# Data Communication Networks, HW#1

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Physical Layer: Orthogonal Frequency-Division Multiplexing Simulation

**Multiplexing Issue** In telecommunications and computer networks, multiplexing (sometimes contracted to muxing) is a method by which multiple analog or digital signals are combined into one signal over a shared medium. The aim is to share a scarce resource. For example, in telecommunications, several telephone calls may be carried using one wire. Multiplexing originated in telegraphy in the 1870s, and is now widely applied in communications. In telephony, George Owen Squier is credited with the development of telephone carrier multiplexing in 1910.
The multiplexed signal is transmitted over a communication channel such as a cable or air. The multiplexing divides the capacity of the communication channel into several logical channels, one for each message signal or data stream to be transferred. A reverse process, known as demultiplexing, extracts the original channels on the receiver end.

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1. Give a paragraph about multiplexing techniques and their well-known applications including FDM, TDM and CDM.

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## 1 Orthogonal Frequency-Division Multiplexing

OFDM is a type of frequency-division multiplexing (FDM) scheme used as a digital multi-carrier modulation method. A large number of closely spaced orthogonal sub-carrier signals are used to carry data on several parallel data streams or channels. OFDM improves the spectral efficiency of conventional FDM by overlapping the subchannels. Each sub-carrier is modulated with a conventional modulation scheme (such as quadrature amplitude modulation or phase-shift keying) at a low symbol rate, maintaining total data rates similar to conventional single-carrier modulation schemes in the same bandwidth. You can refer to [1] to get familiar with OFDM and [2] to learn in deep. Answer the following questions in your report.

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2. Which technologies are using OFDM today? List some of well-known applications.
3. What is advantages of OFDM to FDM or TDM?
4. The document describes that OFDM uses a low symbol rate. Does this effect its throughput? What is its purpose?
5. What is OFDMA and how it is related to OFDM?

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The OFDM implementation of multicarrier modulation is shown in Figure 1. The input data stream is modulated by a digital modulator (QAM in this case), resulting in a complex symbol stream X[0], X[1], $\cdots$, X[N-1]. This symbol stream is passed through a serial-to-parallel converter, whose output is a set of N parallel QAM symbols X[0], $\cdots$, X[N-1] corresponding to the symbols transmitted over each of the subcarriers. Thus, the N symbols output from the serial-to-parallel converter are the discrete frequency

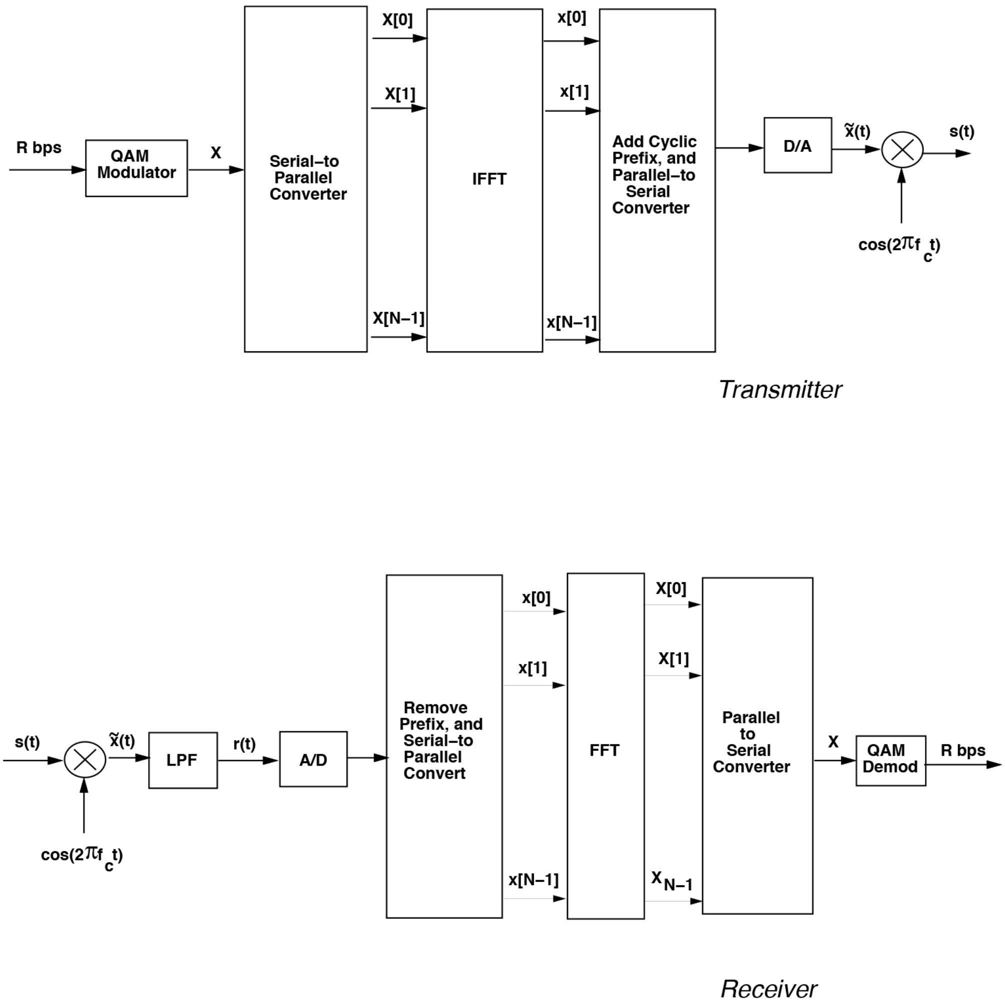


Figure 1: OFDM Block Diagram

components of the OFDM modulator output s(t). In order to generate s(t), these frequency components are converted into time samples by performing an inverse DFT on these N symbols, which is efficiently implemented using the IFFT algorithm. The IFFT yields the OFDM symbol consisting of the sequence x[n] = x[0], $\cdots$, x[N-1] of length N , where

$$x[n] = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X[i] \exp \frac{j2\pi ni}{N}, \forall 0 \leq n \leq N-1 \tag{1}$$

This sequence corresponds to samples of the multicarrier signal: i.e. the multicarrier signal consists of linearly-modulated subchannels, and the right hand side of equation 1 corresponds to samples of a sum of QAM symbols X[i] each modulated by carrier frequency $e^{j2\pi it/TN}$ , i = 0, $\cdots$, N-1.

## 2 OFDM Modules

First of all, we are going to simulate functionality of OFDM transmitter and receiver in Figure 1 using MATLAB. We simulate the system in baseband, so there is no need to upconvert the signal in transmitter and downconvert it in receiver, we also do not add the cyclic prefix in Figure 1.

**Generating Random Source Data** For simulation purposes we always need random source data for testing modules. This random data may come from different distributions. Here we want to use `randsrc` function in MATLAB. Read MATLAB help for how to using it. For making sure that you know how to use this command,

6. Make enough data for 1 user and calculate its mean and variance.

We should use this function to generate 100 kilo-bits of random data for the user.

**Digital Modulation and Demodulation** Quadrature Phase Shift Keying (QPSK) is a form of Phase Shift Keying in which two bits are modulated at once, selecting one of four possible carrier phase shifts (0, 90, 180, or 270 degrees). QPSK allows the signal to carry twice as much information as ordinary PSK using the same bandwidth. We use QPSK modulation for this exercise.

7. Use `pskmod` function for modulating your data. Plot the I-Q plane using `scatterplot` to see the signal constellation.
8. Which function does the demodulation in MATLAB?
9. Try using different parameters for pskmod. How does the plot change?

**NOTE**: You may use communication toolbox functions if they are available in your MATLAB version.

We use parameter 4 for this assignment.

**Serial to Parallel and Parallel to Serial** After generating data we need a module to make data from serial stream to 64 parallel streams (since we have 64 sub-carriers). This parallel data will be the input to IFFT module. In the receiver part we do the same thing backward. It is very easy to implement this functions in MATLAB. Fill out a 64 column matrix, for input to IFFT.

**IFFT and FFT** As Figure 1 shows, we simply use IFFT module for transmitter and FFT module for receiver. MATLAB has simple commands `fft` and `ifft` to perform the calculation. For making yourself more familiar with FFT, answer the following questions in your report:

10. What is the mathematical operation of FFT and how is it implemented?
11. What is the difference between DFT and FFT?
12. What is the difference between FFT and its inverse?
13. MATLAB has a function named `fftshift()`. What is its purpose?

**Simulating the Channel** There are several ways to simulated a channel. Here we use a simple AWGN model for our channel. You should be familiar with AWGN channels and signal to noise ratio. You can simply use `awgn` function in MATLAB to simulate this channel model.

14. Describe what is the additive white Gaussian noise model.
15. What are SNR and BER? How do they relate to each other for QAM modulation?

**Observing the Signals** Your first task is to simply plot output of each module described above and calculate some parameters for them, for a certain random input, to show how the signal is created.

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16. Plot the OFDM signal in time domain. Calculate the Peak to Average Power Ratio (PAPR) for the OFDM signal.
17. One of the disadvantages OFDM signal is its high PAPR, why high PAPR is not desirable?
18. Plot the Power Spectral Density (PSD) of the signal, using `pwelch` function in Matlab. (you will get a better result if you first upsample the signal by 2, using `interp` function)
19. How we can calculate the used bandwidth?
20. Plot the constellation of the received symbols (before QAM demodulation).

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**Bit Error Rate** One of the important parameters in data communication, is BER. BER is somehow related to SNR. In this part we want to find and plot this relation. Simulate your code with different values for SNR from 0 to 12 dB and calculate BER for each one by comparing the received and the transmitted bits. Choose your steps tight enough to have a smoother plot. It is better to compare results for a single input data-set (e.g. one series of random data).

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21. Plot BER versus SNR, for above values.
22. What are typical BER and SNR values for typical applications?
23. Which parameters can affect BER, rather than SNR?

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## 3 Involving More Users

Now consider using this method not for a single user, but for 32 different users at different locations. Each user acquires channels i and i+32 for himself and sends his data on that channels. All parts of this problem are as same as before, but the serial to parallel module. This module should, only fill those columns of the matrix which belongs to that user, and fill zeros for others. The signals produced by each user, will sum up in the air, and the result will be given to individual demodulators after going through the channel.

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24. Plot the PSD of the OFDM signal generated by user 10.
25. Plot BER versus SNR as before, for user 10.

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**Orthogonality** The most important feature for a multiple- access is orthogonality. We use this orthogonality as a separation factor, to distinguish different signals from each other. Two signals are orthogonal if integral of their product in a period is zero.

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26. Check to see if the signals for different users are orthogonal to each other or not. For example check signals of user 10 and user 20.

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**Synchronization Problem** Despite all of OFDM advantages, it has some serious disadvantages. This method is very sensitive to synchronization in time and frequency. In a real communication system the output of the matched filter at receiver should be sampled at proper time to maximize the SNR, but due to variable delay in channel and also offset in the clock of the transmitter and receiver, synchronization is a serious problem. In this part we simulate the effect of timing offset by upsampling channel input, shifting the result and finally downsampling. You can use following two lines of code to simulate the timing offset:

```
tmp = interp(chanIn,40);
chanInDelay = decimate(tmp(2:end),40);
```

`chanIn` is OFDM signal at channel input and `chanInDelay` is its delayed version by $0.025T_{sym}$, where $T_{sym}$ is the duration of a symbol in channel.

27. Simulate the OFDMA again and plot the received signal constellation for user 5, 15 and 25. (you can reduce the length of input data if the runtime is high)
28. Calculate the BER for above users.
29. What is the solution to synchronization problem in OFDM systems?

**Inter-Symbol Interference(ISI)** In telecommunication, intersymbol interference (ISI) is a form of distortion of a signal in which one symbol interferes with subsequent symbols. This is an unwanted phenomenon as the previous symbols have similar effect as noise, thus making the communication less reliable. For simulating this problem, we use a filter to interfere symbols manualy. Use this filter for this purpose:

```
chanResp = [1, 0.4, 0.1, 0.01];
chanInISI = filter(chanResp,1, chanIn);
```

`chanResp` is the channel response, where for the given `chanResp`, $i$'th channel output equals:

$$chanInISI[i] = chanIn[i] + 0.6 \times chanIn[i-1] + 0.2 \times chanIn[i-2] + 0.0.1 \times chanIn[i-3]$$

30. Simulate the OFDMA again and plot the received signal constellation for user 5, 15 and 25.
31. Calculate the BER for above users.
32. What is the solution to ISI problem in OFDM systems?

## 4 What SHOULD I prepare?

You must upload a ZIP file containing report in Portable Document Format (.pdf) and MATLAB script (.m) for this assignment. The document should contain answer to each question, any necessary comments and requested plots. The script should be well-coded and clear.
After this homework you must be familiar with OFDM and its applications. Let us know about any problems in questions or understanding the concepts.

## References

[1] [online] Concepts of Orthogonal Frequency Division Multiplexing (OFDM) and 802.11 WLAN

[2] Andrea Goldsmith. 2005. Wireless Communications. Cambridge University Press, New York, NY, USA.