EE 1473 – Digital Communication Systems
Spring 2019 Simulation Project

In this project, you and a partner will perform an end-to-end simulation of a digital communication system in MATLAB or Simulink. The goals are to visualize signals at various points in the system, and to compare the performance of your system in simulation to theory.

Your simulation must include all of the following elements.

- Generation of random data.
- Baseband signaling.
- Digital modulation.
- Channel effects.
- Demodulation.
- Optimal detection.
- Visualization of signals and spectra.
- Bit error rate calculation and comparison to expected results.

These elements are described below. You will implement each of the elements with one or more MATLAB functions or Simulink blocks, and create MATLAB scripts or Simulink models that call these functions to generate the required results.

The project will culminate with a paper, due near the end of the term, describing the system you have simulated, and the results. Along the way, some of the homework assignments will require you to complete portions of the overall system, and you should look to those assignments for refinements to the system requirements given here.

You should begin by selecting a partner to work with if you have not already done so. You may work alone if wish, but this will make your task more challenging.

Generation of Random Data

Use the `rand` function in MATLAB to create a vector of numbers in the range [0, 1], and round them to 0 or 1. If implemented correctly, this will produce a pseudo-random data sequence for which 0 and 1 are equally likely. Also, it will be reasonable to model each bit as independent of all others.

When using your code to visualize signals, it will be a good idea to use a short data sequence (e.g., 16 bits). But when using your code to calculate bit error rates, you will have to use much longer sequences.

Baseband Signaling

This is the process of creating a baseband signal to represent the random bits. You may choose any of the various line codes we have discussed, or make up your own, and you may use any pulse shape that you choose. But these choices will impact every other element in the system (e.g., intersymbol interference), so you should choose carefully. Also, your baseband signal will be a two-level signal if you choose one of the binary modulation formats (OOK, BPSK, BFSK, etc.), but it will be a multilevel signal if you are choosing one of the multilevel modulation formats (M-ASK, QPSK, QAM, etc.).

In order to accurately represent the shape of the baseband waveform, both for the purposes of visualization and performance analysis, it will be necessary to compute the value of the waveform at multiple instants for each bit (or each symbol in the case of multilevel signaling). The number of samples computed for each bit should be a parameter that is passed to the MATLAB function responsible for binary signaling, to make it easy to change this value. It would be a good idea to compute at least eight samples per bit.

Digital Modulation

You will be assigned one of the digital modulation formats for your system. Each one will have certain parameters that you will be able to choose. The choice of these parameters, as well as the properties of the baseband signal, will affect the spectrum of the modulated signal. The modulated signal must be appropriate for the channel, the specifications for which are as follows.

- The center frequency is 10 kHz, and the channel bandwidth is 10 kHz. The total in-band normalized signal power may not exceed 1 Watt.
- For frequencies that are 5-8 kHz above or below the center frequency, the PSD of the modulated signal must be at least 20 dB below the in-band PSD level.
- For frequencies that are more than 8 kHz above or below the center frequency, the PSD of the modulated signal must be at least 55 dB below the in-band PSD level.

The above standard is modeled after the FCC requirements for a radio channel, but adjusted to fit within the bandwidth that can be produced by a computer sound card. If you find that your modulated signal violates the above specification only slightly, then you may be able to correct the problem through filtering. But if the violation is significant, then you will need to change some of the parameters of the baseband signaling or digital modulation blocks until the specification is met.

You will need to compute values of the modulated signal at multiple instants per period; at least eight samples per period will ensure that the modulated waveform is reasonably accurate for visualization and performance analysis. This requirement may exceed that for the baseband signal, in which case you may want to increase the sampling density of the baseband waveform to match that of the modulated waveform.

In case this is confusing, consider the following example. Suppose you wish to simulate the transmission of $N = 10$ bits over the channel at a bit rate of $R = 500$ bps using a binary modulation scheme such as OOK. Then both the baseband and modulated signals will consist of $T_b = 2$ ms of simulated time for each bit, for a total of 20 ms of simulated time for the entire data sequence. Using eight samples per bit, you would have to compute the baseband signal with a minimum time step of $\Delta t = \frac{1}{8}(2 \text{ ms}) = 250\ \mu\text{s}$. But, at a carrier frequency of 10 kHz, the period of the modulated waveform is $100\ \mu\text{s}$. Therefore, using eight samples per period, you would have to compute the modulated waveform with a time step of $\Delta t = 12.5\ \mu\text{s}$, and you may find it easier to also use this value for the baseband waveform. To represent 20 ms of simulated time, each signal will be represented by a vector containing 1600 signal samples.

Channel Modeling

There are many different kinds of channels, and each will have its own characteristics. Some will have a frequency response that will introduce significant amplitude or phase distortion, many will introduce adjacent-channel interference, and all will have some type of additive noise. For the purpose of this project, you should begin by modeling the channel as simply adding white Gaussian noise. You should write your code so that the power level of the noise can be easily changed. Your code should then calculate the corresponding noise variance, and use the `randn` function in MATLAB to generate noise samples. You will have to vary the noise power in order to determine the bit error rate of your system as a function of E_b/N_0.

Additional channel effects, such as filtering, distortion and interference, can also be implemented in MATLAB. You may choose to add these elements to your project at your discretion.

Demodulation and Optimal Detection.

The demodulation block must reverse the modulation process to extract the baseband signal. The demodulation scheme will of course depend on the type of modulation you choose, and there are a variety of choices of demodulation for each type of modulation. You are required to implement the optimal receiver for whatever kind of modulation you are using, but you are free to investigate additional options for the purposes of comparison. You may choose to simulate the behavior of a classic circuit such as the envelope detector, or you may choose something that could only be implemented in software. This block leaves the greatest amount of freedom in terms of design choices, and will greatly impact the performance of your systems.

The demodulation block will reproduce a version of the baseband signal, but it will be somewhat different from the original baseband signal due to the effects of noise and filtering. The next step will be to apply a detection scheme to determine whether each bit is a 0 or 1, or in the case of multilevel signaling, to determine the value of each symbol.

To decide on the value of each bit or symbol, you should implement a detection scheme that is optimal for the type of signaling you used. For the case of binary signaling, and under the assumption that the baseband channel can be modeled as simply adding WGN, the optimal detector samples the signal at an appropriate time, compares the sampled value to a threshold, and assigns a bit value based on whether the sample value is above or below the threshold. Multilevel signaling is a bit more complicated, as there will be many thresholds with which to compare the sample values.

The key here, of course, is what is the appropriate time to sample each signal? For optimal detection, you must sample each signal in the middle of the bit period or symbol period. Because this is a simulation, you may assign the time $t = 0$ to any point in the signal you choose, and if you choose wisely, finding the proper sample times will be relatively easy.

Visualization of signals and spectra

One goal of the project is to be able to visualize the signals at every stage of the system. Specifically, you must present plots of the baseband signal at the input to the modulator, modulated signal at the input to the channel, noisy modulated signal at the output of the channel, and noisy baseband signal at the output of the demodulator. For the signals that include noise, you should present a few examples at different noise levels.

For all of these plots, it would be a good idea to keep the number of bits small, so that the reader will be able to see the relationships between signals, and see the times where bit transitions occur. It may be necessary to present the same plots on multiple time scales in order to illustrate all of the relevant signal properties.

In addition to the plots described above, you should present a plot of the PSD of the modulated signal, to confirm that it meets the channel specification. In order to do this, you will need to use a longer data sequence and repeat the experiment many times, in order to ensure that your simulated PSD is a reasonable approximation of the actual PSD.

Finally, it would be a good idea to make it easy to disable plotting of the various signals when determining the PSD of the modulated signal, and when calculating the bit error rate as described below, so that your code will run faster.

Bit Error Rate Calculation

This simply means that you should compare the data sequence recovered through optimal detection to the original data sequence, count the number of bits or symbols in error, and divide by the total number of bits or symbols. If you used multilevel signaling, then multiply the symbol error rate by the number of bits per symbol to determine the BER.

For each noise level, you will have to repeat the experiment many times with different data sequences to ensure that your estimate of the BER is reasonably accurate. Then you should prepare a plot of BER versus E_b/N_0, and also plot on the same axes the corresponding theoretical expression of P_e as a function of E_b/N_0, or an appropriate bound on this performance, as provided in Couch Chapter 7.

Finally, evaluate the performance of your simulated system by discussing how close your BER curve is to the theoretical curve, and by comparing the bit rate of your system to the Shannon capacity of the channel.

Project Report - Due Thursday, April 18, 2019

You will write a report summarizing the results of your project. There is no requirement that the report be of any specified length. Just make sure to fully describe all of the various components, and all of the relevant results. Don't go overboard on length. I will be more impressed your ability to communicate ideas concisely than by the number of pages in your report.

Include all of the plots described above, and any others you feel are helpful to understanding your system and its performance. Omit figures if they do not significantly enhance the reader's understanding, and you **must** discuss any figure you present in the body of the report (not just in the caption). Tell the reader what is significant about the figure and why.

Remember that plagiarism is a serious offense and will not be tolerated. If you make use of any source for ideas that are part of your simulation and/or report, then this source must be included in the list of references at the end of the report. You may use printed sources as well as internet sources, and each must be listed in your bibliography using an appropriate fomrat, so that I can look them up myself. Reports that list no sources at all are not acceptable. Also, if you directly copy a figure, table or other item from any source, then in addition to including that source in your list of references, you must provide a direct citation of the source in the caption of the figure that appears in your report (e.g., Figure 4: Block diagram of … courtesy of [3]). Violation of these rules will be grounds for receiving grade of zero for the project, and possibly a failing grade for the semester.