

Wireless communications

Adaptive beamforming

Luca Ferraro (10748116), Bernardo Camajori Tedeschini (10584438),
William Colombo (10537311)

<https://github.com/BernardoCama/WirelessCommunicationProject>

A.Y. 2020/2020

Contents

1	Introduction	3
1.1	OFDM signal	3
1.2	3GPP Standard	4
1.3	Beamforming	4
2	Project description	5
2.1	Beamforming techniques	5
2.2	Channels	5
2.3	Signals	5
2.4	Reported results	6
3	SNR comparison	7
3.1	Geometry and parameters	7
3.2	Steps of the simulation	7
3.3	Results	8
4	Antenna array comparison	10
4.1	Aim of the experiment	10
4.2	Geometry and parameters	10
4.3	Steps of the simulation	10
4.4	Results: <i>QAM</i> constellations	11
4.5	Results: antenna pattern functions	12
4.6	Results: <i>BER</i>	13
5	Tracking	15
5.1	Aim of the Experiment	15
5.2	Geometry and Parameters	15
5.3	Steps of the Simulation	16
5.4	Results of the Tracking	16
6	Conclusions	19
6.1	What we have learned	19
6.2	Our difficulties	19
6.3	Future developments	19

List of Figures

1	Scenario of the simulation	7
2	Relation SNR _{in} - SNR _{out} for different interfering signals and beamformers (LMS initialized with simple BF)	8
3	Scenario of the simulation	11
4	4-QAM constellations	12
5	Antenna pattern functions	13
6	BER	14

7	Scenario	15
8	Beginning of Tx.	17
9	Middle of Tx.	17
10	End of Tx.	18

1 Introduction

In this section, we describe briefly the key concepts that are mandatory for the comprehension of the project.

1.1 OFDM signal

OFDM (Orthogonal Frequency Division Multiplexing) is a multi-carrier modulation whose key features are:

1. **Flexibility** By means of:
 - **Adaptive Bit Loading** Adaptive modulation, coding for each sub-carrier.
 - **Multiple Access** Multiple Access Feature with the use of OFDMA.
2. **Digital Implementation** With the use of DFT and IDFT at Tx and Rx side respectively to pass from Samples in frequency domain to time domain and viceversa.
3. **Simple Equalization** Through the use of Cyclic Prefix that permits the representation of the channel with a single tap (Flat Ch) in each sub-carrier.
4. **MIMO Implementation** Suited for the use of MIMO/MMIMO Systems.

The main parameters of the Modulation are:

1. **Nsc** Number of sub-carrier which usually is in the form 2^b since it is optimized for the FFT and IFFT implementation.
In our case: Nsc = 64.
2. **CyclicPrefixLength** The length of Cyclic Prefix that must be much smaller than Ts (OFDM Symbol Time).
In our case: CyclicPrefixLength = 4.
3. **NumGuardBandCarriers** The number of Guard Bands in frequency domain to protect the OFDM Spectrum from other adjacent transmissions.
In our case: NumGuardBandCarriers = [1;1] one for each side.
4. **Pilot Positions** The sub-carrier location of Pilot signals, known sequence of symbols that are used to estimate the channel.
In our case: PilotIndices = [2]. We really don't use the Pilot, since we consider the first symbols of the transmission as known, but for completeness we dropped off at least one Pilot.

1.2 3GPP Standard

3GPP (3rd Generation Partnership Project) was founded in December 1998 when the European Telecommunications Standards Institute (ETSI) partnered with other standard development organizations (SDOs) from around the world to develop new technologies (technology specifications).

As Channel Model we use QuaDRiGa (QUASI Deterministic RadiO channel GenerAtor) that generates realistic radio channel impulse responses for system-level simulations of mobile radio networks. Quadriga indeed is able to simulate 3GPP channel models like 3GPP-3D and also the latest New Radio channel model.

1.3 Beamforming

A beamformer can be considered a spatial filter that suppresses the signal from all directions, except the desired ones by means of weights applied to the signals coming from the single array elements; resulting in controlling the radiation pattern of the array.

The **Array Pattern Function** $AF(\theta, \phi)$ is the gain that we can obtain with the Beamformer in a given direction specified by:

- θ = Elevation ($\pi/2$ - zenith of arrival)
- ϕ = AoA (angle of arrival)

and it is defined as:

$$AF(\theta, \phi) = w^H s \text{ where:}$$

- s are the Steering Vectors
- w are the weights of the Beamformer

In the project, in particular in section 4, we compare the different **Array Pattern Function** of various type of Beamformer.

2 Project description

In this section, we describe the structure of our project with a brief description of the main points of all the parts composing our work.

2.1 Beamforming techniques

We have implemented 5 beamforming techniques:

1. **Simple beamforming** The phases are selected to steer the array in a particular direction.
2. **Null-steering beamforming** Used to cancel $K \leq N-2$ plane waves arriving from known directions (N = number of antennas).
3. **Minimum variance distortionless response (MVDR) beamforming** This beamformer minimizes the interference-plus-noise power at the output of the beamformer.
4. **Minimum mean square error (MMSE) beamforming** The weights of the antennas are adjusted in a way that the MSE between the output of the beamformer and the reference signal is minimized.
5. **Least mean square (LMS) beamforming** This iterative algorithm adjusts the weights by estimating the gradient of the MSE and moving them in the negative direction of the gradient at each iteration. We have implemented this iterative algorithm both in the time and in the frequency domain.

2.2 Channels

All the 5 beamformers have been tested on 3 different channels:

1. **LOS channel** A simple line of sight channel with no reflections.
2. **Two-ray channel** For each signal, we consider a direct path (LOS) and a single reflection.
3. **QuaDRiGa channel** Here, the scenario we have used is the *QuaDRiGa_UD2D_LOS*.

2.3 Signals

For all the beamformers and in all the channel, the bits we transmit are generated randomly and modulated first with a 4QAM modulation (we have also tested the beamformers with a 16QAM); then, the QAM symbols are modulated with OFDM for transmission.

2.4 Reported results

In this report, we only describe the three most important simulations we have done:

1. Comparison between the SNR at the input and at the output of all the five beamformers in a LOS channel (section 3).
2. Comparison of the performance in terms of constellations revealed, array pattern functions of the antenna array and BER for all the five beamformers considering different antenna arrays (section 4). This has been done in the quadriga channel and using the LMS beamformer in the time domain.
3. Tracking of two vehicles using LMS beamforming in the frequency domain (section 5).

All the other simulations we have done can be found on the *Github* repository of the project (link in title page).

3 SNR comparison

In this simulation, we have tested the performance in terms of gain in the SNR at the output of the five beamformers we have implemented for:

1. Different number of interfering signals
2. Different values of SNRs at the input of the beamformers

3.1 Geometry and parameters

We are using a *LOS* channel in stationary conditions (vehicles are not moving). The vehicles are positioned at a distance of 25 meters from the base station on a circumference and spaced of 20° as in Figure 1.

The antenna array we are using is a 4x4 array.

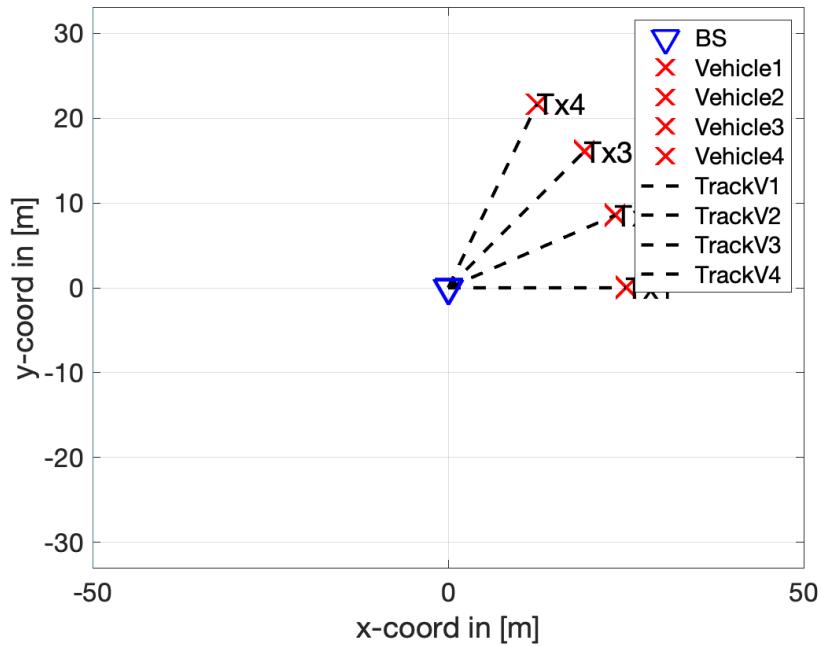


Figure 1: Scenario of the simulation

3.2 Steps of the simulation

Our simulation considers a different number of interferents (0, 1, 2, 3) and for each one of the cases computes the curve input SNR - output SNR for all the beamformers:

1. Definition of the current number of interferents
2. Generation of the scenario and of the signals
3. Passage of signals through the *LOS* channel
4. For all the input SNR levels:
 - (a) Add noise to the good signal in a way that the SNR is the current one
 - (b) Computation of the weights of the antenna elements
 - (c) Application of beamforming techniques to the single signals and noise
 - (d) Computation of the power of all the signals and of the noise
 - (e) Computation of the SNR at the output of the beamformers
5. Plot of the results

3.3 Results

In Figure 2, we can see in the four graphs the curves $\text{SNR}_{\text{in}} - \text{SNR}_{\text{out}}$. In a single figure, the number of interferents is fixed and we show the lines for the different beamformers.

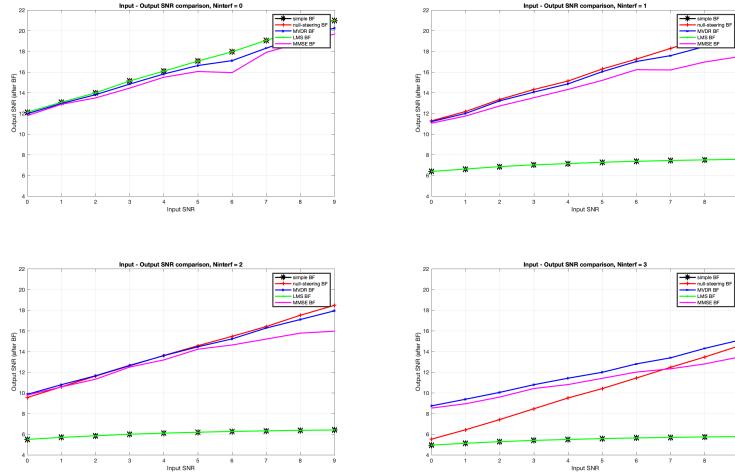


Figure 2: Relation $\text{SNR}_{\text{in}} - \text{SNR}_{\text{out}}$ for different interfering signals and beamformers (LMS initialized with simple BF)

As we can see, without any interfering signals, the behavior of all the beamformers is almost linear and the gain is approximately constant and equal to 12dB.

As the number of interferents increases, we can identify as general behavior:

1. The simple and the LMS beamformer are the worst one; indeed, their curves are the most bended and the ones giving the lowest gain. This is expected for the simple beamformer and, in this case, also for the LMS since we are initializing its state using the simple beamformer. This is not the best choice (and in fact the gain of the LMS is low), but it's a simple way of initializing it.
2. The MVDR and the MMSE are the beamformers that behaves better since they are designed for minimizing respectively the interference-plus-noise power at the beamformer output and the error with respect to a reference singal. Anyway, as the number of interferents increases their gain decreases, but still their curves are almost linear.
3. The null-steering beamformer behaves as the MVDR and the MMSE with for 0, 1 or 2 interfering signals, but its gain decreases with three interferents. This is due to the fact that this beamformer tries to put a null in correspondence of the DoA of the interferents and, in case there are too many ones and too close one to each other, this becomes difficult and the gain decreases.

4 Antenna array comparison

In this part of our project, we have compared the performance of the five beam-forming techniques using different antenna arrays, in particular we have used as arrays:

1. 2x2
2. 4x4
3. 8x8
4. 16x16

4.1 Aim of the experiment

The aim of this experiment is to evaluate the performance of different beamforming techniques using different antenna arrays. In particular, for each beamformer and for each antenna array, we have studied:

1. The shape of the *QAM* constellation revealed.
2. The shape of the array pattern function.
3. The *BER*

4.2 Geometry and parameters

In this simulation, we have considered two sources that we call *V1* and *V2*: the signal we want to receive is the one from *V1*, while *V2* is producing an interfering signal.

Both the vehicles are not moving and they are transmitting 100 4-QAM symbols. The geometry of the simulation can be seen in Figure 3.

4.3 Steps of the simulation

The very first thing we do in our simulation is defining the geometry of our scenario, so positioning the vehicles and the base station.

Then, we prepare the signal to be transmitted, that is an OFDM signal modulating symbols from a 4-QAM modulation.

The simulation proceeds with a loop on the four different antenna arrays. In each loop, the main steps we follow are:

1. Definition of the current antenna array.
2. Passage of the signal through the QuaDRiGa channel (*QuaDRiGa_UD2D_LOS* scenario).

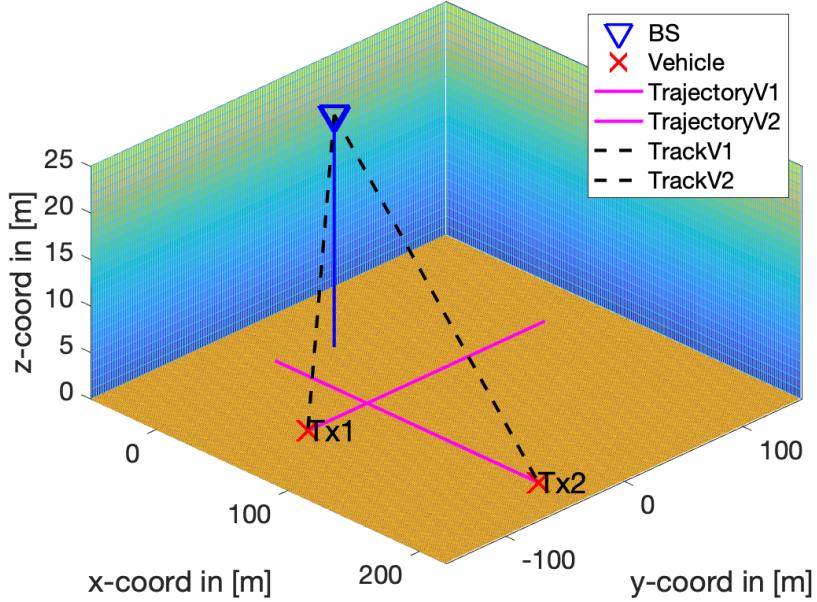


Figure 3: Scenario of the simulation

3. Application of the five beamformers to the received signal. Here, we use the real *DoA*, and not the estimated one for a more consistent comparison of the results.
4. Channel equalization using the gradient descent algorithm. Here, we use a one-tap equalizer since on each subcarrier of the OFDM signal we can consider the channel as flat.
5. OFDM demodulation.
6. QAM demodulation.
7. Computation of the BER.

At the end of the loop, we show the results by making some plots and videos that are commented below in the following sections.

4.4 Results: *QAM* constellations

In the Figure 4 we can see 4 images, one per antenna array; in each one of them, we have plotted the constellation revealed by using the five different beamformers.

As we can see, in general the higher the number of antennas we are using, the more precise is the *QAM* constellation. This is due to the fact that with more antennas the precision in the angular localization of the source is higher; therefore, the beam that points towards it is narrower and the interfering signal is more attenuated (this can be seen even better by looking at the antenna pattern functions).

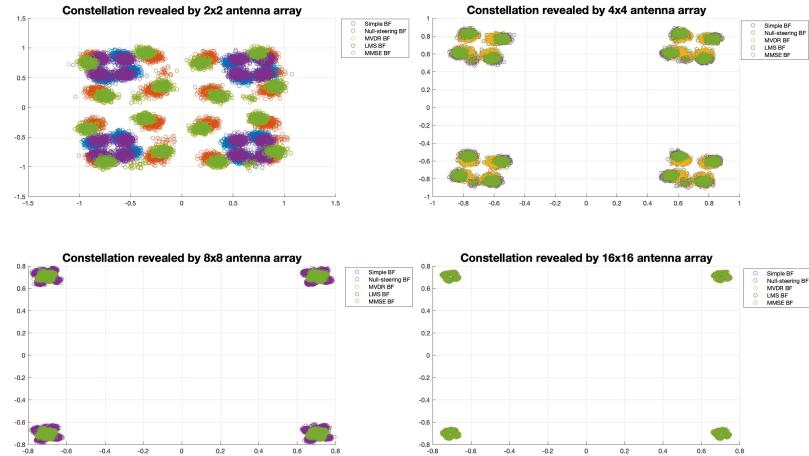


Figure 4: 4-QAM constellations

4.5 Results: antenna pattern functions

The Figure 5 shows for each of the four antenna arrays the array pattern function of the five beamforming techniques we have implemented; the array pattern functions have been plotted on the zenith angles of the source. We have also plotted a vertical line that represents the *DoA* of the source.

The most interesting things to be noticed are two:

1. The maximum of all the antenna array pattern functions is always localized in correspondence of the *DoA* of the source. This is indeed the aim of beamforming.
2. The higher the number of antennas, the narrower the beam that is pointing in the direction of the source. This is due to the fact that with more antenna we have more spatial samples of the signal and therefore a better estimation of its angular positions.

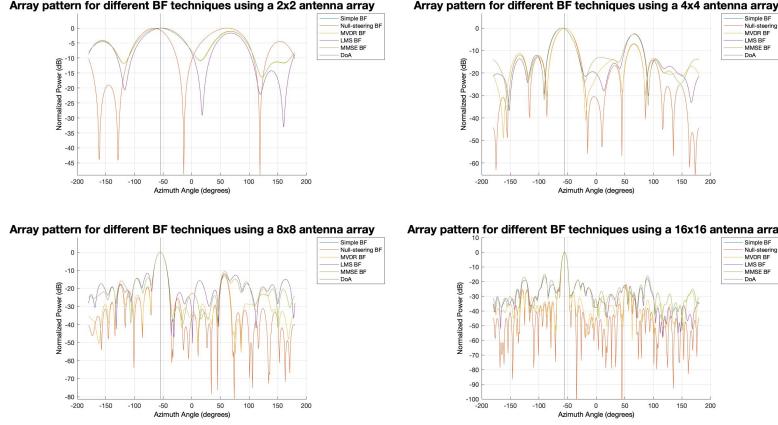


Figure 5: Antenna pattern functions

4.6 Results: *BER*

Finally, the Figure 6 shows how the *BER* varies for the five beamformers as a function of the number of antennas.

As we can see, the *BER* here is always zero, whatever the number of antennas we use. This is a special case since we are using the real DoAs for computing the weights of the antennas; in a real-world situation (in which DoAs are estimated through specific algorithms like MUSIC), the *BER* will be in general higher.

Actually, this result also depends on the beamformer and on the antenna array we are using: given an antenna array, the more sophisticated is the beamformer, the lower the *BER* and, given a beamformer, the higher the number of antennas the better the *BER*.

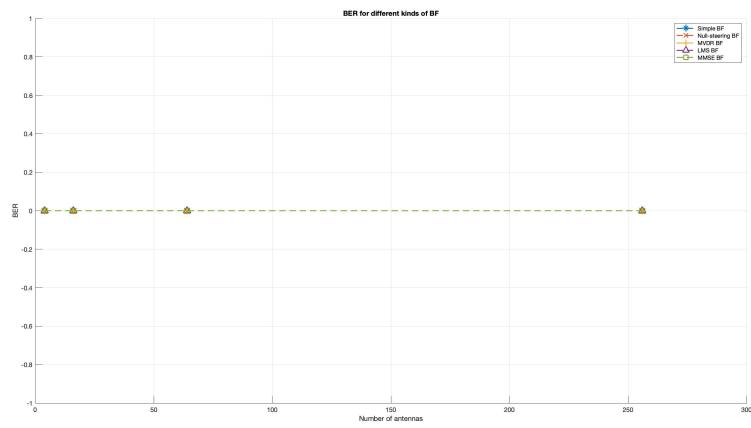


Figure 6: BER

5 Tracking

In this section, we describe the tracking experiment and all the techniques involved.

5.1 Aim of the Experiment

The focus of the last part of the project is to track continuously two vehicles that are moving in a straight line, and in particular to appreciate the advantages that the LMS beamformer in frequency domain can offer.

5.2 Geometry and Parameters

The two vehicles are moving one towards Nord and one towards East at 60 km/h . The antenna is placed in the origin at a height of 25 meters and it is equipped with an array of 16x16 Antennas parallel to the ground. The simulation lasts 12 seconds and each vehicle exchange 24 packets in total.

This is the Scenario:

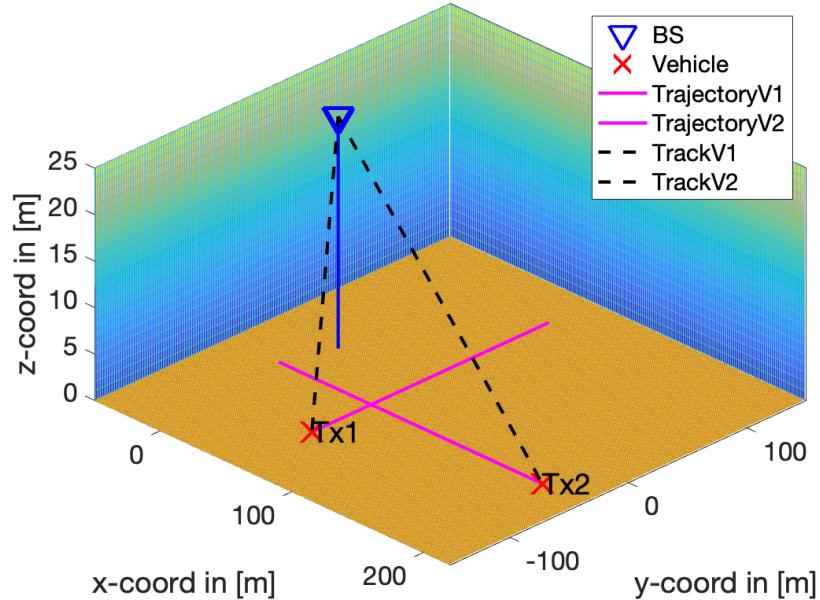


Figure 7: Scenario.

As parameters we used Carrier Frequency $f_c = 2.6 \text{ GHz}$, OFDM with 4-QAM as modulation with 64 sub-carrier and 100 symbols/packet.

5.3 Steps of the Simulation

1. **Generation of the signals** Through the QAM modulator and OFDM modulator.
2. **Creation of the Channel** In this case *QuaDRiGa_UD2D_LOS* channel.
3. **Passage of Waveforms in the channel** By means of the convolution with the channel model.
4. **Estimation of DoA** With the Music Algorithm.
5. **OFDM Demodulation** Applying the FFT on the Signal from each Antenna.
6. **LMS Beamformer** For each sub-carrier (In Frequency Domain) using half of the sequence as training.
7. **Channel equalization** Applying the Gradient-Descent algorithm to each Sub-Carrier.
8. **QAM Demodulation** Final recovery of the bits and calculation of the BER.

5.4 Results of the Tracking

The experiment shows that at the beginning the Tx with Vehicle1 has practically zero errors since it is the nearest to the station and the music algorithm can estimate without problems its position. Instead the Tx with Vehicle2 has many more errors, due to the many multipath of the channel and to the lower received Power (Figure 8).

When they are about the same distance and in normal conditions the track performs without any particular problem (Figure 9).

At the end when Vehicle2 is the nearest to the BaseStation, the situation is inverted and the Tx with Vehicle2 is far more reliable than with Vehicle1 (Figure 10).

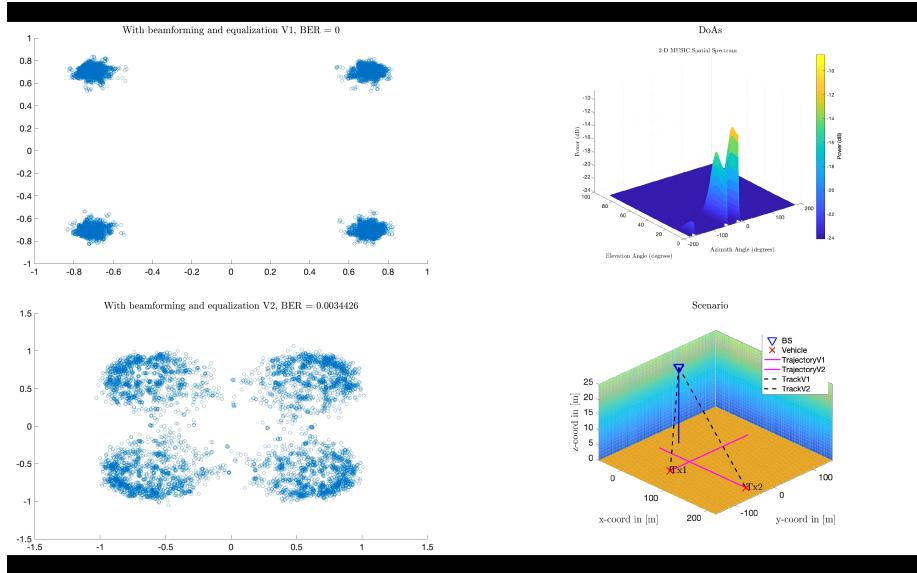


Figure 8: Beginning of Tx.

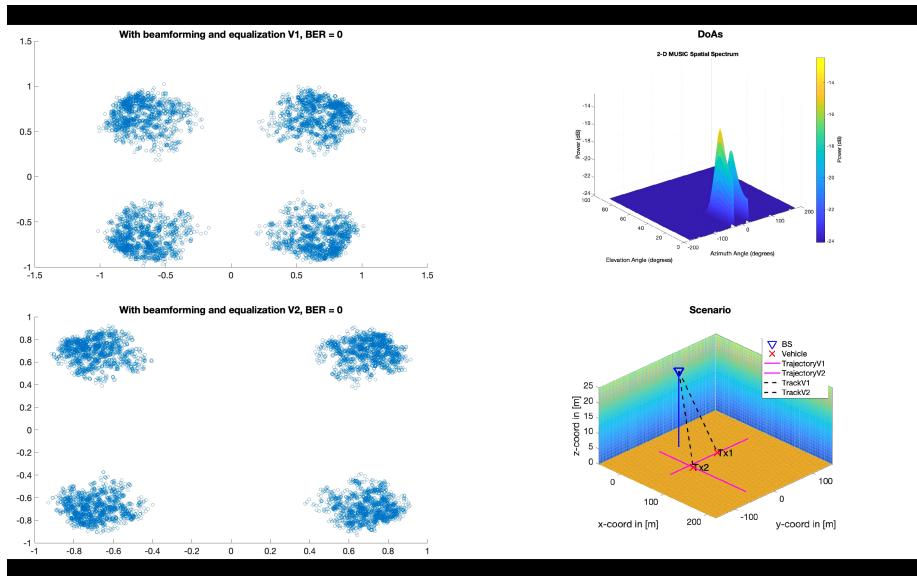


Figure 9: Middle of Tx.

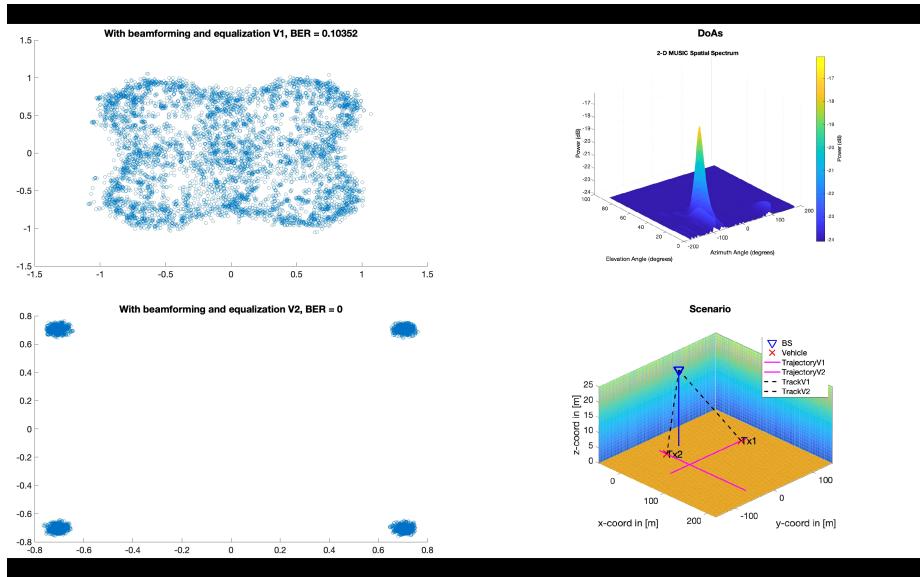


Figure 10: End of Tx.

6 Conclusions

6.1 What we have learned

With this project, we have understood the potentials of different beamforming techniques.

We have used beamforming for isolating a source in an environment full of interference and for tracking users, and these two are the main field in which beamforming is used.

6.2 Our difficulties

The core of the project was the implementation of the beamformers and the design of the system for the communication between the user(s) and the base station.

The main problem we have found was finding the way of implementing digitally the physical formulas and check the physical meaning of the results we have obtained.

6.3 Future developments

With the new generation of cellular systems, massive MIMO is becoming more and more important.

With the availability of such a huge number of antennas (for sure, more than 16x16 arrays, which are the biggest we have used), beamforming becomes more precise, thus allowing a better localization of sources.