ELEX 7860 : Wireless System Design
2021 Winter Term

Communication System Simulation

Introduction

Computer simulations are the most practical way to predict the performance of modern communication systems. These simulations can include the effects of complex processing such as FEC and impairments such as fading.

Simulations of communication systems operate on sampled signals. For example, we can generate random bits and random noise samples and apply the same operations on these signals that an actual transmitter, channel and receiver would[1]. Then we can measure the performance (e.g. the BER) of the simulated system.

Such computer simulations are typically written in a programming language such as C or Matlab using libraries of functions that perform various signal processing functions such as signal and noise generation, filtering, modulation, coding, etc.

In this lab you will simulate the operation of a communication system that uses bipolar NRZ signalling over an AWGN channel together with a rate-$\frac{1}{2}$ convolutional encoder and a Viterbi decoder. You will compare the BER vs. E_b/N_0 curves for systems with and without FEC and determine the coding gain at different BERs.

E_b/N_0

E_b/N_0 is the "metric" (numerical value) used to compare the power efficiency of communication systems operating over AWGN channels. It is the ratio of the energy per information bit[2], (E_b) to the noise power spectral density (N_0).

Comparing systems on the basis of E_b/N_0 rather than the signal-to-noise power ratio (SNR) allows us to compare systems that may transmit at different rates (e.g. due to using FEC or multi-level signalling) or that use different bandwidths (e.g. due to using different modulation).

[1] These simulations are sometimes called "Monte-Carlo" simulations because they use randomly-chosen data.

[2] Information bits do not include the parity bits used for FEC.

Assume that both the signal and noise are strictly bandlimited to a bandwidth B and that we sample at the Nyquist rate $f_s = 2B$. We can convert the signal power S to bit energy E_b by multiplying by the information bit period or by dividing by the information bit rate f_b. We can compute the noise power spectral density, N_0 by dividing the noise power, N, by the bandwidth $B = f_s/2$. Thus:

$$\frac{E_b}{N_0} = \frac{S}{N} \cdot \frac{f_s}{2f_b}$$

With one sample per information bit ($f_b = f_s$), E_b/N_0 is half of the SNR (–3 dB). When using a rate-$\frac{1}{2}$ code the information bit rate (f_b) is halved and E_b/N_0 is equal to the SNR.

For bipolar NRZ with signal levels of ± 1 the value of S is 1 and for AWGN the value of N is σ^2 (the variance).

Procedure

In this lab we will use Gnu Radio Companion to set up and run simulations.

You will build two simulation flowgraphs. The first generates a PRBS, converts the 0,1-valued bits to ± 1, adds zero-mean AWGN with a configurable standard deviation (RMS voltage), applies a threshold (at 0 V) to the sum of the signal plus noise, and compares the transmitted and received bits to measure the error rate. The diagram in figure 1 shows the flowgraph.

An example of a flowgraph created by GRC is shown in Figure 1.

The second flowgraph adds a convolutional FEC encoder before the channel and a Viterbi FEC decoder after the channel. The decoder corrects some errors thus reducing the BER. This provides a "coding gain" as explained in the lectures.

Predictions and Measurements

Prepare a spreadsheet showing the signal and noise RMS voltages, the SNR, and the predicted the BER as a function of SNR when no FEC coding is used. The SNR can be computed as:

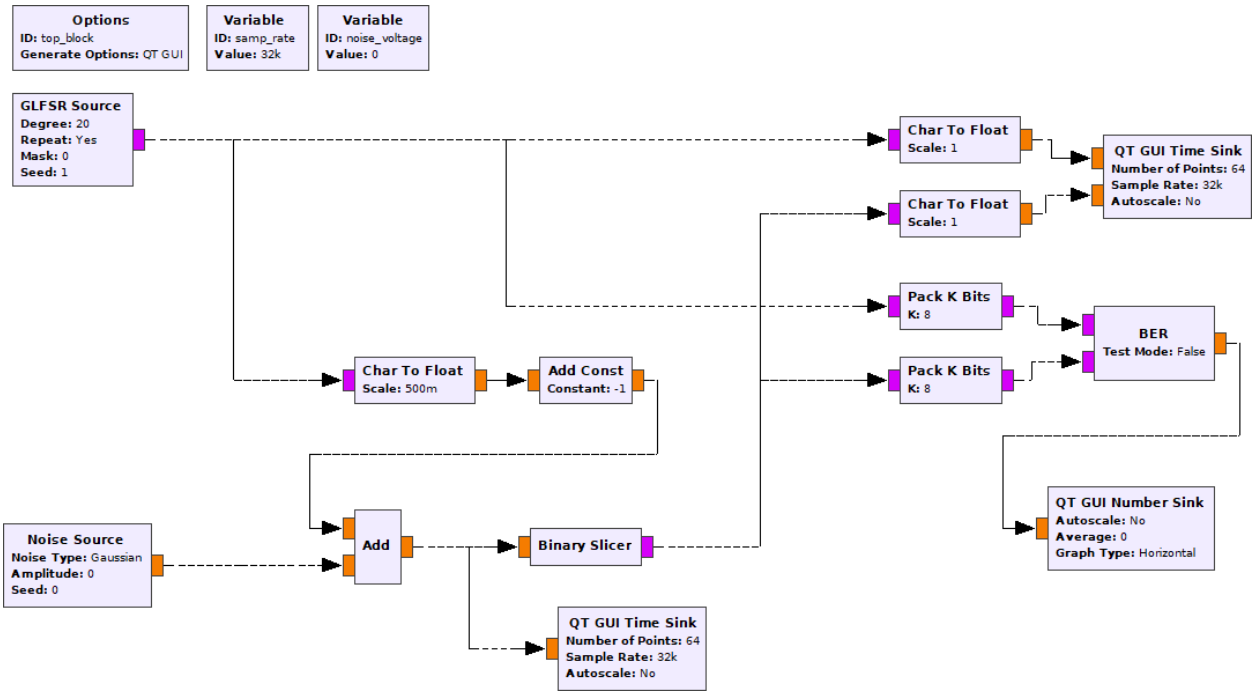


Figure 1: GNU Radio Companion flowgraph for bipolar NRZ over AWGN channel without FEC.

$$\text{SNR} = t^2 = \left(\frac{\pm 1}{\sigma}\right)^2 \quad \text{or} \quad -20\log_{10}(\sigma) \ \text{(dB)}$$

You can compute the BER for bipolar NRZ (without FEC) by computing the probability that a Gaussian random variable x (the noise) exceeds the normalized threshold t where $t = 1/\sigma$ using the Q-function:

$$Q(t) = P(x > t) = \frac{1}{2}\text{erfc}\left(\frac{t}{\sqrt{2}}\right)$$

Include values of SNR in your spreadsheet from about 0 to 14 dB.

Add columns in your spreadsheet showing the corresponding value of E_b/N_0 with and without rate-$\frac{1}{2}$ FEC and for the measured $\log_{10}$(BER) with and without FEC.

	A	B	C	D	E	F	G
1	signal voltage	noise voltage	SNR and Eb/No with FEC	Eb/No without FEC	predicted log(BER) without FEC	measured log(BER) without FEC	measured log(BER) with FEC
2	μ	σ	*t*				
3	Vrms	Vrms	dB	dB			
4	1	1.000	0.0	-3.0	-0.8		
5	1	0.891	1.0	-2.0	-0.9		
6	1	0.794	2.0	-1.0	-1.0		
7	1	0.708	3.0	0.0	-1.1		
8	1	0.631	4.0	1.0	-1.2		
9	1	0.562	5.0	2.0	-1.4		
10	1	0.501	6.0	3.0	-1.6		
11	1	0.447	7.0	4.0	-1.9		
12	1	0.398	8.0	5.0	-2.2		
13	1	0.355	9.0	6.0	-2.6		
14	1	0.316	10.0	7.0	-3.1		
15	1	0.282	11.0	8.0	-3.7		
16	1	0.251	12.0	9.0	-4.5		
17	1	0.224	13.0	10.0	-5.4		
18	1	0.200	14.0	11.0	-6.6		

Using GRC

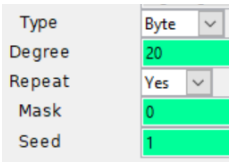
Start GRC. Under the View menu enable the Block Tree Panel, Console Panel and Variable Editor. Make sure 'Hide Variables' is not checked.

Configure the First Flowgraph

Use the File ▶ Open menu item to start a new QT GUI box. Then add, configure and connect up the following blocks:

Variable Add a variable with ID `noise_voltage`. This will be used to set the RMS voltage (which is the standard deviation, σ) of the noise.

GLFSR Source This block generates a pseudo-random bit sequence (PRBS). Configure this block as follows:

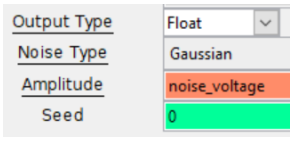


Degree is N, the number of bits in the shift register. The sequence repeats after $2^N - 1$ bits. Use a value that is large enough to test the blocks in your simulation. The value used here is $N = 20$ which will generate a PRBS of about 1 million bits and whose longest run of 1's is 20 bits. **Mask** defines the LFSR taps. If left as 0, a suitable generator polynomial for the specified degree will be chosen.

Type Conversions Various conversions from bits to floating point values will be required. For example, the **GLFSR Source** is configured to output bits (stored in the least-significant bit of each byte) but these need to be converted to Float values for transmission over an AWGN channel. Add a **Char To Float** block wherever this conversion is required.

Since the input to the BER counter is packed bytes (8 bits/byte), a block is required to pack 8 1-bit values to one 8-bit byte. Add and configure **Pack K Bits** blocks with $K = 8$.

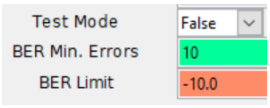
Noise Source Add a Gaussian noise source with a Float output whose amplitude is set by the variable `noise_voltage`. It is configured as follows:



AWGN channel The AWGN channel is composed of three blocks: **Char To Float** converts 0/1 values to Float values and scales by $\frac{1}{2}$ to produce values of 0 and 2 (the scaling value is in the denominator). The **Add Const** adds -1 to produce values of -1 and 1. The **Add** block adds the noise to the signal. These blocks should have types set to Float and Vec(tor) lengths of 1 sample.

Binary Slicer This block compares the input to a threshold at 0 and outputs bits that are 0 or 1.

BER This block compares sequences of byte inputs and computes the number of bits that differ. The output is the log of the bit error rate as a floating point number. The computation includes all bits since the start of the simulation.



QT GUI Time Sink This block is similar to an oscilloscope and displays a graph of the input sample values as a function of time. These can be used to verify that the simulation is operating as expected. Two of these are included in the flowgraph below. One displays the output of the channel (signal plus noise). The second displays the bits into the transmitter and out of the receiver.

QT GUI Number Sink This block displays a single number while the simulation is running. It can show the value as bar graph.

Both GUI blocks have configuration options for how they should be displayed in the window that is created when the flowgraph executes. In addition to input types, ranges, labels, etc, the **GUI Hint** provides some control over the positioning of the GUI elements within tabs. For example, a hint of `[1,2]` means to place that GUI element on the first row, second column.

Measure the BER

Double-click on the **noise_voltage** block or that line on the variables sub-window and set the noise RMS voltage to the first value in your spreadsheet.

Select Run ▶ Execute, press F6, or press on the run (▷) icon. This will convert the flowgraph to a Python script and run it.

The GUI will show the bits at the input to the transmitter, the output of the receiver and the output of the channel. The GUI Number Sink will display $\log_{10}$ of the BER.

Wait until the BER appears stable and record the value. Take a screen capture of the GUI window, then close the GUI window to stop the simulation.

Repeat the steps above, except for the screen capture, for the other E_b/N_0 values in your spreadsheet and verify that the results match your predictions.

Select File ▶ Screen Capture to save an image file showing your flowgraph.

Add FEC

Save and copy the `.grc` file to a new file and modify the flowgraph by adding the following FEC components as shown in Figure 2.

CC Encoder/Decoder Definition These blocks define the convolutional code used by the encoder and decoder. You can define constraint length (K), rate (R) and the generator polynomials used to generate the two output bits. The current implementation is limited to the standard rate-$\frac{1}{2}$ convolutional encoder described in the lecture notes.

Configure these blocks as follows:

ID	encoder
Parallelism	0
Frame Bits	2048
Constraint Length (K)	7
Rate Inverse (1/R) (1/2)	2
Polynomials	[79,109]
Start State	0
Streaming Behavior	Streaming
Byte Padding	No

ID	decoder
Parallelism	0
Frame Bits	2048
Constraint Length (K)	7
Rate Inverse (1/R) (1/2)	2
Polynomials	[79,109]
Start State	0
End State	-1
Streaming Behavior	Streaming
Byte Padding	No

The mode should be set to "streaming" (the other modes are for packet-based systems where the shift-register needs to be flushed).

FEC Extended Encoder/Decoder These blocks perform the encoding and decoding as configured by the encoder and decoder definitions. The encoder has unpacked bits as input and ouput. The decoder expects float input (± 1) and generates unpacked bits as output. Configure these blocks as follows:

Encoder Objects	encoder
Threading Type	None
Puncture Pattern	'11'

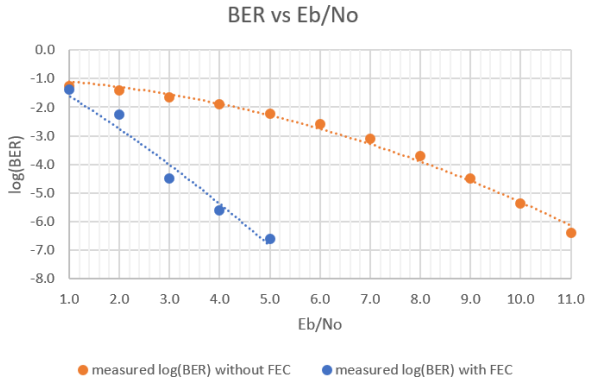
Decoder Objects	decoder
Threading Type	None
Annihilator	None
Puncture Pattern	'11'

Re-Measure the BER

Re-measure the BER vs E_b/N_0 and add the data to your spreadsheet.

Select File ▶ Screen Capture to get an image file showing your second flowchart.

Plot BER vs E_b/N_0 with and without FEC on the same graph. Your graph might look something like:



Lab Report

Plot the measured BER without FEC and the measured BER with FEC against E_b/N_0.

Use the graph to estimate the coding gains at BERs of 10^{-2} and 10^{-6}.

Submit a report in PDF format to the appropriate dropbox on the course web site containing the following:

- your two flowchart diagrams
- your screen capture of the run-time GUI window showing the signal on the channel, the input and output bits and the $\log_{10}$(BER) value
- the spreadsheet showing your data
- the plot with two curves showing BER vs E_b/N_0 with and without FEC
- your calculations of the coding gains for BERs of 10^{-2} and 10^{-6}.

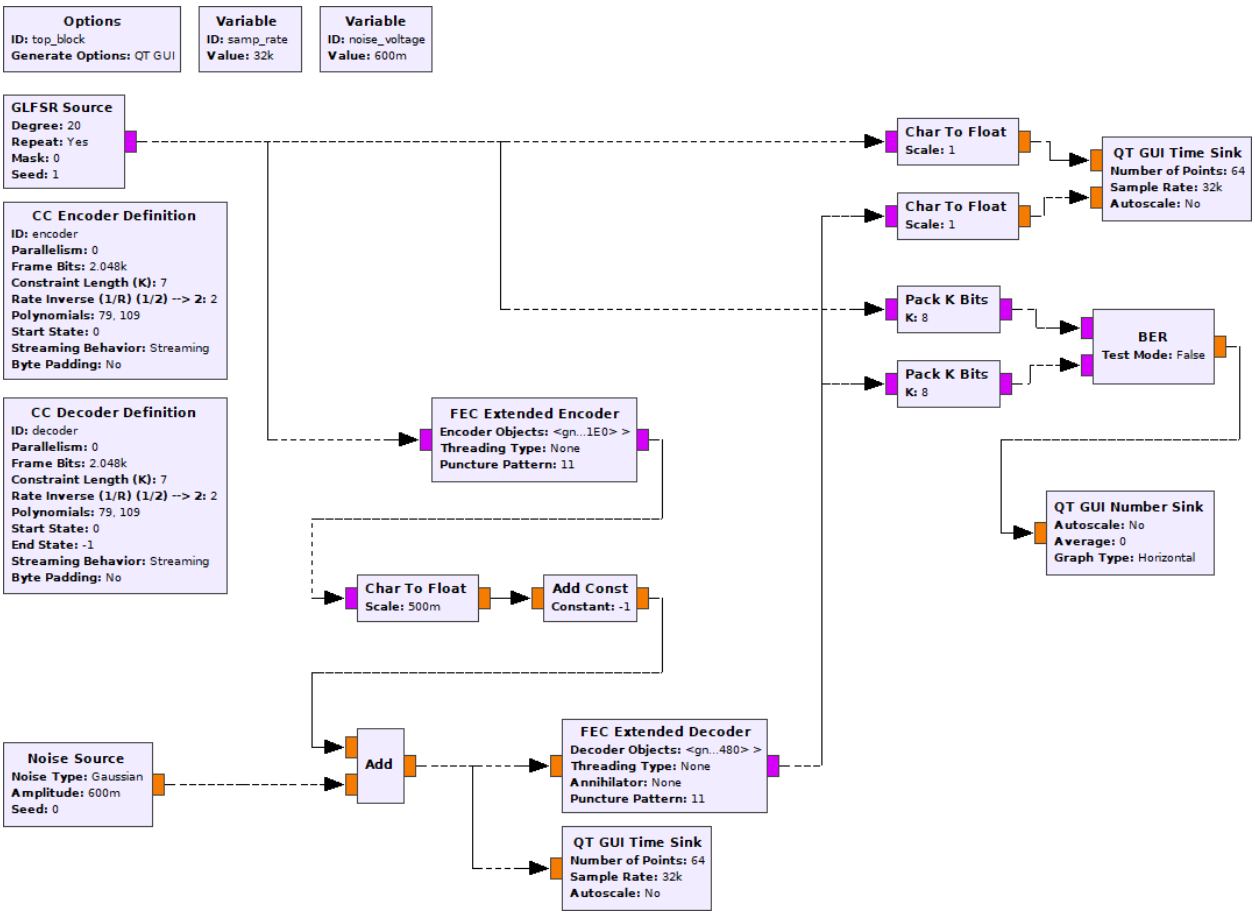


Figure 2: GNU Radio flowgraph for bipolar NRZ over AWGN channel with convolutional FEC code and Viterbi decoder.