EEP55C28: Digital Wireless Communications Lab

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Lab 1

Wireless Channel: Modelling and Simulations

1.1 Introduction

The main objectives of this lab are to generate random data, modulate/demodulate them using quadrature amplitude modulation (QAM), while we analyse the impact of additive white Gaussian noise (AWGN) and fading channels in MATLAB. At the end of this lab, you should be able to:

1. Implement a QAM modulator and demodulator for different modulation orders.

2. Generate the received signal considering the AWGN channel.

3. Generate wireless channel using the 5G standard channel models.

4. Perform Montecarlo simulations to obtain and plot the bit error rate as a function of signal to noise ratio (SNR) and E_b/N_0.

Communication takes place with real-valued signals (also called passband signals) transmitted from the antenna. As it was discussed in the class, most of the signal processing algorithms at both transmitter and receiver are implemented on the discrete baseband signals. At the transmitter side, these discrete complex baseband signals are up-converted to passband using radio frequency (RF) front ends to enable their transmission off the antenna. At the receiver, all passband signals are down-converted to baseband by the receive RF front end and then they are sampled. Hence, to simulate the communication systems, we implement the equivalent discrete baseband models of the transmitter, the channel and the receiver. Using the equivalent discrete baseband model of the overall system, we can evaluate and analyse the performance of different modulation and signal processing techniques with simulations.

1.2 AWGN Channel

The AWNG channel is the simplest channel model. Since the wireless channel is considered as a random process, the noise introduced by the wireless channel is also considered to be a random process with zero mean (Gaussian process). Therefore, the white noise introduced by the wireless channel is generally known as AWGN. In this exercise, we study the effect of AWGN on the performance of QAM modulation.

The n^{th} sample of the received signal in an AWGN channel can be represented as

$$y[n] = s[n] + v[n], \tag{1.1}$$

where $s[n]$ is the transmitted QAM symbol n and $v[n]$ is the noise sample, which is obtained from the complex Gaussian random variable with zero mean and the variance N_0, i.e., $v[n] \sim \mathcal{CN}(0, N_0)$. It should be noted that $v[n] = v_R[n] + jv_I[n]$ with $v_R[n]$ and $v_I[n]$ as the inp-phase and quadrature components of the noise, respectively, each with the variance $\frac{N_0}{2}$.

Signal-to-Noise Ratio (SNR): If the average transmit symbol energy is E_s, and the noise power spectral density is N_0, the SNR of the received signal, $y[n]$ is

$$\mathrm{SNR} = \frac{E_\mathrm{s}}{N_0}. \tag{1.2}$$

Energy per bit to noise power spectral density (E_b/N_0): Let the order of the modulation be M, i.e., $s[n]$ is obtained by mapping $\log_2(M)$ bits to one of the M symbols in the constellation. Then, $E_\mathrm{s} = \log_2(M)E_\mathrm{b}$, where, E_b is the average energy per bit. Hence,

$$E_b/N_0 = \frac{\text{SNR}}{\log_2(M)}. \tag{1.3}$$

SNR and E_b/N_0 are usually expressed in dB. Hence,

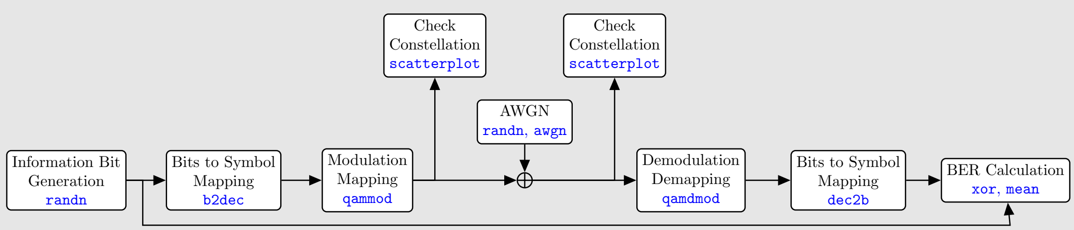
$$\text{SNR}_{\text{dB}} = 10\log_{10}(\text{SNR}), \tag{1.4}$$

$$\left(\frac{E_b}{N_0}\right)_{\text{dB}} = 10\log_{10}\left(\frac{E_b}{N_0}\right), \tag{1.5}$$

$$\left(\frac{E_b}{N_0}\right)_{\text{dB}} = \text{SNR}_{\text{dB}} - 10\log_{10}(\log_2(M)). \tag{1.6}$$

Exercise 1: Effect of AWGN on Signal Constellation

Generate a random information bit sequence and modulate it using $4-$QAM (normalize the signal constellation to unit energy) and then observe the constellation of the transmitted signal. Obtain the received signal for an SNR of 15 dB (calculate the noise variance corresponding to the given SNR). Then, demodulate the received signal and calculate the average number of bits in error or bit error rate (BER) by comparing the detected bits with the transmitted bits. Please refer to the block schematic of the simulation procedure below with the same Matlab functions (and the Matlab documentation) which can aid your simulations.



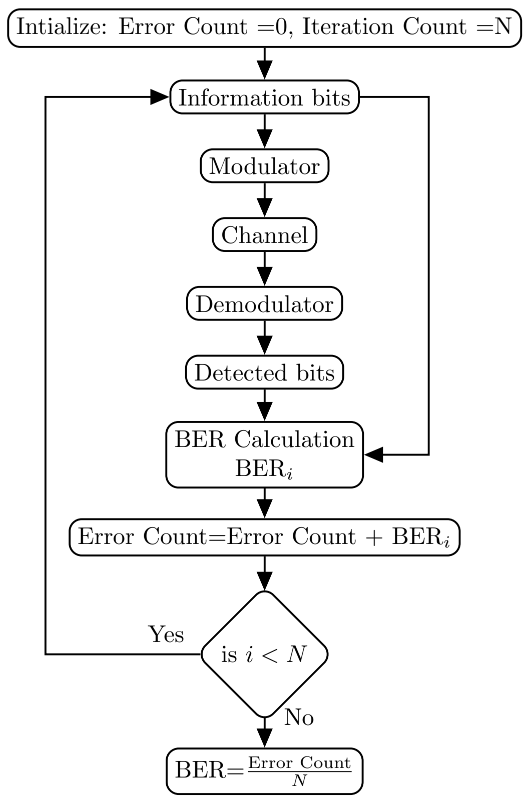
1. What happens to the received signal constellation when SNR is increased?

2. What happens to the BER when the order of modulation is increased?

3. Compare the received signal constellation plots, the BER performance of 4-QAM, 16-QAM and 64-QAM and comment on your observations.

4. Compare the amount of average energy per bit that is required for 4-QAM and 64-QAM to have no more than 1 erroneous bit every 1000 bits.

Flow Chart of Monte Carlo Simulation



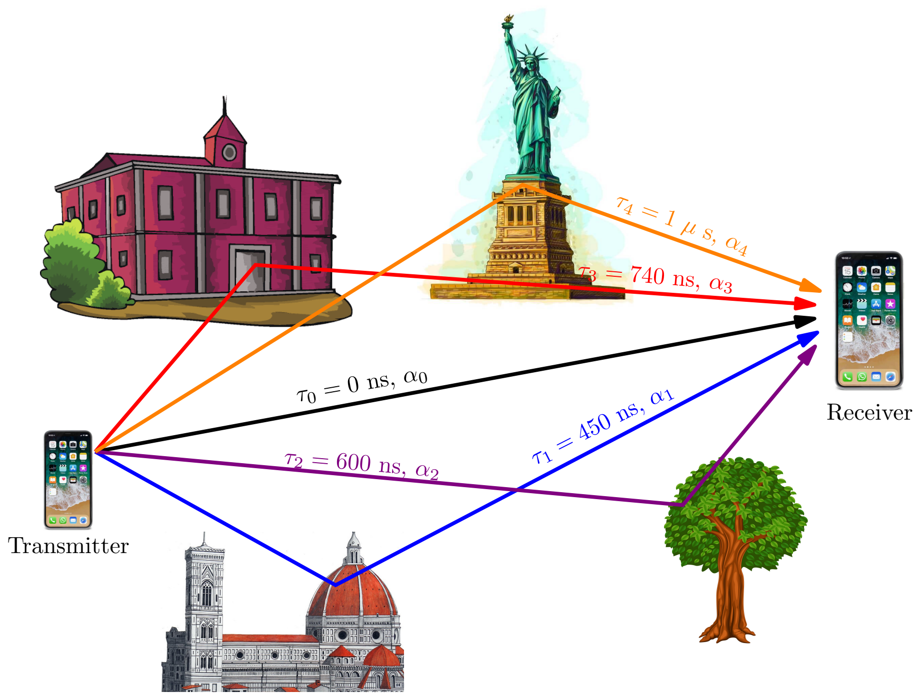


Figure 1.1: Multipath wireless channel.

1.3 Wireless Channel

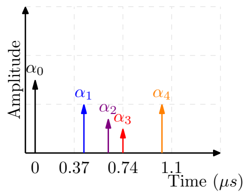
Unlike the wired channel, in a wireless communication system, the transmitted signal reaches the receiver after travelling through multiple paths, see Fig. 1.1. Depending on the length of the path, each received signal copy experiences different delay and attenuation. From Fig. 1.1, it can be seen that there exist 5 different paths from the transmitter to the receiver. For the sake of simplicity, we assumed that the line of sight path (black arrow) has zero delay. Then the received signal can be expressed as

$$y[n] = \alpha_0 s[n] + \alpha_1 s[n-\tau_1] + \alpha_2 s[n-\tau_2] + \alpha_3 s[n-\tau_3] + \alpha_4 s[n-\tau_4] + v[n]. \quad (1.7)$$

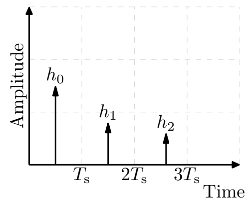
This received signal can also be represented as

$$y[n] = \sum_{i=0}^{P-1} \alpha_i s[n-\tau_i] + v[n] = s[n] * \left(\sum_{i=0}^{P-1} \alpha_i \delta[n-\tau_i] \right) + v[n], \quad (1.8)$$

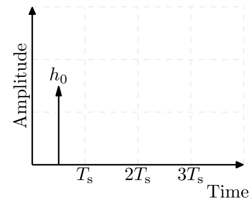
where P is the number of paths in the wireless channel and $\sum_{i=0}^{P-1} \alpha_i \delta[n-\tau_i]$ represents the channel impulse response. For the wireless scenario depicted in Fig. 1.1, if we



(a) Full impulse Response



(b) Bw = 2.7 MHz



(c) Bw = 900 KHz

Figure 1.2: Impulse response for wireless scenario depicted in Fig. 1.1 resolved by receivers with different bandwidths.

assume that an impulse is transmitted at time instant 0, the signal through the black path reaches the destination at the same instant (assumed for the sake of simplicity) and the signal through the blue path reaches the destination after 450 ns. The black path has the lowest delay and the orange path has the highest delay, hence, the delay spread of the multipath channel is

$$T_{\mathrm{m}} = 1 - 0 = 1\ \mu\mathrm{s} \tag{1.9}$$

Even though there exist multiple paths from the transmitter to the receiver, the receiver can separately identify the paths with minimum delay separation of sampling period. The sampling period of a system is determined by its bandwidth i.e., $T_{\mathrm{s}} = 1/W$, where T_{s} is the sampling period and W is the bandwidth. This is illustrated in Fig. 1.2.

Let the bandwidth of the system be $W = 2.7$ MHz, then $T_{\mathrm{s}} = \frac{1}{W} = 0.373\ \mu$s. Then, the receiver will not be able to identify the signal coming through the first two paths (black and blue) in Fig. 1.2a. In other words, the receiver will effectively see them as a single path with delay 0 μs. Similarly, red and purple paths will be seen together with a delay of $2T_{\mathrm{s}} = 0.370\ \mu$s, and the orange path will be separately observed at a delay of $3T_{\mathrm{s}} = 0.740\ \mu$s. Hence the received signal will become

$$y[n] = (\alpha_0 + \alpha_1)s[n] + (\alpha_2 + \alpha_3)s[n-1] + \alpha_4 s[n-2] + v[n]. \tag{1.10}$$

Based on (1.10), even though the channel has 5 paths the receiver will be able to identify only three different delayed signals. Hence, depending on the sampling period of the system the wireless channel can be modelled as a filter with 3 taps where each tap gain depends on the multipath coefficients. Consequently, the received signal can be expressed as

$$y[n] = h_0 s[n] + h_1 s[n-1] + h_2 s[n-2] + v[n], \tag{1.11}$$

where $h_0 = \alpha_0 + \alpha_1$, $h_1 = \alpha_2 + \alpha_3$ and $h_2 = \alpha_4$. Considering the transmit signal bandwidth to be $W = 900$ kHz, then $T_\mathrm{s} = \frac{1}{W} = 1.1$ μs. As a result all of the five paths will be within the $1/W$ interval of the first tap and the received signal will be

$$y[n] = (\alpha_0 + \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4) s[n] + v[n], \tag{1.12}$$

$$y[n] = h_0 s[n] + v[n]. \tag{1.13}$$

It can be observed that in the first scenario, the $T_\mathrm{s} < T_\mathrm{m}$ which resulted in a channel with multiple taps. Such a channel is called a frequency-selective channel. The input-output relationship for the frequency-selective channel is

$$y[n] = \sum_{l=0}^{L-1} h(l) s[n-l] + v[n] = s[n] * \left(\sum_{l=0}^{L-1} h(l) \delta[n-l] \right) + v[n]. \tag{1.14}$$

In the second scenario $T_\mathrm{s} > T_\mathrm{m}$ which resulted in a channel with a single tap, the channel has a frequency-flat response. The input-output relationship for the frequency flat channel is

$$y[n] = h_0 s[n] + v[n]. \tag{1.15}$$

1.4 Simulation of wireless channel

In order to statistically model the wireless channel, we need to specify the following.

1. The number of channel taps and delay of each tap which depends on the sampling period and in turn the signal bandwidth.

2. Power of each delay tap: It is specified by the power delay profile (PDP) of the channel. We take the PDP from the standard channel models, e.g., the 5G channel models TDL-C and TDL-D.

3. Statistical distribution of the delay tap coefficients.

Here, we consider the 5G channel models TDL-C and TDL-D whose PDPs are shown in Fig. 1.3.

Once we specify the system bandwidth, we need to resample this power delay profile to see how many of these taps can be identified by our system. Once we have the new power delay profile based on the signal bandwidth, the channel coefficients can be generated for each channel realization as below.

Generation of Wideband Wireless Channel

Step 1: Fix the sampling period ($T_s = \frac{1}{W}$)

Step 2: Obtain the number of channel taps and the PDP from the standard, i.e, σ_l^2 for all $l = 0, \dots, L-1$, using MATLAB function `interp1` (See Fig. 1.4, which shows how to obtain the PDP for the sampling period from an arbitrary exponential PDP)

Step 3: For all $l = 0, \dots, L-1$, generate $h[l] = h_R[l] + jh_I[l]$, where, $h_R[l] \sim N(0, \sigma_l^2/2)$ and $h_I[l] \sim N(0, \sigma_l^2/2)$. This can be also implemented by $h[l] = \sqrt{\frac{\sigma_l^2}{2}}(h_R[l] + jh_I[l])$, where, $h_R[l] \sim N(0,1)$ and $h_I[l] \sim N(0,1)$.

The channel coefficients generated will have Rayleigh distribution.

Tap #	Normalized delays	Power in [dB]	Fading distribution
1	0	-4.4	Rayleigh
2	0.2099	-1.2	Rayleigh
3	0.2219	-3.5	Rayleigh
4	0.2329	-5.2	Rayleigh
5	0.2176	-2.5	Rayleigh
6	0.6366	0	Rayleigh
7	0.6448	-2.2	Rayleigh
8	0.6560	-3.9	Rayleigh
9	0.6584	-7.4	Rayleigh
10	0.7935	-7.1	Rayleigh
11	0.8213	-10.7	Rayleigh
12	0.9336	-11.1	Rayleigh
13	1.2285	-5.1	Rayleigh
14	1.3083	-6.8	Rayleigh
15	2.1704	-8.7	Rayleigh
16	2.7105	-13.2	Rayleigh
17	4.2589	-13.9	Rayleigh
18	4.6003	-13.9	Rayleigh
19	5.4902	-15.8	Rayleigh
20	5.6077	-17.1	Rayleigh
21	6.3065	-16	Rayleigh
22	6.6374	-15.7	Rayleigh
23	7.0427	-21.6	Rayleigh
24	8.6523	-22.8	Rayleigh

(a) TDL-C

Tap #	Normalized delay	Power in [dB]	Fading distribution
1	0	-0.2	LOS path
	0	-13.5	Rayleigh
2	0.035	-18.8	Rayleigh
3	0.612	-21	Rayleigh
4	1.363	-22.8	Rayleigh
5	1.405	-17.9	Rayleigh
6	1.804	-20.1	Rayleigh
7	2.596	-21.9	Rayleigh
8	1.775	-22.9	Rayleigh
9	4.042	-27.8	Rayleigh
10	7.937	-23.6	Rayleigh
11	9.424	-24.8	Rayleigh
12	9.708	-30.0	Rayleigh
13	12.525	-27.7	Rayleigh
NOTE: The first tap follows a Ricean distribution with a K-factor of K_1 = 13.3 dB and a mean power of 0dB.			

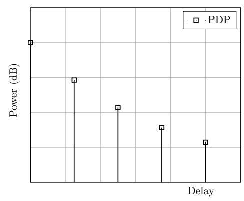
(b) TDL-D

Model	$DS_{desired}$
Very short delay spread	10 ns
Short delay spread	30 ns
Nominal delay spread	100 ns
Long delay spread	300 ns
Very long delay spread	1000 ns

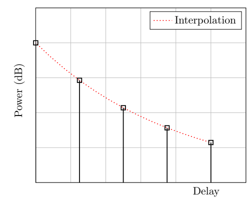
(c) Normalized delay to actual delay conversion

Figure 1.3: 5G channel models [1].

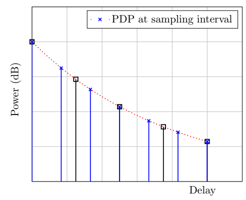
[1] Study on channel model for frequency spectrum above 6 GHz



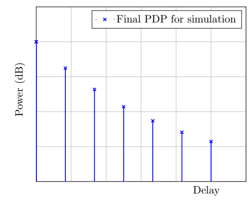
(a) Exponnetial PDP



(b) PDP after interpolating



(c) PDP for the sampling rate



(d) Final PDP

Figure 1.4: Obtaining PDP for simulation from an arbitrary exponentially decaying PDP according to required sampling period.

Exercise 2: Frequency-Selective Fading Channel Simulation

Generate a frequency-selective fading channel using the TDL-C channel model considering the nominal delay spread.

1. With an example show the effect of increasing bandwidth on the delay spread of the channel and the number of taps.
2. With an example show the effect of decreasing bandwidth on the delay spread of the channel and the number of taps.
3. Compare the constellation plots of the received signal in an AWGN channel, frequency-flat and frequency selective channel for an SNR of 15 dB for 4-QAM, 16-QAM and 64-QAM and briefly comment on your observations.

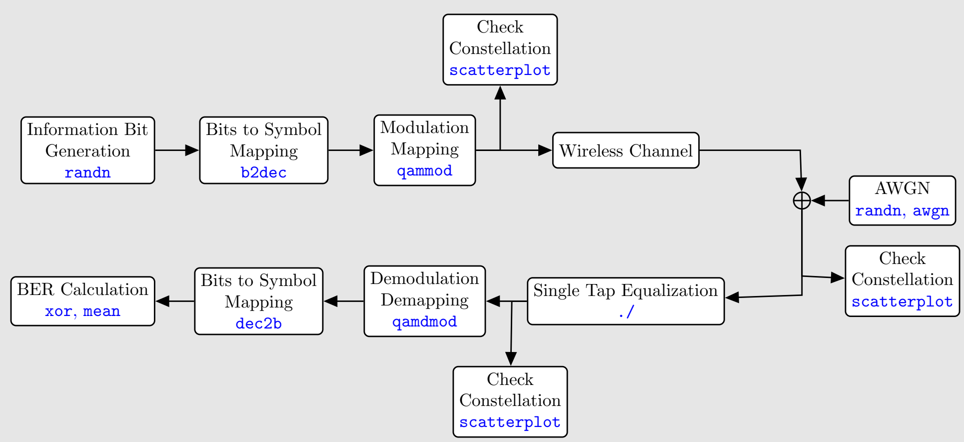
1.5 Channel estimation and equalization

From the received signal described in (1.14) and (1.15) it is clear that in order to detect the transmitted information bits, the receiver needs to know the wireless channel response (h_0 for flat fading channel and $h_0, h_1, \ldots h_{L-1}$ for frequency selective channel). The signal processing performed at the receiver to estimate the channel is called channel estimation. The signal processing technique performed to undo the channel effect is called equalization. Since the channel estimation is beyond the scope of this module, we will only look into the channel equalization.

Considering the flat fading channel the simple multiplication of the channel coefficient with the transmitted signal makes equalization quite simple. The equalization in the flat fading channel can be simply performed by dividing the received signal by the channel coefficient.

Exercise 3: Effect of Flat-Fading Channel on Signal Constellation

Generate a flat-fading Rayleigh channel, (adjust the system bandwidth so that the channel is a single-tap channel). Then, calculate the BER for the system parameters described in Excercise. 1.



1. What happens to the constellation when you increase the SNR?
2. What happens to the BER when the order of modulation is increased?
3. Compare the BER vs SNR curves for an AWGN and flat fading channel and briefly comment on the challenges in a fading channel.

For the frequency-selective channel, due to the convolution operation, channel equalization becomes complex. However, we will learn in the next lab that by using OFDM, as a multi-carrier modulation technique, frequency selective channels can be split into a set of frequency flat sub-channels and simple single-tap equalization per subcarrier can be utilized to equalize the channel.

Lab 2

OFDM: Performance Evaluation

In Lab 1, we learned that channel equalization is quite challenging when the channel is frequency-selective. With the help of multi-carrier modulation techniques, a frequency-selective channel can be converted to a set of frequency-flat sub-channels where single-tap equalization can be deployed. The main objective of this lab is to implement the OFDM transmitter, OFDM receiver with single-tap frequency domain equalization and to evaluate the BER performance. After completing this lab, you should be able to

1. Implement the OFDM modulator and demodulator.
2. Understand the role of cyclic prefix (CP).
3. Implement single-tap frequency domain equalization at the receiver side.
4. Understand the advantage provided by OFDM in a wideband multipath channel.

2.1 OFDM Transmitter

Consider an OFDM system with N subcarriers, and the subcarrier spacing of ΔF. Then, the total signal bandwidth will be $W = N\Delta F$. For such a system,considering the transmit QAM symbols, $x[n]$, each OFDM symbol will consist of N time domain samples which can be expressed as

$$s[k] = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x[n] e^{j2\pi \frac{nk}{N}},\ k = 0, 1, ..., N-1. \tag{2.1}$$

The above equation can be expressed in vector-matrix notation as

$$\mathbf{s} = \mathbf{F}_N^{\mathrm{H}} \mathbf{x}, \tag{2.2}$$

where

$$\mathbf{s} = \begin{bmatrix} s[0] \\ s[1] \\ \vdots \\ s[N-1] \end{bmatrix}, \ \mathbf{x} = \begin{bmatrix} x[0] \\ x[1] \\ \vdots \\ x[N-1] \end{bmatrix} \tag{2.3}$$

and the $(k,n)^{\mathrm{th}}$ element of the normalized DFT matrix is $\mathbf{F}_N[k,n] = \frac{1}{\sqrt{N}} e^{-j2\pi \frac{kn}{N}}$. In MATLAB, $mathbf F_N$ can also be generated using `(1/sqrt(`N`))*dftmtx(`N`)`.

Cyclic Prefix

After generating the time domain signal, a cyclic prefix (CP) of length N_{CP} is appended to the beginning of $\mathbf{s}$ to form the transmit signal of length $N + N_{\mathrm{cp}}$, i.e.,

$$\mathbf{s}_{\mathrm{tx}} = \begin{bmatrix} s[N_{\mathrm{CP}}-1] \\ s[N_{\mathrm{CP}}-2] \\ \vdots \\ s[N-1] \\ s[0] \\ s[1] \\ \vdots \\ s[N-1] \end{bmatrix}. \tag{2.4}$$

The transmit signal $\mathbf{s}_{\mathrm{tx}}$ can be also obtained by matrix multiplication as

$$\mathbf{s}_{\mathrm{tx}} = \mathbf{A}_{\mathrm{CP}} \mathbf{s}, \tag{2.5}$$

where $\mathbf{A}_{\mathrm{CP}} = \begin{bmatrix} \mathbf{I}'_N \\ \mathbf{I}_N \end{bmatrix}$, $\mathbf{I}_N$ is an identity matrix of size N and $\mathbf{I}'_N$ is formed by the last N_{CP} rows of $\mathbf{I}_N$.

2.2 Wireless Channel

The wireless channel can be generated with the same procedure as in Lab 1 with a bandwidth $W = N\Delta F$. Let the generated wireless channel has L taps, $\mathbf{h} = \begin{bmatrix} h[0] \\ h[1] \\ \vdots \\ h[L-1] \end{bmatrix}$.

Then, the received signal can be expressed as

$$y_{\text{rx}}[n] = \sum_{l=0}^{L-1} h[l] s_{\text{tx}}[n-l] + v[n],\ n = 0, 1, \ldots, N + N_{\text{cp}} - 1 \tag{2.6}$$

This can be represented in vector-matrix notation as

$$\mathbf{y}_{\text{rx}} = \mathbf{H}_{\text{t}} \mathbf{s}_{\text{tx}} + \mathbf{v}, \tag{2.7}$$

where $\mathbf{v} = \begin{bmatrix} v[0] \\ v[1] \\ \vdots \\ v[N-1] \end{bmatrix}$ is the AWGN noise vector and $\mathbf{H}_{\text{t}}$ is the time domain channel convolution matrix. As it was explained in the class, matrix is described as

$$\mathbf{H}_{\text{t}} = \begin{bmatrix} h[0] & 0 & 0 & 0 & 0 & \ldots & 0 & 0 \\ h[1] & h[0] & 0 & 0 & 0 & \ldots & 0 & 0 \\ h[2] & h[1] & h[0] & 0 & 0 & \ldots & 0 & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots & \ldots & 0 & \vdots \\ h[L-1] & h[L-2] & \ldots & \ddots & h[0] & \ldots & 0 & 0 \\ 0 & h[L-1] & h[L-2] & \ldots & \ddots & h[0] & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & h[L-1] & \ldots & h[1] & h[0] \end{bmatrix}. \tag{2.8}$$

It can be observed that $\mathbf{H}_{\text{t}}$ is a convolution matrix of size $(N + N_{\text{cp}}) \times (N + N_{\text{cp}})$. This matrix is obtained by appending $N + N_{\text{CP}} - L$ zeros to $\mathbf{h}$ and then shifting it downwards at each column to form the $N + N_{\text{CP}}$ columns .

2.3 Receiver

At the receiver, the first operation is removing the cyclic prefix from the received signal vector $\mathbf{y}$. Then OFDM demodulation is performed.

Removing cyclic prefix

The received signal after cyclic prefix removal can be expressed as

$$y[n] = y_{\mathrm{rx}}[N_{\mathrm{CP}} + n],\ n = 1, 2, \ldots, N. \tag{2.9}$$

This operation can be expressed in matrix form as

$$\mathbf{y} = \mathbf{R}_{\mathrm{CP}}\mathbf{y}_{\mathrm{rx}}, \tag{2.10}$$

where $\mathbf{R}_{\mathrm{CP}} = [\mathbf{0}_{N\times N_{\mathrm{CP}}}, \mathbf{I}_N]$, and $\mathbf{0}_{N\times N_{\mathrm{CP}}}$ is zero matrix of size $N \times N_{\mathrm{CP}}$.

OFDM Demodulation

After removing the CP, OFDM demodulation is performed to convert the time domain signal to the frequency domain, i.e., the received samples in frequency domain can be expressed as

$$r[n] = \frac{1}{\sqrt{N}}\sum_{m=0}^{N-1} y[m]e^{-j2\pi\frac{mn}{N}},\ n = 0, 1, ..., N-1. \tag{2.11}$$

Using the DFT matrix, $\mathbf{F}_N$, (2.11) can be also expressed as

$$\mathbf{r} = \mathbf{F}_{\mathrm{N}}\mathbf{y} \tag{2.12}$$

Combining (2.2), (2.5), (2.7), (2.10) and (2.12), the received signal in the frequency domain can be expressed as

$$\mathbf{r} = \mathbf{F}_{\mathrm{N}}\mathbf{R}_{\mathrm{CP}}\mathbf{H}_{\mathrm{t}}\mathbf{A}_{\mathrm{CP}}\mathbf{F}_N^{\mathrm{H}}\mathbf{x} + \mathbf{F}_{\mathrm{N}}\mathbf{R}_{\mathrm{CP}}\mathbf{v} \tag{2.13}$$

$$= \mathbf{H}_{\mathrm{f}}\mathbf{x} + \tilde{\mathbf{v}} \tag{2.14}$$

It can be observed that the matrix $\mathbf{R}_{\mathrm{CP}}\mathbf{H}_{\mathrm{t}}\mathbf{A}_{\mathrm{CP}}$ is a circulant matrix. Due to the property of DFT matrix and circulant matrix, $\mathbf{H}_{\mathrm{f}} = \mathbf{F}_{\mathrm{N}}\left(\mathbf{R}_{\mathrm{CP}}\mathbf{H}_{\mathrm{t}}\mathbf{A}_{\mathrm{CP}}\right)\mathbf{F}_N^{\mathrm{H}}$ is a diagonal

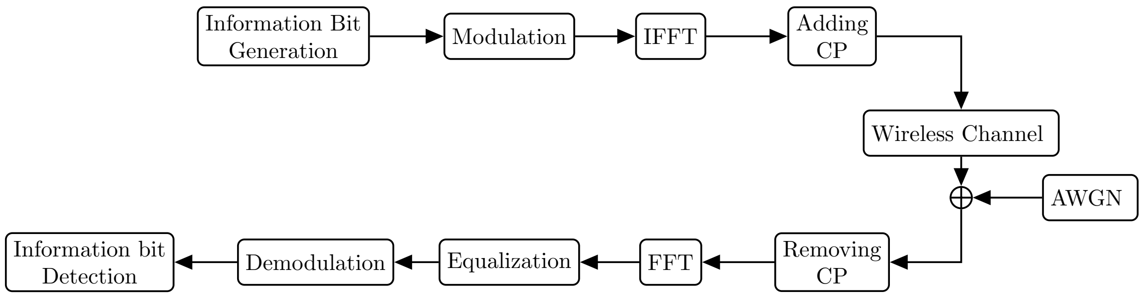


Figure 2.1: OFDM system diagram.

matrix with the diagonal elements as the N point DFT of $\mathbf{h}$ that is zero-padded to have the length equal to N. Since $\mathbf{H}_\mathrm{f}$ is diagonal, equalization can be easily performed by dividing each element of $\mathbf{r}$ by the corresponding diagonal elements of $\mathbf{H}_\mathrm{f}$, i.e., single-tap equalization. The equalized symbol in the n^{th} subcarrier can be expressed as

$$\tilde{r}[n] = \frac{r[n]}{H_\mathrm{f}[n,n]}. \tag{2.15}$$

Once we obtained the equalized received signal vector, QAM demodulation can be performed to estimate the transmitted information bits. The block schematic for the simulation of the OFDM system diagram is shown in Fig. 2.1.

Exercise 1: OFDM System in AWGN Channel

Implement an OFDM system with $N = 64$ subcarriers and bandwidth $W = \frac{i}{50}$ in MHz, where i is the last two digits of your student number. Use $4-$QAM as the modulation scheme. Perform the OFDM demodulation in an AWGN channel for SNRs ranging from 0 dB to 20 dB using Monte Carlo simulation runs and plot the resulting BER.

1. What is the subcarrier spacing, duration of transmitted OFDM symbol and duration of CP in seconds?

2. Compare the results with a 4-QAM BER in AWGN channel and comment on your observations.

2. Change the CP length and comment on its effect in AWGN channel.

Exercise 2: OFDM System in Frequency-Selective Channel

Implement the OFDM system with parameters specified in Exercise 1 in a frequency-selective channel. Perform the simulations for a wireless channel, using the TDL-C channel model from Lab 1, with nominal delay spread and short delay spread (refer to Fig. 1.3). Plot the BER for SNR ranging from 0 to 30 dB in both scenarios.

1. Compare the BER results for 4-QAM in AWGN Channel and comment on your observations.
2. What is the minimum CP length required in the channel with nominal delay spread and the channel with short delay spread?
3. What happens to the BER when having insufficient CP length?