EQUALIZATION FOR ISI

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ACHIEVEMENTS: discover how to use a simple phase equalizer to reduce intersymbol interference (ISI) and improve the symbol rate in bandwidth constrained channels

PREREQUISITES: completion of the experiment D3-01, entitled ISI: PAM & ASK over band-limited channels.

ADVANCED MODULES: BASEBAND CHANNEL FILTERS, DECISION MAKER, DIGITAL UTILITIES, LINE-CODE ENCODER

SCOPE: availability of a digital or PC-based oscilloscope would be an advantage for eye pattern displays.

what is equalization?

In the experiment D3-01, entitled ISI: PAM & ASK over band-limited channels we investigated techniques for dealing with the interference between neighbouring symbols resulting from the unavoidable pulse overlapping in bandwidth limited channels when used for digital communications\(^1\). We found that when oscillatory tails had zero crossings occurring at suitable instants in relation to the pulse frequency, intersymbol interference (ISI) is minimized, or eliminated (Nyquist’s First Criterion).

We obtained good outcomes fortuitously, with filters in the BASEBAND CHANNEL FILTERS module. The only tuning used was the choice of pulse frequency. In the case of the Butterworth filter we noted that transmission around 4200 Hz with minimal ISI seemed feasible, however initial sluggishness in the leading edge of the symbol pulseform would prevent good ISI performance at this pulse rate. This kind of problem is common in digital communications, and occurs even when suitable pulseforms are generated, due to distortion in transmission. In modern modems this is corrected in the receiver with adaptive equalization. Adaptive equalizers are able to analyse distortion and inject precise compensation for it “on the fly”, i.e. without interruption to normal communication.

\(^1\) most digital communications applications are over channels with finite bandwidth.
In this experiment a PHASE SHIFTER will serve as a phase equalizer for a Butterworth pulseform. It will be manually tuned on the fly, by observing changes to the eye pattern display at the receiver.

**to do before the lab**

This experiment is a direct sequel to the experiment D3-01 entitled *ISI: PAM & ASK over band-limited channels*. It’s a further journey of discovery into techniques for managing ISI. The same set-up is used. To save time, you will find it useful to have your notes about that experiment close at hand.

Theoretical background about equalization of group-delay and phase distortion can be researched later. However, in the meantime, it should be noted that one aspect of equalization is to obtain the highest possible pulse transmission rate for a given channel. Hence, it would be worthwhile to arrive at the workbench with some intuitive notion of what constitutes a reasonable expectation of achievable pulse frequency for a given bandwidth. One way to get started is to consider the relationship between bandwidth and step response rise-time in a low-pass filter. A well known rule of thumb asserts that the product $2 \times \text{rise-time (seconds)} \times \text{bandwidth (Hz)} \cong 0.35$. The minimum pulse width will be between two and three times the rise-time, i.e. approximately the reciprocal of the bandwidth.

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**EXPERIMENT**

In this exercise the Butterworth pulse is phase equalized to obtain low ISI for a transmission rate around 4200 Hz, i.e. twice the speed used in the experiment D3-01 entitled *ISI: PAM & ASK over band-limited channels*.

An important parameter for bandlimited channels is the symbol-rate-to-bandwidth ratio. The gain-frequency response of the channel will be needed to obtain this. To avoid disturbing the main set-up, this is measured after completion of the pulse and sequence observations.

**equalizing the Butterworth pulseform**

We begin with an inspection of the Butterworth pulseform using the snapshot set-up in Figure 1.

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2 this formula gives reasonable outcomes using the 3dB bandwidth when the amplitude response has a moderately sharp transition to stop band. Hence it may not be very good for the Bessel filter. The Butterworth case should give reasonable agreement. You will have the opportunity to measure the step response rise-time in the lab.
Figure 1: set-up for displaying isolated pulseform

The modules to the left of the PHASE SHIFTER emulate the combined effects of a transmitter shaping filter, a bandlimited channel, and a receiver input filter.

T1 patch the model of Figure 1. Before inserting the VCO, set the on-board switch to VCO mode.

T2 set the front panel toggle switch of the VCO to HI. The TTL output is divided by four before connection to the M.CLK of the LINE-CODE ENCODER. Tune the VCO for a frequency between 4000 and 4500 Hz at the B.CLK output.

T3 connect the LINE-CODE ENCODER M.CLK & B.CLK, frequency division\(^3\) by 8 in DIGITAL UTILITIES\(^4\).

T4 connect the DECISION MAKER B.CLK IN & OUT and adjust the front panel control if needed, to obtain a pulse at the B.CLK output. The on-board switch SW1 may be in any position).

T5 ensure that you are using the UNI-RZ output of the LINE-CODE ENCODER

T6 set the front panel rotary switch of the BASEBAND CHANNEL FILTERS to Butterworth (position 2), and the toggle switch UP for DC coupling.

T7 before inserting the PHASE SHIFTER set the on-board switch to LO. Set the front panel COARSE control fully clockwise. The FINE control should be at the 12 o’clock position.

T8 observe the appearance of the pulses at the input and output of the PHASE SHIFTER.

T9 adjust the amplitude and DC offset at the output of the ADDER as in previous experiments\(^5\). Pulse amplitude should be about 1.5 V.

T10 turn the COARSE control gradually anticlockwise until an undershoot appears in the leading edge of the output pulse. Bearing in mind that fine tuning will be done using the eye pattern display, this initial setting should be for an undershoot of around 30% – 50% of the amplitude of the first undershoot in the tail. Figure 2 shows typical pulses before and after equalization (symbol width is 228\(\mu\)s).

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\(^3\) note that the PHASE SHIFTER is AC-coupled. To minimize the effect of the baseline drift it’s preferable to avoid long intervals between successive pulses. Division by 8 is a good choice in this instance.

\(^4\) for a more detailed description, refer to experiment D3-01, entitled ISI: PAM & ASK over band-limited channels.

\(^5\) reminder: the PHASE SHIFTER is AC coupled
This set-up provides an opportunity to quickly generate and display the step response and measure the rise-time. This is relevant for students interested in the rule of thumb mentioned under preparation. All that is needed is to change two connections at the LINE-CODE ENCODER:

**T11** first: remove the DATA input lead from the TTL inverter output and connect it to the divide by 8 output in the DIGITAL UTILITIES,

**T12** second: connect the filter input to the NRZ-L output instead of Uni-RZ. The scope settings need not be altered if the triggering has not been disturbed.

**T13** sketch the step responses at PHASE SHIFTER input and output, and record their rise-times (from 10% to 90% of final amplitude).

The next part requires the eye pattern display. The set-up is given in Figure 3.

**T14** patch up the model of Figure 3. Remember to use the RZ-AMI output of the LINE-CODE ENCODER.

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6 the new set-up can be assembled without disturbing the DIGITAL UTILITIES and DECISION MAKER set-up – it may be needed again. The only change required there is to move the LINE-CODE ENCODER DATA input lead from the TTL inverter output to the SEQUENCE GENERATOR output.

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**eye pattern equalized for top speed**

The next part requires the eye pattern display. The set-up is given in Figure 3.

**T14** patch up the model of Figure 3. Remember to use the RZ-AMI output of the LINE-CODE ENCODER.
adjust the frequency for the best eye opening, then, gradually tune the FINE control of the PHASE SHIFTER for further improvement. If there is insufficient range with the FINE control, adjust the COARSE control very moderately in the appropriate direction. Re-adjust the VCO, and PHASE SHIFTER. Repeat a few times if you are achieving further improvement, however, convergence to the best result is normally quite rapid. The eye should have the general appearance in Figure 2.

measure and record the vertical eye opening and note the pulse rate.

compare this with the eye pattern obtained without the equalizer.

compare also with the best result previously obtained with the Bessel pulseform.

measure and record the horizontal eye opening, and again compare with the Bessel case, and with the Butterworth results previously obtained at the lower frequency.

A worthwhile exercise is to examine a snapshot of the equalizer output.

using a short sequence if needed, trigger the scope with the sequence SYNC signal and display both the unfiltered RZ-AMI signal and the equalized output.

consider whether the data can be ‘recovered’ from a visual inspection of the equalized waveform.

measure the gain frequency response of the filter to verify the rule of thumb. Measure and plot the filter frequency response. Observe that the PHASE SHIFTER response is all-pass; hence it should have no effect on the filter’s gain response. Determine the 3dB, 6dB and 40dB bandwidths. Obtain the symbol-rate-to-bandwidth ratio for each of these.

We use the 40dB frequency (rather than 3dB) to define channel occupancy bandwidth where frequency-division is used for channel allocation. This is necessary to preclude spectrum overlap and interference to adjacent channels. Symbol-rate-to-bandwidth ratio performance is explored further in experiment D3-03, entitled ISI: pulse shaping for band-limited channels.

Subject to conditions not fully met here, Nyquist theory indicates that the ratio symbol-rate-to-6dB bandwidth should be equal to unity. Is this borne out in this instance? If you have time, compare with the Bessel case.

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7 as in the experiment D3-01 entitled ISI: PAM & ASK over band-limited channels.
8 using the VCO with external frequency control is a good option for this as it makes possible fine frequency control.
9 the theoretical limit for pulse transmission free of ISI in an ideal sharp cut-off baseband channel is 2 pulses per Hz of bandwidth. For the TIMS Butterworth filter, with transition band almost as wide as the 6dB bandwidth, the ratio obtained is around unity.
10 channel occupancy bandwidth is sometimes called slot bandwidth
TUTORIAL QUESTIONS

Q1 Show a block diagram of a baseband ASK system that gives the essential elements of the transmitter, the channel and the receiver, with equalizer. Clearly indicate the basics of the receiver and how the transmitted data is recovered from the analog waveform when noise is present. Describe the purpose of the equalizer, and how it improves the performance of the system. Indicate why the equalizer is “adaptive” in modems operating over telephone systems.

Q2 In the block diagram in Q1, indicate the precise location where you would monitor the eye pattern for the Nyquist format.

Q3 In this lab the TIMS PHASE SHIFTER module was improvised as a phase equalizer. This is a first-order “allpass” circuit. However this is not the type of circuit normally used for adaptive equalization in data modems. Find out the type of realization used in such applications.

Q4 This question is included for students keen to acquire an understanding of the operation of the TIMS PHASE SHIFTER as a phase equalizer. Elementary knowledge of linear (“s-plane”) circuit theory and transfer functions is required. Access to Matlab or similar software is assumed (however, the first part of the exercise can be completed analytically).

(a) The transfer function of the TIMS PHASE SHIFTER is of the form

\[ H(s) = H_0 \frac{(s – \alpha)}{(s + \alpha)} \]

Where \( H_0 \) and \( \alpha \) are constants (assumed real here) and \( s \) is the complex frequency variable. Setting \( s=j\omega \), where \( \omega \) is in radian/sec, show that the magnitude response is constant (i.e. “allpass”). Obtain also expressions for the phase response and group-delay\(^{11} \). Plot the group-delay and phase versus frequency in Hz for various values of \( \alpha \). Try to determine the value of \( \alpha \) you used to equalize the Butterworth response in the lab.

(b) Using software you may have available, verify the result you obtained in part (a). Next, obtain graphs of the gain and group-delay characteristics of a 7th order Butterworth filter with 40dB stopband frequency equal to that of the Butterworth filter in the TIMS BASEBAND CHANNEL FILTERS module (near 4 kHz). Finally, obtain displays of the combined group-delay response of the filter-equalizer cascade. Comment on your findings.

\(^{11}\) Group-delay is the derivative of negative phase with respect to \( \omega \), -d(phase)/d\( \omega \). Tip: Using implicit differentiation and the identity \( \sec^2 = \tan^2 + 1 \), the group-delay can be derived in 3 or 4 simple steps. Also, a reminder, phase and group-delay are additive over complex-valued factors of the transfer function.
equalization for ISI