ECSE 308, Winter 2024
Introduction to Communication Systems and Networks
Laboratory L1 – Report

STUDENT 1	STUDENT 2
Name: __Feiyang Huang______	**Name:** __Jingxuan Li____________
ID: __261022835__________	**ID:** _261013860___ ____________

INSTRUCTIONS:

- **Student(s) need to upload one report per team on *myCourses* before the due date.**
- **Upload a single, clearly readable pdf file, including this cover page plus answers.**
- **DUE DATE: Monday Jan. 23, 9am.**

REPORT:

Part	Question	Mark
1	1	/5
	2	/4
	3	/4
	4	/4
	5	/5
	6	/4
	7	/5
	8	/5
	9	/5
2	1	/5
	2	/5
	3	/4
	4	/5
	5	/5
	6	/5
	7	/5
	8	/5
		/80

GRADE:

	Student 1	Student 2
Participation	-	-
Report	/80	/80
TOTAL	/80	/80

McGill University, Montreal, Canada

Signals and Noise

***Abstract*—This two-part laboratory experiment was designed to explore the effects of various input signals on a system's performance, with an emphasis on the role of noise, cut-off frequency, and bandwidth using Simulink. The Part 1 of the lab involved analyzing signal characteristics and their interaction with noise. Subsequently, we studied how altering the cut-off frequency affects signal bandwidth and system performance in the Part 2 of the lab. These exercises provided valuable insights into the principles of signal processing and the importance of managing bandwidth and noise in communication system design.**

Keywords—Signal, Noise, Bandwidth, SNR, Power, Simulink

Introduction

Understanding the intricate behaviors of signals in various conditions is fundamental to advancements in communication systems. In Lab 1, we aim to dissect the core characteristics of signals and their interaction with noise through two primary objectives: first, to grasp the foundational concepts of periodic and non-periodic signals, deterministic and random signals, and the nature of Gaussian and thermal noise; second, to comprehend the critical aspects of signal power, bandwidth, and the signal-to-noise power ratio (SNR), including the effects of filtering. Employing Simulink's simulation environment, this lab report will detail our approach and findings in addressing these objectives, highlighting the importance of time-domain and frequency-domain analysis techniques in understanding, and analyzing signals for effective communication system design.

Part 1: Presentation of signals and noise

A. Periodic Signals

In this part of the lab, we first observed how a sine wave behaves in the system using Simulink, then we replaced the sine wave with a triangular wave to compare the differences. Finally, we used a pulse generator to see how the system handles sharp, non-sinusoidal signals. Each step allowed us to see the effects of different waveforms on signal analysis in both the time and frequency domains.

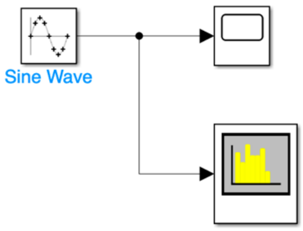

Figure 1: Sine Wave Signal System

Q1. Observe the outputs on Scope and Spectrum. Plot the sine wave over three periods. Indicate the amplitude, the period, and the frequency of the sine wave. What are the fundamental and harmonic components?

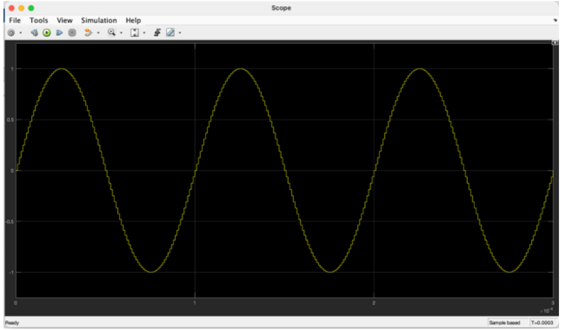

Figure 2: Output Signal on Scope

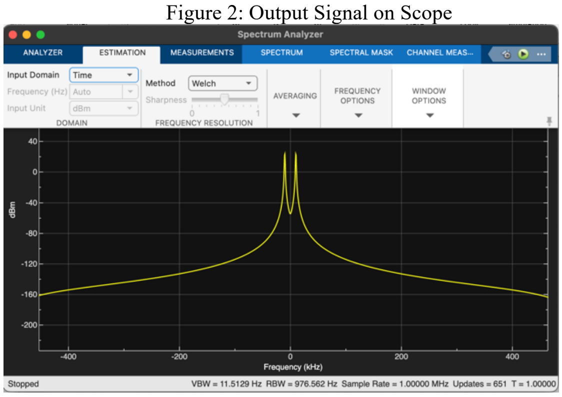

Figure 3: Output Signal on Spectrum

The amplitude of this sine wave is 1V, the period is $1 \times 10^{-4} sec$ and the frequency is $\frac{1}{period=1\times10^{-4}} = 10\ kHz$. The fundamental frequency is 10 kHz, and there is no harmonic frequency since it contains only one frequency component.

Q2. Repeat Step 1 with a triangular wave generated by Triangle Generator.

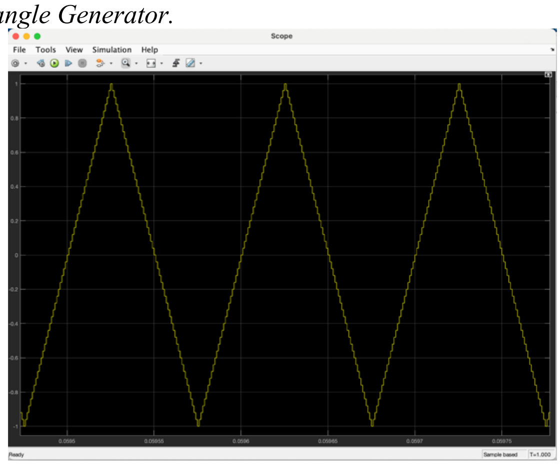

Figure 4: Output Signal on Scope

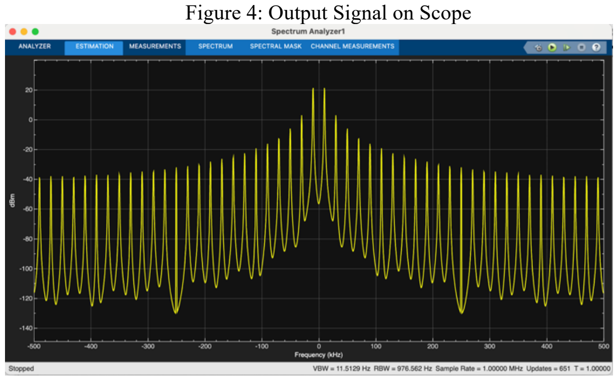

Figure 5: Output Signal on Spectrum

The amplitude, the period and the frequency remain the same as the result generated by the sine wave block.

The fundamental frequency is still the basic frequency which is 10 kHz. The harmonics of a triangular wave are present at odd multiples of the fundamental frequency (3rd, 5th, 7th, etc.), and they are the frequencies that are integer multiples of the fundamental frequency, which are 30 kHz, 50 kHz, 70 kHz, etc.

Q3. Repeat Step 1 with a 50% duty cycle square wave generated by Pulse Generator.

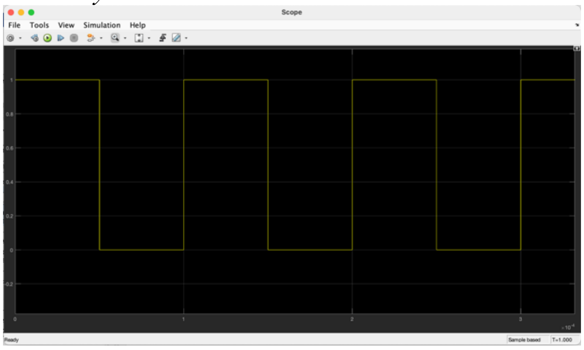

Figure 6: Output Signal on Scope

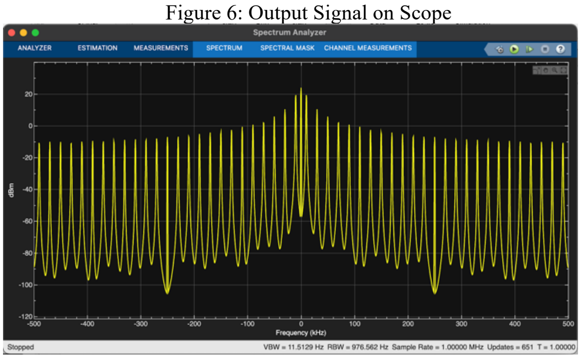

Figure 7: Output Signal on Spectrum

The amplitude, the period and the frequency remain the same as before.

The fundamental frequency is 10 kHz. A 50% duty cycle square wave contains odd harmonics as well as the triangular wave, hence the harmonic frequencies are 30 kHz, 50 kHz, 70 kHz, etc. as well.

Q4. Observe the scope and spectrum analyzer for the following setup and comment on fundamental and harmonic components of the three signals.

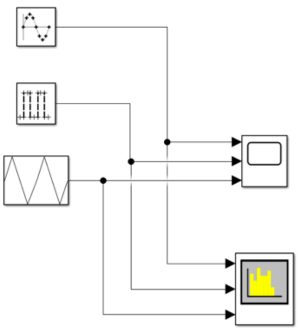

Figure 8: The assorted setup

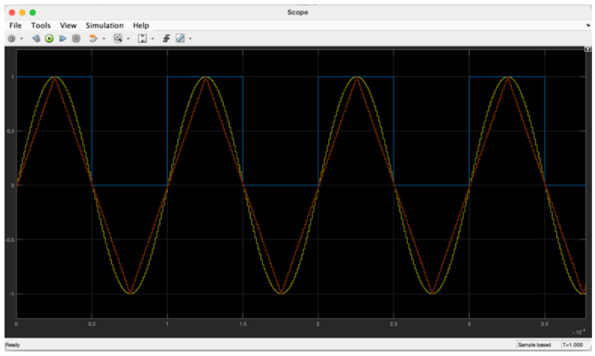

Figure 9: Output Signal on Scope

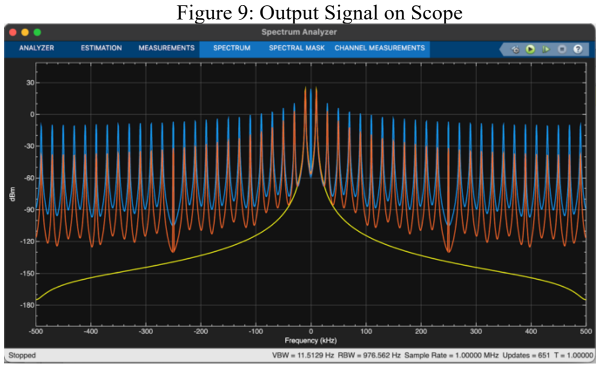

Figure 10: Output Signal on Spectrum

Their fundamental frequencies are same. The sine wave has no harmonic component. The harmonic frequencies for the triangular wave and the square wave signals are same, but they have different harmonic signal's amplitude.

B. Sum of Periodic Signals

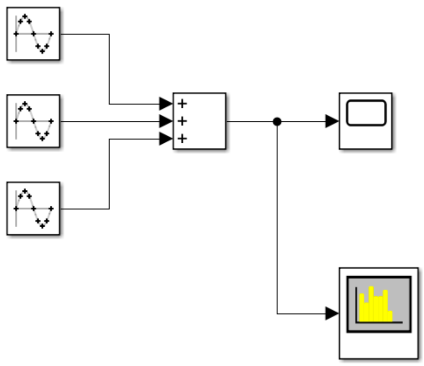

Figure 11: Sum of Periodic Signals System

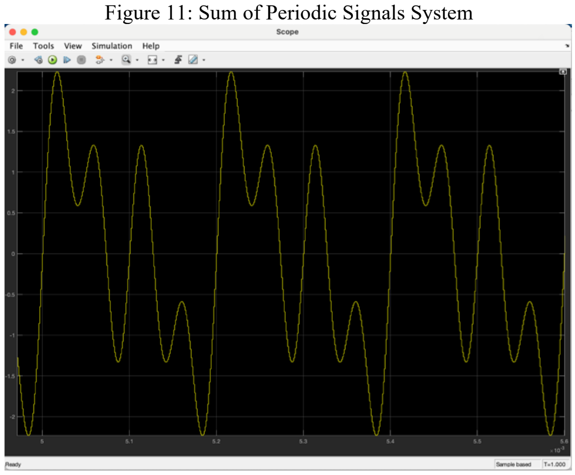

Figure 12: Output Signal on Scope

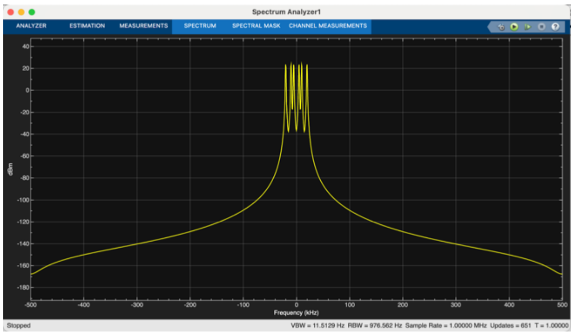

Figure 13: Output Signal on Spectrum

Q5. Repeat Step 1 with a sum of 3 sine waves as illustrated.

The amplitude of the sum of periodic signals is 2.25 V, the period is $2 \times 10^{-4} sec$, and the frequency is $\frac{1}{period=2\times10^{-4}} = 5\ kHz.$

The fundamental component is 5 kHz which is the lowest common frequency. The harmonic components are 5 kHz, 10 kHz and 20 kHz which are the three fundamental frequencies of these three sine wave signals. Since there are no harmonics for pure sine waves, these are all harmonic components.

C. Sum of Signals

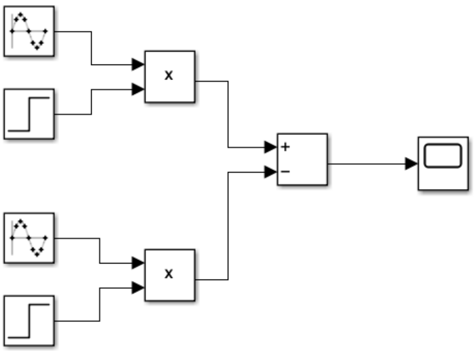

Figure 14: Sum of Signals System

Q6. Observe the output on Scope. Comment on the periodicity of the sine wave.

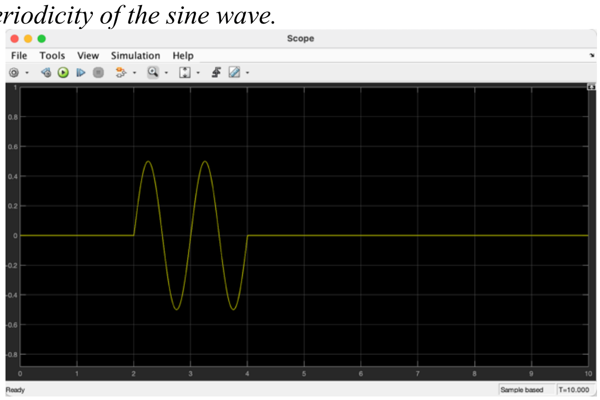

Figure 15: Output Signal on Scope

The sine waves are being multiplied by the step input initially, hence the signal is initially flat with 0 amplitude because the step functions haven't activated yet.

After the first step function activates, the step input changes from 0 to its step value, which then multiplies the sine wave. This results in the sine wave having its normal amplitude of 0.5 V for the duration that the step function maintains this value.

Once the second step function activates, the step input changed back to zero. When the step input is zero again, the sine wave is once again multiplied by zero, resulting in a flat signal at 0 V.

In summary, the step functions act as gates that turn the sine wave 'on' and 'off' at 2 to 4 seconds. When the step value is positive, the sine wave is allowed to pass through with its actual amplitude.

D. Thermal Noise

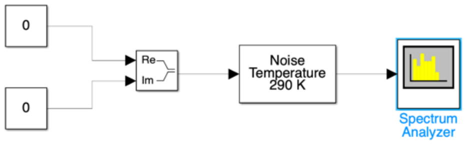

Figure 16: Thermal Noise System

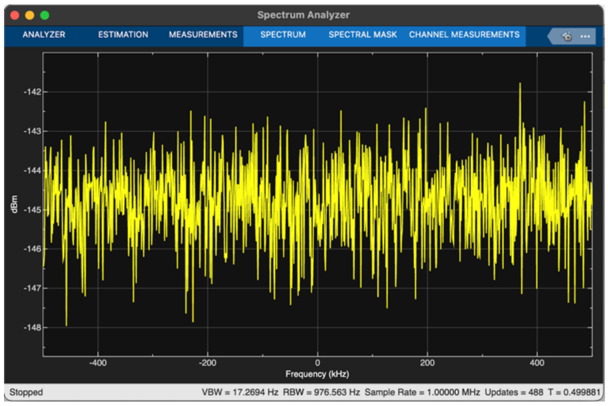

Figure 17: Output Signal on Spectrum

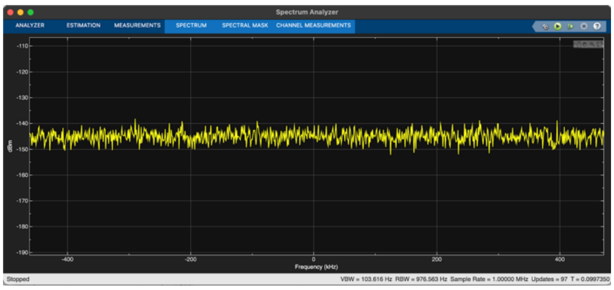

Figure 18: Output Signal on Spectrum Zoomed Out

The thermal noise is generally considered to be white noise, which has a flat spectrum over the band of interest.

Q7. What is the bandwidth and the power spectral density of thermal noise?

The bandwidth is the full range of frequencies over which the noise power is measured.

The power spectral density of thermal noise is $N_0 = k_B T$, which is $= \left(1.38 \times 10^{-23} \frac{J}{K}\right) \times (290\ K) = 4.002 \times 10^{-21}\ W/Hz.$

E. Noise power

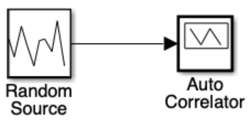

Figure 19: The Noise Power System

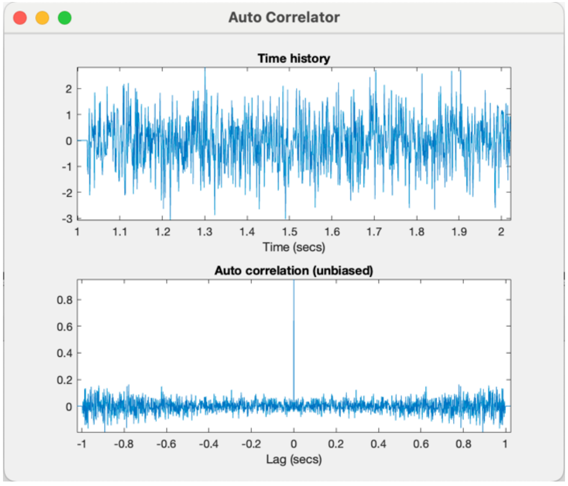

Figure 20: Output on Auto Correlator with Variance of 1

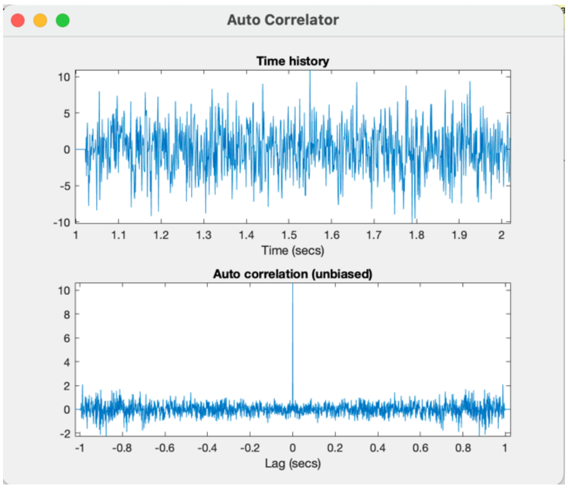

Figure 21: Output on Auto Correlator with Variance of 10

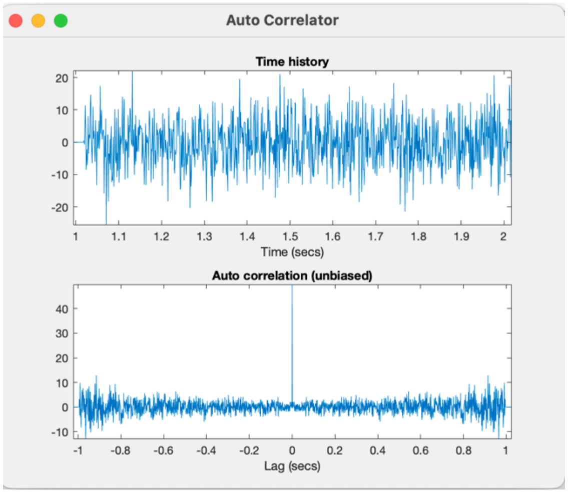

Figure 22: Output on Auto Correlator with Variance of 50

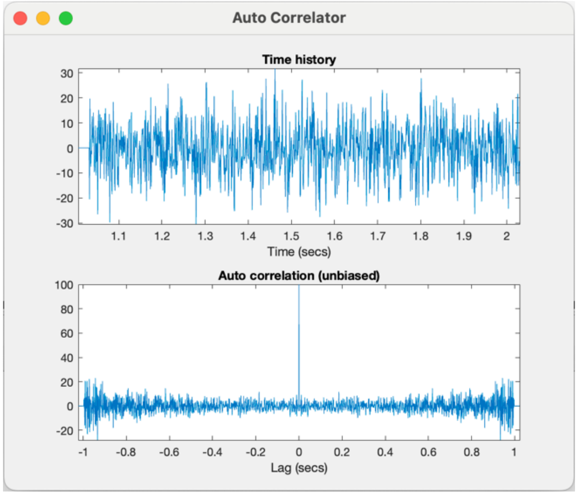

Figure 23: Output on Auto Correlator with Variance of 100

Q8. Observe the output on Auto Correlator. Vary the variance of the source. Explain how the peak value of the output on Auto Correlator is related to the variance, and thus the noise power.

As the variance of the noise increases from 2 to 10 to 50 and then 100, the peak of the autocorrelation function at zero lag will also increase correspondingly.

This shows that the noise power is increasing, which is consistent with the variance increasing since the noise power is proportional to the variance for a given resistance in a thermal noise system.

Q9. Explain the difference between random signals and deterministic signals such as sine waves, triangular waves, etc. in terms of mathematical characterization.

Deterministic signals can be described exactly by a mathematical equation. They are repeatable over time. These signals have a specific frequency, amplitude, and phase that can be precisely defined and observed at any future time.

Random signals cannot be described by a single mathematical equation. Their future values cannot be predicted even knowing all past values. They are characterized by their statistical properties, such as mean, variance, and probability density functions. For instance, thermal noise is often characterized by a Gaussian distribution with a mean of zero and a certain variance.

Part 2: Power, bandwidth & SNR

A. Single Signal Input

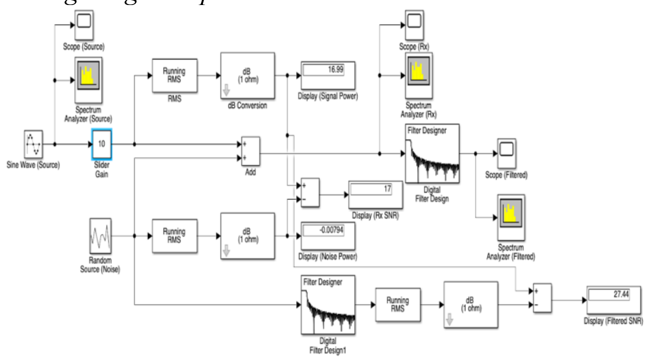
Figure 24: Single Signal Input and Noise Input System

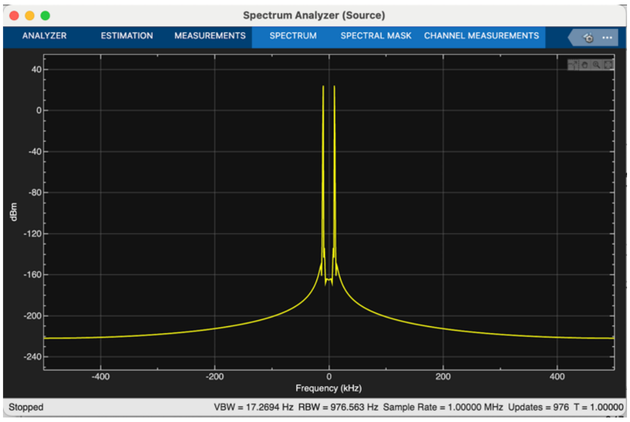

Figure 25: Sine Wave Source Spectrum

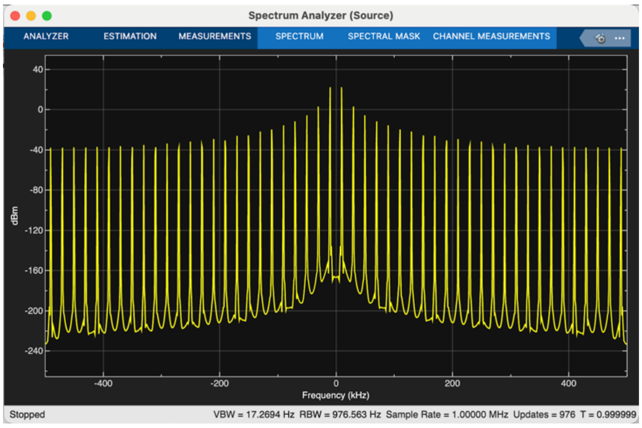

Figure 26: Triangle Wave Source Spectrum

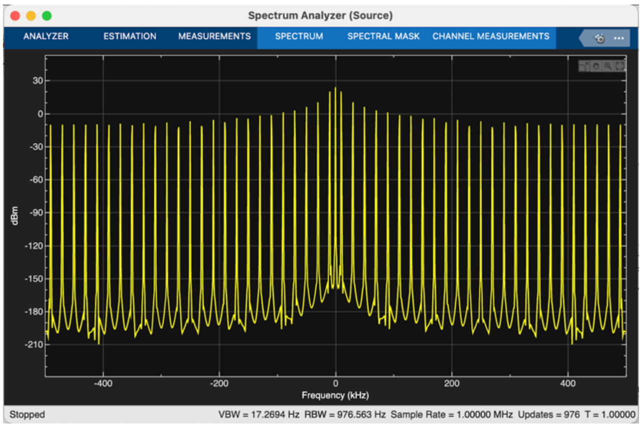

Figure 27: 50% Duty Cycle Square Wave Source Spectrum

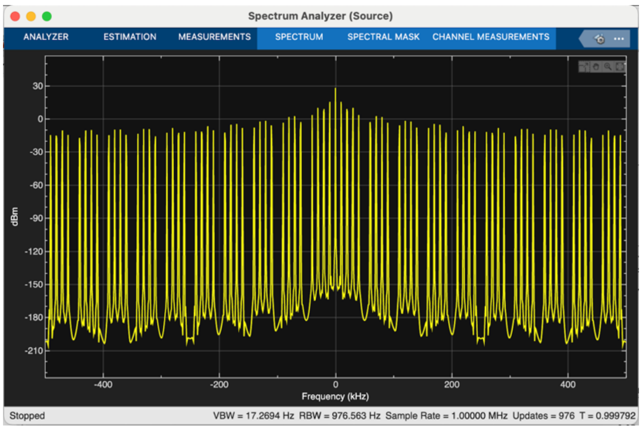

Figure 28: 50% Duty Cycle Square Wave Source Spectrum

The blocks are connected as the Figure 24 shown above. With the parameters all set to the value as the instructions state, we are able to run the simulation and observe the results.

Q1. Observe the output on Spectrum (Source). What are the power and the bandwidth of the sine wave?

The spectrum of the single sine wave is shown in Figure 25 above. From the figure, we can observe that the peak value of this spectrum lies approximately at 25 dbm while theoretically, the power of this sine wave is 26.99 dbm. The bandwidth of this sine wave is approximately 20 Hz in the spectrum while the sine wave has zero bandwidth theoretically.

Q2. Observe the output on Spectrum (Source). What are the power and the bandwidth of the triangle wave?

Figure 26 displays the spectrum of the triangle wave. The peak value in the spectrum is approximately 25 dbm, closely aligning with the theoretical power of the triangle wave, which is 25.229 dbm. The spectrum indicates a bandwidth of 976.563 Hz for this triangle wave, although, in theory, a triangle wave possesses infinite bandwidth.

Q3. Observe the output on Spectrum (Source). What are the power and the bandwidth of the 50% duty cycle square wave?

Figure 27 presents the spectrum of the square wave. Observations from the figure indicate that the spectrum's peak value is roughly 25 dbm, closely matching the theoretical power of the square wave at 25.229 dbm. The bandwidth is noted as 976.563 Hz in the spectrum, identical to that of the previously mentioned triangle wave. However, the harmonics of the square wave diminish at a slower rate compared to those of the triangle wave.

Q4. Observe the output on Spectrum (Source). What are the power and the bandwidth of the 80% duty cycle square wave?

The spectrum of the square wave is shown in Figure 28 above. From the figure, we can observe that the peak value of this spectrum lies approximately at 25 dbm. The bandwidth of this square wave is 976.563 Hz as shown in the spectrum, which is the same with that of the 50% duty cycle square wave demonstrated above, but the harmonics of the square wave will decrease less rapidly than the 50% duty cycle square wave.

B. Multiple Signal Input

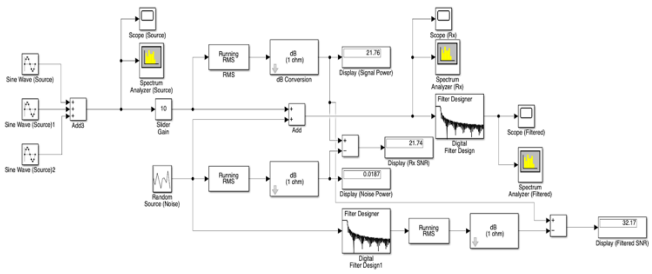
Figure 29: Sum of Three Sine Waves Input and Noise Input System

The blocks are arranged as depicted in Figure 29. By setting the parameters according to the given instructions, we can execute the simulation and analyze the outcomes.

Q5. Observe the output on Spectrum (Source). What are the power and the bandwidth of the sum of three sine waves?

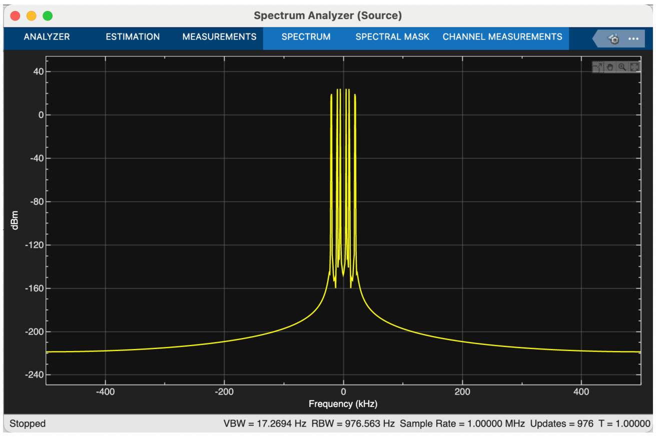

Figure 30: Sum of Three Sine Waves Source Spectrum

Figure 30 displays the spectrum of the sum of three sine waves. The peak value in the spectrum is approximately 25 dbm. The spectrum indicates a bandwidth of 976.563 Hz for this wave.

Q6. Observe the outputs on Scope (Rx) and Spectrum (Rx). Comment on the effect of noise on the signal in the time domain and the frequency domain.

The figures of the scope and the spectrum are shown below.

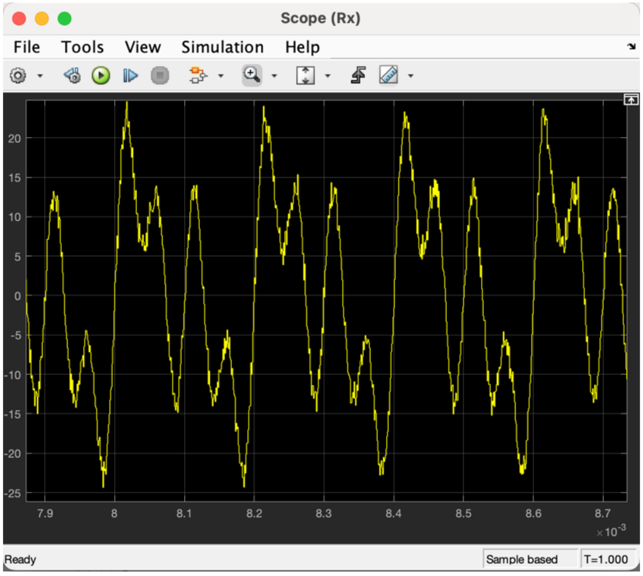

Figure 31: Sum of Three Sine Waves Rx Scope

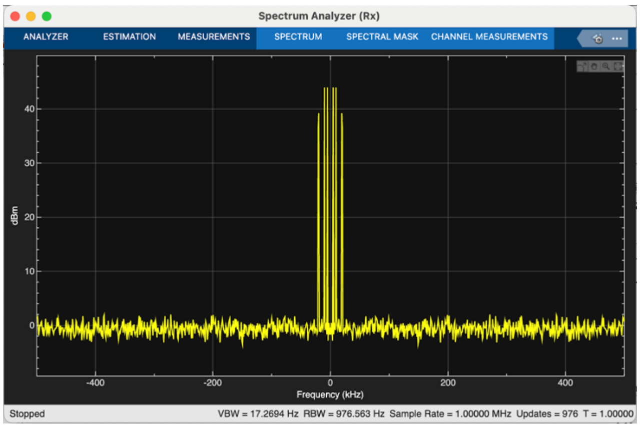

Figure 32: Sum of Three Sine Waves Rx Spectrum

The scope figure reveals that the signal displayed in the scope is not smooth, suggesting that noise has impacted the input signal in the time domain. Moreover, the presence of noise has disrupted the periodicity of the signal, rendering it non-periodic.

The spectrum figure shows that in addition to the spectrum of the three sine waves, white noise has been introduced into the system, resulting in the presence of all frequencies in the frequency domain.

Q7. Compare the outputs on Scope (Filtered) and Spectrum (Filtered) with those on Scope (Rx) and Spectrum (Rx) respectively. Comment on the effect of filtering.

The figures of the scope (filtered) and the spectrum (filtered) are shown below.

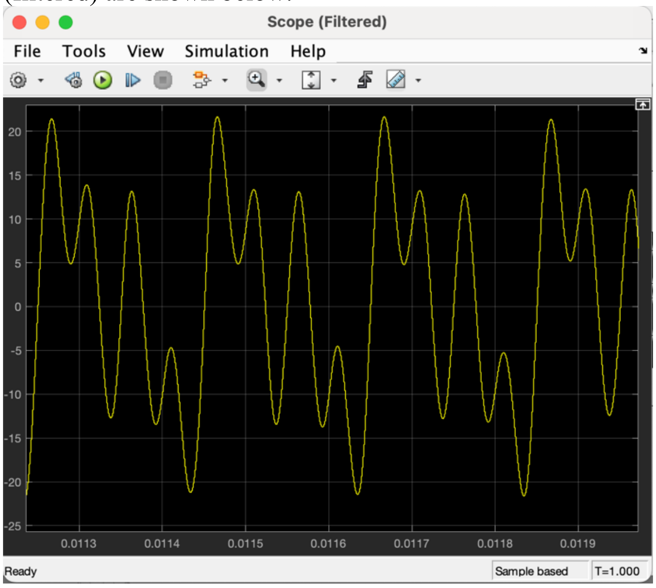

Figure 33: Sum of Three Sine Waves Filtered Scope

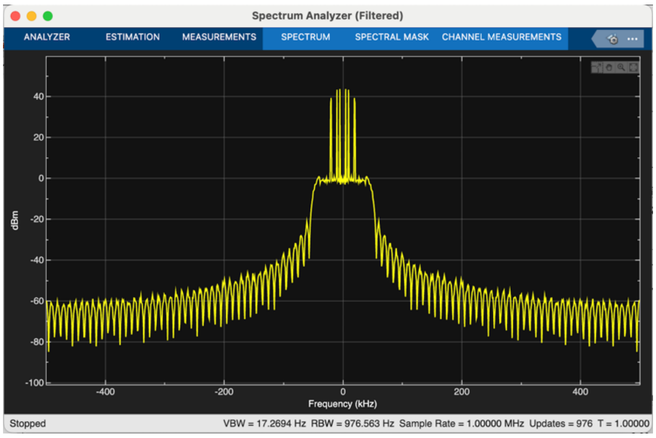

Figure 34: Sum of Three Sine Waves Filtered Spectrum

As we can tell from these two figures comparing to the ones which are not filtered yet, the filtered signal in the scope is smoother than before, which can be achieved by applying a digital filter across the path. In time domain, the signal returns to periodic after the filter included. On the other hand, in the frequency domain, as we can observe in the Figure 34, it shows a significant reduction in the amplitude across the frequency range, which suggests that a band-pass filter has been applied.

Q8. Vary Slider Gain from small to large Observe the outputs on Scope (Filtered) and Spectrum (Filtered). Comment on how the effect of noise varies in accordance *with the SNR at the filter output. Repeat for a varied cut-off frequency Fc in Digital Filter Design.*

We decide to vary the slider gain from 5 to 20. The following figures are the scope and spectrum filtered when the slider gain is at 5.

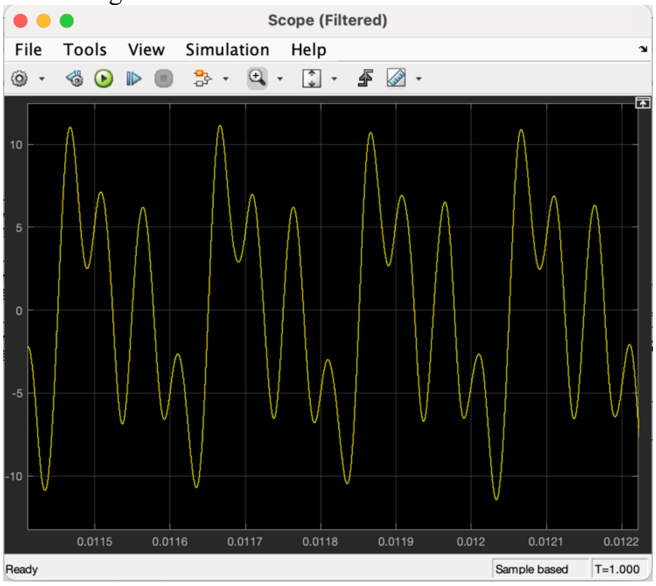

Figure 35: Sum of Three Sine Waves Filtered Scope at slider gain = 5

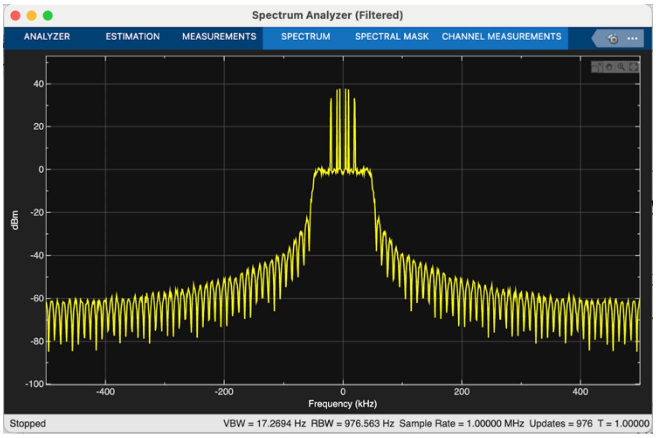

Figure 36: Sum of Three Sine Waves Filtered Spectrum at slider gain = 5

After capturing the figures, we change the slider gain to 20 to observe the difference between these two circumstances.

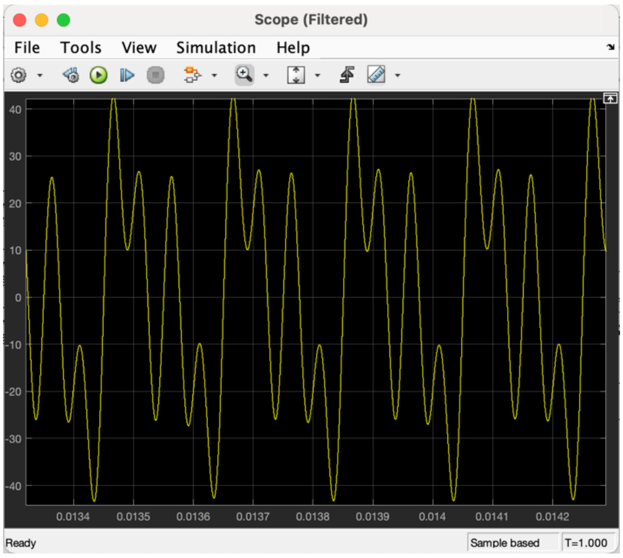

Figure 37: Sum of Three Sine Waves Filtered Scope at slider gain = 20

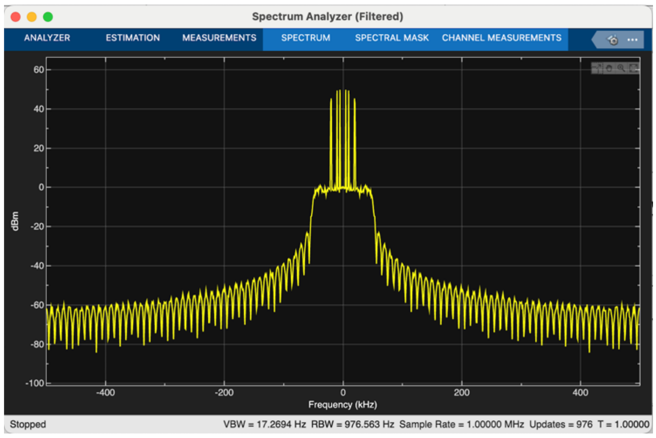

Figure 38: Sum of Three Sine Waves Filtered Spectrum at slider gain = 20

The above figures represent the scope and spectrum filtered when the slider gain is at 20.

In both situations, the waveform retains its shape. The variation in gain, ranging from 5 dB to 20 dB, leads to a heightened amplitude of the signal peaks. This amplification influences solely the magnitude of the waveform, without modifying its fundamental frequency or inherent shape. The heightened gain proportionally scales the amplitude of the entire signal.

On the other hand, in the spectrum cases, the distributions maintain their shapes. The main distinction between the two spectra lies in the peak power level. The gain increment has led to a rise in peak power.

Comparing both figures, it's evident that the increased gain not only amplifies the signal but also enhances the Signal-to-Noise Ratio (SNR). This implies that the signal components have been amplified more significantly than the noise, resulting in a more pronounced separation between the signal and noise within the spectrum.

The instructions also acquire us to vary the cut-off frequency in Digital Filter Design. We examine the system with two distinct cut-off frequencies which are 10 Hz and 4e5 Hz. The scopes and spectrums are as follows.

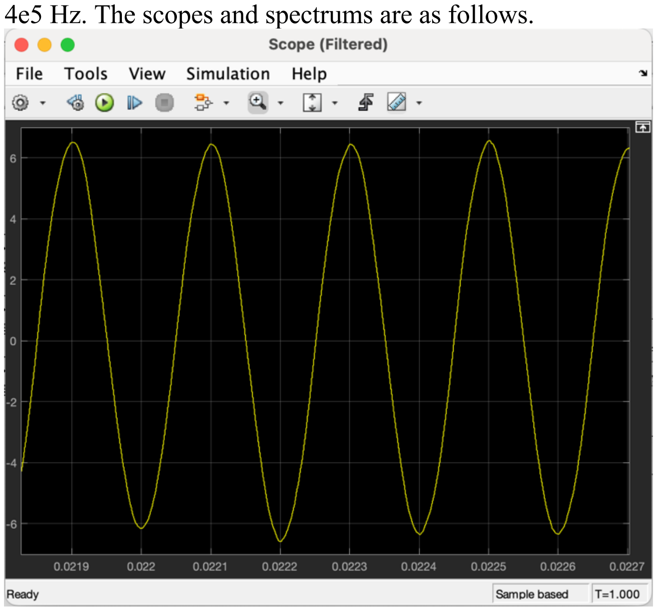

Figure 39: Sum of Three Sine Waves Filtered Scope at Fc = 10 Hz

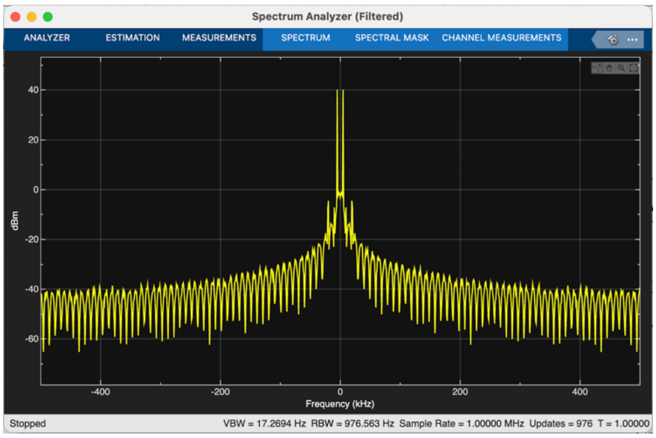

Figure 40: Sum of Three Sine Waves Filtered Spectrum at Fc = 10 Hz

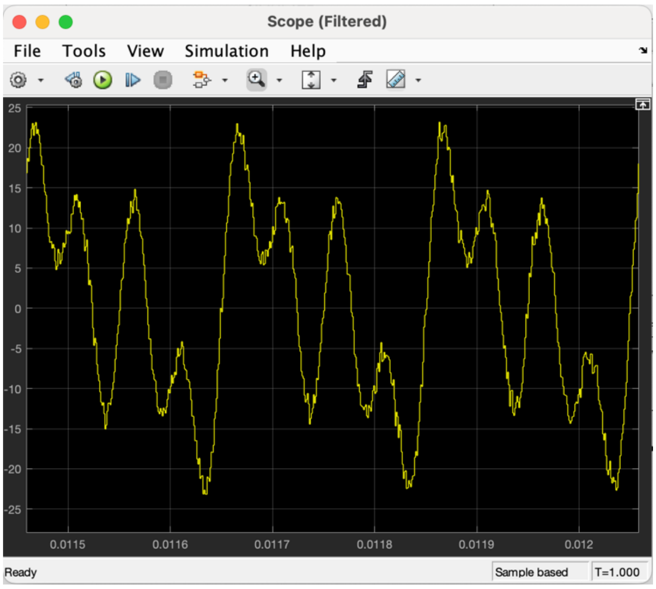

Figure 41: Sum of Three Sine Waves Filtered Scope at Fc = 4e5 Hz

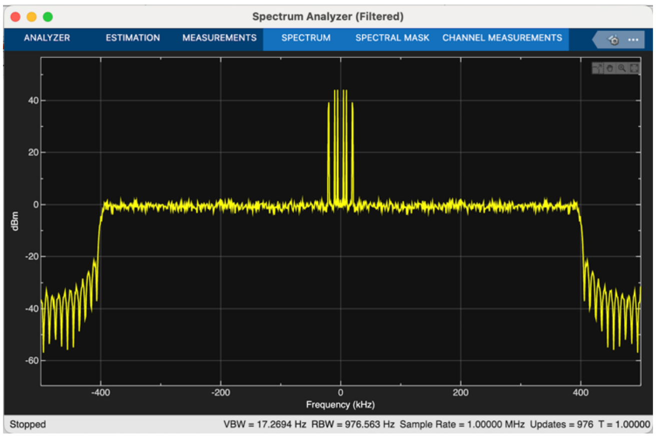

Figure 42: Sum of Three Sine Waves Filtered Spectrum at Fc = 4e5 Hz

In the figure with a 10 Hz cut-off frequency, the SNR stands at a significant 40.81, signifying a substantially stronger signal compared to the noise. The waveform's smoothness indicates the low-pass filter's efficacy in eliminating high-frequency noise, hence purifying the signal.

Conversely, in the figure with a 4e5 Hz cut-off frequency, the SNR drops to 21.87, pointing to a comparatively higher noise presence against the signal. The waveform is noticeably erratic, exhibiting spikes and fluctuations. This suggests the high-frequency noise persists, attributed to the elevated cut-off frequency not sufficiently filtering it out.

In the figure of 10 Hz cut-off frequency spectrum, the spectrum analysis highlights a distinct peak at the signal frequency with minimal spectral energy elsewhere, showcasing the filter's success in largely eliminating noise. This is in line with the high SNR observed in the scope image, where the output signal waveform is predominantly composed of the signal, appearing clean and smooth with minimal noise interference.

On the contrary, Figure 42 displays a spectrum with a wider energy distribution, characterized by numerous peaks and a significant level of background noise. This suggests that the filter permits a substantial amount of noise, correlating with the lower SNR seen in the scope image, where the waveform is noticeably erratic, infused with high-frequency noise.

To summarize, as the filter's cut-off frequency rises, it allows more noise to penetrate, leading to a reduced SNR at the output and a noisier signal. Conversely, a lower cut-off frequency yields a higher SNR, signifying a cleaner signal with reduced noise. The influence of noise on the filter's output is inversely related to the SNR: a higher SNR implies minimal noise impact on the signal.

Conclusion

In conclusion, this lab has provided a comprehensive exploration into the behavior of different types of signals within a simulated communication system. Through a series of experiments, we have observed the characteristics of deterministic signals, such as sine and triangular waves, and their distinct mathematical descriptions. We've analyzed how these signals manifest in both the time and frequency domains, gaining insights into their periodicity, harmonics, and spectral content.

Moreover, we've delved into the realm of random signals, examining thermal noise and its impact on system performance. By employing tools such as the autocorrelator, we've investigated the statistical nature of random signals, contrasting them with the predictability of deterministic signals. We've seen firsthand how the variance of a noise source influences its power, and how this is reflected in the autocorrelation function.

The lab has emphasized the importance of understanding both deterministic and random signals for the design and analysis of communication systems. The mathematical characterization and simulation of these signals in Simulink have provided a strong foundation for recognizing the challenges that noise and signal structure pose to the fidelity of communication.

Overall, the exercises completed in this lab serve as a critical step in grasping the complexities of signal processing, offering a practical perspective on the theoretical concepts that underpin modern communications. The skills and knowledge acquired here will undoubtedly be invaluable for future studies and applications in the field of electrical and communication engineering.

References

[1] "L1: Signals and Noise" McGill University. https://mycourses2.mcgill.ca/d2l/le/lessons/688501/topics/7606209 (accessed Jan. 20, 2024)

Experiment was taken in the laboratory section of ECSE 308 at McGill University, Montreal, QC, H3A 0E9, Canada.