Effects of Intersymbol Interference on Digital Information Transmission due to channel bandlimitation.

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***Abstract*—In this report we examine the effects of bandlimitation and channel properties on the maximum data transmission rate of a channel. First we characterise the channels by considering their amplitude responses to determine this gives a strong sense for the bandlimitation of the channel. Then we consider the channels pulse response for information such as overshoot, delay and intersymbol interference. We use this information to predict the transmission rate at higher frequencies. Finally we compare our hypothises against the experimental transimission rate cut off and examine the eye diagrams of the different channels.**

I. Introduction

A bandlimited channel is a channel that can not carry all frequencies as certain frequencies are attenuated. As a result, certain input waveforms (e.g. waveform with high frequencies components) can not be transmitted through the channel without distortion as the channel itself acts as a filter losing some of the higher frequencies. [1] All real channels are bandlimited in some sense. In this lab we will explore the transfer function of bandlimited functions in part 1, what link is there between the transfer function and the bit and the waveform response? Can the bit rate be performance be predicted from the transfer function?

It is likely that the roll-off factor should be a strong indicator of ISI performance from the transfer function.

$$\alpha = \frac{f_{3dB}}{f_{\text{passband}}}$$

Bandlimitation in the frequency domain results in waveform distortion in the time domain. This is as to create time limited signal requires an infinite spectra. As our channels are bandlimited we will be transmitting an non-limited time signal. This means that component parts of the symbols that we transmit can "leak" into other symbols causing *intersymbol interference*, interference due to other symbols being transmitted in the channel. We will explore the effects on band limitation on pulse responses in task 2. What do we learn about the channel from the pulse response that we can't get from the amplitude responses?

In order to achieve reliable detection in bandlimited channels we need to somehow overcome this inter-symbol interference. But how? One popular method of doing this is by following Nyquist's ISI criterion. This technique reduces intersymbol interference by choosing a sampling instant as to remove/minimise the intersymbol interference. What do real world intersymbol interference values look like and do the results align with the drop off values found in task 1? Does this theory transfer over to real world systems or does noise and real world effects introduce the possibility for better sampling techniques?

Eye diagrams are the standard technique for determining a channel's maxmium bit rate experimentally. If you overlay a random (or pseudo-random) sequence of bit an eye pattern will emerge. Inside the eye there is a noise margin, so long as this is open implies that intersymbol interference doesn't dominate the transmission and a signal could be received.

AC and DC coupling AC coupling removes very low frequency components. DC coupling is just a wire connected to the input. AC coupling places a capacitor in series with the input signal. This capacitor blocks off high frequency components, removing any DC offset. It can also remove important low frequency components[1].

1) Types of filters:

1) **Straight through** There is no filter and it is simply a contact inside of the baseband selector.
2) **Bessel Filter**
   - Low pass filter that minimise group delay/phase delay for underneath cut-off frequency (in this case 1kHz). See figure 1
   - Slow cut off
   - No overshoot for square wave input as high frequencies are attenuated

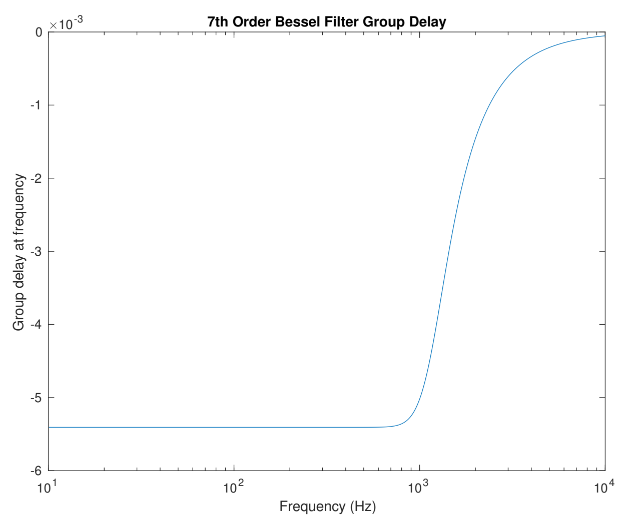

Figure 1: 7th order Bessel Filter with 1kHz cut-off

[1] A channel does not necessarily have to behave as a low pass filter.

3) **Butterworth Filter**
   - Has maximal flatness for pass band frequencies i.e. same gain for wanted frequencies.
   - Slow cut-off
4) **OpFill Filter**
   - Proprietary filter with sharp cutoff with linear phase in the passband[2] .
5) **Basic Model of Data transmission:** A digital message is sent through to a digital output by going through an analogue system. This can be described by the following equation:

$$y(t) = s(t) * [h_R(t) * h_c(t) * h_R(t)] + [n(t) * h_r(t)]$$

Inside of this system the design-able components are the transmitters filter's response h_t and the receivers response h_R. A first iteration design of the transmitters response could be k

II. Methods

A. Equipment

- TIMS telecommunications modelling system
- TIMS modules required for this experiment
  - 1 Sequence generator
  - 1 Baseband channel filters
- Agilent MSOX2012A mixed signal scope
- HP 33120A Function generator
- Optional - BWD 50 MHz analog oscilloscope (for viewing eye diagram) [3]
- USB
- Cables

Figure 2: Image of TIMS Module

B. Task 1

In this first task we are applying sinusoidal of varying frequencies to the four different channels to characterise the experimental frequency amplitude response of the channels. The emulated channel characteristics:

1) Straight-through
2) 7^{th} order Butterworth
3) 7^{th} order Bessel
4) 7^{th} order OpFil linear phase

Steps:

1) **Wiring** We setup connections in the TIMS module as shown in figure 2.
   - We connect the output of the waveform generator (HP 33120A) to the input of both the channel 1 on the MSOX2012A and the input of the Baseband channel filter.
   - Then we connect the output terminal of the Baseband channel filter to channel 2 of the MSOX2012A.
2) **Output Waveform:** We set the output waveform to a $1V_{RMS}$ sinusoidal output by ensuring the amplitude is set to $1V_{RMS}$ and is sinusoidal by pressing the sinusoid button on the waveform generator.
3) **Experiment Loop/Data Collection** once the wiring and waveform generator are set up we are able to vary the frequency of the input sinusoidal and record the output sinusoidal amplitude using channel 2 of the osciloscope. We record this data by saving images to the USB osciloscope. This is done by Save/recall→ Save → Format saving as a PNG. An initial plot is generated to get a rough understanding of the channels transfer function by testing over the following frequencies: 20, 50, 100, 200, 500, 1000, 2000, 3500. We then plot these rough transfer functions then later come back to collect more data around crucial areas where the 3-dB point is passed. The data collection is then repeated around the 3-dB point. Table I indicates the tests to be done, there should be 64 data points.

Table I: Table of Examined Channel

Channel	Frequency (Hz)	Coupling
Straight Through	(20-3500)	DC
Straight Through	(20-3500)	AC
Butterworth	(20-3500)	DC
Butterworth	(20-3500)	AC
Bessel	(20-3500)	DC
Bessel	(20-3500)	AC
OpFil	(20-3500)	DC
OpFil	(20-3500)	AC

Updating (optional) After the initial pass-through of values we find the -3dB point which occurs at the $V_{\text{Passband}}/\sqrt{2}$ and take more points around this value.

C. Task 2

We examine the waveform response of the different channels at varying different bit rates. Steps:

1) To emulate repeatedly sending a "00001" message with a bit rate of 1kb/s, we set the function generator to output a rectangular pulse with an amplitude of 2V with a 20% duty cycle and a frequency of 200Hz. We also add a 1V DC offset to ensure that the pulse is unipolar. This means we are sending a bit at 1kHz which means we are satisfying our bit rate of 1kB/s.
2) We then choose a sample instant that we think would be the best time to sample the signal and then calculate the inter-symbol interference we would expect at that sampling point from other points around it. To get the

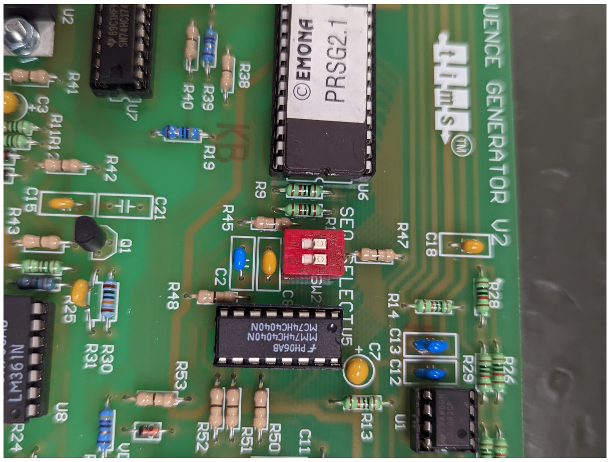

Figure 3: DIP Switched on sequence generator

inter-symbol interference from a bit N periods away you simply find the output voltage at $r(T_{\text{Sample Time}} \pm NT_b)$.

3) It should be noted that we chose to sample the sample instants to be at the local maximums.
4) Find this value either by recording the CSV file and finding it in Matlab or by using the cursors on the oscilloscope and recording the values.
5) This is repeated for each of the three filters and repeated for 2kb/s and 3kb/s. (Increase the waveform frequency to the required value.)

The intent is to use this data to predict which channel allows for the highest transmission rate.

D. Task 3

This task is about experimentally determining the maximum bit rate. To do this we have to create a random sequence. We then examine the output sequence and examine the eye diagrams.

1) We change the signal source to come from a “random” sequence generator. The sequence is set to 32-bits by ensuring both DIP switches are in the on position on the sequence generator see fig 3. We connect the function generator to the sequence generator at the TTL port.
2) Record the random sequence that is generated and ensure that it is producing a random sequence (using the straight through).
3) Record the random sequence output from other sequences at 1kb/s, 2kb/s and 3kb/s.
4) Then record the eye diagrams for each of the channels at 1kb/s, 2kb/s and 3kb/s. This will be used to discuss the worse case eye-opening for each of the channels.
5) Then the bit error is experimentally determined by recording when the eye diagram closes for each channel.
6) Repeat the eye patterns at 2kb/s with AC coupling and discuss the effects of this.

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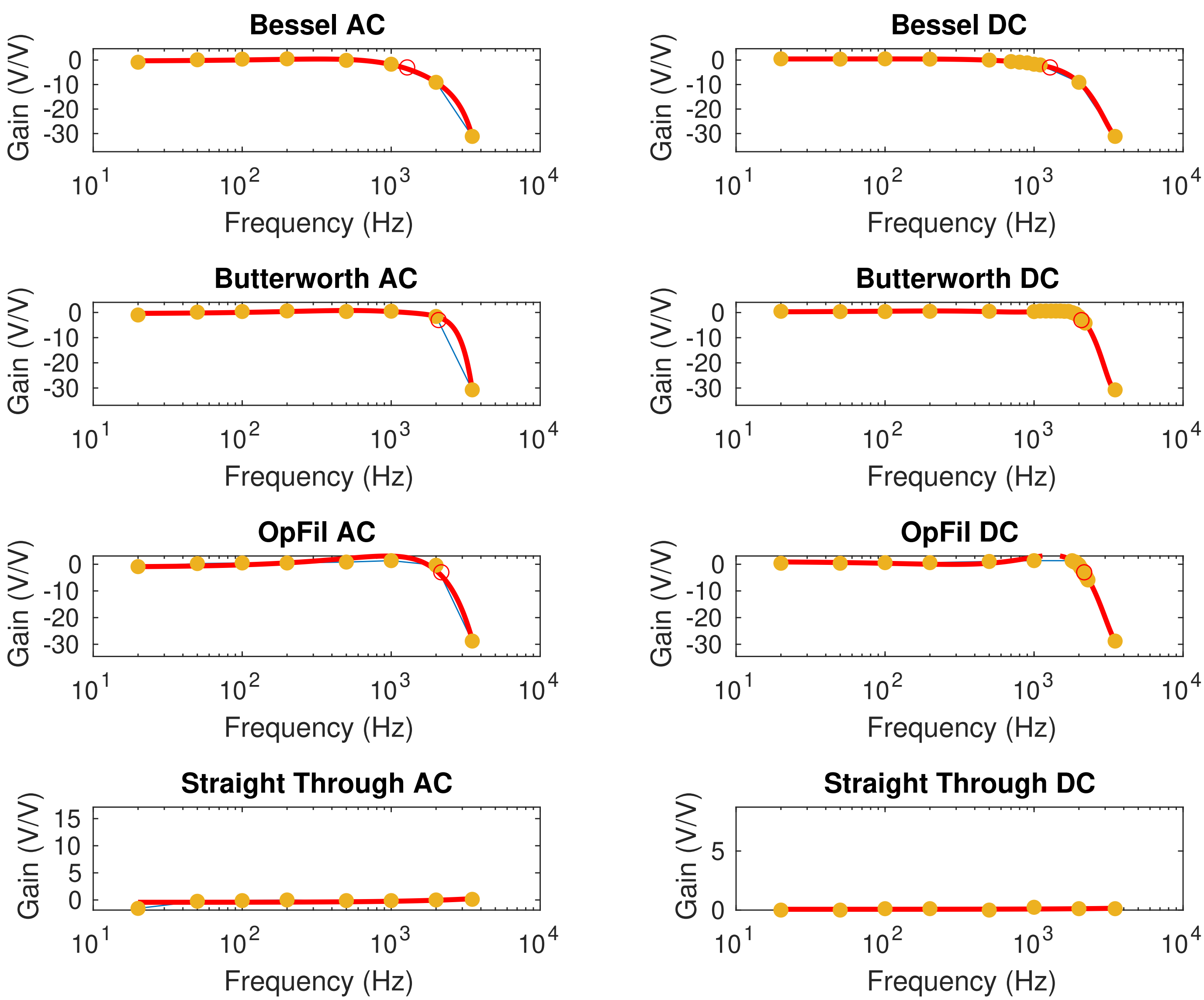

Figure 4: Amplitude Frequency Responses of Different Channels.
The red line is a polynomial line of best fit, it does not seem to be able to follow the data perfectly and seems to introduce a resonance peak in the OpFill DC graph. The blue line is a point to point line. The points are data points. It should be noted that at 20Hz the in the AC plots the output is 90% of the input.

III. Task 1 Results and Discussion

We can see from figure 4 that each of the channels behave quite differently. For the AC coupled channels there is a consistent small dip in gain at very low frequencies ($f < 80$). The passband ripple of the filters is around 0.5dB as expected for the bessel but the OpFil and the Butterworth filters have some values above that in the passband. The passband and 3-dB points respectively are noted at:

- Butterworth: 1800Hz and 2080Hz
- Bessel: 500Hz and 1280Hz
- OpFil: 1950Hz and 2170Hz

We have added additional data points around the 3-dB however they are largely before the 3-dB point. It should be noted that AC coupling has no impact on high frequencies.

A. Bessel Observations

- The Bessel filter is the least flat of all the channels. It is only flat until around 500Hz.
- The Bessel has the closest shape to the ideal Nyquist criterion due to high roll-off factor.
- It is the lowest of all the filters at 35kHz going to -31.5dB.
- Starts attenuating 900-1000Hz quicker than the other two channels.

The Bessel channel behaves as expected. The Bessel's strength lies in flat group delay (as can be seen in the next task) and comfortable roll-off, the trade-off being that the passband is relatively small and the gain drop-off begins quite early.

B. Butterworth Observations

- The Butterworth filter has relatively flat passband until around 1.8kHz

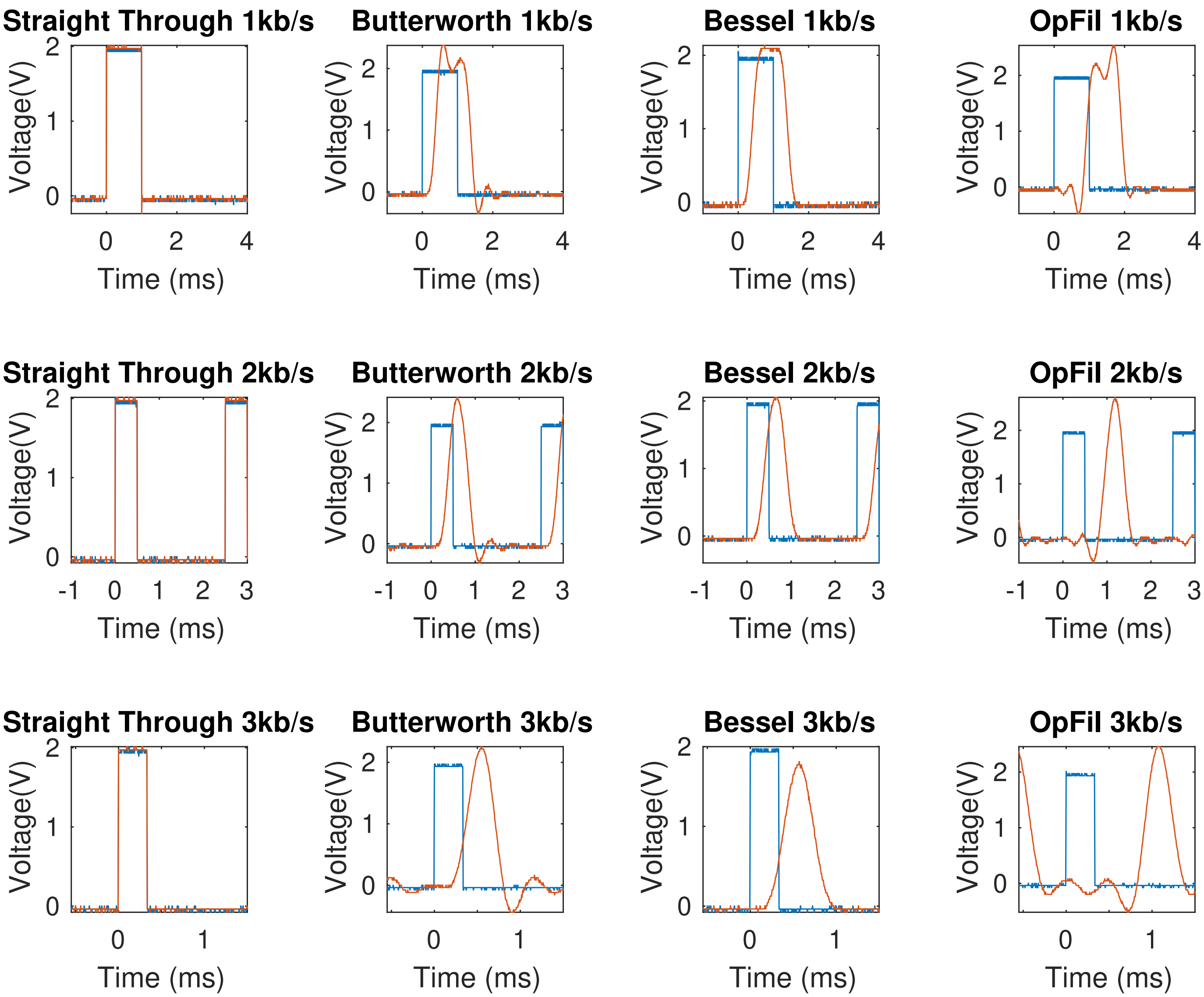

Figure 5: Waveform Responses of the different Channels at Varying frequencies.
It can be seen that there is an interesting behaviour in the bandlimited channels at 1kb/s. Whilst at 2kb/s and 3kb/s the behaviour is clealy similar

- The Butterworth has faster gain loss than the OpFil
- The Butterworth has a slight amount of overshoot of around 0.2dB

The Butterworth behaves as expected giving practically 0 overshoot and delivers what it is expected to which is a flat gain over the passband and a monotonic gain reduction.

C. *OpFil Observations*

- The OpFil has the smallest gain reduction at 3500Hz
- It has the highest slight overshoot getting up to 1dB from a passband around 0.3-0.6dB.
- The OpFil has the smallest negative gain gradient after the 3-dB point

The OpFil balances a tiny bit of resonance just before the 3-dB point, to get increased gain performance by maintaining a passband for longer. We can see in the roll-off table (table II) that the bessel has the highest roll off value which should give it the least intersymbol interference. This could potentially give it the highest bit/rate. [2]

Table II: Roll Off Table

Channel	Roll-Off Value
Butterworth	0.1346
Bessel	0.609
OpFil	0.101

[2]This bit rate will be competing with it's own attenuation at high frequencies.

Waveform	Bit Rate	T_b	SI* (ms)	SI* Amp(V)	$-T_b$(s)	$+T_b$(s)	$-2T_b$(s)	$+2T_b$(s)
Straight Through	1kb/s	1ms	0	1.97				
Butterworth (Decision at first peak)	1kb/s	1ms	0.595	2.37581	-0.0362	-0.357857		
Butterworth (Decision at second Peak)	1kb/s	1ms	1.085		-0.362	-0.0764		
Bessel	1kb/s	1ms	0.665	2.0944	-0.032	0.0039		
OpFil (Decision at first peak)	1kb/s	1ms	1.215	2.21501	-0.116651	-11665		
OpFil (Decision at second peak)			1.695	2.53662	-0.47	-0.0764		
Straight Through	2kb/s	0.5ms						
Butterworth	2kb/s	0.5ms	0.595	2.37	-0.0764	-0.0317		
Bessel	2kb/s	0.5ms	0.665	2.0542	-0.0362	0.003		
OpFil	2kb/s	0.5ms	1.19	2.617	-0.47846	-0.1568		
Straight Through	3kb/s	0.33ms						
Butterworth	3kb/s	0.33ms	0.56	2.215	0.204	-0.438	-0.0362	0.0441528
Bessel	3kb/s	0.33ms	0.575	1.7728	0.124555	0.12455	-0.03	-0.0362
OpFil	3kb/s	0.33ms	1.085	2.456	-0.47846	-0.1166	0.00395	0.003951

Table III: Sampling Instant at Peak.
The above table details the amplitudes at ± 1 and ± 2 bit periods away for varying different channels and bit rates. **SI stands for sampling instant.

IV. Task 2 and Discussion

The waveform responses can be seen above in fig 5. The sampling instant was chosen to be at the maximum value of the bandlimited channel. We took the intersymbol interference by looking at the amplitude of the signal at a bit period away from this point. General Observations:

- As the bit rate increase there is a reducing amount of time between the rising edge and the sampling instant.
- As the bit rate increases there is a clear increase in the intersymbol interference in all of the channels as anticipated.

$$r(t) = r(T_0) + r(T_{-1}) + r(T_1) + r(T_{-2}) + r(T_2)$$

- Some worse case intersymbol conditions would be 0.4018V for "11100" (butterworth), "101" 0.249V (bessel) and "111" (OpFil)
- The worst case sequences vary based on the waveforms responses.

A. Butterworth Observations

- The Butterworth has a large first overshoot in the 1kb/s waveform this is expected as the filter is order >1. This is not necessarily a bad property for a channel to have as it does conceivably increase the SNR at the sampling instant.
- There is a significant undershoot after returning to zero once again a characteristic of an order>1 butterworth filter this contributes to intersymbol interference.
- There is a bit of a trade off in picking if you want to sample at the first peak or the second peak (at 1kHz). If you sample at the first peak you're sampling earlier in time, however you pay for it with a large intersymbol interference at $+T_b$. If you sample at the second peak you get you're inter symbol interference largely at $-T_b$. The overall intersymbol interference is approximately the same at around -0.394057 and -0.4384. So you are better off sampling at the first peak.
- There is some slight attenuation as the frequency increases.
- The Butterworth has the earliest decision instant. (Has the least delay from the input)

B. Bessel Observations

- There is no over or undershoot for the Bessel.
- The Bessel most closely resembles the raised cosine function out of all the the different channels.
- Has the smallest decision instant amplitude at all frequencies.
- The Bessel is quite severely attenuated at 3kb/s
- Has the lowest overall intersymbol interference.

C. OpFil Observations

- Has the highest amplitude at the decision instant.
- Has significant intersymbol interference at -T_b of around $-0.47V/2.456 = 19\%$ through out the different frequencies.
- The OpFil has an order of magnitude less intersymbol interference at $\pm T_b$

The waveforms attenuate as expected from the transfer functions with the Bessel dropping beneath the input voltage, as expected and the Butterworth attunuating slightly more than the OpFil at 3kb/s. Whilst the OpFil does have a large intersymbol interference at $-T_b$ it has significantly less intersymbol interference at times $2T_b$, this inter symbol interference is likely to be what is going to kill your bit rate. As large amounts of inter-symbol interference "build up" in the channel this effect will be the limiting factor on the bit rate at high frequencies. If the OpFil is able to continue this performance of having significantly less intersymbol interference at multiple bit periods away from the sampling instant. This in conjunction with the least high frequency attenuation which will boost the signal to noise ratio should allow for the best bit rate performance.

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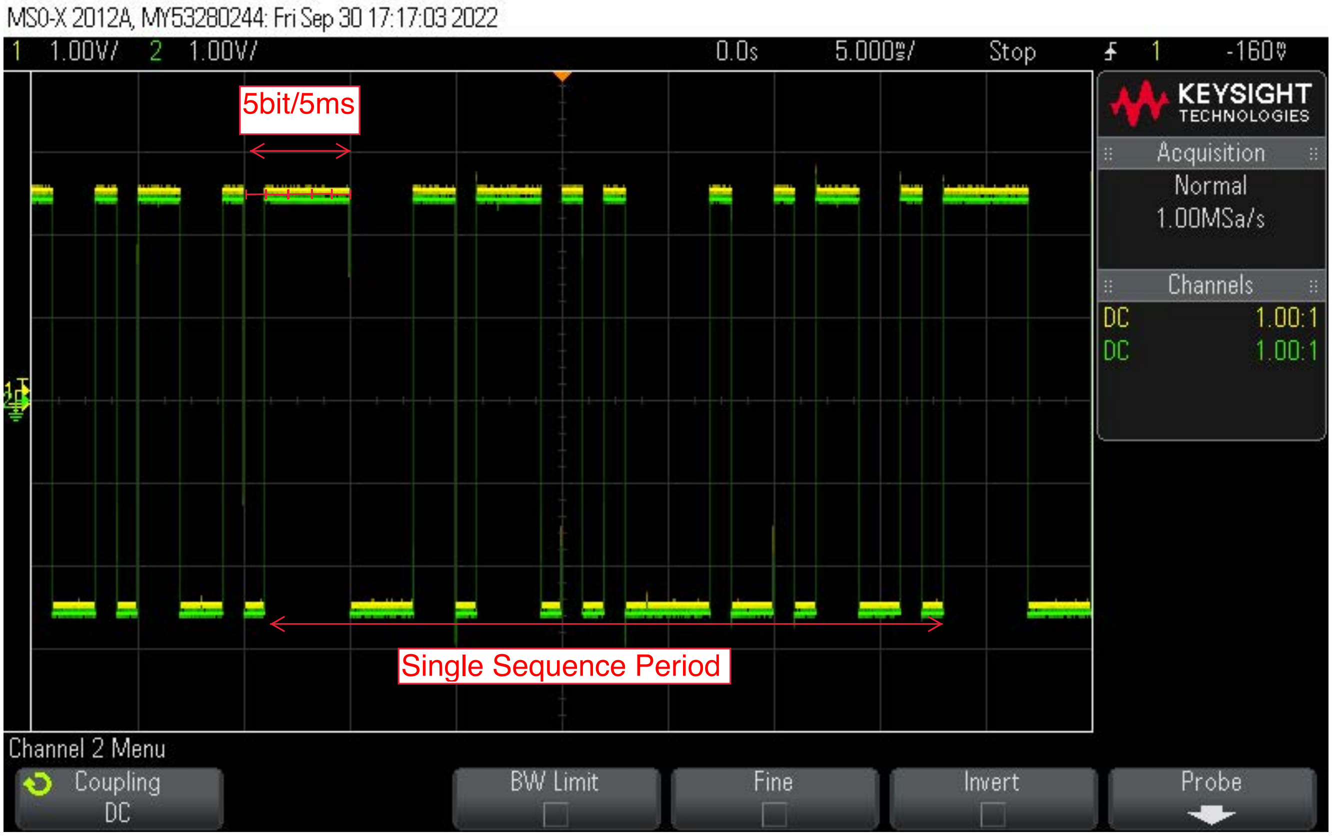


Figure 6: 32 Bit Sequence

The sequence is $\{1,1,1,1,0,0,0,1,1,0,1,1,1,0,1,0,1,0,0,0,0,1,0,0,1,0,1,1,0,0,1,0\}$.

V. Task 3 Results and Discussion

A. Verifing 32 bit Sequence

Basic properties of a random sequence:

1) Number of binary "1"s and "0"s is approximately equal, can be off by 1.
2) The number of runs of consecutive symbols of length L is twice the number of the actual length+1 (L+1) of the runs themselves
3) The auto correlation of the sequence has a peak at the origin and decreases to approximately 0 after 1 bit period away.

Verifying properties:

- We can see from fig 6 that the number of 1 and 0s in the sequence is 16 bits each. Which does satisfy the first condition.
- Interestingly it appears that our random sequence does not satisfying the conditions of having consecutive runs for runs of size $L = 4$. If we increased the sample sequence length this condition would like be satisified.
- We can see in figure 7 that the auto-correlation of the sequence goes down to 0 at the 32-bit mark. It is also peaks at 0.

Table IV: Number of Repetitions of Consecutive Sequences

Length of Sequence	Runs of 0	Runs of 1	Run of 0/1	Satisfies condition
$L = 2$	2	1	3	Yes
$L = 3$	1	1	2	Yes
$L = 4$	1	1	2	No

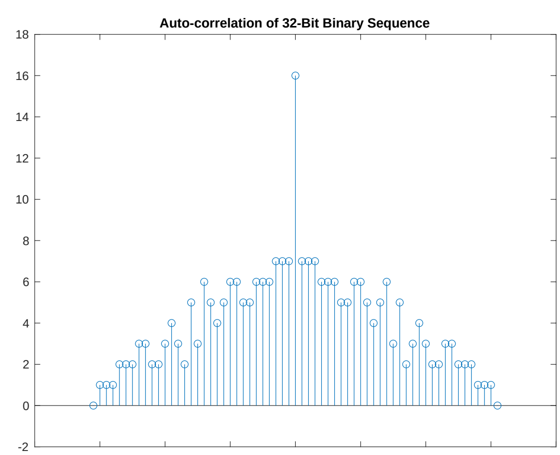
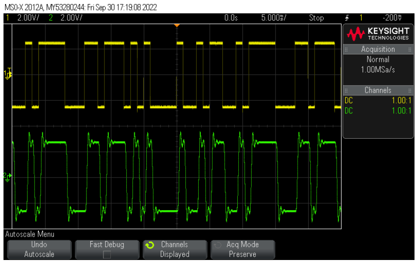
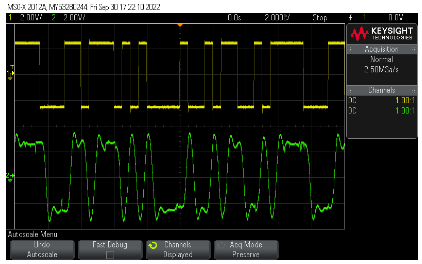


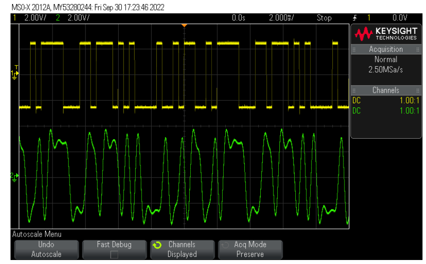
Figure 7: 32 Bit Sequence Autocorrelation



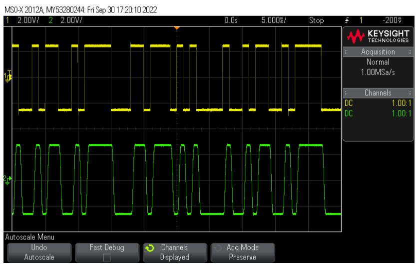
(a) Butterworth 1kHz



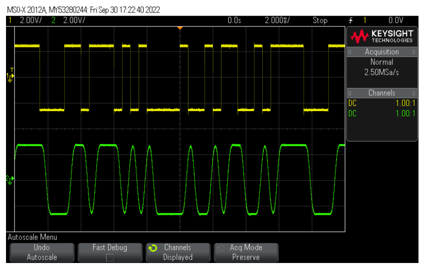
(b) Butterworth 2kHz



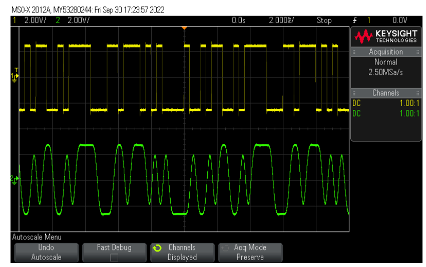
(c) Butterworth 3kHz



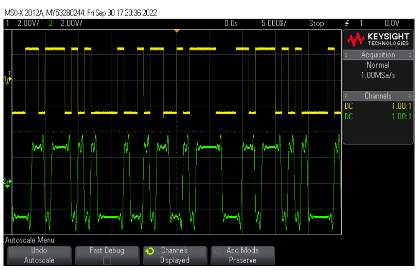
(d) Bessel 1kHz



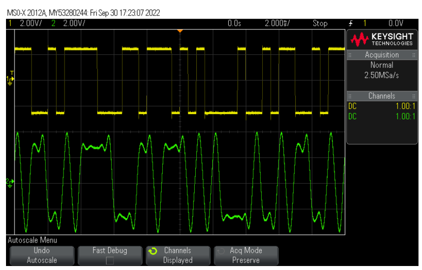
(e) Bessel 2kHz



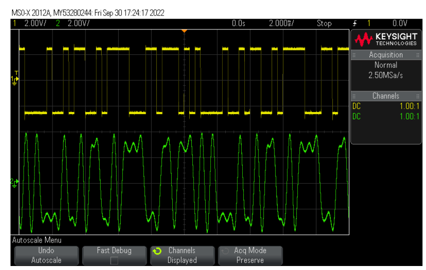
(f) Bessel 3kHz



(g) OpFil 1kHz



(h) OpFil 2kHz

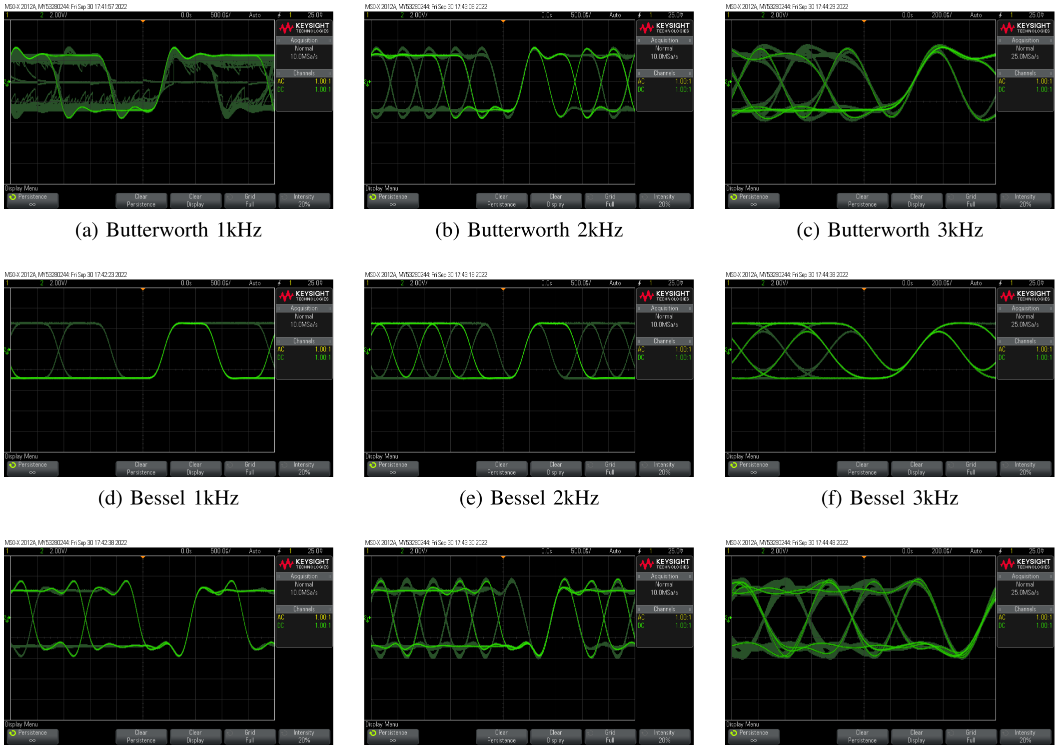


(i) OpFil 3kHz

Figure 8: BCF 32-bit Sequence outputs

B. Output Sequences

For all the different channels at all of the different frequencies, the output messages can still be reconstructed using a threshold from the received waveform. It can clearly be seen that certain messages sequences particularly in the bessel channel have lower amplitudes as seen in figure 8 (f). The sequences that the bessel struggles to produce are ones like “1010” as to produce this tight waveform requires higher frequency components which the Bessel will attenuate and will also still be significantly impacted by inter-symbol interference from previous symbols.



(a) Butterworth 1kHz
(b) Butterworth 2kHz
(c) Butterworth 3kHz
(d) Bessel 1kHz
(e) Bessel 2kHz
(f) Bessel 3kHz
(g) OpFil 1kHz
(h) OpFil 2kHz
(i) OpFil 3kHz

Figure 9: Eye diagrams

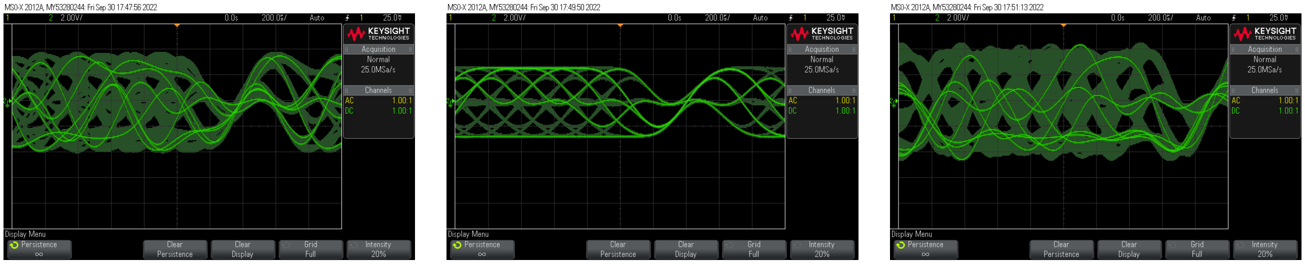
C. *Eye Diagrams*

The eye diagrams behave largely as expected. With increasing intersymbol interference as bit rate increases compounded with attenuation. Which decreases the signal to noise ratio. Taking the (Signal to Intersymbol Interference Ratio) $SIIR = \frac{\text{Noise Margin}}{\text{ISI}}$ we can see that the best SIRR at 3kHz is given by the Bessel (Butterworth = 0.9743, Bessel = 1.8, OpFil = 1.24). However the trade off here is that the Bessel has the lowest Noise margin so in a noisy environment this channel would suffer the most.

- **Butterworth observations:** The first wavelength shows a squarish wave at 1kb/s which is expected due to the waveform shape at 1kb/s. We can see a significant amount of inter-symbol interference at low voltages due to the high intensity voltage at 0.
- **Bessel observations:** the eye width is consistent, the inter-symbol is less “messy” than the other two filters. You can see straight line across the top unlike the others. This is as when the bessel receives multiple 1s it does not have any overshoot. You can however observe that the message sequences require high frequencies such as 010 attenuate are attenuated particularly in figure 9 (f)
- **OpFil observations:** the overshoot in producing short sequences of 1s observable. The OpFil has similar appearance to the butterworth however it has better noise margin and ISI performance.

Table V: Table of Eye Diagram Values for 3kb/s

Diagram	Zero crossing	Eye width (ms)	Bit period	ISI	Noise Margin	Worse opening
Butterworth 1kb/s		0.998		1.24V		3.74V
Bessel 1kb/s		0.99		0.355V		4.4V
OpFil 1kb/s		0.976		1.63V		4.45V
Butterworth 2kb/s		0.488		1.38V		4.724V
Bessel 2kb/s		0.49		0.37V		4.4V
OpFil 2kb/s		0.49		1.95V		4.45V
Butterworth 3kb/s	0.0275ms	0.299ms	0.331ms	1.79V	1.744V	3.85V
Bessel 3kb/s	0.0203ms	0.3181ms	0.337ms	1.00V	1.80V	3.633V
OpFil 3kb/s	0.016ms	0.307	0.3298ms	1.67V	2.07V	4.477



(a) Butterworth Eye Closing (b) Bessel Eye Closing (c) OpFil Eye Closing

Figure 10: Eye closing Osciloscope Recordings

(a) Butterworth AC 2kB/s (b) Bessel AC 2kB/s (c) OpFil AC 2kB/s

Figure 11: AC Coupled recordings of eye diagrams at 2kB/s

D. *Eye closing results*

Our experimental bit rates were 5.7kHz, 5.9kHz and 5.5kHz for the ButterWorth, Bessel and OpFil Channels respectively. Screen-captures were taken at these instances in figure 10. The way we determined the eye closing was by observing when the eye was just about to close and one could conceivably implement a decision instant in the eye opening. There appears to be an inverse correlation with bit rate and bandwidth.

E. *AC Coupling Effects*

The effects of AC coupling can be seen in significantly more smudging then what was seen in DC coupled. This is as digital signals (e.g. squarewaves) have a significant low frequency (<100Hz) component. Removing this low frequency component greatly distorts the signal of a square wave as it reduces the signal to intersymbol interference ratio. This has significantly increased the zero crossing variation and the ISI ratio in particular.

Table VI: Eye Diagram for AC Coupled Channel

Diagram	Eye width	ISI	Worse opening
Butterworth AC 2kb/s	0.499ms	2.3V	2.57V
Bessel AC 2kb/s	0.405ms	2.9V	2.8V
OpFil AC 2kb/s	0.399ms	1.98V	2.8V

VI. Conclusion

Experimentally the best performing channel in terms of bit was the Bessel.
This result seemed counter-intuitive. The initial hypothesis in the first two tasks was that the best channel would be the OpFil as it had a greater bandwidth so it would be able to produce tighter waveforms with smaller intersymbol interference at sampling periods greater than one bit period away.
The main issue with the OpFil is that there is significant intersymbol interference at $-T_b$ greater than any other channel. This is a result of the having a sharp gain drop-off around the 3-dB point which results in non-monotonic behaviour in response to positive and negative triggers on the input which causes significant ISI.
The butterworth was very similar to the OpFil with similar trade offs. Both the OpFil and Butterworth had better bandwidth but worse pulse responses due to higher ISI.
The bessel has strongest bit rate performance. This can be credited to having the smallest intersymbol interference out of all of the channels. The reason for having this minimal ISI is due to it having the best frequency roll off making it the closest of

the three filters to the the ideal Nyquist channel which meant that at sampling periods it was oscillating through zero. This results in very small ISI.
There is a trade-off for this.
The bessel had the lowest noise margin (due to having a high frequency roll off factor) so in higher noise environments the bessel would likely not be the best choice.
Key take away:

- Having information on the response waveform shape and characteristic transfer function for the channel gives some predictive power over understanding the bit rate.

Further exploration:

- There is possibly a design choice in balancing noise robustness and intersymbol interference that would be interesting to investigate further.

VII. References

[1] T. Labs, “Selecting Between an Instrument’s AC and DC Coupling Options.” https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=14182 (accessed Sep. 19, 2022).
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[3] Y. Rong, “Lab 3 Bandlimitation and ISI.” https://lms.curtin.edu.au/webapps/blackboard/content/listContent.jsp?course_id=_118709_1&content_id=_10223535_1 (accessed Sep. 19, 2022).