ELG3175: Introduction to Communication Systems

Laboratory IV: Binary PAM and PCM

Introduction:

In this lab we will explore some of the fundamentals of binary pulse amplitude modulation signals and pulse code modulation.

References:

Sections on pulse-amplitude and pulse-code modulation in the course textbook and lecture notes. Equipment manuals are posted on the course web page.

Preparation:

1. Bring the parts necessary to construct a low-pass RC filter (Part I, step 2) to the Lab. 4. Bring a USB stick to the Lab to record all your measurements (as screenshots in .png or .jpg files). For each group, it is recommended to bring more than 1 USB stick in case one fails.

2. Sketch the eye diagram of the output of an RC low-pass filter for an input which is a non-return-to-zero (NRZ) binary PAM signal with levels A and $-A$. Show that if T_0 is the symbol period, the eye opening is given by

$$2A \{ 1 - 2 \exp(-T_0/RC)\}$$

    and the eye width is given by

$$T_0 + RC \ln (1 - \exp[-T_0/RC]),$$

    provided the signaling period is greater than $1/(RC \ln 2)$. Find the relationship between the maximum signaling rate (so that the eye is still open) and the filter's 3 dB cut-off frequency.

3. A student decides that he would like to generate experimentally an eye diagram corresponding to an NRZ binary PAM signal applied to a good low pass filter. To simulate an NRZ signal, the student decides to use a 50% duty cycle square wave. He applies this signal to his filter and observes the output on an oscilloscope. Rather than an eye diagram, he finds the response is just a sine wave. Why does this attempt to generate an eye diagram fail?

4. A sinusoid of amplitude $A=1$, frequency $f_1 = 500$ Hz, and phase θ, is sampled at rate $f_s = 1$ kHz using an n-bit PCM modulator (A/D converter) and these samples are passed to a PCM demodulator (D/A converter) whose output is just the quantized PAM signal (recovered by the demodulator without a reconstruction filer). The modulator is designed for signals in the range [-1,1]. Sketch the demodulator's output (in time domain) for $n = 1, 2, \infty$ and $\theta = 0, 45, 90, 180$ degrees. Hint: for $n = \infty$, the output is a flat-top PAM pulse train which can be expressed as follows:

$$\Pi\left(\frac{t}{T_s}\right) * \sum_{k=-\infty}^{\infty} A\sin(2\pi f_1 k T_s + \theta)\delta(t - kT_s),$$

    where $\Pi(t)$ is the standard rectangular pulse. For $n = 1, 2$, the samples are quantized to the nearest allowed level so that the output is the quantized flat-top PAM pulse train.

    What is the spectrum of the output? Sketch it. Repeat for $f_s = 4$ kHz and comment on the difference.

5. If a sinusoidal signal of amplitude 1 V is sampled by an *n* bit PCM encoder and the samples are transmitted to a PCM decoder as in the previous question, determine the signal to quantization noise power ratio (SQNR) in the recovered signal for *n*=1,2,3,4, 5, 6, 7 and 8. Hint: use the SQNR equation in the textbook or in Lecture 11.

All preparation questions have to be answered in writing before coming to the lab and will be inspected by the TA.

All measurements have to be done and analyzed in the Lab. It is <u>very important</u> to do a preliminary analysis and interpretation of the measured data in the Lab so that if any inconsistences or gaps are discovered, they can be corrected with extra measurements while still in the Lab.

Equipment:

1. Dual channel oscilloscope (OS)
2. Waveform generator (WG), Agilent 33500B Series
3. Krohn-Hite 3384 filter
4. LabVolt 9444 PCM Encoder unit
5. LabVolt 9445 PCM Decoder unit
6. Bit interruption cable
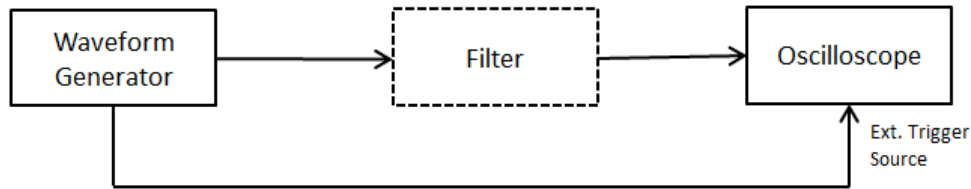
Procedure

Part I: Eye Diagram

Fig. 1 Measurement setup for eye diagram part

1. Connect the Waveform Generator (WG) as a pseudo-random binary sequence generator to produce a binary NRZ (non-return to zero) signal at 10 kbits/s in the above set-up without the filter. Observe the eye diagram on the oscilloscope [the oscilloscope should be externally triggered by the WG]. Change the trigger source from the external to internal and observe the oscilloscope display. Compare internal and external triggering, comment on and explain the difference.

2. Construct an RC-low-pass filter where $R = 2$ kΩ and $C = 10$ nF and use it to filter the WG output. Vary the data rate and observe the eye diagram at different rates. Measure eye openings and eye widths and compare with the preparation part. Determine the rate at which the eye closes. What happens to the oscilloscope display when internal triggering is used (vary the trigger level)?.

3. Replace the RC low-pass filter with the Krohn-Hite 3384 filter set to be a 10 kHz low-pass filter. Observe the eye pattern in this case. Which of these two filters causes less distortion to the data signals? Why?

4. Using the setting of step 3, vary the cut-off frequency to larger (15, 20, 30 kHz) and smaller (9, 8, 7, 6, 5….kHz) values, observing the eye diagram. At what cut-off frequency the eye closes? What is the smallest cut-off frequency at which the eye is (almost) fully open? Explain these measured results based on your knowledge of the subject and the preparation part.

Part II: Pulse Code Modulation (PCM)

In this section we shall observe some basic attributes of Pulse Code Modulation (PCM) and shall endeavor to measure the quantization noise in a PCM system whose input is a simple sinusoid. For this, we shall employ a LabVolt PCM encoder (modulator), which has the ability to sample any signal provided at its input at rates determined by an external clock (up to a maximum frequency of 40 kHz) and represent the samples as an octet (i.e., 8 bits/sample). In quantizing the signal samples, it can employ regular linear PCM (Direct PCM), or A-law or μ-law companding. The encoder is set to handle inputs only from approximately -1V to +1V and so no signal should exceed these limits. The encoder can present the samples in a serial form at the output, or in a byte form, either of which may be sent to the decoder from which to recover the analogue signal. If the byte format is employed, we can obtain the effect of using fewer than 8 bits/sample by passing on to the decoder only the n most significant bits and setting the inputs for the others to zero. This is the function of the switches on the "interrupter cable": they either pass the bit from the encoder to the decoder or ground that line. To obtain the action of a n bit quantizer, we can simply use the interrupter cable to pass the n most significant bits from the encoder to the decoder, leaving the least significant $8–n$ bits to be interpreted as being zero. This has the side effect of perhaps introducing a DC shift into the output of the PCM decoder (demodulator), which is unimportant when the signals are AC coupled.
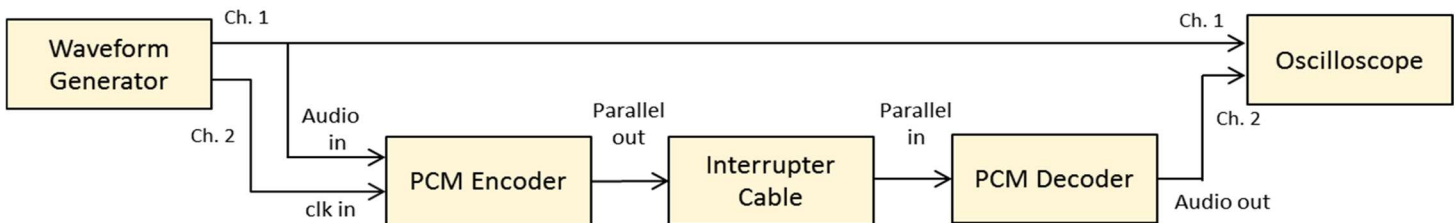
A. Basics

Fig. 2: PCM measurement setup

1. Set up the system shown above with the input to the encoder set to a 500 Hz, 1.0V p-p sinusoidal signal on the WG (which corresponds to the actual input amplitude, as observed on Ch. 1 of the oscilloscope, equal to 2Vpp; the reason for this was found in Lab 1); the clock input to the encoder should be a TTL pulse train (50% duty cycle) at the rate of 40 kHz (this is the sampling frequency of the PCM encoder) and amplitude of 2.0V p-p. The PCM encoder should be operating in "DIR" mode with the PCM decoder in OFFSET mode. The interrupter cable should be set to pass all bits from the encoder to the decoder. Adjust the gain on the PCM decoder so that the output is a 2V p-p signal, as observed on Ch. 2 of the OS, to match the signal amplitude of Ch. 1. Now vary the level of the PCM encoder input and observe the PCM decoder's output, noting at what input level the decoder system starts "clipping" the signal. Explain this effect.

2. Set the input to 1Vp-p on the WG. Observe the PCM decoder output when only the most significant 7, 6, 5, 4, 3, 2, and 1 bits are passed to the decoder. Do this part for both first for AC coupled input to the Ch. 2 of the oscilloscope. Comment and explain the impact of the number of bits pass through on the decoder output. For each number of bits, determine the quantization interval from the measurements and compare it to the theory. Now switch Ch. 2 of the OS to DC-coupled and observe the impact of the number of bits passed-through on the decoded signal. Comment on the difference between the AC-coupled and DC-coupled observations. How can you explain it?

3. Return to the settings of Step 1. Reduce the sampling rate (the rate of the square wave on the SG) to 30, 20, and 10 kHz, each time observing the output on the OS. Explain your observations. Now decrease the sampling rate to 2, 1 and 0.5 kHz and explain the observed output. What is the best sampling frequency? Why? What is the smallest sampling frequency from which you can recover the input signal reasonably well? Compare your answer to what you studied in the class and explain the difference, if any.

4. Now set the sampling frequency to 1 kHz (which is the Nyquist rate for our input) and change the phase of the clock signal (in channel 2 of the waveform generator) from 0 to 360 degrees. Observe the PCM decoder output for different phase values and explain it based on your knowledge of sampling. Is it a good idea to sample a sinusoid at Nyquist rate? What about other band-limited signals?
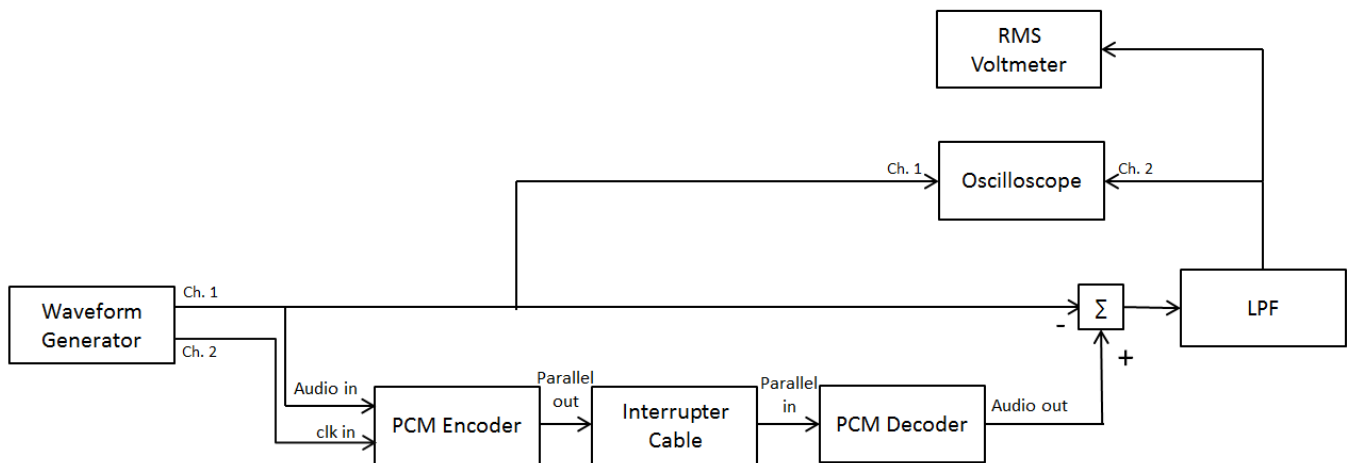
B. SQNR measurement

Fig. 3: SQNR measurement setup

1. To measure the SQNR, apply a 10 Hz, 1 Vp-p (as set on the WG) sinusoid to the PCM encoder and Ch. 1 of the OS. Use the Subtractor to find the difference between the original signal and the decoded one as in Fig. 3 above. Pass the output of the Subtractor to an LPF with $f_c = 200\ KHz$ and observe the final output on OS and measure its root-mean-square (RMS) value on RMS voltmeter. Minimize the RMS output by adjusting the two potentiometers when all bits passing through. One of the potentiometers is for a rough tuning and the other one is for a fine tuning.

2. Now repeat this measurement when only 7, 6, 5, 4, 3, 2 and 1 most significant bit pass through. At each step, record the RMS value of the difference and, from it, compute the measured SQNR, expressing it as a function of the ratio of the RMS values at RMS voltmeter. Compare the measured SQNR with theoretically computed in the preparation part, plotting a graph of the SQNR [dB] vs. number of bits. Explain the difference, if any.

3. Repeat the experiment for 50 and 500 Hz sinusoidal input.

4. Do your measurements support the 6 dB per bit rule we discussed in the class? What are the limits to this rule in practice?