NOVA SCHOOL OF
SCIENCE & TECHNOLOGY

MEEC/MIEEC

Analog Integrated Circuits

Analysis and design of a reference voltage buffer for an ADC

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single tone e musica

3 Digital Communication

For this section two Quadrature Amplitude Modulation (QAM) techniques were used, **Quadrature Phase-Shift Keying (QPSK)** and **16-QAM**. This process involved generating a random stream of bits, modulating them into **QPSK** and **16-QAM** symbols and simulating their transmission through GNU Radio. In the simulation the effects of non-linear Power Amplifier (PA) and Low Noise Amplifier (LNA) were simulated as well as the noise of a Additive White Gaussian Noise (AWGN) channel.

3.1 Digital Modulation

QPSK places four equally spaced points on the unit circle:

$$s_k = e^{j\frac{\pi}{2}\left(k+\frac{1}{2}\right)}, \qquad k \in \{0, 1, 2, 3\}.$$

Figure 1a, shows the mapping in the cartesian plane.

The mapper groups the encoded bit stream into two-bit tuples (b_1, b_0), converts each tuple to an integer index ($k = 2b_1 + b_0$) and outputs s_k.

The theoretical bit-error probability for QPSK in an AWGN channel is given by Equation 1.

$$P_b^{\text{QPSK}} = Q\left(\sqrt{2\frac{E_b}{N_0}}\right) \quad [1] \tag{1}$$

For **QPSK**, demodulation is performed by simply de-mapping the bit values.

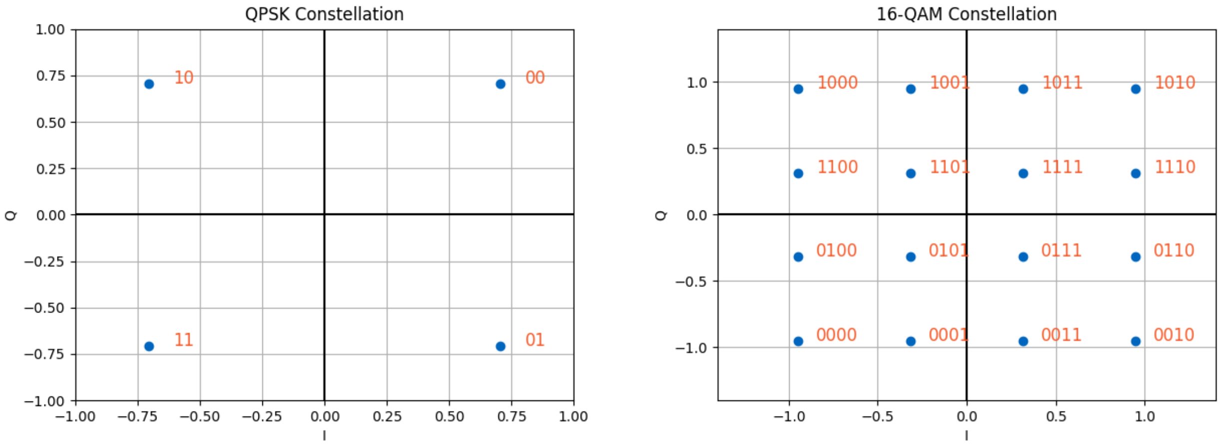
With **16-QAM** a 4×4 square constellation was used. What changes comparing to the previous mapping approach is the fact that the amplitude also changes and for this specific mapping the phase and amplitude will not change consistently. The symbol position in the cartesian frame will be:

$$I, R \in \{\pm 3,\ \pm 1\}$$

For **16-QAM** the theoretical **BER** for an AWGN channel with gray mapping is given by Equation 2.

$$P_b^{\text{16QAM}} \approx \frac{3}{4} \cdot Q\left(\sqrt{\frac{4}{5}\frac{E_b}{N_0}}\right) \quad [1] \tag{2}$$

The constellation points are labelled with *Gray coding*, thus every nearest neighbour differs in *exactly one* bit, this will minimize **BER**, since the most likely symbol error produces only one wrong bit. Figure 1b, shows how the codes are mapped.



(a) QPSK Constellation. **(b)** 16-QAM Constellation.

Figure 1: Digital Modulation Constellations.

3.2 GNU Radio Implementation

The GNU Radio design aims to simulate an RF (radio frequency) QAM communication between a transmitter and a receiver through an AWGN channel. This simulation also includes non linear elements from the power amplifiers used in these circuits [Fig.7], and channel imperfections, such as signal attenuatin that occurs in the channel [Fig.6].

3.2.1 IQ Modulation

The transmitter modulates two different signals effectivly transfering the original signals from the original baseband to the channel frequency (Fc). These signals are modulated with a 90° angle phase shift between them [Fig.2 and 3]. This means the modulated signals are in quadrature with each other, thus allowing the transmitter to transmit both signals at the same time without them interfering with each other.

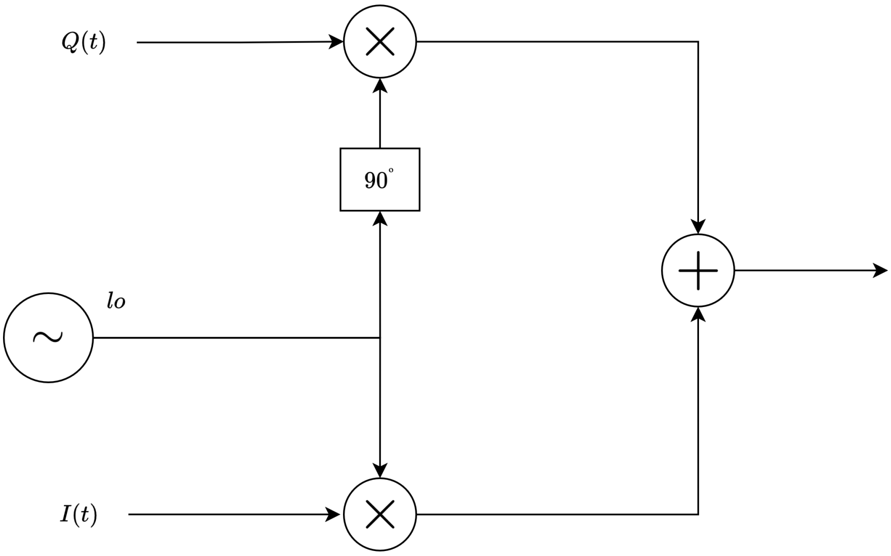


Figure 2: IQ Modulator Block Diagram

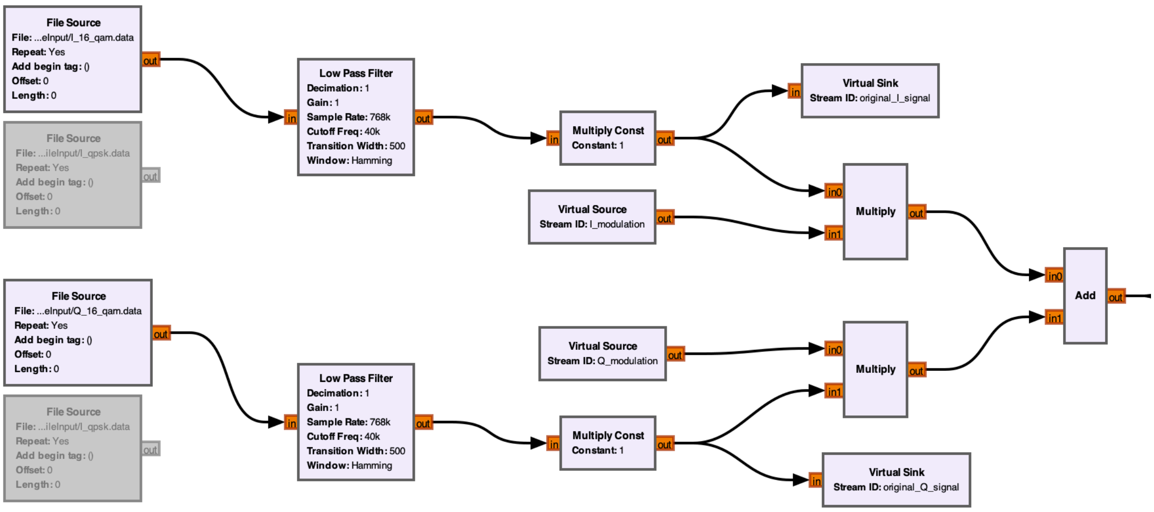


Figure 3: GNU IQ Modulator

On the receiver's side, the same method is applied to demodulate the received signal and recover both the original signals, [Fig.4 and 5].

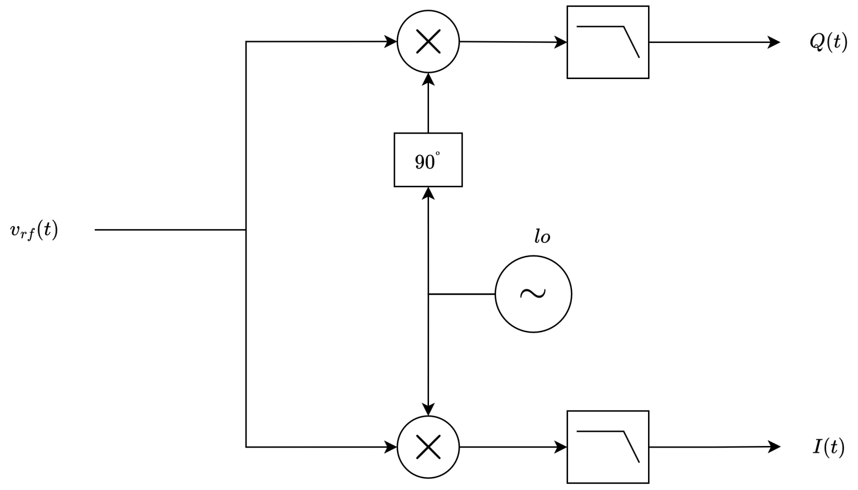


Figure 4: IQ De-Modulator Block Diagram

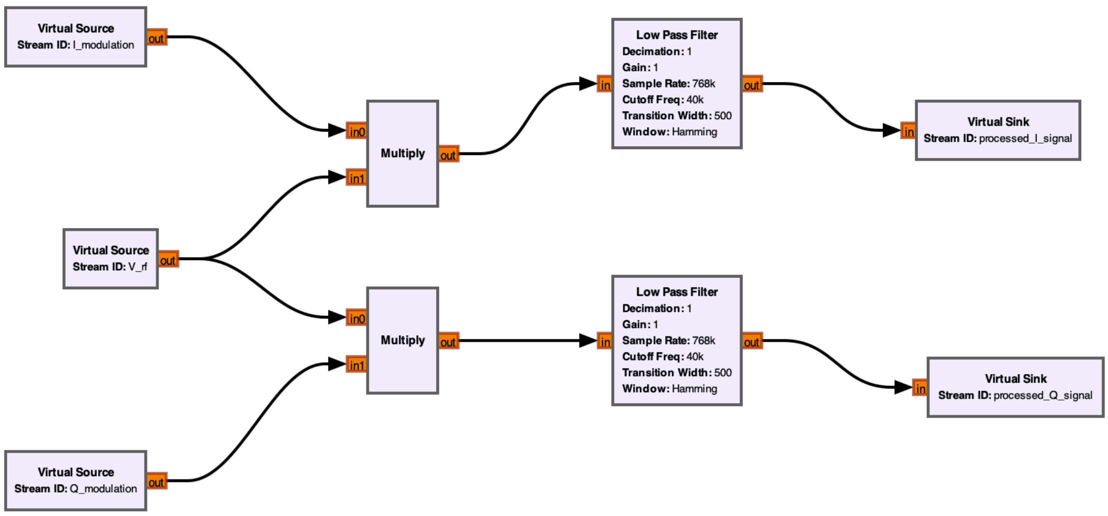


Figure 5: GNU IQ De-Modulator

Since the received signals are in quadrature with each other demodulating them with the same signal used on the transmitter, (a signal with the same frequency and pahse as used in the transmitter to modulate), the original signal is recovered.

3.2.2 Nonideal simulation elements

Arranjar outro titulo e texto a explicar 3 ordem de nao lin, limitacoes que vao apararecer e dizer que pro lNA é mais do mesmo

The cahnnel used for RF communications, in the real world, attenuates the transmitted signal and adds some white noise as well.

These effects are replicated in the simulation using a constant value multiplier in the channel with a constant value smaller than 1, and a adding a the transmitted signal to a signal produced by the signal generated by a white noise source, [Fig.6].

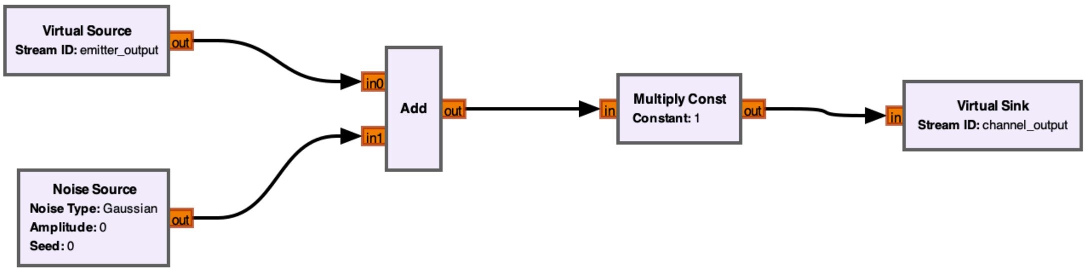


Figure 6: GNU Radio Channel

Dizer que o noise é adicionado antes da atenuaçao para manter o SNR mais facil de quantificar

To counteract the undesired effects of the channel an amplifier is introduced, both in the transmitter and the receiver.

Idealy these amplifiers would provide a linear gain to the signal, however the components used to create these amplifiers are ideal, in which case, the real amplifiers add a nonlinear component the signal gain.

Assuming the gain of these amplifiers can be expressed as a function of the input signal, then the output of these amplifiers can be described as $y(t) = Amp(x(t))$, then using taylor series' the output can be approximated to the result fo Equation 3.

$$y(t) = \sum_{n=1}^{\infty} \frac{\partial^n Amp(x_0)}{\partial x^n \cdot n} \cdot (x - x_0)^n \leftrightarrow y(t) \approx a_1 x(t) + a_2 x(t)^2 + a_3 x(t)^3 \tag{3}$$

Where x_0 is the dc operating point voltage of the input, was set to 0 to simplify calculations, a_n is the value of the nth derivative in respect to $x(t)$ evaluated at $x(t) = 0$ divided by the number of derivates taken.

To simplify the GNU Radio schematic only the 3 higher order Taylor series' components were used, these are also the most influencial components in the real circuit. The GNU Radio circuit is shown in Figure 7.

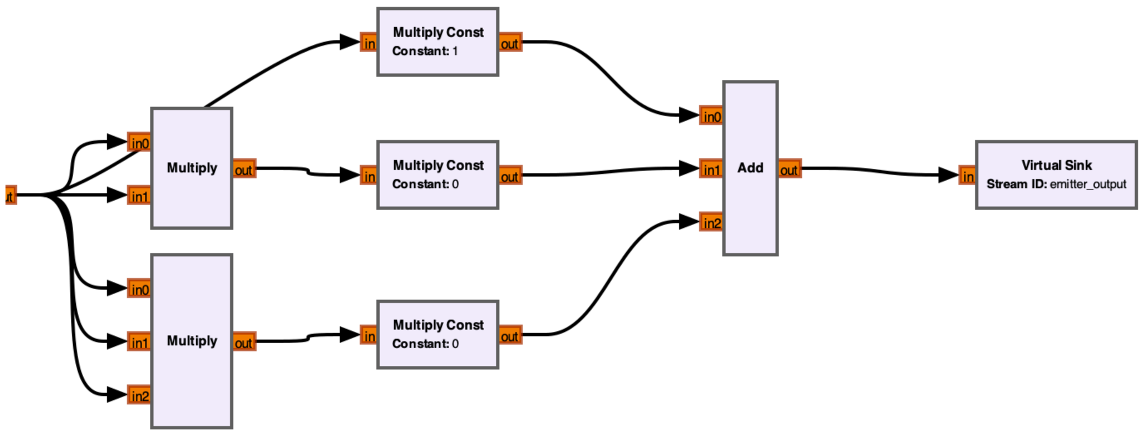


Figure 7: GNU Radio PA non Linear

3.3 Performance Analysis

The primary goal was to evaluate the system's performance by measuring the Bit Error Rate (BER) as a function of the Signal-to-Noise Ratio (SNR) in an AWGN channel.

A random bitstream of 3×10^6 bits was generated using `Gen_symbs.py` Meter cite aos anexos?. This stream was modulated and fed into the GNU Radio simulation. At the receiver, the `Read_Output.py` script was used to read the output files and calculate BER.

Finally with BER values were plotted against the theoretical performance curves, Equations 1 and 2, for both modulation schemes. As shown in Figure 8, in this figure there were no non-linear effects simulated.

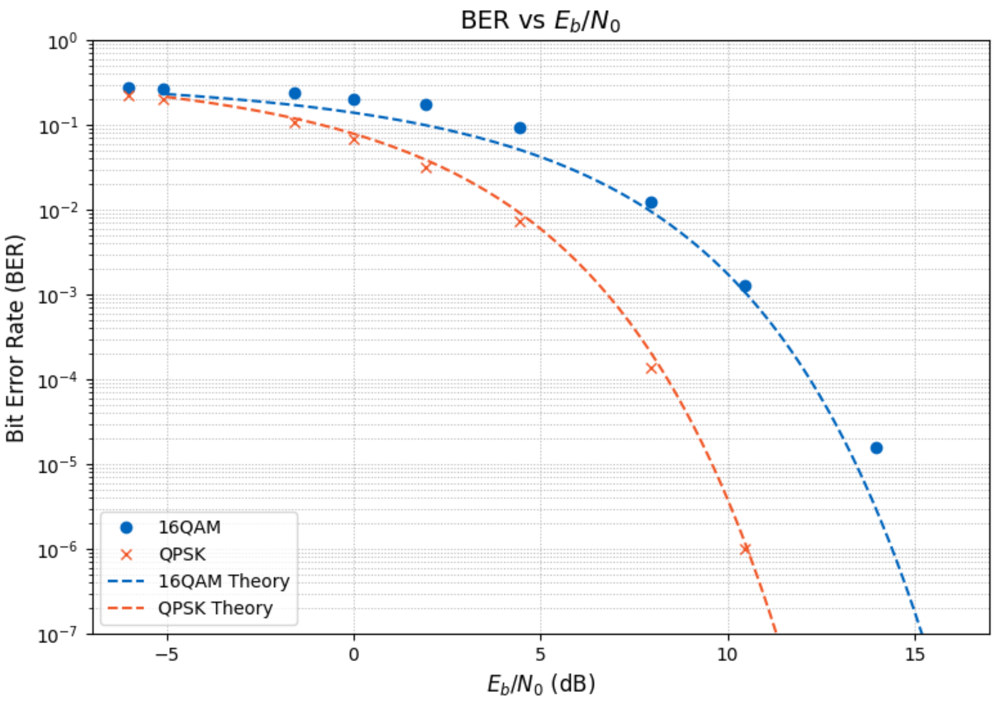


Figure 8: BER vs E_b/N_0

The results in Figure 8 clearly validate our simulation.

QPSK BER points (shown in orange) align almost perfectly with the theoretical QPSK performance curve. This confirms that the simulation chain, including the noise model and demodulator, is functioning correctly.

16-QAM similarly, the simulated 16-QAM data (in Blue) closely follows its theoretical curve.

4 SPICE simulation results and analysis

5 VNA measurements and impedance transformation discussion

This section details the practical experiments conducted with the Vector Network Analyzer (VNA) and the assembly and testing of a Radio-Frequency Front-End (RFFE) receiver.

5.1 Impedance transformation with an L-Match network

The L-Match network is a simple and effective way to match a source impedance to a load impedance using two reactive components, typically an inductor and a capacitor. In this section, we will analyze the performance of an L-Match network designed to match a source impedance of $Z_0 = 50\Omega$ to a load impedance of $Z_L = 200\Omega$, as shown in Figure 9.

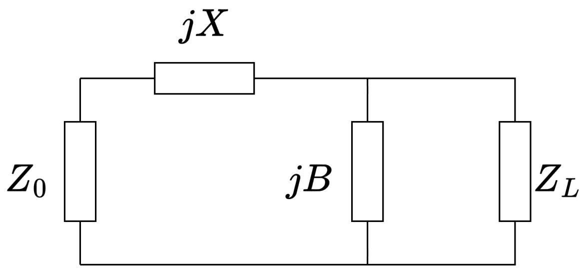


Figure 9: L-Match Network for Impedance Transformation

5.1.1 Theoretical Demonstration

The L-Match network shown in Figure 9 is designed to transform a load impedance Z_L into a desired input impedance Z_0.

The total input impedance Z_0 is the sum of the series reactance jX and the impedance of the parallel combination of Z_L and jB [2]:

$$Z_0 = jX + (Z_L \parallel jB)$$

The impedance of the parallel portion (Z_p) is:

$$Z_p = \frac{Z_L \cdot (jB)}{Z_L + jB}$$

To simplify, we can rationalize this expression:

$$Z_p = \left(\frac{jBZ_L}{Z_L + jB}\right) \cdot \left(\frac{Z_L - jB}{Z_L - jB}\right) = \frac{jBZ_L^2 + B^2 Z_L}{Z_L^2 + B^2}$$

Separating the real (R_p') and imaginary (X_p') parts of Z_p:

$$Z_p = \underbrace{\left(\frac{Z_L B^2}{Z_L^2 + B^2}\right)}_{R_p'} + j \underbrace{\left(\frac{Z_L^2 B}{Z_L^2 + B^2}\right)}_{X_p'}$$

Now, substitute this back into the equation for Z_0:

$$Z_0 = R_p' + jX_p' + jX_A = \left(\frac{Z_L B^2}{Z_L^2 + B^2}\right) + j\left(X + \frac{Z_L^2 B}{Z_L^2 + B^2}\right)$$

For a perfect impedance match, Z_0 must be purely resistive and equal to R_{in} (e.g., 50Ω). This imposes two conditions:

1. **Real Part:** The real part of Z_0 must equal R_{in}.

$$Z_0 = \frac{Z_L B^2}{Z_L^2 + B^2}$$

2. **Imaginary Part:** The imaginary part of Z_0 must be zero.

$$X + \frac{Z_L^2 B}{Z_L^2 + B^2} = 0 \implies X = -\left(\frac{Z_L^2 B}{Z_L^2 + B^2}\right)$$

These equations demonstrate that by choosing appropriate values for X and B, the transformation is possible. Condition 2 shows that X and B must have opposite signs (one must be an inductor, the other a capacitor) for the reactances to cancel, leaving a purely resistive input.

5.1.2 Design Example and Quality Factor

6 RFFE experiment setup, results, and analysis

7 Conclusions

References

[1] P. Montezuma, "Transmissão de alta capacidade - topics," 2025, departamento de Engenharia Eletrotécnica, Universidade Nova de Lisboa, FCT.

[2] G. Gonzalez, *Microwave Transistor Amplifiers: Analysis and Design*, 2nd ed. Prentice Hall, 1997.