Assignment 3

EE6143: Advanced Topics in Communications

Due: 11:59 PM, 7 April 2021

1 Problem Statement

This assignment extends the work you did in your initial programming assignment. You will simulate a bits to bits OFDM system in which data is transmitted through a multipath fading channel. The goal is to study the variation of bit error rate (BER) with $\frac{E_b}{N_0}$ for different constellations- 4 QAM, 16 QAM, 64 QAM and 256 QAM under different channel conditions. Upon completing the assignment you will develop a better understanding of the following

- OFDM
- Multipath fading- TDL channel models in MATLAB
- Channel estimation
- Effect of CFO
- Effect of timing offset

In this assignment, you will adhere to the 5G NR specifications for time domain and frequency domain structure. These will be detailed for you in Sections 2 and 3.

Further, this assignment can either be done individually or in a group of two. Details regarding collaboration can be found in Section 5.

2 Setup

As mentioned in Section 1, you will stick to the 5G standards while implementing this assignment.

2.1 5G NR specific constraints

Consider the following constraints

1. You are to transmit one slot of information at a carrier frequency of 3.5 GHz with a subcarrier spacing of 30 kHz. How many OFDM symbols is this?
2. You are allocated 50 resource blocks per OFDM symbol (how many resource elements- equivalently QAM symbols- is this?) to transmit data.
3. Data can be transmitted in each symbol of the slot. All the resource elements (REs) starting from the first RE can be used for transmission.

2.2 System to be implemented

Figure 1 provides a schematic of the system you need to implement. Please note that Figure 1 has been provided only as a tentative schematic. Make any suitable modifications as needed.

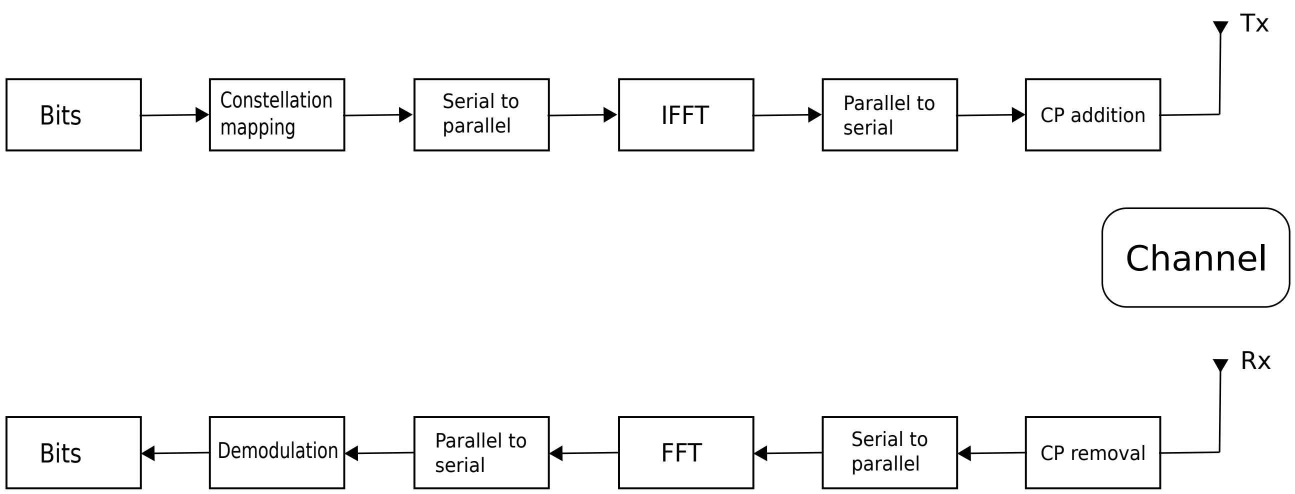

Figure 1: A schematic of the OFDM chain

The following steps describe one possible way of realising the system depicted in Figure 1-

1. Select a range of SNR values for transmission. Remember that this range needs to be chosen so that a BER of 10^{-3} can be seen for all constellations. This range can also be made specific to different constellations.
2. For each constellation

(a) From the description in Section 2.1, determine how many modulated (QAM) symbols and correspondingly how many bits need to be generated. Ensure that the generation of either bit is equally likely.

(b) For each value of SNR

i. Compute the corresponding value of $\frac{E_b}{N_0}$.

ii. Generate the complex QAM symbols from the bits that you generated previously. Make sure to use gray encoding.

iii. Populate the resource grid with the generated symbols.

iv. Obtain the IFFT of the data to be transmitted. With the constraints of Section 2.1, the FFT size is no longer the same as the number of resource elements allocated to you. Therefore, you are required to pad the data with zeros and manipulate it suitably to obtain the IFFT. Study the documentation of the IFFT function in MATLAB and compare it with the theoretical definition you know to determine how to do this.

v. Add the cyclic prefix for each OFDM symbol.

vi. Transmit through an AWGN channel.

vii. Remove the cyclic prefix.

viii. Perform FFT on vectors of received symbols.

ix. Obtain the resource grid (RG) from the frequency domain data.

x. Demodulate the received symbols and compute the BER.

You will modify the above setup as described in Section 3 to obtain various results and analyse its behaviour under different conditions. You will find details regarding the values of parameters such as FFT/IFFT size, cyclic prefix length and so forth in Section 3.

3 Simulations

Once the setup described in Section 2 is developed, you will perform the simulations listed below. You will use the parameter values specified in order to obtain the results required for your evaluation. However, feel free to play around with these values and record anything interesting you might observe in your report!

3.1 Common parameter values

For all the simulations assume the following unless otherwise specified-

1. FFT size : 4096

2. CP length for first OFDM symbol in slot : 352
3. CP length for remaining 2^{nd} to 14^{th} OFDM symbol : 288
4. SCS : 30 kHz
5. Number of slots : 1
6. Number of resource blocks : 50
7. QAM constellations : 4, 16, 64, 256

Determine the sampling rate from the above parameters.

3.2 Simulation 1- transmission through an AWGN channel

In this simulation, you will complete the setup described in Section 2. Following this, you will

1. plot the variation of BER with $\frac{E_b}{N_0}$ for all the constellations on the **same graph**. Ensure that the Y axis is logarithmic and that you are plotting $\frac{E_b}{N_0}$ in dB scale (i.e $10\log\left(\frac{E_b}{N_0}\right)$) on the X axis.
2. plot the **theoretical** BER vs $\frac{E_b}{N_0}$ curves (in the AWGN case) for all the constellations on the same plot.

What do you observe? Do the theoretical and empirically obtained curves agree? If not, identify the range of $\frac{E_b}{N_0}$ values for which they disagree and provide an explanation as to why they disagree.

3.3 Simulation 2- effect of timing offset

For this simulation, continue with the setup of Section 3.2. Introduce timing offset in the received signal. This is done by adding zeros at the beginning of the received time domain signal. This will lead to samples from the CP creeping into the OFDM symbol fed into the FFT block. This is illustrated in Figure 2.

Following this you will

1. plot the received constellation i.e obtain a scatter plot of the real parts of the received frequency domain data vs the imaginary parts of the received frequency domain data. Do this with and without timing offset only for the **16 QAM constellation at a high SNR value**.

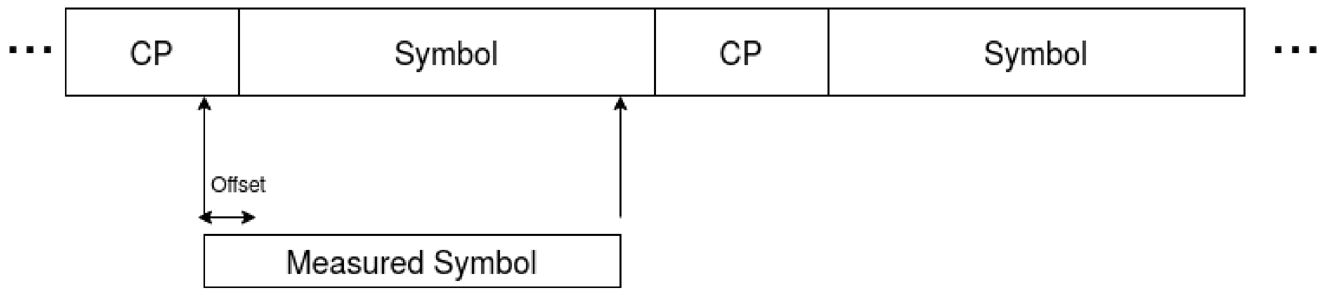

Figure 2: A schematic of the timing offset scenario you will be analysing

2. plot the variation of BER in the presence of timing offset with $\frac{E_b}{N_0}$ for all the constellations on the one graph. Plot the theoretical BER vs $\frac{E_b}{N_0}$ curves (same ones as in Section 3.2) on the same graph for comparison.

3. devise a technique to correct for timing offset and implement it. While doing this, assume that the timing offset is known at the receiver. Plot the received constellation after correcting the timing offset. Do this only for the **16 QAM constellation at a high SNR value**.

4. plot the variation of BER after the correction of timing offset with $\frac{E_b}{N_0}$ for all the constellations on the one graph. Plot the theoretical BER vs $\frac{E_b}{N_0}$ curves (same ones as in Section 3.2) on the same graph for comparison.

Discuss your observations, the timing offset correction technique you used and your conclusions in your report.

3.3.1 Parameter values

For the discussion and constellation plots in the report, use

1. timing offset : 5 samples

3.4 Simulation 3- effect of CFO

For this simulation, continue with the setup of Section 3.3. Set timing offset to zero (this is the same as continuing with the setup of Section 2). Following this, you will

1. introduce Carrier Frequency Offset into the system (Hint: What does an offset in the frequency domain amount to in the time domain?). In this simulation,

$$\text{CFO} = \frac{\Delta f}{f_{scs}} \tag{1}$$

where Δf is the offset frequency and f_{SCS} is the subcarrier spacing.

2. Use the following CFO values [0, 0.0005, 0.001, 0.0015, 0.002, 0.003]. For each of these values obtain the BER vs $\frac{E_b}{N_0}$ curves for only the **4 QAM constellation**. Plot these four curves along with the theoretical curve on **the same graph**.

3. Present your observations in your report on the behaviour of the curves with increase in CFO.

3.5 Simulation 4- multipath fading, channel estimation and equalization

In this simulation, you will replace the AWGN channel with a frequency selective channel. In order to estimate the channel you will also make use of pilot symbols. Figure 3 depicts how the setup in Section 2 is altered.

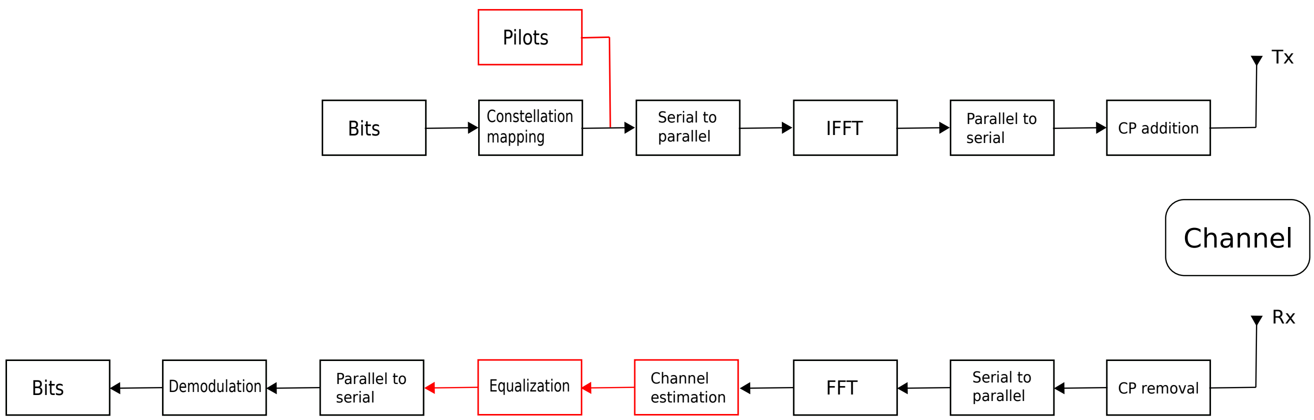

Figure 3: A schematic of the OFDM chain with TDL channel

The following elucidates what you must do-

1. Replace the AWGN channel with the TDL-C channel model. You will use the *nrTDLChannel* function for this in MATLAB. Refer to the documentation online to better understand how to do this- detailed examples are provided to explain the use of this function.

2. Transmit grid pilots in the fashion showed in Figure 4. Use $\frac{1+1i}{2}$ for the pilot value.

3. On the receiver side, perform channel estimation using the pilots. Determine the channel for the entire resource grid appropriately. Describe your method in your report in detail.

4. Perform ZF equalization to obtain the relevant data symbols and compute the BER.

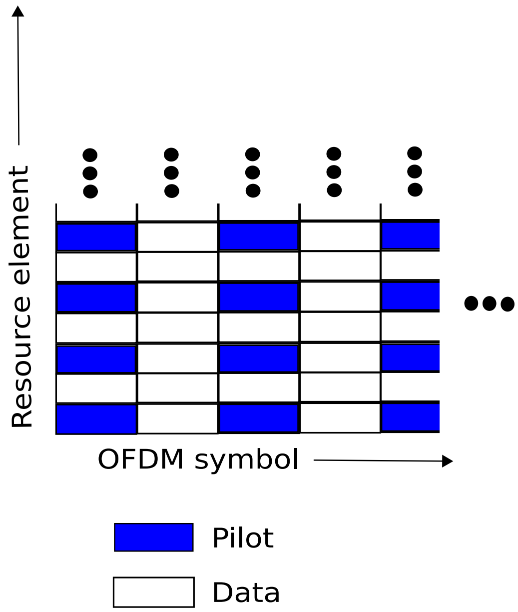

Figure 4: Grid pilot placement to be used

5. Obtain the BER vs $\frac{E_b}{N_0}$ curves for 4, 16, 64, 256 QAM constellations and plot them on the **same graph**. Also plot the theoretical AWGN BER curves on this graph for comparison. Are they identical? If not, explain why.

6. Note that in order to obtain reliable curves, you will need to repeat the above steps several times and average the BER obtained for each SNR for each constellation point. In each case, ensure that the channel instantiation is different for the same set of parameters specified in Section 3.5.1. Put this value in the **title of your graph**.

7. Discuss your results in the report.

3.5.1 Parameters

Use the following parameters when using the TDL channel model given by the *nrTDLChannel* function in MATLAB.

1. Doppler shift : 0 Hz

2. Delay profile : “TDL-C”

3. Delay spread : 30e-9 s

4. Number of Transmit antennas : 1

5. Number of Receive antennas : 1

For any other parameters relevant to the *nrTDLChannel* function, refer to the documentation.

3.6 Bonus simulation (optional)

The following tasks are not mandatory. They will, however, give you a better understanding of the system you have built.

1. Obtain the spectrum of the OFDM signal. What do you observe? What are the characteristics of the spectrum? Do they agree with those from theory? If not, explain why.
2. Repeat the simulation in Section 3.5 with Doppler shift not equal to zero. Set it to 58.3 Hz (this corresponds to a relative velocity between transmitter and receiver of 5m/s. Keep increasing the Doppler shift (maybe even till 1 kHz). What do you observe? Are the curves you obtain similar to any of the previous simulations? Why does this happen? Note that for this simulation, it is quite necessary to average over multiple (maybe 20 or so) iterations of the channel.

4 Submission

The assignment is due by **11:59 PM, 7 April 2021**. **Late submissions will be penalized heavily.**

Adhere to the following guidelines when submitting your assignments

1. Submit a single .zip file with your submission in it. Compress all the files into one .zip file with the name "Assignment3_[your_roll_no].zip". If you are not a student at IITM then name the file as "Assignment3_[your_first_name_your_last_name].zip" and submit it.
   For instance, if you are a student at IITM with the roll number EE16B025, then your submission will be Assignment3_EE16B025.zip
   If you are a participant from DoT and your name is (say) Milind Kumar, then your submission will be Assignment3_Milind_Kumar.zip

2. Each submission file must contain the following
   (a) OFDM_AWGN.m
   (b) OFDM_TDL.m

(c) Report_[your_roll_no].pdf (for IITM students) or
Report_[your_first_name_your_last_name].pdf (for DoT participants). This report is optional for DoT participants.

Descriptions of each file are given below. Further, also include any associated functions that you may have written or files that complete your code.

4.1 OFDM_AWGN.m

When run, this file should perform the simulations described in Sections 3.2, 3.3, 3.4 and the OFDM spectrum task of Section 3.6.

The following variables should be present (**with the exact same name!**) at the top of this script-

1. **timing_offset** : a parameter that describes the number of samples by which the time domain signal is offset. When submitted, it should be set to 0 i.e no timing offset should be present. This value will be changed during evaluation to verify if the code is functioning.
2. **CFO** : the CFO value as described in Equation 1. Set it to 0 when submitting. This value will be changed during evaluation to verify if the code is functioning.

When run, the following should be the outputs-

1. A plot of both empirical and theoretical BER vs $\frac{E_b}{N_0}$ for all 4, 16, 64 and 256 QAM constellations on the same graph for the specified timing offset and CFO.
2. A plot of the received constellation for 16 QAM at the highest value of SNR (only one figure per run! Do not generate multiple figures) you are considering.
3. A plot of the spectrum of OFDM (only one figure per run! Do not generate multiple figures) if you are solving the bonus question.

No other outputs should be generated. Further, make sure nothing else is printed onto the console.

4.2 OFDM_TDL.m

When run, this file should perform the simulations described in Section 3.5 and the Doppler shift task of Section 3.6.

The following variable should be present (**with the exact same name!**) at the top of this script-

1. **fd** : value of the doppler frequency in Hz. Set it to 0 at the time of submission.

When run, the script should produce the following outputs-

1. A **single figure** with BER vs $\frac{E_b}{N_0}$ curves for 4, 16, 64, 256 QAM constellations for the TDL channel. The theoretical AWGN BER curves should also be present on the graph for comparison. The title should indicate the number of channel instantiations over which the average of the BER is obtained.

4.3 Report_[identity].pdf

A LaTeXreport is mandatory for IITM students. DoT personnel are **very strongly encouraged** to submit a report- made using LaTeX or even MS Word/Google Docs. However, the report is not mandatory for DoT personnel.

The report must contain the following-

1. Results, details and observations for the simulations as described in Section 3.

Feel free to add any theoretical insights or observations you might have made during the completion of the assignment. Further, the report must have a Table of Contents, a List of Figures and a References Section. Refer to the Appendix for details regarding plotting, collaboration and the code.

5 Evaluation

This assignment will be evaluated for 100 points with the following split-

1. Code documentation: 5 points
2. Simulation 1 (transmission through an AWGN channel) - 20 points
   (a) Functioning code and output plot : 15 points
   (b) Observations in report : 5 points
3. Simulation 2 (effect of timing offset) - 20 points
   (a) Timing offset implementation and scatter plot (output of code and documented in the report) : 5 points
   (b) BER curves for timing offset (output of code and documented in the report) : 5 points

(c) Timing offset correction (implemented in code and described in report) and scatter plot (output of code and documented in the report) : 5 points

(d) BER curves after timing offset correction (output of code and documented in report) : 5 points

4. Simulation 3 (effect of CFO) - 20 points

   (a) Implementation of CFO and BER plot : 15 points

   (b) Observations in report : 5 points

5. Simulation 4 (multipath fading, channel estimation and equalization) - 35 points

   (a) Implementation : 30 points

   (b) Details (of channel estimation techniques, equalization) and observations in report : 5 points

Additional points will be awarded for the completion of the bonus questions in Section 3.6 and detailing of the solution in the report.

1. OFDM spectrum : 10 points

2. Effect of Doppler shift : 10 points

Appendices

A Plotting guidelines

Ensure the following when preparing scientific plots

- All plots must have a grid.
- All plots must have a legend.
- All plots must have a title.
- The X and Y axes must be labelled in all the plots.
- All figures must have captions in the report.

B Coding guidelines

- Provide detailed documentation for the code in form of comments and Docstrings.
- Remove all debug statements (such as print statements) from the code before you submit.

C Collaboration guidelines

- You can either work individually or in a group of two.
- Do not plaigiarise or copy either the code or the report! If you have discussed with someone else or some other team, make sure to mention their names in the code and report.