MCC125 - Wireless link project
Final report

Walkie-talkies
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2022–01–16

Abstract

In this report a wireless communication project is described. The project aims to create a wireless link between a transmitter and receiver at a distance of 100 m at 2.4 GHz using 16-QAM and QPSK. The project contains two parts software (SW) and hardware (HW) which are then merged into a complete communication system. In Table 1 the results for the project is shown.

Table 1: Results for project.

	QPSK	16-QAM	16-QAM
Symbol rate	50000	12500	40000
Number of symbols	492	548	646
Bit errors	0	0	18

Contents

1 Introduction

This report covers the construction and the derived results of the simplex wireless communication project. The system is designed to operate at QPSK and 16-QAM, with a bit rate of 50 kbps and two different carrier frequencies for transmitter and receiver. The report will start with the link budget, then the hardware design after that the software design followed by the result. Lastly, the report will present the performance of the system and some summarizing conclusions.

2 Link budget

2.1 Software Design

The system is designed to operate at QPSK and 16-QAM. The transmitted message is a text message using a bit rate, R_b, of 50 Kbps making the symbol rate,R_s, 25 KHz for QPSK and 12.5 KHz when using 16-QAM. The sampling rate, f_s, is 1.56 MHz and the bandwidth, B, is 781250 KHz. Assuming a maximum bit error rate of $BER = 10^{-5}$ requires a $SNR = 19.2$ dB for QPSK and a $SNR = 38.4$ dB for 16-QAM respectively according to equation (1), where E_b is bit energy, N_0 is noise power.

$$SNR = \frac{E_b}{N_0} \cdot \frac{R_b}{B}. \tag{1}$$

In Table 2 the result of the SNR calculations are shown.

Table 2: Modulation parameters with QPSK and 16-QAM.

Modulation	Eb/N_0	Rb/B	SNR **[dB]**
QPSK	9.6	2	19.2
16-QAM	13.4	4	38.4

2.2 Hardware Design

2.2.1 Transmitter

The transmitter is designed as shown in the Figure 1.

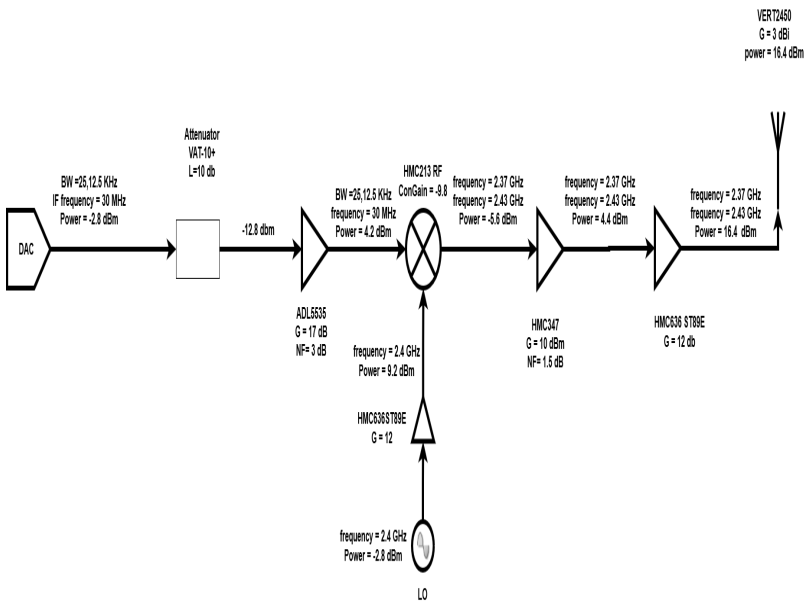

Figure 1: Transmitter Block Diagram

The specifications of the transmitter elements @2.4 GHz@+25C are shown in the Table 3. The calculated gain delivered by the transmitter is 19.2 dB with an output power of 16.4 dBm.

Table 3: Transmitter Block Elements.

Elements	**Input Power (dBm)**	**Output Power (dBm)**	**Gain (dB)**	**Noise Figure (dB)**	**Input P1dB (dBm)**
USRP Transm (N210)	-	-2.8	-	-	-
Attenuator: (VAT-10+)	-2.8	-12.8	-10	-	-
Power Amplifier -1: (ADL5535)	-12.8	4.2	17	3	8
Mixer: (HMC213 RF)	4.2	-4.6	-9.8	5	9
Power Amplifier - 2: (HMC347)	-5.6	4.4	10	3	8
Power Amplifier - 3: (HMC636ST89E)	4.4	16.4	12	3	22

2.2.2 Free space propagation

In equation (2) the distance (d) is 100 meters, it is considered a short distance where the attenuation can be neglected and therefore there will only be free space loss. The free space loss, according to equation (2), is depending on the frequency and antenna gain G_t and G_r. For both the transmitter and the receiver an antenna (VERT2450) with 3 dBi gain is used.

$$
\begin{aligned}
&FSPL = 20 \cdot log_{10}(d) + 20 \cdot log_{10}(f) + 20 \cdot log_{10}\left(\frac{4\pi}{C}\right) - G_{Tx} - G_{Rx} \\
&FSPL = 74 \quad dB
\end{aligned}
\tag{2}
$$

2.2.3 Receiver

The specifications of the Receiver elements @2.4 GHz@+25C are shown in the Table 4.

Table 4: Receiver Block Elements.

Elements	**Input Power (dBm)**	**Output Power (dBm)**	**Gain (dB)**	**Noise figure (dB)**
Bandpass filter: VBF2435+	-57.6	-59.5	-1.9	-
Low Noise Amplifier: HMC374E	-59.5	-49.5	10	1.5
Mixer HMC213 IF	-49.5	-59.5	-10	5
Power Amplifier ADL5535	-59.5	-42.5	17	3
Power Amplifier ADL5535	-44.5	-25.5	17	3
Low-pass Filter SBLP-39+	-29.5	-27.5	-2	2

The receiver is designed as shown in the Figure 2. The noise figure of receiver is 4 dB, calculated in Eq.(3) with a total gain of 30.1 dB.

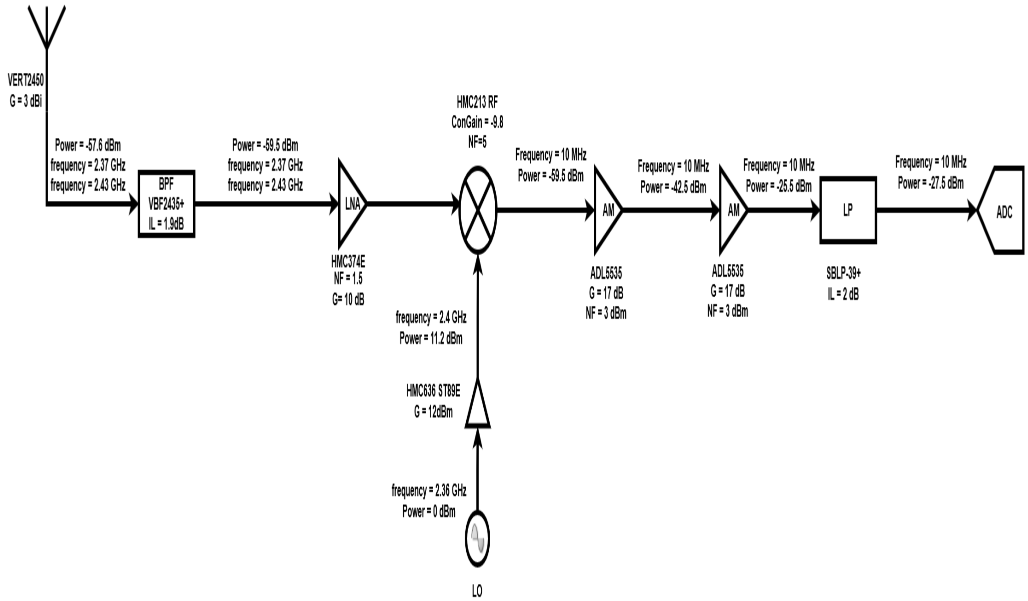

Figure 2: Receiver Block Diagram

2.2.4 Receiver calculation

Noise figure (NF), gain (Gain) and 1 dB compression point (P_{1dB}) are calculated as the equations (3), (4) and (5), where n_{f1}, n_{f2} and n_{f3} are the noise figures and $Gain_1$, $Gain_2$ and $Gain_3$ are the gains of the first three blocks in the receiver. P_{1dB} is the 1 dB compression point of the first three blocks of the receiver.

$$NF = 10 \cdot log_{10}\Big(n_{f1} + \frac{n_{f2}-1}{Gain_1} + \frac{n_{f3}-1}{Gain_1 \cdot Gain_2}\Big)\bar{4} \quad dB\ (for\ first\ 3\ stages) \tag{3}$$

$$Gain = Gain_1 + Gain_2 + Gain_3 = 28.3 \quad dB \tag{4}$$

$$P_{1dB} = 10 \cdot log_{10}\Big(\frac{1}{p_{1dB1} \cdot Gain_2 \cdot Gain_3} + \frac{1}{p_{1dB2} \cdot Gain_3} + \frac{1}{p_{1dB3}}^{-1}\Big) = 4.8 \quad dBm \tag{5}$$

2.3 Frequency

The frequency of the local oscillator (F_{lo}) is set to 2.4 GHz. The intermediate frequency (F_{IF}) is set to 30 MHz. The transmitted frequency can be calculated as in equation (6), hence, the $F_{RF} = 2.4 \pm 0.03$.

$$F_{RF} = F_{lo} \pm F_{IF} \tag{6}$$

On the receiver side, the frequency of the local oscillator (F_{lo}) is set to 2.37 GHz, the resultant intermediate frequency (F_{IF}) will be 10 MHz.

2.4 Noise Performance

The noise figure (NF) of the receiver is calculated to be 4 dB and the noise floor spectrum of the USRP receiver was measured to be -176 dbm/Hz. The IF signal bandwidth at the receiver is 25 KHz, and 12.5 KHz resulting in noise floor power of -132 dBm and -135 dBm respectively. By adding the noise figure of 4 dB the input noise power is -128 dBm and -131 dBm at the receiver input, which implies that the minimum detectable signal needs to be larger than those values, for detection of the QPSK and 16-QAM signals. The needed SNR is 19.2 dB and 38.4 dB, which means the signal power at the USRP receiver input should be -112.8 dBm and -96 dBm, compared with the receiver expected output level of -27.6 dBm, there will be around 70 dB of margin.

3 Hardware PCB

The PCBs are designed in Keysight ADS Layout Editor on a PCB with a 1mm thick FR4 dielectric with a dielectric constant of 4.4 and dissipation factor of 0.017. The DC Lines are made 0.7mm thick in order to make sure the lines are tolerant to high currents while all the width of all RF lines is calculated to have an impedance of 50 Ohm at 2.4 GHz using LineCalc tool in ADS. The foot prints are generated in ADS for each component based on the CAD drawing from respective datasheets. Extra pads for capacitor are added close to the RF line right after the RF choke (inductor) to block the higher frequencies entering DC lines and then having a feedback effect causing oscillations.
In Figure 3 and 4 the PCB for the transmitter is shown and in Figure 5 and 6 the receiver PCB design is shown.

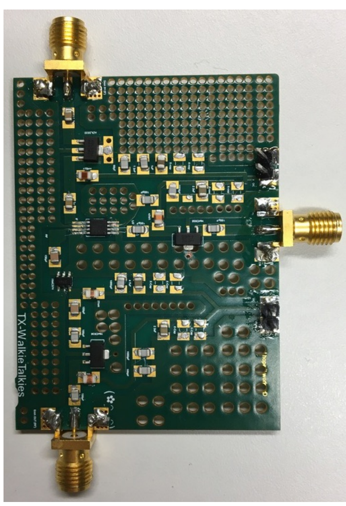

Figure 3: Transmitter PCB.

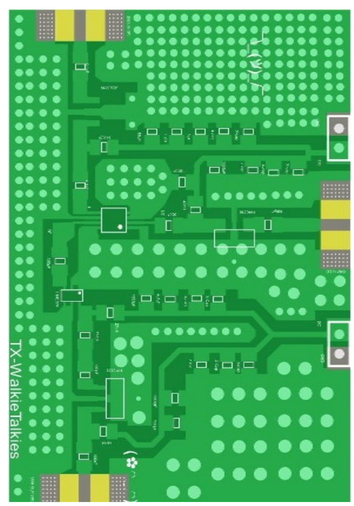

Figure 4: Transmitter PCB.

The saturation plot between the RF power and output power is plotted for different LO Powers in the figure 7 which shows a fairly linear dependence. The power consumption for the circuits are noted as 1.7W for the receiver and 2.55W for the transmitter.

Figure 5: Receiver PCB.

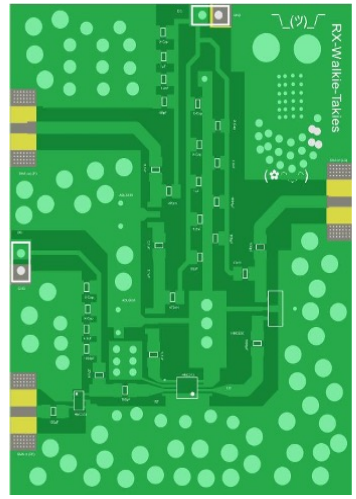

Figure 6: Receiver.

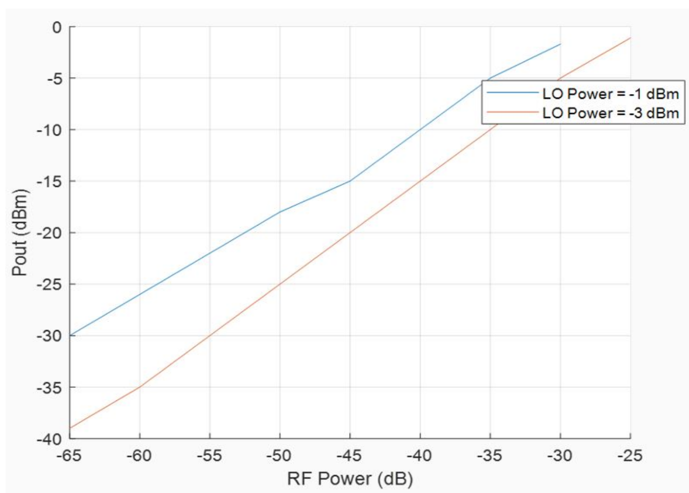

Figure 7: Saturation plot

4 Software

In this section the software for the project is described. All software was coded in Matlab. Table 5 shows the basic parameter used for the software. The system is designed to transmit and receive a text message.

Parameter	**Value**
Sampling Frequency (Fs)	1.56 MHz
Bit Rate (Rb)	50 Kbps
Rollof factor	0.3
Span	4

Table 5: Main parameters for software.

4.1 Transmitter

The structure for the transmitter is shown as a block diagram in figure 8.

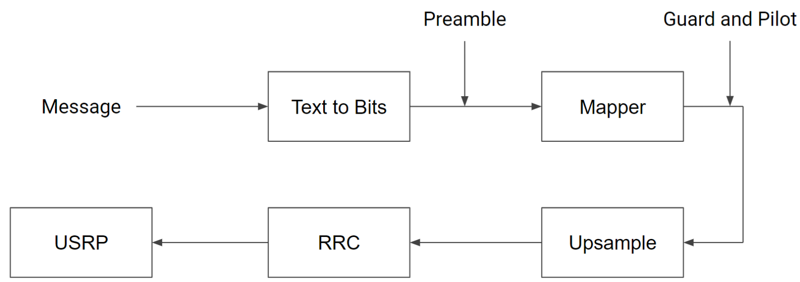

Figure 8: Block diagram for the transmitter.

The first step in the transmitter was to construct the frame, in order to do this the text message is converted to bits. Then a preamble is added and all bits were mapped to the desired modulation constellation. Guard and pilot bits are also added to the message and these added together created the frame. In Table 6 the bits and symbols that are creating the frame are presented depending on the different modulations. The symbol length for the guard, pilot and the preamble were constant for both QPSK and 16-QAM. The message symbols varied depending on what message that is transmitting.

Table 6: Table showing the bits in the frame depending on modulation.

Modulation	Guard bits	Pilot bits	Preamble bits	Message symbols
QPSK	50 zeros	300 ones	100 random bits	Varied
16-QAM	50 zeros	300 ones	200 random bits	Varied

The pilot bits are needed to create a peak in the power spectrum for the signal this is then used for the coarse frequency correction in the receiver. The preamble is used in the receiver for frame detection, frequency- and phase synchronization. The guard is not used in the receiver at the moment, but could be used to create a more complex frequency and phase synchronization. The guard and pilot also prevent interference between the transmitted messages.
The next step in the transmitter is then to upsample the whole frame. The upsampled frame is then filtered through a root raised cosine pulse to give the frame its desired shape. Then the signal is then sent to the USRP.
In Figure 9 and 10 the signal sent to the USRP is shown, both when using QPSK and 16-QAM.

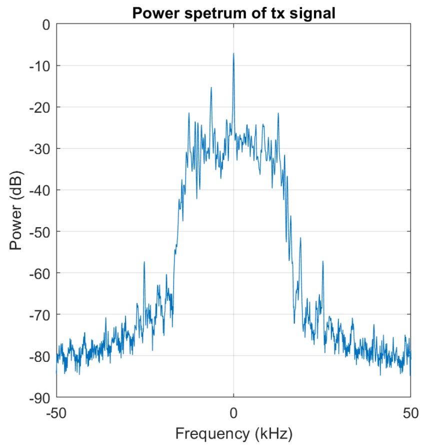

Figure 9: Transmitted signal for QPSK.

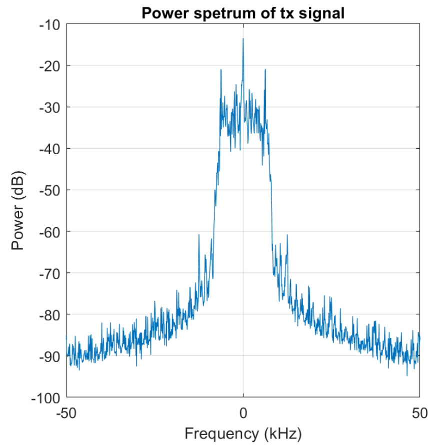

Figure 10: Transmitted signal for 16-QAM.

4.2 Receiver

The structure for the receiver is shown as a block diagram in Figure 11.

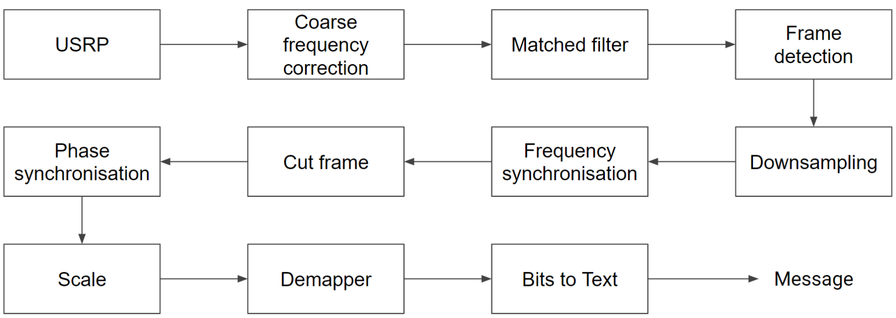

Figure 11: Block diagram for the receiver.

The first step in the receiver after the signal is received from the USRP is to do the coarse frequency correction. This is done by finding the highest peak in the power spectrum and taking the index of that peak to shift the whole signal so the peak is at zero Hz. The power spectrum of the received signal before and after coarse frequency correction is is shown in Figure 12.

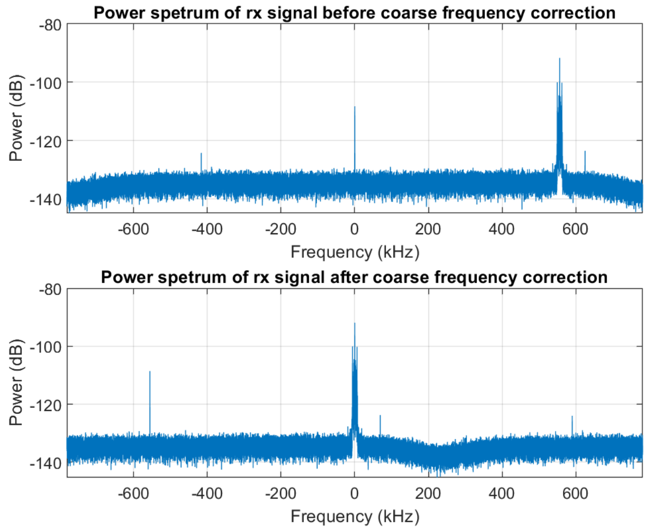

Figure 12: Before and after coarse frequency correction on received signal

The signal is then filtered with a matched filter to reduce the noise. The output of the matched filter is shown in Figure 13.

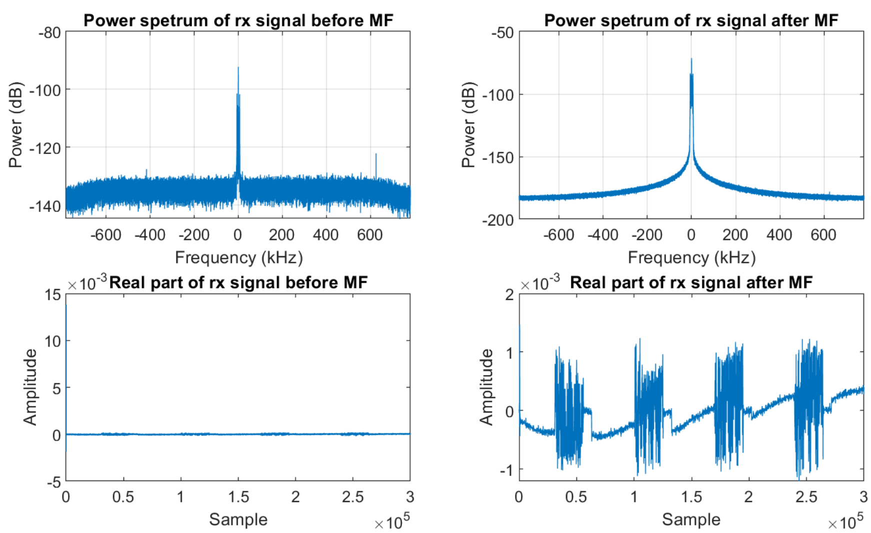

Figure 13: Power spectrum as well as real part of signal before and after matched filter.

The next step in the receiver is to detect the frame. This is done by calculating the correlation between the received and now filtered signal and the transmitted preamble. The highest peak in the correlation correlates to the end of the preamble symbols and therefore the start of the message.

When this point is found, the whole frame can be detected and cut from the signal. The correlation plot and the detected frame can be seen in Figure 14.

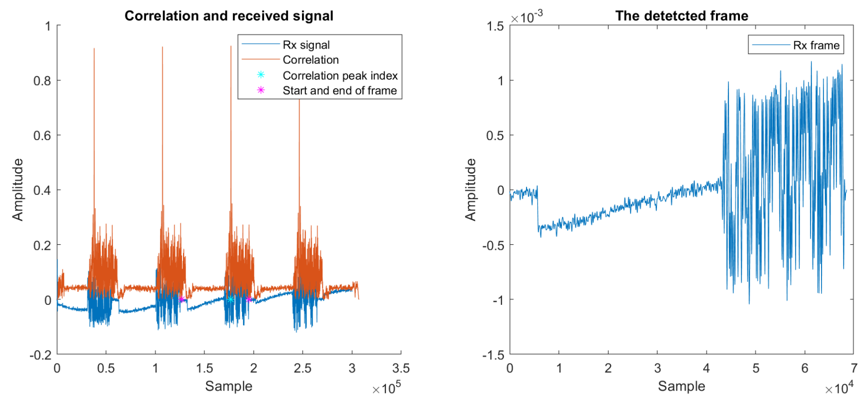

Figure 14: Correlation plot as well as detected frame according to correlation peak.

When the received frame is detected and cut the signal is downsampled which as seen in Figure 15.

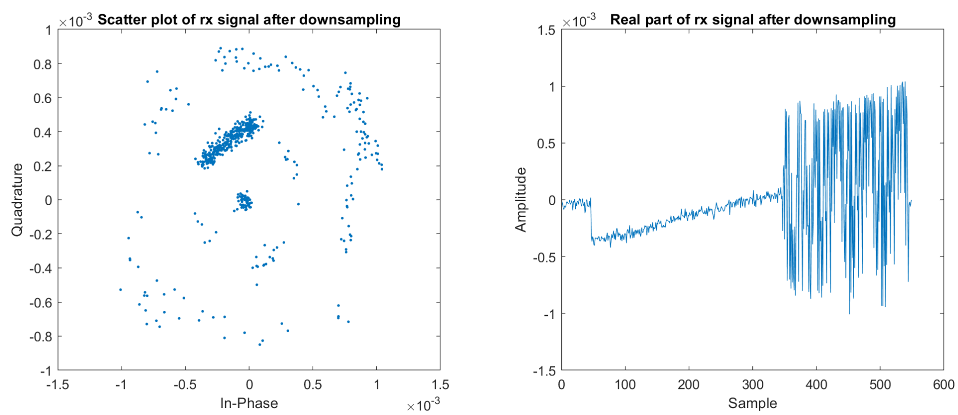

Figure 15: Scatter plot and plot of downsampled frame in real time.

Then the frequency synchronization is made, this was done by calculating the angle difference between the transmitted preamble and the received preamble. The difference is used to do a polynominal curve fitting. This givers us a sloped line where the gradient of the line is used to calculate the frequency shift for each symbol. The result of the frequency synchronization can be seen in Figure 16.

After the frequency synchronization, the preamble and the message are extracted from the frame. This is done by doing a second correlation and repeating the method for frame detection, but now only to extract the preamble and message from the frequency synchronized frame.

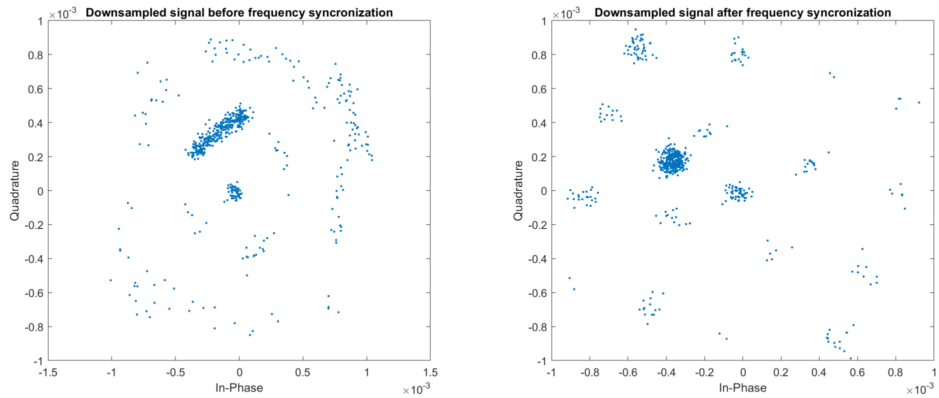

Figure 16: Scatter plot of frame before and after frequency synchronization.

The next step is to do phase synchronization. This is done be repeating the method for frequency synchronization, but with the already frequency synchronized preamble and only using the first value in the polynominal curve fitted line. The phase synchronized message symbols can be seen in Figure 17.

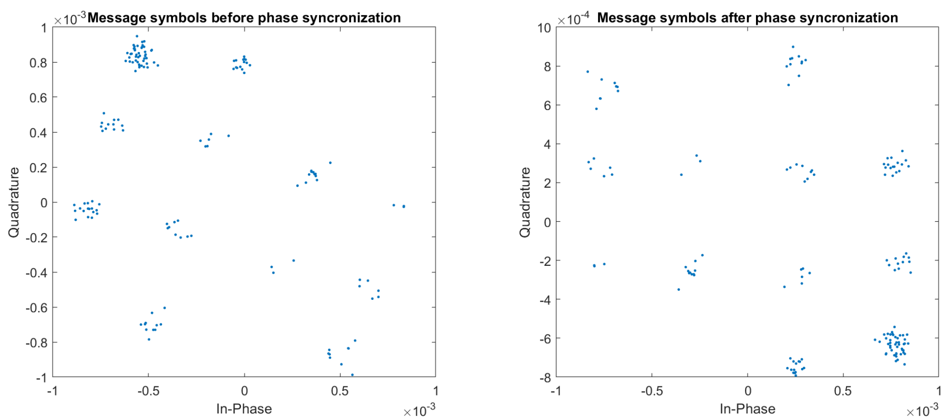

Figure 17: Scatter plot for phase synchronized message symbols.

Then the symbols are scaled to match the amplitude for the modulation constellation. The scaled message symbols can be seen in Figure 18.

The last step in the receiver is to demapp the symbols and convert the bits to text. This text is the received text message.

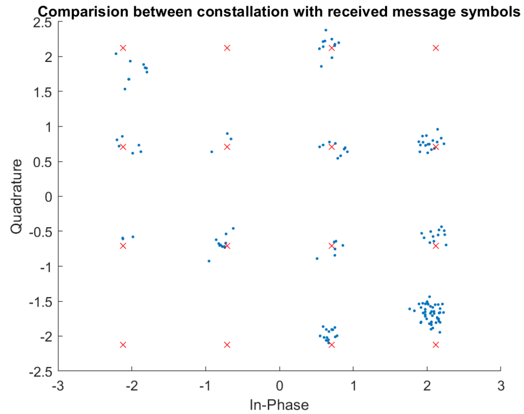

Figure 18: Scatter plot for scaled message symbols.

5 Results and result evaluation

The system has been tested through different stages. First when the transmitter and receiver are connected via cable. Second, a channel with a simulated distance effect was added (-70 dB attenuators) through transmission. Finally, transmission by an antenna through the wireless channel was tested for 1, 50, 100 meters.

Figure 19 show the result for a received 16-QAM modulated message with no errors. For the transmission a symbols rate of 12,5 ksps was used for a 548 symbol long frame. This resulted in 0 bit errors, verifying that the system worked properly.

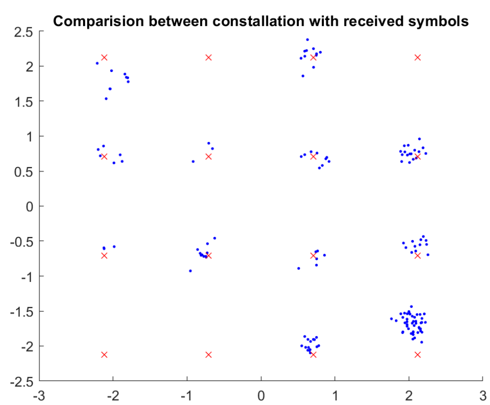

Figure 19: Scatter plot of message symbols for perfect 16-QAM.

To investigate the capacity for the system the symbol rate was increased to 40 ksps and the frame length was extended to 646 symbols. In Figure 20 the scatter plot for the received symbols can be seen. This transmission resulted in 18 bit errors. A possible limit that can be derived from this result is that the system can not handle too long frames, since the the frequency and phase synchronization seemed to be performing worse for longes messages and higher symbol rates. The bit errors were observed at the end of the message which also points to this conclusion being accurate.

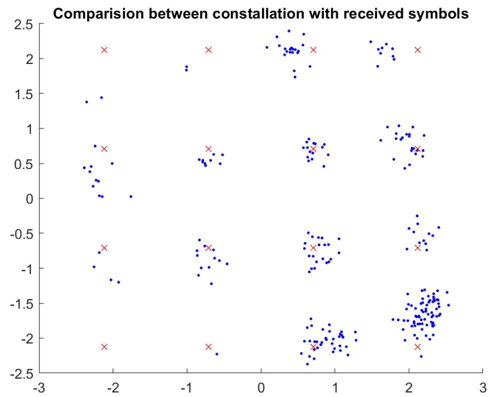

Figure 20: Scatter plot of message symbols for when pushing the limit for 16-QAM.

Next, the system was also tested for QPSK since it is not as sensitive to phase and frequency errors. 892 QPSK symbols were sent with a symbol rate of 50 ksps and was received perfectly. The result can be seen in Figure 21. Unfortunately, when trying to increase the symbol rate further the USRP crashed for some unexpected reason and no further testing was made.

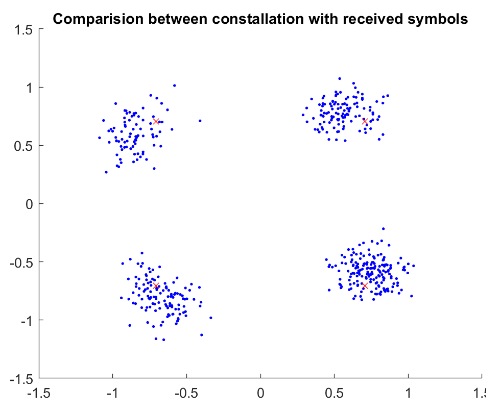

Figure 21: Scatter plot of message symbols for when pushing the limit for QPSK.

6 Deviation, Problems and System Improvment

The system was working as almost as intended compared with the parameters defined in the link budget for 100 meters. However, the achieved result for system has some deviations from the theoretically expected results. The deviation can show in Table 7.

Parameter	**Theoretical results**	**Actual Results**
Symbol Rate (R_s)	12.5 KHz for 16-QAM	40 KHz for 16-QAM
Bit Rate (R_b)	50 Kbps	160 Kbps
Transmitter Power	16 dBm	14 dBm
Transmitter Gain	19.2 dB	15 dB
Receiver Gain	30 dB	20-25 dB

Table 7: Main deviation

6.1 Hardware

The main problems in the system are the oscillations and non-linearity's at the receiver, the transmitter worked with a output power lower than what was intended but with only 2 dB below it is considered within specification. The oscillations in the receiver are coming from the cascaded amplifiers at the IF stage. They mainly appear at frequencies below the IF frequency (10 Mhz), hence by adding more decoupling capacitors to the DC bias line, the oscillations can be suppressed. By injecting a lower power level to the receiver LO (-6dBm) the mixer can work with higher conversion loss. This will reduce the early stage gain or output power of the receiver, and that will make the receiver working with acceptable gain and linearity.
There were difficulties for the link to work over air inside the lab environment, even with smaller distance between the TX and RX antennas, that was mainly due to the multi path, interference, situation and antenna near field operation.

6.2 Software

The main problem in the software is the limited bandwidth, this leads to longer messages not being transmitted correctly. Additionally, the frequency correction does not always work correctly especially if the message is too long. The method of frequency correction can be improved in the future work. Most problems were not detected and resolved at a early stage due to a tight schedule in the course and the need for a functioning system for testing. The focus was on getting the system to work in the best and most efficient way possible but can be improved for a higher performance and more consistent results.

7 Conclusion

The project achieved the set goal by working at a distance of 100 meters at a frequency of 2.4 GHz using QPSK and 16QAM. Because of time constraints, the hardware was not achieving the results that was expected from the hardware design. However the results of the software results were better than the goals set at the beginning.

The major problem with the hardware was caused by human error and the oscillation that added non-linearity to the system and was solved by adding more capacitors at the receiver side and an attenuator at the transmitter side. While the software problems mainly were because of inaccurately correction of frequency shift and phase shit which was solved by finding the slope of the preamble then finding the mean of it rather than finding the deference in the angle of the received preamble with the transmit preamble.

Appendix: Division of work

Hardware

Pavan, and Hozaifa were responsible for the hardware part and worked together to achieve it correctly. The workload was divided into link budget calculation, PCB design, PCB assembly and initial testing and debugging, hardware support for the software group, final Link testing and debugging

Software

Josefine, Haitham, and Oscar were responsible for the software part and worked together to achieve it correctly. The workload was divided into first, individual simulations of the project. Then, test it in the lab out of together out of lab time schedule due to crowded lab at a lab time schedule.

Name	**Hours**
Haitham Babbili	133
Hozaifa Abdelgadir.	119
Josefine Åberg	166
Oscar Wallin	136
Yagnasri Eswarasai Pavankumarreddy Telluri	147

Table 8: Working hours