MCC125 - Wireless Link Project
Group 4
Antennas AB

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This paper aims to describe the development process and key characteristics of a communication system which sends and receives data over 100 m at a frequency of 2.4 GHz using 16-QAM. In order to design, analyze and evaluate such system our different backgrounds were combined for the best resulting HW and SW. Due to timing constraints the achieved results failed to fulfill the theoretically calculated ones, however, the system still functions as intended. One of the major challenges of this project is to make the real-time realization of the system agreeing with its theoretical design. As an example, the design of the physical layout of the HW board was not thoroughly examined, which caused the received signal being excessively oscillated.

I. Introduction

The following report covers the process and obtained results of implementing a one-way wireless communication system. The system was designed to use 16-QAM and achieved a bit rate of 50 kbps when tested. The report firstly presents the link budget calculations and performance of the hardware (HW). This is followed by an overview of the software (SW) realization challenges. Finally, an evaluation and discussion of the performance of the whole system is presented.

II. Link Budget

The first step of the project was to calculate the link budget in order to find suitable components for the design. The system was modeled to work for both QPSK and 16-QAM, to make both solutions a viable option, and with a bit-error rate (BER) of less than 10^{-5}. The smallest signal-to-noise ratio (SNR) to be received for QPSK was 12.6 dB while 16-QAM would require an SNR above 23.6 dB.

A. Transmitter

The block diagram of the transmitter can be seen in fig. 1, where the power levels and frequencies of the signal at different points of the system are marked, as well as the characteristics of the chosen components are listed.

With the hardware available at the lab as reference, namely the USRP, the intermediate frequency, f_{IF}, was set to 20 MHz. The carrier frequency was chosen to be at the 2.4 GHz range, hence the locally oscillated frequency, f_{LO}, was set to 2.4 GHz and 2.44 for the receiver (RX) and transmitter (TX) respectively. The transmitted frequencies, f_{RF}, are as follows 2.44 ± 0.02 GHz.

B. Receiver

The block diagram representing the receiver can be seen in fig. 2. The total noise figure (NF) of the receiver is calculated to be around 6.7 dB. The SNR at the end of the receiver is calculated as equation (1), where N_{in} is the received noise and N_{added} is the noise added by the RX. The SNR, as earlier mentioned, a minimum of 12.6 dB for QPSK and 23.6 for 16-QAM.

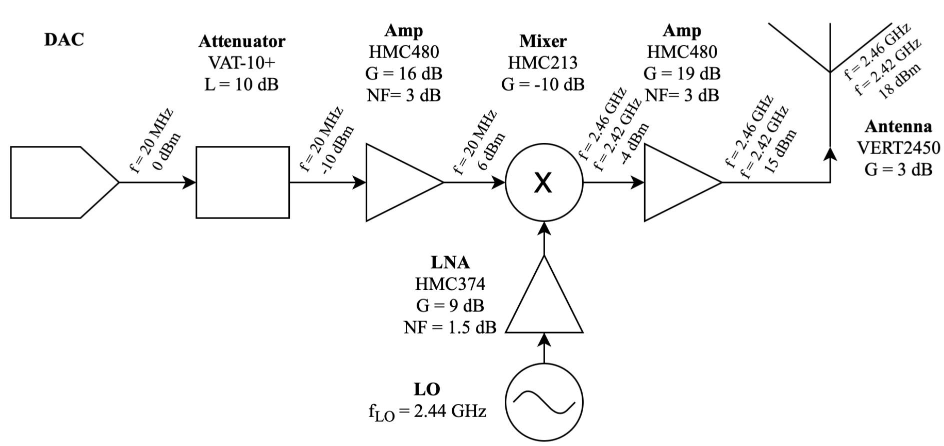

Fig. 1: Block diagram and link budget of TX. The name of the component is below the bold component type, followed by its gain and/or loss. Frequencies and power levels are placed at different nodes in the block diagram.

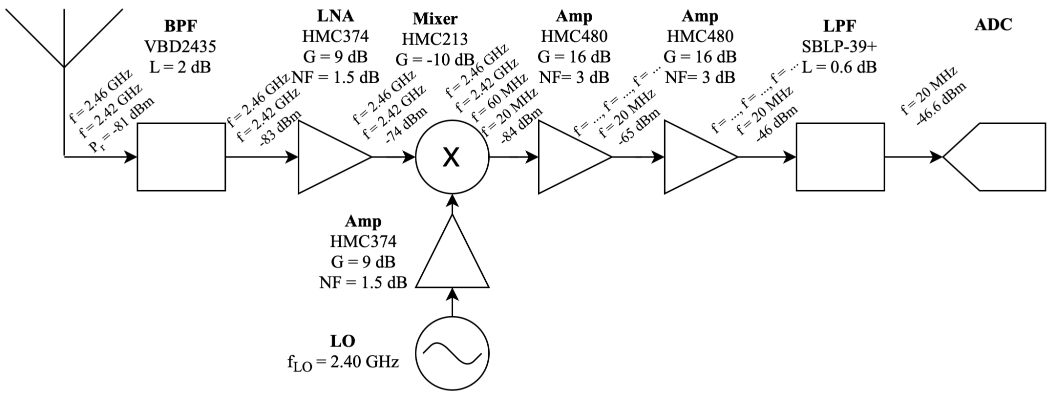

Fig. 2: Block diagram and link budget of RX. The name of the component is below the bold component type, followed by its gain and/or loss. Frequencies and power levels are placed at different nodes in the block diagram.

$$SNR_{out,RX} = \frac{P_r}{N_{in} + N_{added}} \tag{1}$$

The equation (1) can be rewritten in order to find the required received power. Calculating this yields a received power, P_r, of -81 dBm for QPSK and -70 dBm for 16-QAM. The receiver power, including free space loss, can be written as equation 2, where P_t is the transmitted power, G_t and G_r is the gain of the transmitter and receiver antenna respectively, λ is the wavelength and R is the distance between the receiver and transmitter antenna.

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \tag{2}$$

By using equation (2) to find P_t, the transmitted power is estimated to be at least -9.2 dBm using QPSK and 4.37 dBm using 16-QAM. As can be seen in fig 1, the transmitted power in the design is 15 dBm, in order to include some margin.

III. Software

A block diagram depicting the SW can be seen in fig. 3 where the transmitter is shown on top and the receiver at the bottom. The block diagram also includes the USRPs, which perform up-conversion and down-conversion of the signal. The data in table I depicts some noteworthy parameters used in the software design.

TABLE I: Parameters that affected the outcome of the SW.

Parameter	Value
Bitrate	50 kbps
Rolloff factor and span (pulse paramters)	0.3 resp. 4
Bandwidth	42 kHz
Sampling Frequency	15.6 MHz

A. Transmitter

Starting with the TX, the input message is converted from bits to symbols by mapping the data into symbols using a 16-QAM constellation. A preamble (consisting of 16-QAM symbols), a pilot (consisting of ones) and a guard interval (consisting of zeros) is then added prior to the symbols. The whole frame structure is depicted in fig. 4.

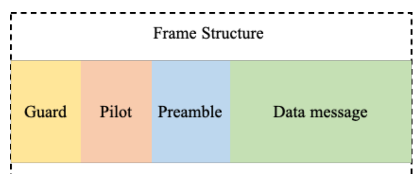

Fig. 4: The structure of one frame.

The frames are then upsampled before being convoluted with a RRC-pulse. The resulting signal's spectrum is shown in fig. 5, which depicts the signal at baseband before being moved to passband (IF frequency) by the USRP.

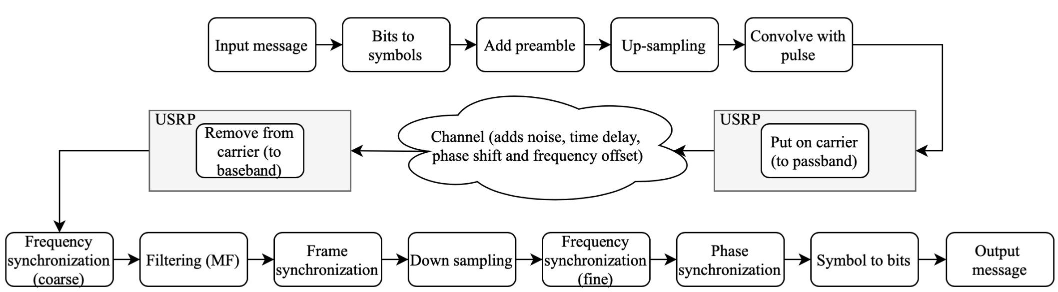

Fig. 3: Block diagram of the SW. The transmitter is depicted on top and the receiver on the bottom. The channel is represented by the cloud.

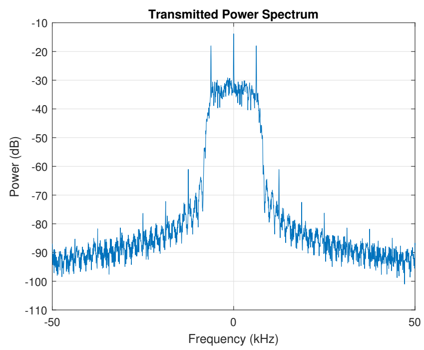

Fig. 5: The shape of the transmitted signal after being upsampled and convoluted with a RRC-pulse, but before moved to IF frequency by the USRP.

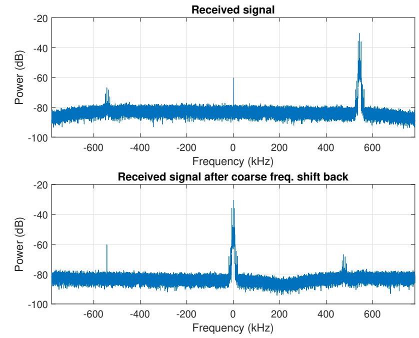

Fig. 7: The received signal before frequency shift (top) and after coarse frequency shift (bottom).

Figure 6 depicts the transmitted signal and as it can be seen from the spectrum analyzer the signal has enough power (around 10 dBm) to be transmitted and well detected at the RX side.

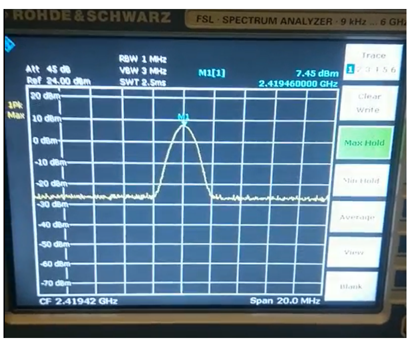

Fig. 6: The transmitted signal displayed via a spectrum analyzer.

B. Receiver

The channel affects the signal in different ways which need to be compensated for by the RX. The first step at the RX is to perform a frequency synchronization in order to mitigate the frequency offset. The received signal before and after frequency synchronization is depicted in fig. 7. The frequency synchronization is done twice in the RX, the first step is a coarse synchronization and the second is a finer synchronization, which is done after frame synchronization and down-sampling. The coarse frequency synchronisation utilizes the fact that the pilot form a dirac pulse in the frequency domain. By making the pilot long enough a distinct peak can be seen and by localizing that maximum in the frequency domain the signal can be found and compensated for accordingly.

When the coarse frequency synchronization has been performed, the signal is filtered through a matched filter (MF) to regain a signal more similar to our original one. The incoming signal consists of multiple frames but only one is needed to extract our data. By correlating the known preamble with the signal, peaks can be found at the start of a frame, as shown in fig. 8. This peak is used for finding and extracting the needed frame from the signal. After performing these two steps, our signal is ready for further processing.

Only peaks in the middle of the signal were analyzed in order to not find a frame with missing data since the too early ones might have lost information at the beginning, and later ones may have lost the end of the frame.

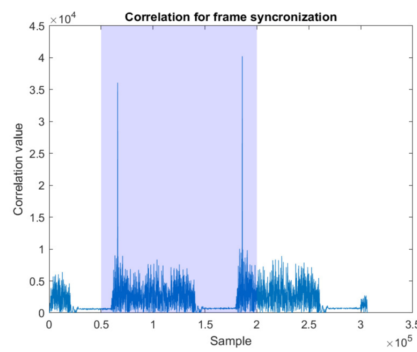

Fig. 8: Correlation between known preamble and multiple frames. A peak is found after correlation with the known preamble. The shaded region shows in which areas we are searching the peaks.

Once a frame has been found it can be down-sampled in order to regain our symbols. By comparing the difference between every consecutive sample we find the minimum difference which indicates the extremum of the signal. After cataloging this information in relevance to each symbol, we find the most occurring positions of these extremum and choose to sample from there. By sampling at the most common position we obtain the maximum opened eye, indicating the SNR of the sample being largest, which is where we want to sample at.

Now the fine frequency synchronization takes place. By correlating the known preamble with the rotated version of the received preamble, the rotated preamble with highest correlation corresponds to the correct frequency offset. Once found, the signal is shifted back accordingly. However, at our link demonstration at 100 m, the coarse was very exact and the fine-tuning did not generate a better image. But to show that our implementation works an older implementation's result from frequency compensation can be seen in fig. 9.

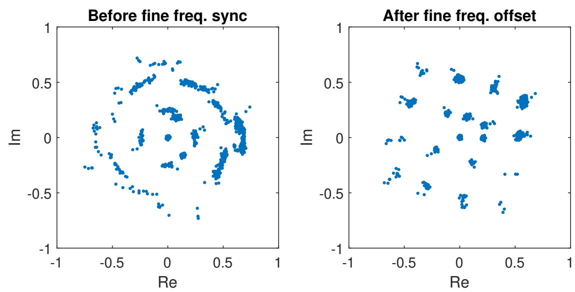

Fig. 9: Comparison between before and after fine frequency offset compensation. Note, this is not from when the final HW design but an earlier implementation where the signal was affected more. However, the principle still stands and this is only shows how the fine frequency compensation works.

The final step before converting symbol to bits is to do phase synchronization. The phase synchronization mitigates the errors by comparing the angular difference between the known preamble and the received preamble, and shifts the constellation accordingly. Finally, the symbols are converted back to bits and the message can be read (see Appendix A).

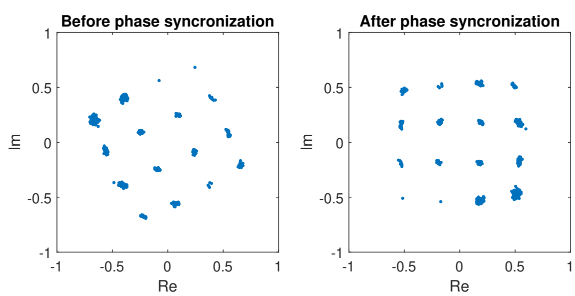

Fig. 10: Comparison between the constellation before and after phase correction.

IV. Performance of System

The performance testing of the system was done through different test cases, first, lab cases: cable and Wireless connections within the lab, and then corridor wireless link cases: starring with 10 m, 50 m and lastly the 100 m wireless connection.

For the final system (demonstration of 100 m), the measured values were presented in table II.

TABLE II: Comparison showing the theoretical values and achieved values of the communication system.

Parameter	Theoretical values	Real system
Bandwidth	23 MHz	42 kHz
Bit rate	92 Mbps	50 kbps
Transmitted power	-9.2 dBm	10 dBm
Received power	-83.7 dBm	-81 dBm
Received SNR	>23.6 dB	24.6 dB
Gain in TX HW	16 dB	14 dB
Gain is RX HW	32 dB	31 dB

V. System Problems and Potential Improvements

The communication system was not without flaws and could be improved in different ways. This section will explore issues which we faced during system realization and also what could be done to improve these issues.

A. Hardware

The PCB design of the TX and RX board can be seen in fig. 11.

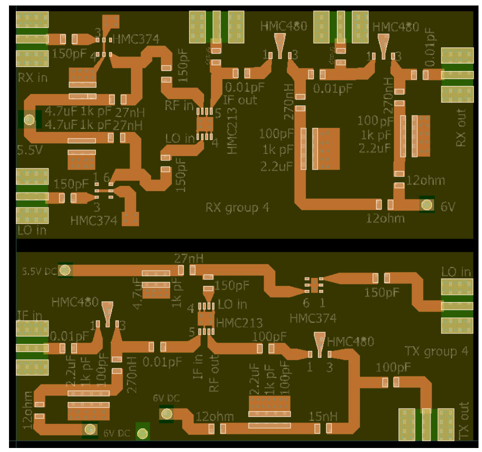

Fig. 11: PCB design with the RX board on top and TX board in the bottom.

One major design constraint was that the voltage bias inputs were not always properly separated by the initial design and instead shared between components, as can be seen in fig.11.

Some amplifiers share voltage bias. This caused oscillation and had to be fixed by cutting the copper in the board and creating separated biases.

A mistake in the same category was that only one ground hole, where the ground pin was to be soldered, was placed on each respective board. In the design depicted in fig. 11 there is no ground hole on the RX board, this was added by the TAs before sending the board to print. This made it difficult to keep the ground properly connected to the board while testing and running it.

For the HMC374 amplifiers on the RX board, the ground holes were not placed directly beneath the amplifiers, as can be seen in fig. 11. It would be a better option to have the ground holes underneath the amplifiers to have the ground closer to the amplifiers, which was done for the HMC374 on the TX board.

Oscillation did also occur due to bias components placed too far from the amplifiers. The inductors and capacitors should be placed closer to the amplifiers to avoid oscillation.

The TX board was not equipped with a debug port. It would have been beneficial to have designed the board to have at least one debug port placed, for example, after the mixer.

For both boards, in general, they should both have been designed smaller. This should be done to keep the connections between signal inputs/outputs short as well as the distance from bias components close to the amplifiers, as earlier mentioned.

Lastly, another error was that the amplifiers for the transmitter were saturated and worked in their 1 dB compression point. This was due to human error, since the PCB was designed to have an attenuator placed after the USRP and before the TX board. This was in some cases forgotten while troubleshooting and testing the system which caused a noisy signal and non-linearity effects.

B. Software

The main issue with our software was the setting of the low bit rate which in turn affected bandwidth. Having such low values did make our frequency shift very small which almost guaranteed a low bit error rate, however the bit rate itself is beneath contempt thus rendering our system impractical for real world usage scenarios with current demands for higher data rate speeds.

Another improvement which can be done is to redesign the data frame. As mentioned before the length of the pilot was relevant to the detection of the signal in the spectrum. It was lengthened to be more visible when the hardware performed worse, but should have been shortened to decrease the redundancy of the data when the hardware worked better. Same goes for the guard interval as it mostly was used for debugging and could have bean removed or shortened since the pilot can give the same result when debugging. Since the correlation of the preamble and our signal was very good we could most likely decrease the length of this one as well.

All these problems would most likely have been noticed and modified if the time schedule was not as tight as it was and the issues with the hardware would be resolved a bit earlier.

VI. Conclusion

The main issue with the hardware was due to the board layout and human error which caused oscillation and added non-linearity to the system. The main issue related to the software was mostly due to faulty parameter setting. We recognize if both parts of the project would have being finished earlier, more testing could have been performed, and hence more improvements and fine tuning would have taken place.

Nonetheless, all of the members of our group have learnt a lot while working on their parts of the project. The knowledge obtained throughout the whole studying process was shared within the team and it turned out to be a beneficial experience in terms of gained theoretical and practical knowledge. Working together in a team to solve a common task is also a valued experience as it is a skill needed in professional life.

VII. acknowledgement

We would like to direct our thanks and gratitude to Prof. Vessin Vassilev and the TAs Parastoo, Ahmed, Husileng and Zonglong for their valuable support and advices through out the project. We wouldn't have made it without your help! Also, we would like to thank our colleagues for the discussions and knowledge sharing during the so many hours we spent in the lab.

Appendix A
Transmitted and received text

'Johnson traveled to Brussels on Wednesday for dinner with European Commission President Ursula von der Leyen. But the last-ditch effort failed to produce a breakthrough on thorny issues including fishing rights, government aid for companies and how disputes would be settled.'

Appendix B
Division of work

Hardware

Boyang, Simon and Mohamed have been responsible for the HW part during the project. Boyang did the initial link budget calculations and re-works of the link budget. The link budget was also discussed on Zoom-meetings by all HW group members. The PCB design was done by Boyang and Simon, also discussed on Zoom-meeting by all HW members and also TAs when needed. The assembly of boards were done by all members in the HW group. Troubleshooting, re-soldering and fixing of the boards was done by all members when possible. The report was mostly written by Simon, and revised by Mohamed and Boyang.

Software

Ekaterina and Sarah have together worked on producing a working software based on the requirements of the link budget. Most of the time spent on the project has been together in the lab with added work from home trying to finalize the software. Both parts has equally contributed to the finalization of the software. When writing the report Kate and Sarah were responsible together for the SW part, as well as revising the whole report.