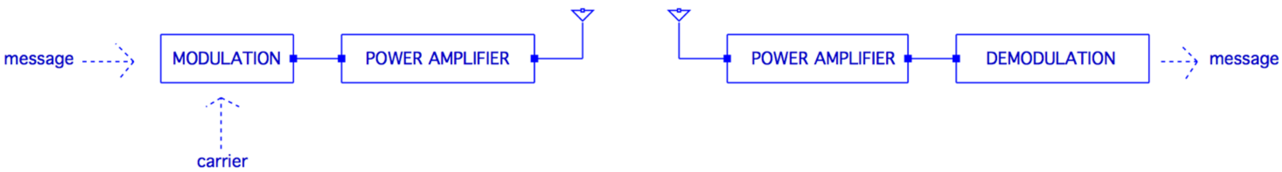

Figure 1 – Generic RF link

The focus of this work will be the transmitter end of the link, more specifically, its power amplifier. The modulation scheme was chosen to be OFDM, a digital technique that combines aspects of modulation and channel access by multiplexing. This technique is currently used by modern communication patterns such as LTE. A brief introduction to OFDM is presented below.

1.2 Orthogonal Frequency Division Multiplexing – OFDM

As mentioned before, the amount of users in communications systems has increased through the years, however, it was not possible to continuously increase the number of communications channels to support the growing number of users, since the frequency spectrum is limited, and its division is determined by laws and regulations. In order to support the growing number of users considering the limitations in the available resources, multiple access techniques were developed so that signals could be transmitted simultaneously in the same channel, without interference between these signals. It is possible to share a communication channel reserving time slots for each signal. This technique is known as Time Division Multiple Access - TDMA. It is also possible to divide the total available frequency band into many channels and reserve one channel per signal. This is known as Frequency Division Multiple Access - FDMA. Another way of sharing a channel is making the signals orthogonal to one another using a coding technique, in which each signal will be modified by a code, and they will be transmitted at the same time, in the same frequency band (these codes must be orthogonal to one another). This technique is known as Code Division Multiple Access – CDMA.

Orthogonal Frequency-Division Multiplexing, OFDM, is a recent technique that uses Frequency Division Multiple Access in order to transmit the signal by multiple subcarriers, instead of one sub-carrier like in the traditional modulation schemes. The main advantage of OFDM is that the subcarriers are orthogonal to one another in the frequency domain, which allows for their central frequency to be very close to one another, without the need for band guard. Therefore, the resulting frequency band of the signal to be transmitted is thinner than what would be obtained by a traditional modulation technique, allowing for a more efficient use of the frequency spectrum, since a great part of the band reserved for this transmission will be occupied by the actual message carrying signal. The pictures below show an example of the frequency spectrum for the subcarriers in an OFDM system and in a FDMA system.

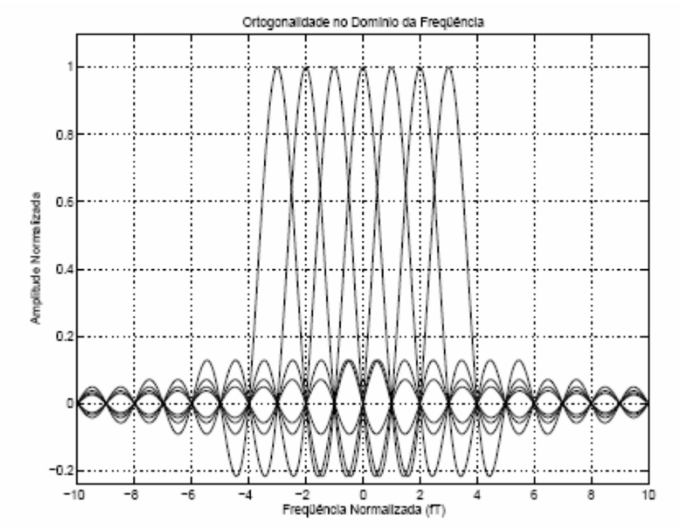

Figure 2 – Frequency spectrum for OFDM subcarriers

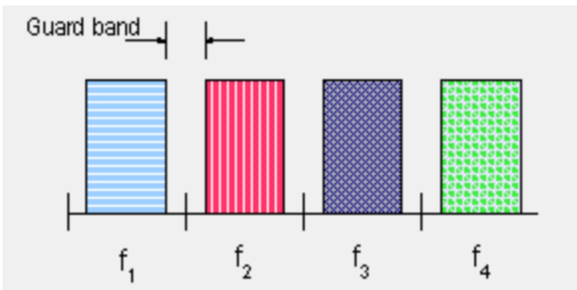

Figure 3 – Frequency spectrum for FDMA channels

In the graph shown in Figure 2, we have a classic representation for the frequency spectrum of an OFDM modulated signal, with the normalized frequency values in the horizontal axis and the amplitude values in the vertical axis. In this graph, it is possible to notice that, between the normalized frequency values -4 and 4, the modulated signal occupies most of the band, with the amplitude peaks very close to one another, without blank spaces in which the frequencies would not be used. On the other hand, we have a representation of the frequency spectrum in a FDMA system with four channels in Figure 3, showing that each channel occupies its own band, without overlapping due to the guard bands between the channels. Due to this configuration, there is a significant part of the frequency spectrum that is not used for data transmission, hence, resulting in a less efficient use of the frequency spectrum than the one obtained in the OFDM system.

To sum up, OFDM can be seen as either a modulation or a multiplexing technique, since it uses multiple subcarriers. Each subcarrier can be modulated with different schemes, such as QAM or PSK. A disadvantage of OFDM is its relatively large peak-to-average-power ratio (PAPR), a relation between the maximum power achieved by a signal and its average power. In a multi-carrier system such as OFDM, the large PAPR occurs because the different sub-carriers are out of phase with each other, then, when all the different waves within the signal achieve their maximum value at the same time, the overall envelope suddenly rises, achieving a high value, resulting in a peak in the amplitude. Moreover, since there can be different modulation schemes among the sub-carriers in an OFDM system, these peak values can be very high when compared to the average of the whole system, and even to the maximum values of an individual modulated sub-carrier. High values of PAPR tend to reduce the power efficiency of the RF amplifier used within the communication system. This issue will be mentioned furthermore. Pictures 4, below, shows an example of different sub-carriers in an OFDM signal.

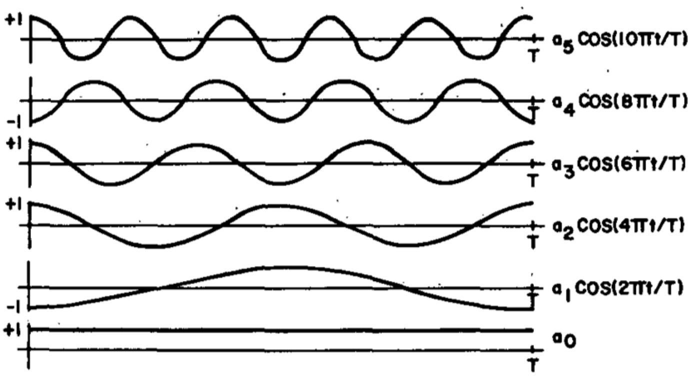

Figure 4 – Example of different waves to be used as sub-carriers

In Figure 4, we can see that the waves are out of phase and, illustrating what was mentioned for PAPR in OFDM signals.

1.3 OFDM in current communication patterns

Along the years, as the communication systems evolved and the number of users grew, different communication patterns were developed in order to accommodate the growing number of users and their requests. Multiple access techniques were developed to accomplish these purposes, while also trying to use the frequency spectrum efficiently, since it is a limited resource. In cell phone communication patterns, CDMA and TDMA were used until 3G patterns and early 4G patters. With the development and evolution of LTE and LTE Advanced techniques, OFDM was preferred over the previous ones, and it is currently in use not only in cell phone networks, but also in digital TV and radio patterns and in WiFi and Wimax networks.

The next cell phone networks generation, 5G is being developed, and an important aspect for the definition of the new patterns is the waveforms, modulation and access technique to be used. Due to its performance in already implemented systems and its great spectrum efficiency, OFDM is a good option for 5G networks, and is currently in analysis.

Since OFDM is an important modulation/channel access technique, currently in use in modern networks and is also on the running towards becoming the technology to be applied in 5G, it is important to understand how this technique is implemented, which includes not only the communication pattern definition, but also the electronic circuits and equipment that will be used. As it can be seen in Figure 1, the power amplifier is an important part of a communication link. The goal of this work is to compare different classes of power amplifier, observing their performance to see if they are appropriate for application in an OFDM system.

1.4 Objectives

The main objective of this work is to compare three different power amplifier classes (A, B and AB) in order to determine which one would be most appropriate in an OFDM system. This will be achieved through the following steps:

- Generation of an OFDM signal, in order to illustrate the characteristics mentioned in 1.2;
- Simulation of the three circuit layouts for each amplifier class;
- Analysis of the performance of each amplifier, regarding power efficiency and linearity.

Chapter 2 – Literature Review

2.1 Radio Frequency Power Amplifiers

A power amplifier (PA) is a crucial component in a wireless communications system. In this type of system, the signals are sent through the air, so they will lose power when traveling from transmitter to receiver, hence the need of the amplifier. By amplifying the signal, these losses can be compensated, allowing for the message to be correctly interpreted by the receiver.

The main elements that compose a power amplifier used in RF applications are the transistor used, the output and input networks and the RF choke.

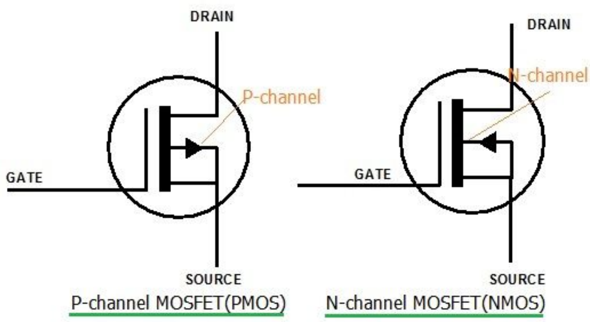

Figure 5 – PMOS and NMOS transistors

The PA's transistor, such as the ones shown in Figure 5, can be used as a dependent current source, as a switch or it can be alternating between these two, it depends on its operating point and region of operation, determined by the polarization used. If the transistor is operating as a current source, it means that it is in saturation region, where i_d (current flowing between "DRAIN" and "SOURCE" in Figure 5) and v_{DS} (voltage from "DRAIN" to "SOURCE" in Figure 5) are practically proportional to v_{GS} (voltage from "GATE" to "SOURCE" in Figure 5). This linearity is important for AM signals, which explains why this region of operation is used in power amplifiers. The operating point and region of operation of the transistor also determine the class of the amplifier. Classes A to F of power amplifiers are differentiated by the conduction angle of the drain current. In classes A, B, AB and C, the transistor operates as a current source, and in classes D, E and DE, it operates as a switch. Class F allows it to operate as either one of them. For classes A to C, considering a sinusoidal gate-to-source voltage, the conduction angle can be 360º (class A), 180º (class B), between 360º and 180º (class AB) or less than 180º (class C), which will cause the transistor to conduct current for the whole cycle of the v_{GS} waveform, for half its cycle, somewhere in between these two or for less than half a cycle, respectively. The DC value of v_{GS} will determine the PA class, since it determines whether the transistor conducts current or not, having the threshold voltage as its parameter to compare to.

In order to transmit and receive electromagnetic waves through space, it is necessary to use antennas, a device that transforms an electric signal into an electromagnetic wave and one that receives the transmitted wave and converts it into an electrical signal. It is common to compare the power transmitted by an antenna to the power that would be transmitted by an isotropic antenna, a hypothetical device that radiates power uniformly through space. Real antennas have a preferential direction for power radiation, and the radiated power is given by the antenna gain in this direction multiplied by the power transmitted by an isotropic antenna. The receiving antenna will capture part of the wave's power density, which is proportional to the area of the antenna. The received power is then given by the antenna effective area (A_e) multiplied by the power density of the transmitted wave at that point ($p(r)$):

$$P_R = A_e\, p(r) = (G_R \frac{\lambda^2}{4\pi})(G_T \frac{P_T}{4\pi r^2}) \qquad (1)$$

where G_T is the gain of the transmitting antenna, G_R is the gain of the receiving antenna, λ is the wavelength in free space ($\lambda = \left(\frac{c}{f}\right), c = 3x10^8 m/s$), P_T is the output power and r is the distance between the antennas. The antenna gain depends on the type of the antenna. The equation for the received power doesn't consider the losses involved in a communications link, for example the space loss and the atmospheric loss, among others. Concatenating all these losses in one parameter, L_{sys}, we can consider that the received power is given by $P_R L_{sys}$. As it can be concluded from equation (1), the power transmitted reduces proportionally to the square distance, which represents a significant loss in the received power. One of the goals of the power amplifier is to provide enough power for the signal transmission, compensating for the intrinsic power loss due to the distance between the antennas.

2.2 Computer tools

In order to achieve this work’s objectives, mentioned in item 1.4, two computer tools were used: MATLAB and LT Spice®.

MATLAB is a program developed by MathWorks® that combines a desktop environment tuned for iterative analysis and design processes with a programming language that expresses matrix and array mathematics directly, and it can be used for data analysis, algorithm development or model creation. In MATLAB, there are a few different packages that offer many functions and tools to be used in signal generation and processing, and OFDM technique is among the types of signals that can be treated in MATLAB.

LT Spice® is a high performance SPICE III simulator developed by Analog Devices, for circuit simulation, schematic capture and waveform viewer. LT Spice includes models for many different analog devices, including, but not limited to, op amps, resistors, transistors and MOSFET models.

Chapter 3 – Methodology

3.1 OFDM code in MATLAB

As mentioned in the previous chapter, MATLAB has many different toolboxes that allow the simulation and data analysis in different areas. The communication toolbox offers a variety of tools to generate signals and simulate their transmission and reception. MATLAB developer, MathWorks®, has an online environment in which users can upload their codes. The code in Annex 1 was uploaded by Baher Mohamed, it is a simple yet complete example of OFDM signal processing, including both transmitter and receiver. Since we are only interested in the transmitter end of the hop, this code was slightly modified, resulting in the OFDM transmitter code in Annex 2.

3.2 LT Spice Models and Simulations

LT Spice, like other similar SPICE type software, offers different options for device characterization and different simulations, each with a corresponding set of output waveforms.

The options for device characterization differ in their LEVEL, a program specification that will dictate how many parameters can be set to user chosen values, instead of using the default ones, that is, the amount of changeable parameters as well as the complexity of the simulation varies with the selected level. For the analysis presented in this text, LEVEL 1 Spice simulation was used due to its low complexity, and to the fact that most of the important MOSFET parameters can be set in this level, such as the threshold voltage, the oxide characteristics (thickness and capacitance) and the parasitic capacitances in this device. The devices parameters were extracted from [1].

In [1], the author has characterized PMOS and NMOS transistors in XFAB CMOS 0.18µm technology. This technology was the only one available in LDCI and has interesting features for mixed signal design. It provides a good compromise between current capacity, size and switching performance, thus it can be used in mixed signal projects. Combining the results of [1] and the default values for this technology in LT Spice, the transistors parameters were determined, as shown in the tables below.

Parameter	Value
V_{t0}	0.6 V
k_p	$166.8x10^{-6}$ A/V^2
C_{ox}	$3.45x10^{-5}$ F
t_{ox}	$4.1x10^{-3}$ m
CJ	$2x10^{-4}$ F/m^2
$CJSW$	$1x10^{-9}$ F/m
$CGBO$	$2x10^{-10}$ F/m
$CGDO$	$4x10^{-11}$ F/m
$CGSO$	$4x10^{-11}$ F/m

Table 1 – LT Spice level 1 parameters for NMOS transistor

Parameter	Value
V_{t0}	0.6 V
k_p	$32.6x10^{-6}$ A/V^2
C_{ox}	$3.45x10^{-5}$ F
t_{ox}	$4.1x10^{-3}$ m
CJ	$2x10^{-4}$ F/m^2
$CJSW$	$1x10^{-9}$ F/m
$CGBO$	$2x10^{-10}$ F/m
$CGDO$	$4x10^{-11}$ F/m
$CGSO$	$4x10^{-11}$ F/m

Table 2 – LT Spice level 1 parameters for PMOS transistor

The simulation type will determine which set of waveforms will be available after the program runs. For the purposes of this work, it was used the transient analysis (declared in LT Spice as ".tran", in order to be able to observe voltage and current signals in time domain.

The parameters mentioned above were used for all simulations performed in this text, for each amplifier class analyzed.

3.3 Power Amplifier Classes

The power amplifier classes differ from one another according to the transistors operation (as a switch or as a current source) and to the conduction angle of the current, as already mentioned in this text.

In this work, classes A, B and AB will be compared. For each class, two different circuit layouts were simulated: one with an open circuit at the amplifier output and one with a resistor at the amplifier output, to represent an antenna connected to the amplifier. The resistance value for all simulations with the resistive load was 75 Ω, a common resistance value for antennas. Two characteristics will be used to compare the amplifier classes: linearity and power efficiency.

The linearity aspect will be analyzed by observing the input and output waveforms of the circuit, to see how similar they are in shape. The more distortions the output waveform presents, the less linear that amplifier will be considered.

In order to compare the power efficiency aspect for the amplifier classes, the following equations will be used to determine the efficiency in class A, class B and class AB, respectively, extracted from [3]:

$$\eta = \frac{1}{2} \cdot \left(\frac{V_L}{V_{L\max}} \right)^2 \cdot \frac{1}{1 + (R_{DSon} / R_L)} \cdot \frac{1}{1 + 2\gamma} \tag{2}$$

$$\eta = \frac{\pi}{4} \cdot \frac{V_L}{V_{L\max}} \cdot \frac{1}{1 + (R_{DSon} / R_L)} \tag{3}$$

$$\eta = \frac{\pi}{4} \cdot \frac{V_L}{V_{L\max}} \cdot \frac{1}{1 + \frac{R_{DSon}}{R_L}} \cdot \frac{\frac{V_L}{V_{L\max}}}{\theta_Q \cdot \operatorname{sen} \theta_Q + \frac{V_L}{V_{L\max}} \cdot \cos \theta_Q} \tag{4}$$

Equations (2), (3) and (4) have two terms in common: VL/VLmax and RDSon/RL. In all three cases, VL=VLmax is the maximum voltage in the output load, so VL/VLmax = 1. RDSon is the resistance between the MOSFET's drain and source, and it can be obtained from the device's datasheet. In this case, the value for RDSon, extracted from [2] is 0.0032 Ω and RL is the load resistance, 75 Ω, as mentioned before. The other terms of these equations will be determined with the simulations results, presented in Chapter 4 of this text.

3.3.1 Class A

In class A, the conduction angle is 360º, which means that the transistors conduct current during all the input wave's cycle. In order to do so, the transistors need to be biased in a way that v_{GS} is always higher than the threshold voltage, meaning that the transistor is in saturation region, working as a current source during the entire cycle. Since the transistor is conducting for all of the cycle, the output wave will follow the input wave, resulting in a good linearity. Class A amplifiers have the best linearity characteristics among all classes, but it has low efficiency, since part of the energy is used to bias the transistors. The maximum theoretical efficiency for class A amplifiers is 50%.

The picture below shows the layout used to simulate a class A amplifier in LT Spice. For this class, it is not necessary to use a push-pull configuration, it could be implemented with only one transistor, since it would conduct current for the entire cycle. However, classes B and AB are assembled with this configuration, as it will further be explained in this text, so, in order to compare the performance of the circuits herein in the most uniform way possible, it was also chosen a push-pull configuration for class A amplifier.

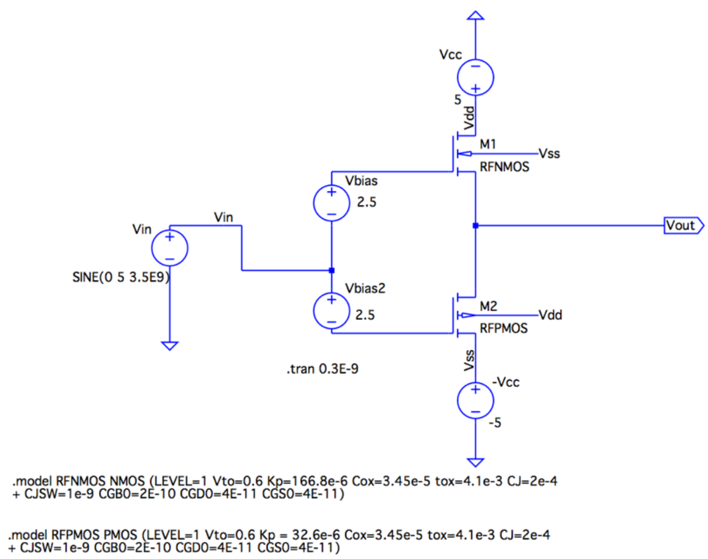

Figure 6 – Class A amplifier layout

In Figure 6, we have the circuit layout for a push-pull class A amplifier, with an open circuit at its output. The input is a sine wave with 5 volts amplitude and 3.5 GHz frequency, which will be the same for the other amplifier classes further in this text. As already mentioned in this text, 5G technology is currently in development, and this frequency value can be the one chosen for its implementation with OFDM. Two voltage sources Vbias were used to guarantee the correct biasing for each transistor, allowing them to conduct current for the whole input wave cycle. This could also be obtained by adding a DC value to the input wave, however, this solution with independent voltage sources was chosen in order to achieve, once again, a more uniform comparison between the different amplifier classes. In addition, it was possible to test for different values of Vbias, until this choice for half the value applied in the drain of each transistor.

A small change was made in this circuit and a resistive load of 75 Ω was connected to its output, since the amplifier's efficiency will be calculated with Equation (2), that depends on the load resistance. The next picture shows the resulting layout.

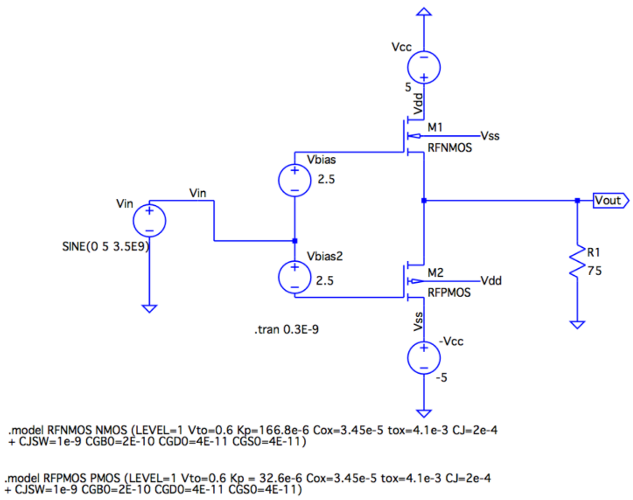

Figure 7 – Class A amplifier with resistive output load

The only difference between Figures 6 and 7 is the 75 Ω resistor. This small change allows us to observe not only the voltage, but also the current in the amplifier's output, as well as to determine the circuit's power efficiency.

3.3.2 Class B

In class B amplifiers, there is no biasing current for the transistors, which causes them to conduct current for half the wave cycle, being in cut off region for the other half. This results in a conduction angle of 180º. As mentioned before, here we see the need for a push-pull configuration: one of the transistors (NMOS) will conduct current for the positive part of the input wave, when vgs is higher than the threshold voltage for this transistor, and the other transistor (PMOS) will conduct current for the negative part of the input wave, allowing for the output wave of the circuit to reflect the input wave, without flat parts. The picture below shows the circuit layout used to simulate a class B amplifier in LT Spice.

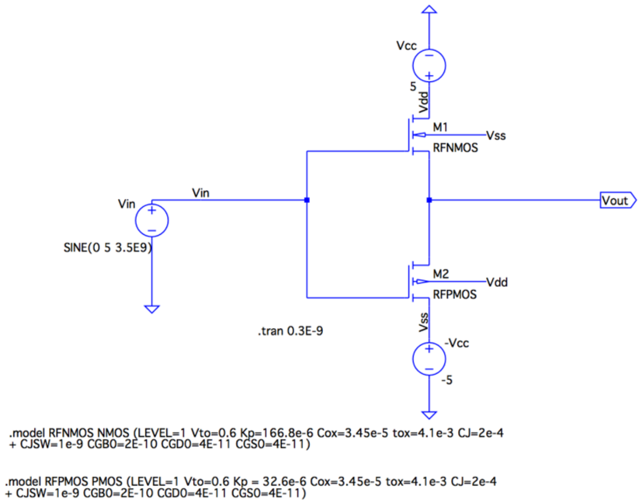

Figure 8 – Class B amplifier layout

Figure 8 shows the layout used for simulation of a class B amplifier, with an open circuit at its output. As it can be seen when comparing this circuit to the one shown in Figure 6, there are no voltage sources used for transistor biasing.

For the same reasons mentioned in the previous items, this circuit was also modified by adding a 75 Ω resistor at its output, resulting in the layout shown below.

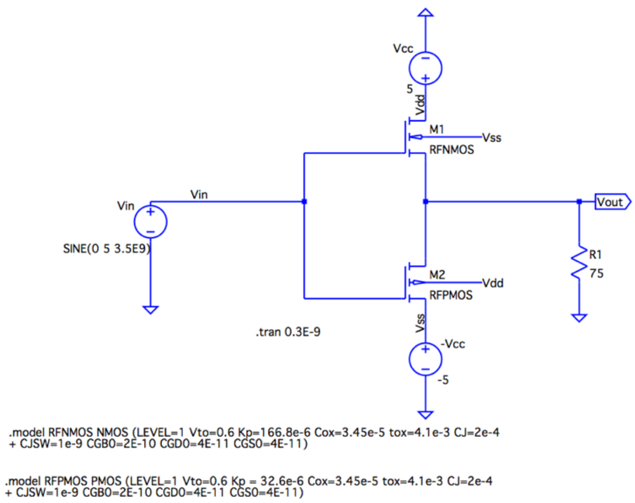

Figure 9 - Class B amplifier with resistive output load

3.3.3 Class AB

Class AB is an intermediate stage between classes A and B. In this class, the transistors are biased at a small current, which can be obtained by applying a voltage at the gate approximately equal to the threshold voltage, or slightly above, guaranteeing that the transistors will conduct current for the whole cycle, without spending a significant amount of energy for biasing, like what happens in class A. The conduction angle for this amplifier class is larger than 180º and smaller than 360º.

The circuit layout for this amplifier class is presented below, already with the resistive load connected to its terminals, so its behavior can be better analyzed in a RF hop context.

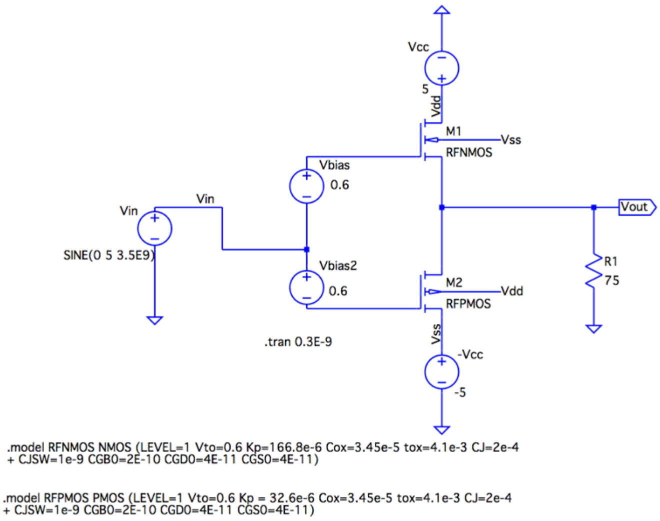

Figure 10 - Class AB amplifier with resistive output load

In Figure 10, we can see the circuit layout used for simulating a class AB amplifier. The transistors biasing was implemented in the same way described for class A amplifier, that is, with the use of independent voltage sources instead of a DC value in the input sine wave. Each voltage source Vbias has a value equal to the transistors' threshold voltages, which is the limit for this amplifier class.

Chapter4 – Results and Analysis

4.1 OFDM signal generated in MATLAB

The code in Annex 2 has three different graphs as outputs, allowing for the construction of the OFDM code to be observed step by step. This code randomly generates 64 data points, that will later be modulated in a QPSK scheme. Each number represents a crop of two bits in a longer sequence of digital binary message, data or instruction. The picture below is the first output of this code, showing the 64 points:

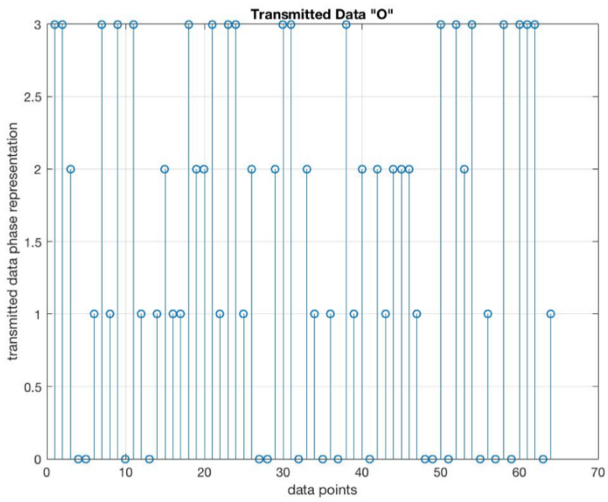

Figure 11 – First output of MATLAB code

The size of the constellation used in the QPSK modulation is defined by "M" in the code. In this case, M=4, resulting in the constellation points in the next picture, another output of the code:

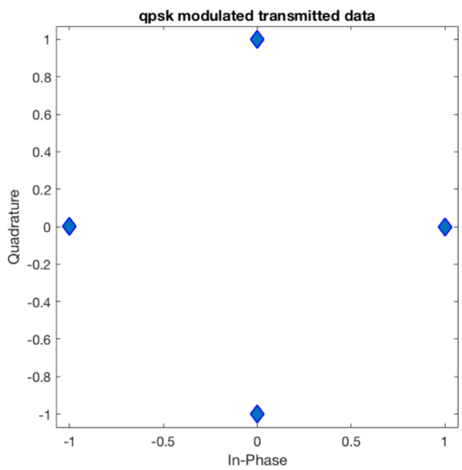

Figure 12 – Second output of MATLAB code

The QPSK modulation performed in the data points is achieved using specific MATLAB functions in the Communications System Toolbox. The final step of signal processing, after the modulation is performed, is the Fourier Transform of the signal, considering the correct size for the final OFDM signal. After these steps, the resulting OFDM signal, ready for transmission, is shown in the next picture, the last output of the code:

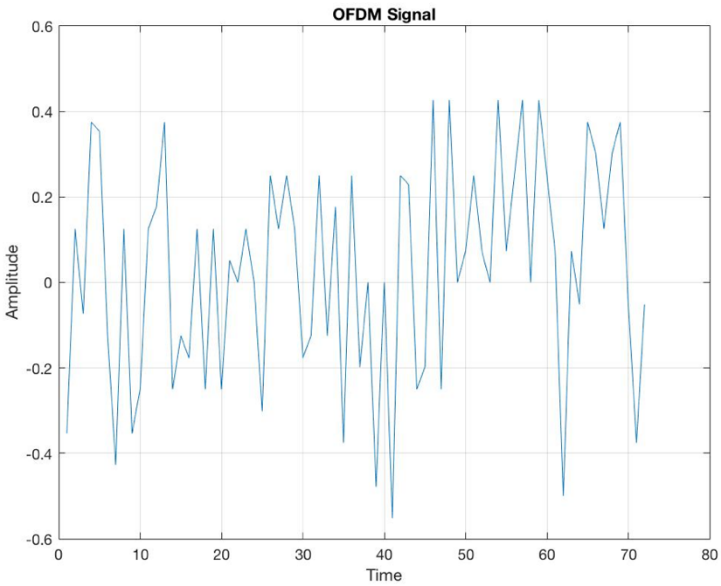

Figure 13 – Third output of MATLAB code

The graph in Figure 13 is the real part of the OFDM generated signal, since this is a complex signal.

The length of the generated vector that represents the OFDM signal is 72, which means that there will be 72 equally spaced samples of the represented OFDM signal to be fed in the input of the RF amplifier. This configuration caused the data points to be widely spaced, and in some parts of the signal it appears that it has been clipped, as it can be seen if we zoom in on some points in Figure 13:

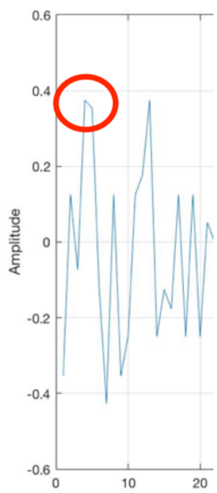

Figure 14 – Zoom in on Figure 13

The red circle in Figure 14 exemplifies the mentioned problem, which causes the loss of information about the peak amplitude value. The peak values are an important factor in OFDM codes, because they affect the PAPR. In order to obtain more data points, including the peak amplitude values, this signal was interpolated using spline interpolation, another MATLAB functionality that includes the determination of the spacing between the new, generated samples. The code below was used for the interpolation, resulting in the next picture:

```
%%Interpolation of OFDM generated signal
r = real(ofdm_signal);
t = 0:1:71;

% Spline Interpolation
i = 0.2;        %step size between samples
tq = 1:i:72;
rq1 = spline(t,r,tq);
plot(t,r,'bo-',tq,rq1,'rx')
```

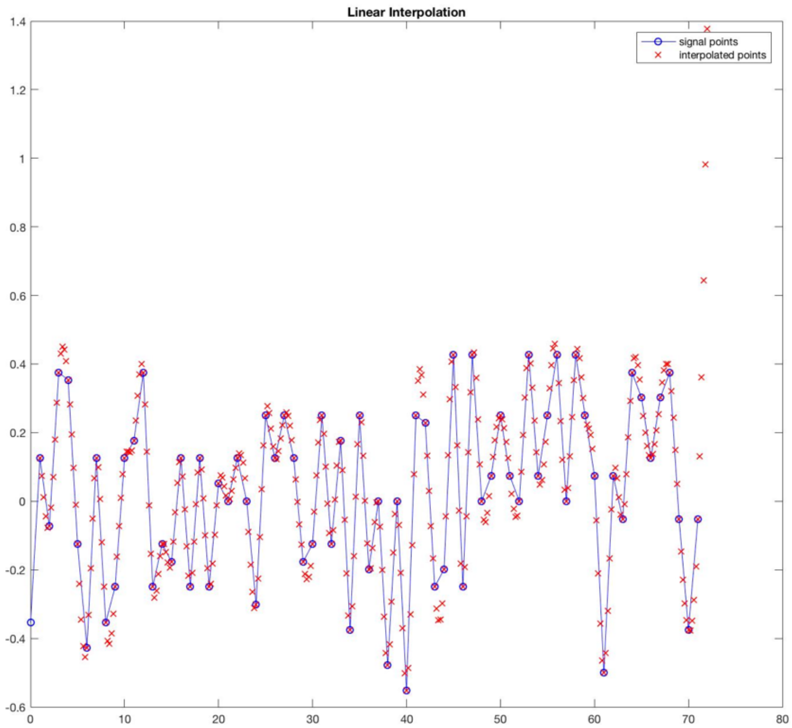

Figure 15 – OFDM signal

In Figure 15 we can see the original generated points and the extra ones obtained with the interpolation, showing that the problem of losing information about the peak amplitude values was solved. In MATLAB command window, it was possible to obtain the maximum and average values of this signal, allowing for the PAPR to be determined as follows:

$$PAPR = 20\log\left(\frac{maximum}{average}\right) = 11.58\ dB$$

Therefore, it is possible to conclude that the generated OFDM signal has a high PAPR value, close to the LTE PAPR value of 12 dB.

4.2 Class A amplifier

The picture below was obtained by running the LT Spice simulation in the circuit in Figure 6, and by selecting which waveforms were to be seen in LT Spice's window.

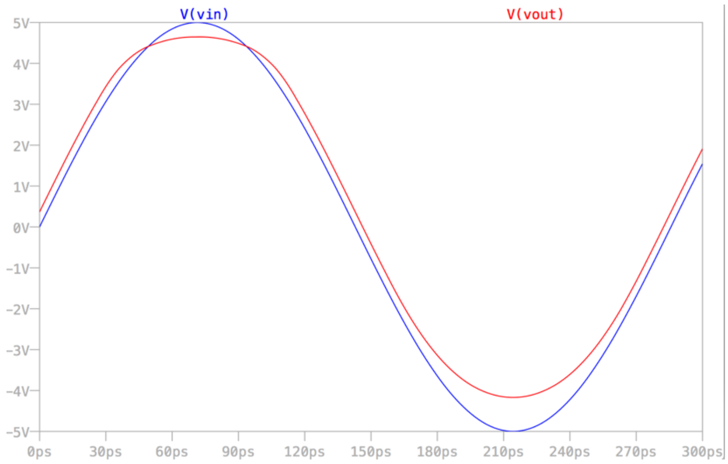

Figure 16 – Input and output voltage waves in class A amplifier

In Figure 16, we can see the input voltage wave, in blue, and the output wave, in red. By analyzing this picture, it is possible to conclude that the overall shape of the input wave was approximately maintained in the output, without significant distortions. As mentioned in item 3.3.1, the amplifier was also simulated for a resistive load connected to its terminals. The next picture shows the result of the simulation of the circuit layout in Figure 7, using the same waveforms and color scheme as the ones presented in Figure 16.

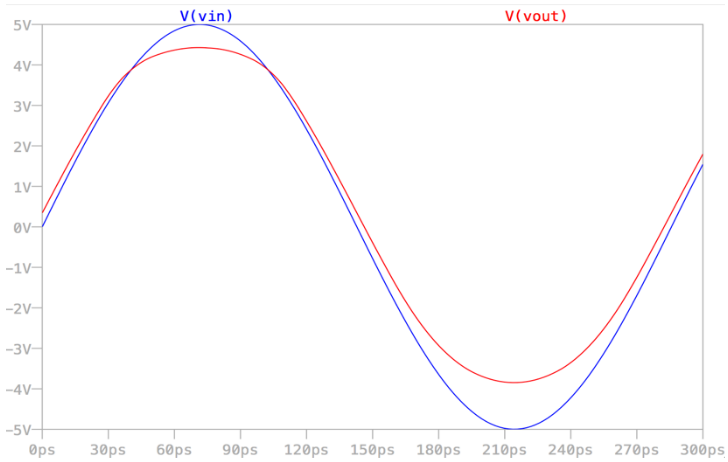

Figure 17 - Input and output voltage waves in class A amplifier with resistive output load

The waveforms in Figure 17 are very similar to the ones in Figure 16, once again allowing the conclusion that the circuit has a good linearity, without significant distortions in the overall shape of the output voltage wave when compared to the input voltage wave.

In order to apply Equation (2) to calculate this circuit's efficiency, it is necessary to determine the parameter γ. According to [3], this parameter is the ratio between the transistor's maintenance current (Iman) and the maximum value of the load current

(ILmax). These values can be obtained through a graphical analysis of the currents in the top transistor and in the load. The next picture was also obtained by simulating the circuit in Figure 7, this time selecting these two currents among the available waveforms in LT Spice window.

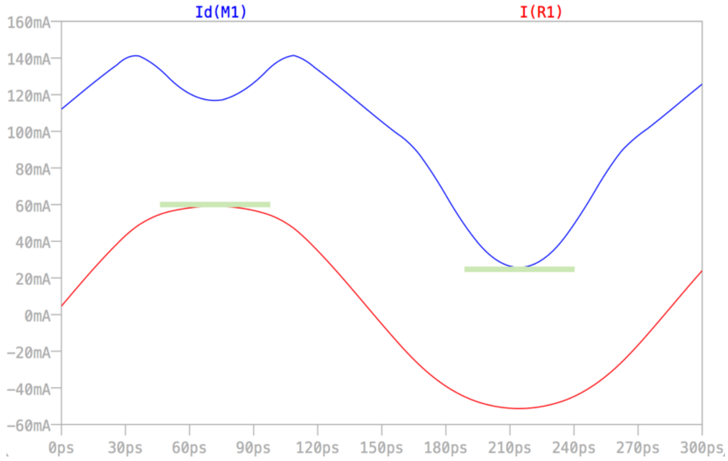

Figure 18 – Transistor and load currents in class A amplifier

Figure 18 shows the current in the transistor, in blue, and the current in the output resistor, in red. The green bars were added to highlight the values for the maintenance current, in the blue curve, and the maximum load current, in the red curve. Through graphical analysis, these values were, respectively, 20 mA and 60 mA, resulting in γ = 1/3. Substituting all the parameters values in Equation (2), the efficiency of this class A amplifier circuit was 30%, lower than the maximum theoretical value of 50%. This was expected, since Equation (2) uses parameters that depend on the circuit performance, affected by the device's characteristics such as the parasitic capacitances declared in the model declaration in LT Spice, instead of ideal devices used to determine the theoretical value.

4.3 Class B amplifier

Using the same procedures mentioned in the previous item for class B circuits, the picture below was obtained with the simulation of the circuit layout in Figure 8.

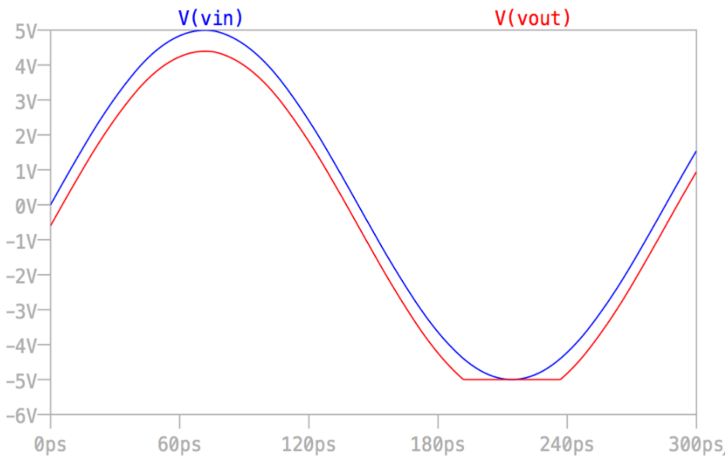

Figure 19 - Input and output voltage waves in class B amplifier

Figure 19 shows the input and output waves in the class B amplifier, in blue and red, respectively. Here, we can already see a distortion in the output wave when compared to the input wave. Once again, in order to better observe the amplifier's behavior in a communication link context, a resistor was added to the output to represent an antenna, resulting in the circuit layout in Figure 9, whose simulation result is shown in the picture below.

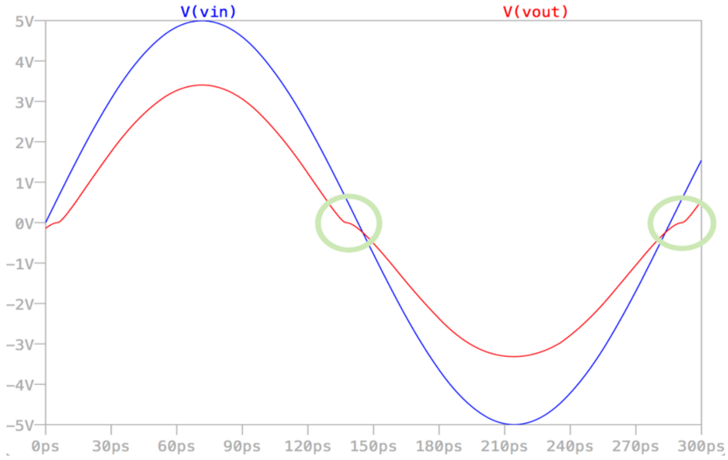

Figure 20 - Input and output voltage waves in class B amplifier with resistive output load

In Figure 20 we can see the crossover effect, highlighted by the green circles added to the picture. This happens in the transition between the region of operation of the two transistors. There is no DC voltage applied to the gate, so it takes some time for the input wave cycle to achieve a value higher than the threshold voltage so the second transistor can conduct, resulting in a significant distortion in the output wave when comparing it to the input wave. Therefore, we can conclude that the class B amplifier has a lower linearity than the class A one.

Substituting the parameter values in Equation (3), the efficiency calculated for class B amplifier was 78.5%, higher than the efficiency in class A.

4.4 Class AB amplifier

The simulation of the circuit in Figure 10, class AB amplifier, resulted in the waveforms below.

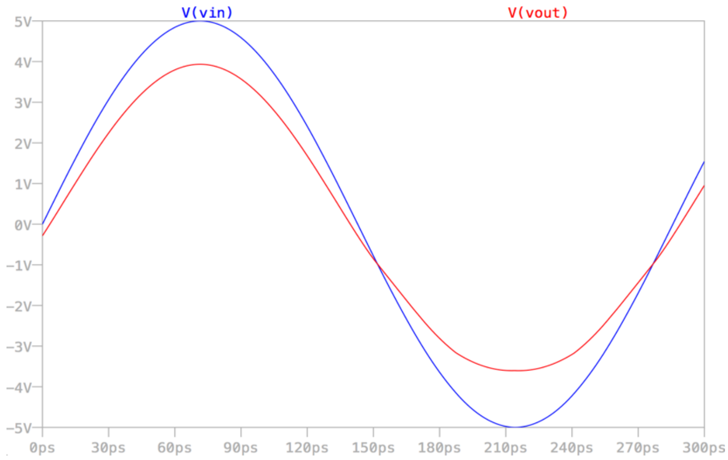

Figure 21 - Input and output voltage waves in class AB amplifier with resistive output load

In Figure 21, we have the input and output waves in class AB amplifier, with the same color scheme used for classes A and B. In this graph, the crossover effect can barely be perceived, but there is a difference in the overall wave shapes in the input and output. Hence, it is possible to conclude that this amplifier has a better linearity than the one presented by class B, but a slightly worse one when compared to class A. This corroborates the fact that class AB is an intermediate stage between classes A and B.

In order to determine the efficiency for this circuit, it is necessary to calculate thetaQ, to be used in Equation (4). According to [3], thetaQ=sen-1(2IQ/ILmax), where IQ is the polarization current and ILmax is the maximum load current. Similar to what was described for class A amplifier, these parameters can also be determined through graphical analysis, plotting the currents in both transistors and in the resistive load. The picture below was also obtained by simulating the circuit in Figure 10, this time selecting the desired current waveforms in LT Spice window.

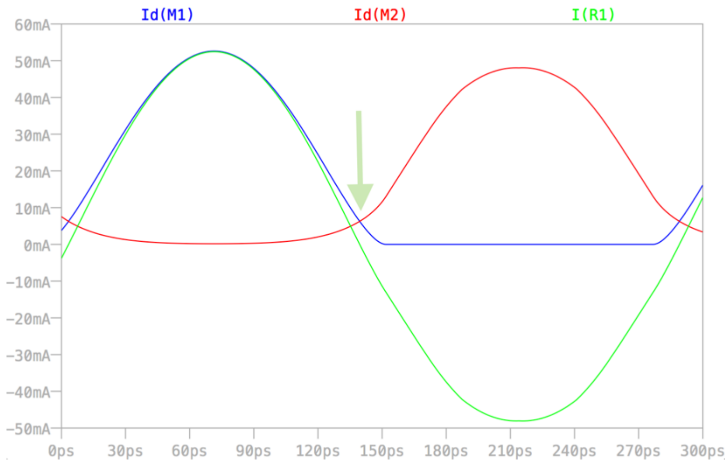

Figure 22 – Transistors and resistor currents

In Figure 22, we can see the currents in each transistor, in blue and red, and the current in the output resistor, in light green. The green arrow added to the graph highlights the point in which the transistor currents meet, which represents the polarization current, according to [3]. Then, as it can be seen in the graph, IQ=5mA and ILmax=50mA. So, the value of thetaQ could be determined and substituted in Equation

(4) to result in an efficiency of approximately 77% for class AB amplifier, once again placing class AB amplifier in an intermediate stage between classes A and B.

Through the analysis presented, it is possible to conclude that class AB is the most appropriate amplifier type among the ones studied in this text, since it presents a good performance in terms of both linearity and power efficiency, without choosing one over the other like what happens in classes A and B.

Chapter 5 – Conclusions

5.1 OFDM signal

One of the objectives of this text was to generate an OFDM signal using MATLAB. This was achieved by modifying a code downloaded from MATLAB developer's website, MathWorks®. The signal obtained with the resulting code was then interpolated so that the final signal could represent an actual OFDM one, including its characteristic high amplitude peaks. An important parameter in an OFDM signal is the peak-to-average-power ratio, PAPR, which was calculated for the generated signal, resulting in a value very close to the reference one for actual OFDM signals, allowing the conclusion that the signal generated in this text is a good representation of an OFDM modulated signal. These two PAPR values can be seen and compared in the table below.

PAPR reference value	PAPR calculated	Difference between them
12 dB	11,58 dB	3.6%

Table 3 – Comparison between reference and calculated values of PAPR

5.2 Comparison of power amplifier classes

Through LT Spice simulations, it was possible to compare classes A, B and AB, by observing the voltage and current waves available with the simulation and combining these results to the definitions in [3].

In terms of linearity, we can conclude from the observation of Figures 17, 20 and 21 that class A amplifier has the best performance, delivering an output voltage wave very similar to the input voltage wave, without significant distortions, while class B presented the worse performance, with a strong crossover effect. Class AB amplifier is in between these two, with an output voltage wave similar to the input one, with barely perceived distortions.

In addition to linearity, another aspect of the power amplifier behavior was analyzed in this text: power efficiency. By using the equations defined in [3], the efficiency for each class could be calculated, and the results were as expected in theory. The table below shows the calculated efficiency values for each amplifier class.

Power Amplifier Class	Efficiency
Class A	30%
Class B	78.5%
Class AB	77%

Table 4 – Comparison between the amplifiers' efficiencies

The values in Table 4 allow the conclusion that class A amplifier has the worst efficiency and class B has the best one. Once again, class AB appears at an intermediate stage between the other two.

5.3 Final conclusions

The analysis of the results presented in this text allows the conclusion that class AB amplifier is appropriate for application in an OFDM transmitter in a communication link, based on this amplifier’s aspects of linearity and efficiency. This amplifier has a satisfactory performance regarding these two aspects, placing it at an intermediate stage between classes A and B.

It was possible to achieve the objectives set for this work through computer simulations, that used definitions in order to represent the real devices and signals appropriately.

References:

[1] PEREIRA, I.S.P. *Módulo Analógico para um Conversor A/D por Aproximações Sucessivas*. UnB, 2018 (Trabalho de Conclusão de Curso, Universidade de Brasília).

[2] XFAB. *0.18 Micron CMOS Analog Mixed-Signal Process Technology*, 2017.

[3] BORTONI, R.; NOCETI FILHO, S.; SEARA, R. *Dimensionamento Avaliação de Estágios de Potência de Amplificadores de Áudio Classes A, B, AB, G e H, Assistido por Análise Computacional*. LINSE, UFSC; STUDIO R Eletrônica Ltda, 1999.

[4] KAZIMIERCZUK, M.K. *RF Power Amplifiers*. 1. ed.: John Wiley & Sons, 2008.

[5] BORTONI, R. *Amplificadores de Potência. Encontro de Sistemas de Áudio*, STUDIO R/SELENIUM.

[6] WEINSTEIN, S.B.; EBERT, P.M. *Data Transmission by Frequency-Division Multiplexing Using the Discrete Fourier Transform*. IEEE, 1971.

[7] PRASAD, R. *OFDM for Wireless Communication Systems*. 1. ed.: Artech House, 2004.

[8] *Formas de Onda Candidatas ao 5G*. RHODE & SCHWARZ.

[9] *What is PAPR (Peak to average power ratio), Why it matters to Power Amplifier?*. Techplayon, 2017.

[10] GANGWAR, A.; BHARDWAJ, M. *An Overview: Peak to Average Power Ratio in OFDM system & its Effect*. International Journal of Communication and Computer Technologies, 2012.

[11] BAHAI, A.R.S.; SALTZBERG, B. *Multi-Carrier Digital Communications. Theory and Applications of OFDM*. 1. ed.: Algorex, 2002.

[12] MADUREIRA, H.M.G.M. *Study and design of CMOS RF power circuits and modulation capabilities for communication applications*. HAL, 2015.

Annex 1

```
%==============================================================================
% The mfile investigates the generation, transmission and reception of
% the OFDM signal without channel noise or HPA effect. Written By: Baher Mohamed
clear all; clc; close;
%   ---------------
%   A: Setting Parameters
%   ---------------
M = 4;                          %   QPSK signal constellation
no_of_data_points = 64;        %   have 64 data points
block_size = 8;                 %   size of each ofdm block
cp_len = ceil(0.1*block_size);  %   length of cyclic prefix
no_of_ifft_points = block_size;           %   8 points for the FFT/IFFT
no_of_fft_points = block_size;
%   ---------------------------------------------
%   B:  %   +++++   TRANSMITTER    +++++
%   ---------------------------------------------
%   1.  Generate 1 x 64 vector of data points phase representations
data_source = randsrc(1, no_of_data_points, 0:M-1);
figure(1)
stem(data_source); grid on; xlabel('data points'); ylabel('transmitted data phase
representation')
title('Transmitted Data "O"')
%   2.  Perform QPSK modulation
qpsk_modulated_data = pskmod(data_source, M);
scatterplot(qpsk_modulated_data);title('qpsk modulated transmitted data')
%   3.  Do IFFT on each block
%   Make the serial stream a matrix where each column represents a pre-OFDM
%   block (w/o cyclic prefixing)
%   First: Find out the number of colums that will exist after reshaping
num_cols=length(qpsk_modulated_data)/block_size;
data_matrix = reshape(qpsk_modulated_data, block_size, num_cols);

%   Second: Create empty matix to put the IFFT'd data
cp_start = block_size-cp_len;
cp_end = block_size;

%   Third: Operate columnwise & do CP
for i=1:num_cols,
    ifft_data_matrix(:,i) = ifft((data_matrix(:,i)),no_of_ifft_points);
    %   Compute and append Cyclic Prefix
    for j=1:cp_len,
       actual_cp(j,i) = ifft_data_matrix(j+cp_start,i);
    end
    %   Append the CP to the existing block to create the actual OFDM block
    ifft_data(:,i) = vertcat(actual_cp(:,i),ifft_data_matrix(:,i));
end

%   4.  Convert to serial stream for transmission
[rows_ifft_data cols_ifft_data]=size(ifft_data);
len_ofdm_data = rows_ifft_data*cols_ifft_data;

%   Actual OFDM signal to be transmitted
ofdm_signal = reshape(ifft_data, 1, len_ofdm_data);
figure(3)
plot(real(ofdm_signal)); xlabel('Time'); ylabel('Amplitude');
title('OFDM Signal');grid on;
%   ------------------------------------------
%   E:  %   +++++   RECEIVER    +++++
%   ------------------------------------------
%   1.  Pass the ofdm signal through the channel
recvd_signal = ofdm_signal;

%   4.  Convert Data back to "parallel" form to perform FFT
recvd_signal_matrix = reshape(recvd_signal,rows_ifft_data, cols_ifft_data);
%   5.  Remove CP
recvd_signal_matrix(1:cp_len,:)=[];
%   6.  Perform FFT
for i=1:cols_ifft_data,
    fft_data_matrix(:,i) = fft(recvd_signal_matrix(:,i),no_of_fft_points);
end
%   7.  Convert to serial stream
recvd_serial_data = reshape(fft_data_matrix, 1,(block_size*num_cols));
%   8.  Demodulate the data
qpsk_demodulated_data = pskdemod(recvd_serial_data,M);
scatterplot(qpsk_modulated_data);title('qpsk modulated received data')
```

Annex 2

```
%==============================================================================
% The mfile investigates the generation, transmission and reception of
% the OFDM signal without channel noise or HPA effect Written By: Baher Mohamed
%==============================================================================
clear; clc; close;
%   ---------------
%   A: Setting Parameters
%   ---------------
M = 4;                          %   QPSK signal constellation
no_of_data_points = 64;        %   have 64 data points
block_size = 8;                 %   size of each ofdm block
cp_len = ceil(0.1*block_size);  %   length of cyclic prefix
no_of_ifft_points = block_size;           %   8 points for the FFT/IFFT
no_of_fft_points = block_size;
%   ---------------------------------------------
%   B:  %   +++++   TRANSMITTER    +++++
%   ---------------------------------------------
%   1.  Generate 1 x 64 vector of data points phase representations
data_source = randsrc(1, no_of_data_points, 0:M-1);
figure(1)
stem(data_source); grid on; xlabel('data points'); ylabel('transmitted data phase
representation')
title('Transmitted Data "O"')
%   2.  Perform QPSK modulation
qpsk_modulated_data = pskmod(data_source, M);
scatterplot(qpsk_modulated_data);title('qpsk modulated transmitted data')
%   3.  Do IFFT on each block
%   Make the serial stream a matrix where each column represents a pre-OFDM
%   block (w/o cyclic prefixing)
%   First: Find out the number of colums that will exist after reshaping
num_cols=length(qpsk_modulated_data)/block_size;
data_matrix = reshape(qpsk_modulated_data, block_size, num_cols);

%   Second: Create empty matix to put the IFFT'd data
cp_start = block_size-cp_len;
cp_end = block_size;

%   Third: Operate columnwise & do CP
for i=1:num_cols,
    ifft_data_matrix(:,i) = ifft((data_matrix(:,i)),no_of_ifft_points);
    %   Compute and append Cyclic Prefix
    for j=1:cp_len,
       actual_cp(j,i) = ifft_data_matrix(j+cp_start,i);
    end
    %   Append the CP to the existing block to create the actual OFDM block
    ifft_data(:,i) = vertcat(actual_cp(:,i),ifft_data_matrix(:,i));
end

%   4.  Convert to serial stream for transmission
[rows_ifft_data, cols_ifft_data]=size(ifft_data);
len_ofdm_data = rows_ifft_data*cols_ifft_data;

%   Actual OFDM signal to be transmitted
ofdm_signal = reshape(ifft_data, 1, len_ofdm_data);
```