Wireless communications
-
Adaptive beamforming

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https://github.com/BernardoCama/WirelessCommunicationProject

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Contents

List of Figures

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 that is able to obtain:

1. **Flexibilty** 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 rapresentation of the channel with a single tap (Flat Ch) in each sub-carrier.
4. **MIMO Implemetaion** 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 implementaion.
   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 trasmissions.
   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 tha channel.
   In our case: Pilotindices = [2]. We really don'use 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) and 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:

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

- s are the Steering Vectors
- w are the weigths 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 out 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 <= N-2 plane waves arriving from known directions.
3. **Minimun variance distiortionless 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 weigths 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 algorithms adjust 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 channel:

1. **LOS channel** A simple line of sigth 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 fist 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, weigths of the antennas 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. Traking 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

4 Antenna array comparison

In this part of our project, we have compared the performance of the five beamforming 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 $4QAM$ symbols. The geometry of the symulation can be seen in Figure 1.

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 4QAM 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).

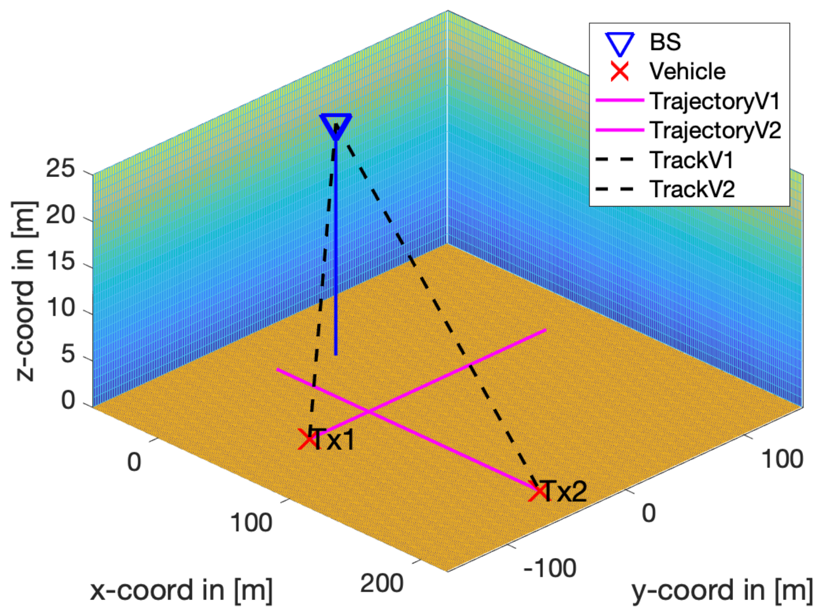

Figure 1: Scenario of the simulation

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 2 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 antenna we are using, the more precise is the QAM constellation. This is due to the fact that with more antenna the precision in the angular localization of the source is more precise; 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).

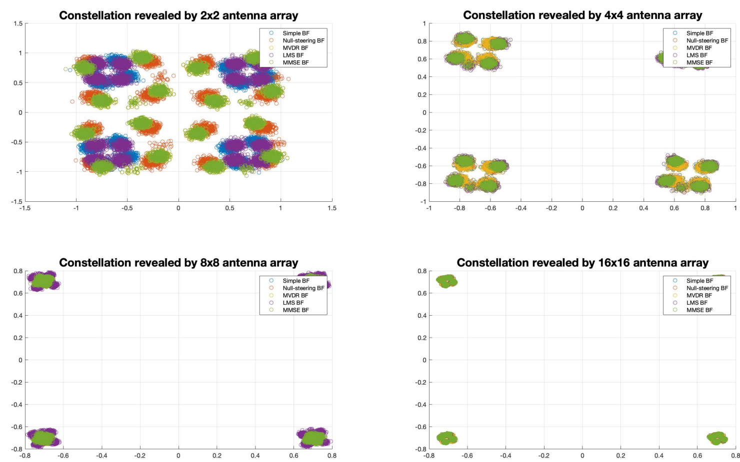

Figure 2: 4-QAM constellations

4.5 Results: antenna pattern functions

The Figure 3 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.

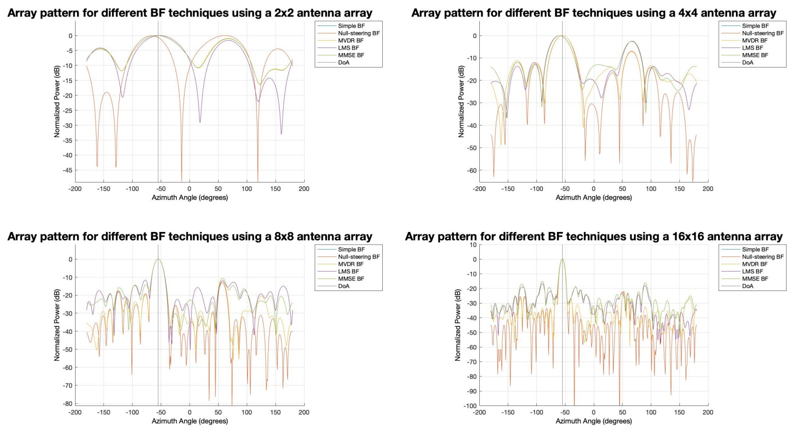

Figure 3: Antenna pattern functions

4.6 Results: BER

Finally, the Figure 4 shows how the BER varies for the five beamformers as a function of the numberr of antennas.
As we can see, the BER is different from zero only when we use the 2x2 antenna array. This means that four antennas may not be sufficient for applying an effective beamforming technique. Actually, this also depends on the beamformer that we are using: the more it's sophisticated, the less antennas we can use. But this also depends on the specific scenario.
What we can in general conclude is that the higher the number of antennas, the lower the BER; the actual number of antennas needed depends on the target BER and on the model considered.

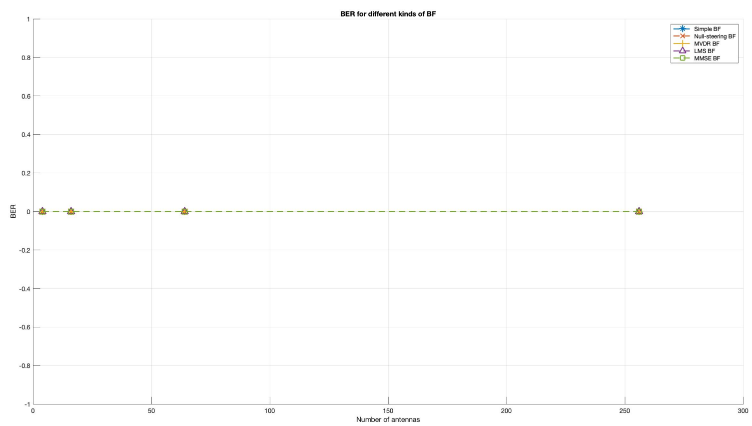
BER for different kinds of BF
Simple BF
Null-steering BF
MVDR BF
LMS BF
MMSE BF
BER
Number of antennas
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
50
100
150
200
250
300

Figure 4: BER

5 Tracking

In this section, we describe the tracking experiment and all the tecquiques 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 Paramters

The two vehicles are moving one towards Nord and one towards Est 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:

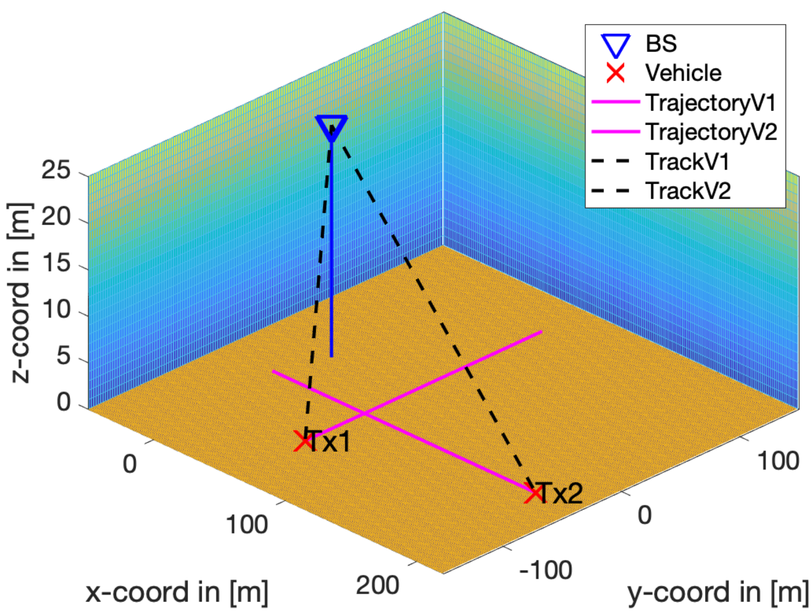

Figure 5: Scenario.

As parameters we used Carrier Frequency fc $= 2.6$ 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** Finally 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 6).

When they are about the same distance and in normal conditions the track performs without any particular problem (Figure 7).

At the end when Vehicle2 is the nearest to the BaseStation, the situation is inverted and the Tx with Vehicle2 is far more reliable that with Vehicle1 (Figure 8).

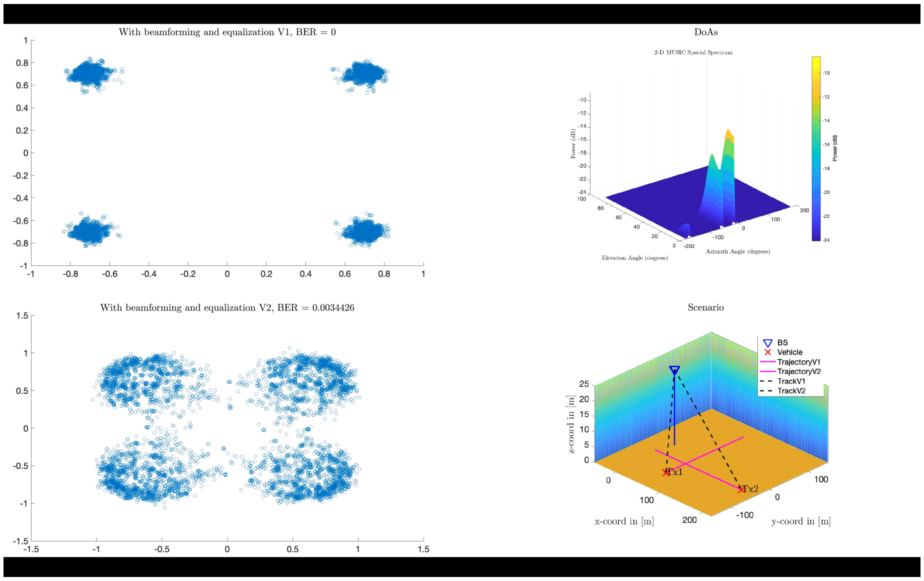

Figure 6: Beginning of Tx.

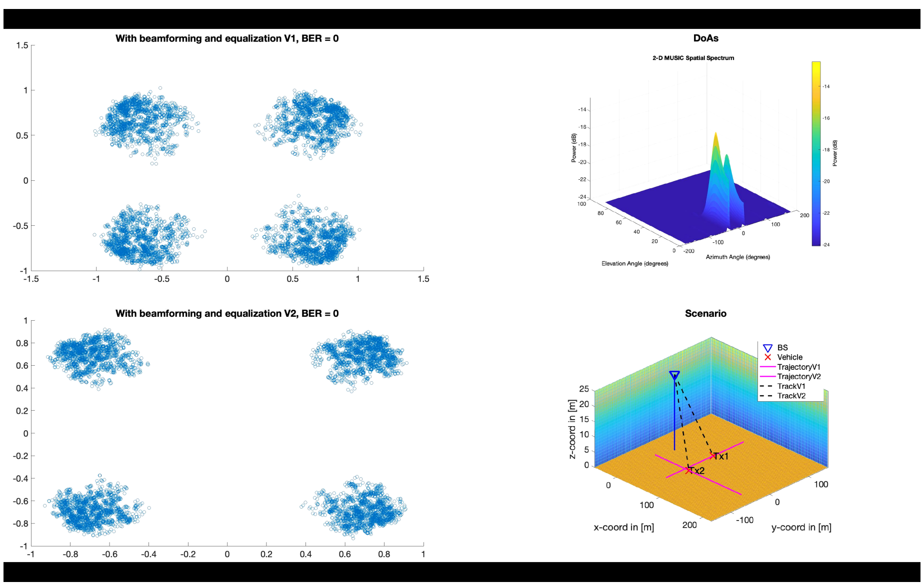

Figure 7: Middle of Tx.

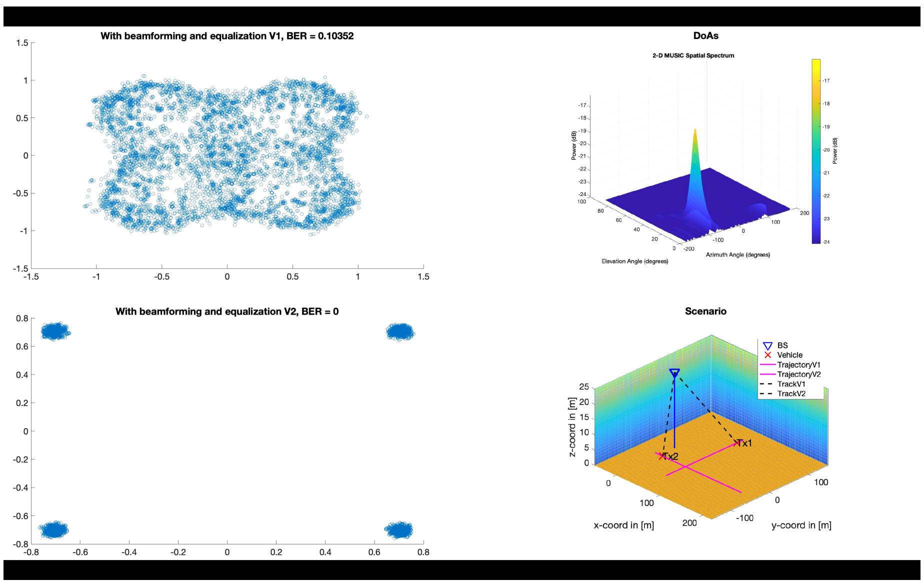

Figure 8: End of Tx.

6 Conclusions