EE453 Software Defined Communication

RTL-SDR FM Demodulation & Image/Audio Receiver

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1. Project Implementation

In this project, an Image/Audio Receiver was used. The project implementation can be seen in Figure 1.

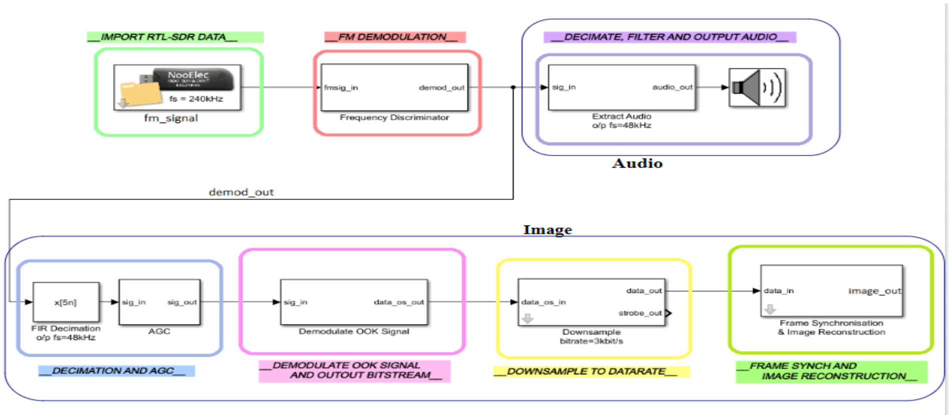


Figure 1: Project Implementation

The receiver was analyzed in two parts. The first part was performed for the Audio Extraction and the second part was performed for the Image Reconstruction.

1.1. RTL-SDR Data

In this project, a modulated and recorded RTL-SDR data was used. The data includes both audio and image signal. The audio data was at 48 kHz and modulated with 5 kHz carrier signal. Image data was converted to binary bits then modulated with a 12 kHz On-Off Keying (OOK) signal which was a modulation that keys a sinusoidal signal on and off with a unipolar binary signal [1]. The recorded signal was obtained by the addition of the audio and image signals. The recorded signal was sampled with the sampling frequency of 240 kHz which is the sampling frequency of RTL-SDR. The modulated image audio signal and its stages can be seen on Figure 2.

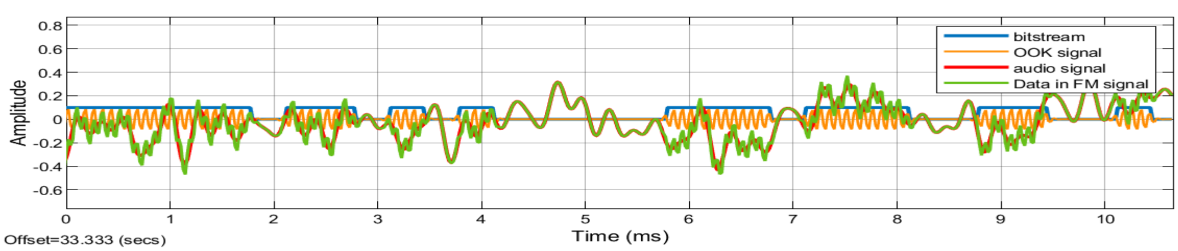


Figure 2: Representation of The Modulated Signal and The Stages

1.2. Audio Extraction

In the first part of the experiment, audio signal was extracted and listened from the Speaker. The audio extraction process can be seen in Figure 3 below.

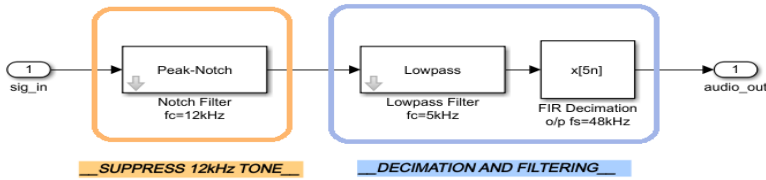


Figure 3: Audio Extraction Process

The Image/Audio data was filtered with a Notch filter which is used for filtering a specific frequency. The 12 kHz image data was suppressed to obtain only the audio signal and all the other frequencies were passed. The filtered signal then filtered again with a lowpass filter for acquiring the 5 kHz carried audio signal. Decimation was performed to reduce the sampling rate of the signal from the RTL-SDR sampling frequency of 240 kHz to audio signal sampling frequency of 48 kHz. The output was listened from the speaker.

1.3. Image Reconstruction

In the second part of the project, the image was reconstructed. The reconstruction process can be seen in Figure 4.

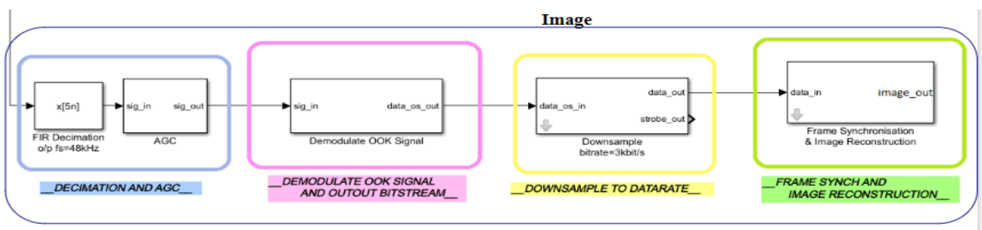


Figure 4: Image Reconstruction Process

Image was decimated to 48 kHz same as the audio signal then passed through the Automatic Gain Control (AGC) block to obtain a constant level by adaptively adjusting the gain and keeping it in the given range to prevent overlaps.

1.3.1. OOK Signal Demodulation

The 12 kHz OOK signal was demodulated to reach the image data as a first step of the reconstruction. The detailed inside of the block can be seen in Figure 5.

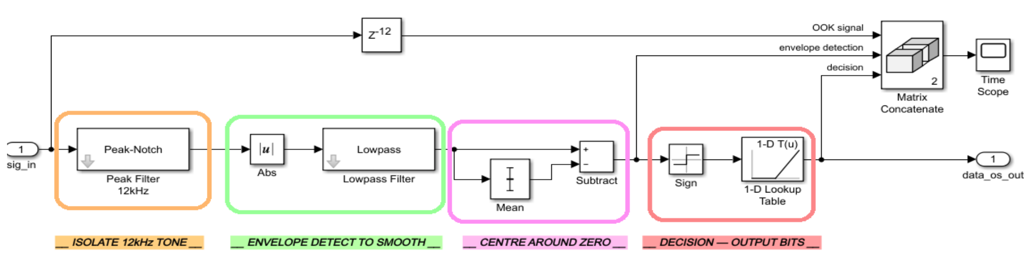


Figure 5: OOK Demodulation Blocks

A Peak filter was used to eliminate the frequencies except the 12 kHz image data. Envelope detection was performed and the detected signal was centered around zero by subtracting the mean from itself. Demodulated signal was converted to 1's and -1's with signum function and the hard decision process was performed to obtain 1's and 0's. A bitstream was obtained at the output. The signals in each step were shown in Figure 6.

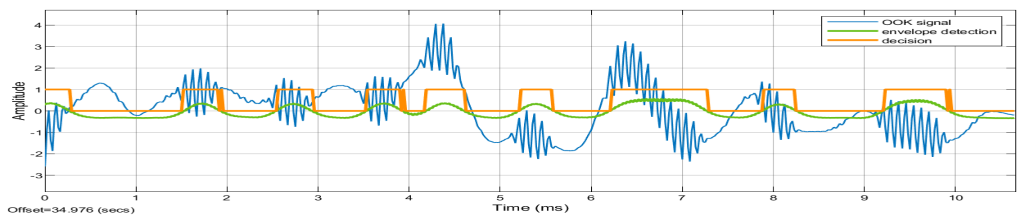


Figure 6: Signals in Each step of OOK Demodulation

1.3.2. Down sampling To Bitrate

Because of having a 3-kbps bitrate of the modulated signal, the need of having the same bitrate was occurred. In the Figure 7 below, the down sampling can be seen.

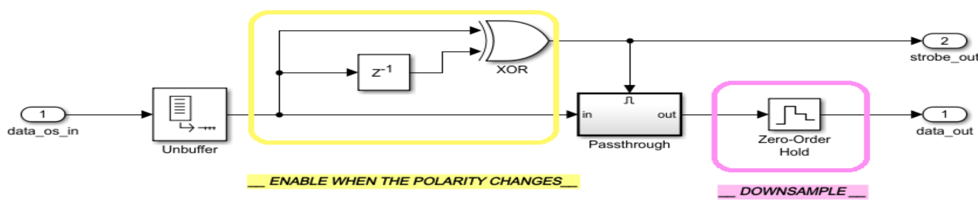


Figure 7: Down sampling to Bitrate Blocks

The obtained bitstream was unbuffered and the frames were converted to samples. By using a logical XOR gate the circuit was enabled with the change of the polarity and it passed through the incoming sample. Down sampling to 3 kbps bitrate was performed with the Zero-Order Hold block.

1.3.3. Frame Synchronization

The frames were synchronized using the blocs shown in Figure 8.

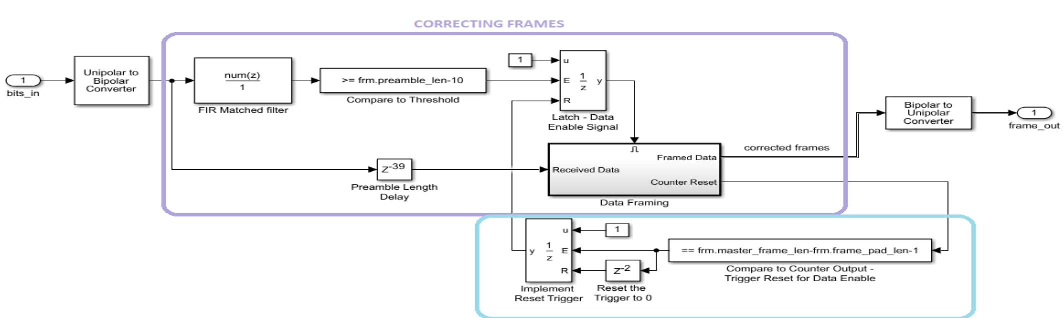


Figure 8: Frame Synchronization

The preamble frames were used to find out the first frame of the image. When the threshold became greater than or equal, data framing was enabled and acted as a clock. Unbuffered samples were buffered to frames again and a reset mechanism was use to stop the simulation and show the image when the necessary number of frames were obtained.

1.3.4. Image Reconstruction

Image reconstruction block was given in Figure 9.

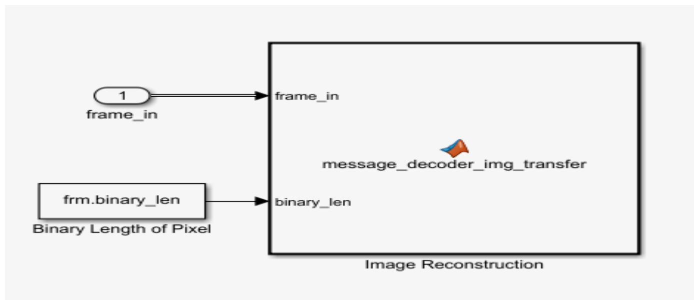


Figure 9: Image Reconstruction

Corrected frames and the binary length of pixel was used as an input to the MATLAB code which was used to plot the images when the appropriate number of frames were retrieved.

2. Demodulation Types

2.1. Frequency Discriminator

The Complex Delay Line Frequency Discriminator is a much simpler noncoherent FM demodulator than the complex differentiation discriminator. The four DSP blocks shown in Figure 10 can be used to build this gadget.

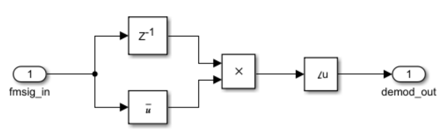


Figure 10: Representation of The Complex Delay Line Frequency Discriminator.

Real and imaginary components are present in the complex FM signal. This signal is expressed in exponential form. Two parallel blocks receive this complex signal. One of them uses the signal's conjugate to shift its phase, while the other adds a time delay to slow it down. These signals are then mixed in a process called phase detection. The resulting signal's real and imaginary components, as well as its magnitude, have nothing in common with the sinusoidal information signal. The information is encoded in the angle of the transmission. To extract it, argument is taken [2]. Thus, by applying differentiation:

$$s_d(t) =- \left[\frac{d}{dt}\left(w_\Delta t\right) + \frac{d}{dt}\left(\theta_{fm}(t)\right)\right] =- \left[w_\Delta + \theta'_{fm}(t)\right] =- \left[w_\Delta + 2\pi K_{fm} s_i(t)\right]$$

2.2. Complex Differentiation

The Complex Differentiation Discriminator uses a dual branch differentiator to handle the In-phase and quadrature-phase components independently as can be seen in Figure 11.

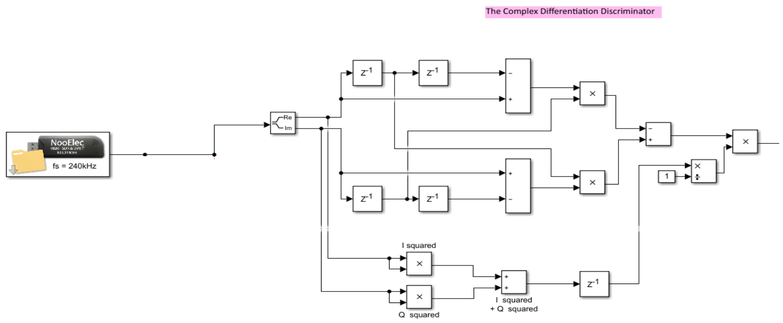


Figure 11: Representation of The Complex Differentiation Discriminator.

The complex FM signal consists of both real and imaginary components. Considering them separately, one of them specifies the In-phase component, other specifies the Quadrature component. Firstly, each of these components differentiated separately. Only signals with an envelope can be demodulated using envelope detectors. Before the information can be recovered, these differentiated components must be manipulated. This can be accomplished by mixing the differentiated equations. After that, these signals are combined by subtracting. Then, we need to normalize the amplitude. Instantaneous value of the received signal power can be determined by squaring and summing the in phase and Quadrature channels. Thus, normalized signal can be obtained [2].

$$s_n(t) = \frac{s_\alpha(t)}{s_p(t)} = \frac{\left[\left[s_{qp}^{'(t)}\ x\ s_{ip}(t)\right] - \left[s_{ip}^{'(t)}\ x\ s_{qp}(t)\right]\right]}{s_{ip}(t)^2 + s_{qp}(t)^2} = \frac{\frac{A_c^2}{4}\left[w_\Delta t + \theta_{fm}'(t)\right]}{\frac{A_c^2}{4}}$$

$$= w_\Delta t + \theta_{fm}'(t) = \left[w_\Delta + 2\pi K_{fm} s_i(t)\right]$$

Comparison of Outputs

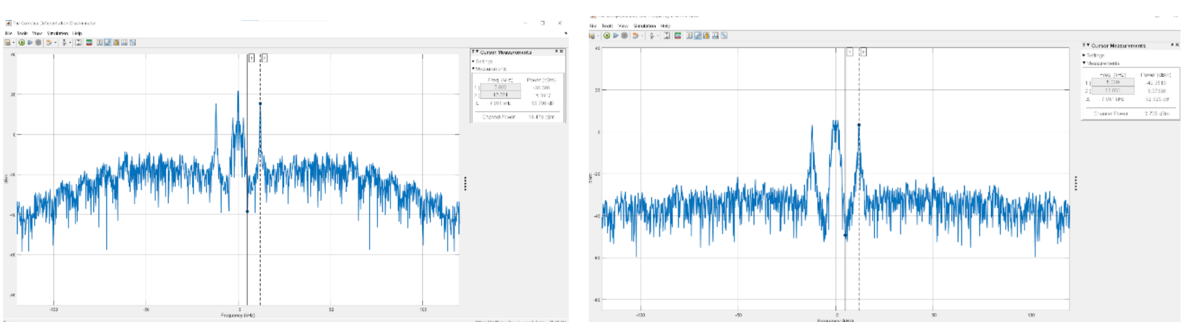


Figure 12: Output Signal Comparison of Demodulators.

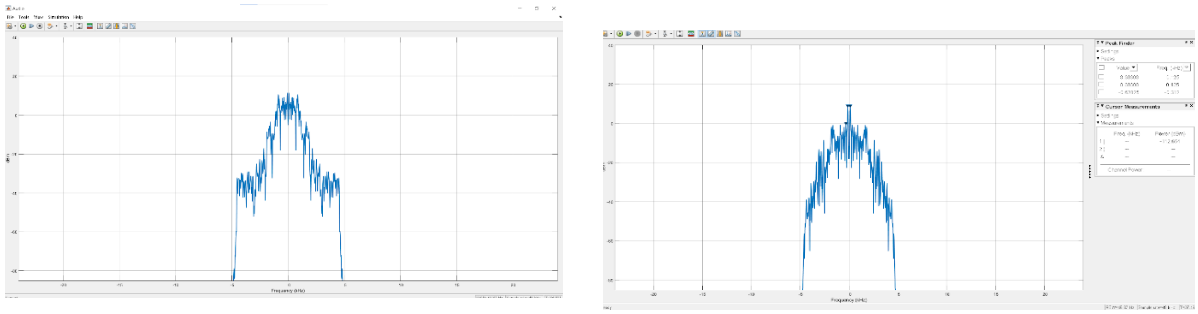


Figure 13: Output Audio Signal Comparison of Demodulators

The spectrum analysis of the demodulated signals can be seen in Figure 12 for the Complex Delay Line Frequency Discriminator and the Complex Differentiation Discriminator, respectively. Also, output audio signals of both demodulators are shown in Figure 13. An audio signal with a center frequency of 5 kHz and an image signal with a center frequency of 12 kHz are observed. As we can see the result of the Delay Line Complex Frequency Discriminator is similar to the output by the complex differentiation discriminator but they have some differences. There are some random negative peaks at output of the Complex Differentiation Discriminator.

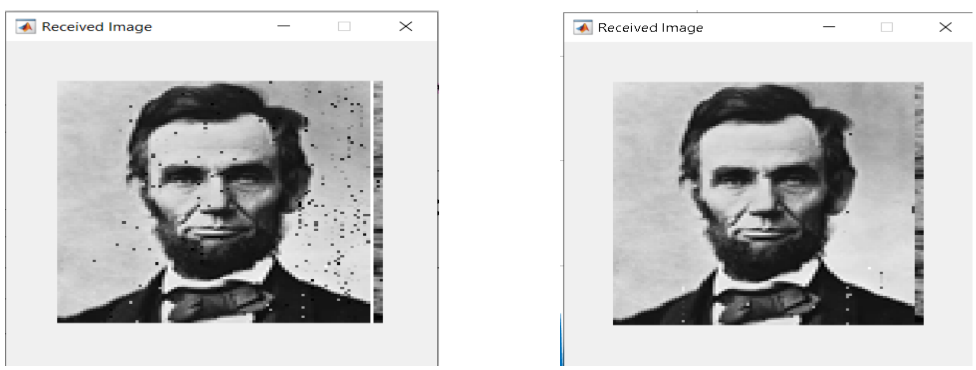


Figure 14: Output Image Comparison of Demodulators

Finally, the output image comparison can be seen in figure 14. It can be seen that a clearer image is obtained when The Complex Delay Line Frequency Discriminator is used. There is no frame loss for The Complex Delay Line Frequency Discriminator although, the frame loss is observed at the output of the Complex Differentiation Discriminator because the peak did not occur in the 97th column. Also, there is much more pixel error for The Complex Differentiation Discriminator because of small bit errors.

3. NOISE MODEL

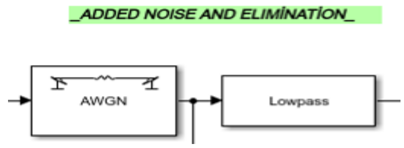


Figure 15: Added Noise and Elimination

In real life, signals are exposed to noise for many reasons while being transmitted. The effect on audio and images obtained after simulating this noise and reducing the noise was observed. In order to reduce this effect, the parameters of some elements in the circuit have been changed. Added AWGN to simulate noise and a low pass filter to reduce noise as seen in Figure 15.

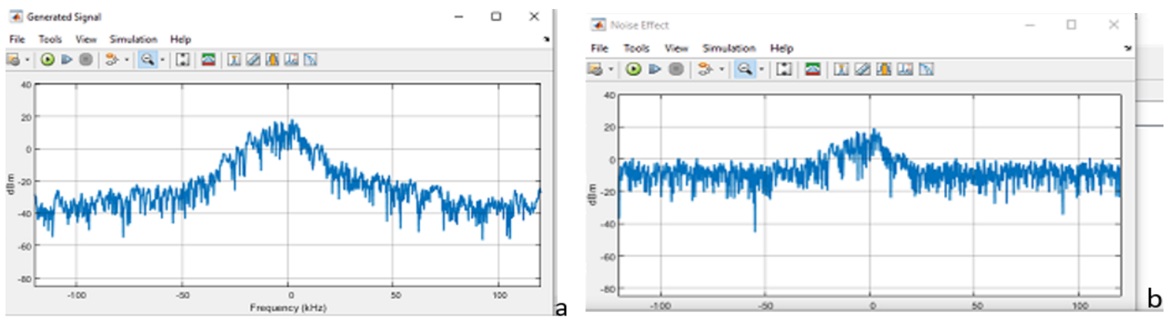
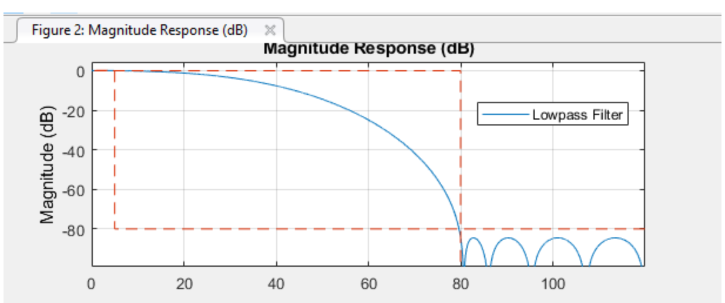


Figure 16: a) Generated Signal b) Noise Added in Signal

10 dB SNR was added by selecting the SNR parameter from the AWGN Channel block added to Simulink. The effect of the added noise is observed in the right-side outputs. The generated signal is seen in the spectrum analyzer in the figure a. The spectrum in Figure 16 shows the signal with added noise.



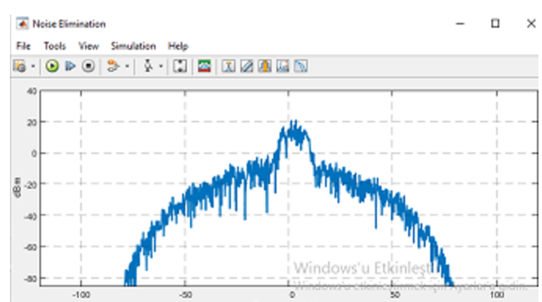
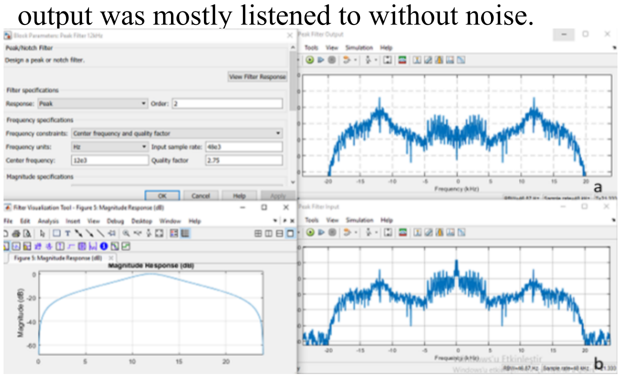


Figure 17: Magnitude Response of Low Pass Filter **Figure 18:** After Low Pass Filter Signal Spectrum

Added a low pass filter block to reduce the effect of noise. The stopband edge frequency of the filter was chosen as 80 kHz and the cutoff frequency as 5 KHz. The magnitude response of the low pass filter created in Figure 17 is seen. The reason for choosing a wide stopband edge frequency here is to minimize the noise effect on the image. As seen in Figure 18, it is seen that the signal coming out of the low-pass filter is similar to the generated signal.

To listen to audio, decimate and filter processes were applied after demodulation. The audio output was mostly listened to without noise.



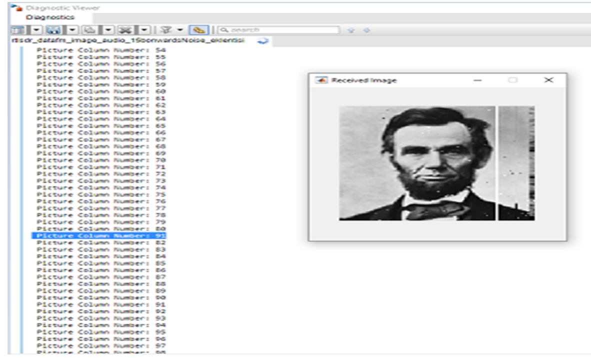


Figure 19: a) Peak Filter Output Spectrum

b) Peak Filter Input Spectrum

Figure 20: Output of Image

A peak filter is a frequency filter that passes a narrow band of frequencies and stops all other frequencies. The original quality factor was changed after the center frequency was determined.

$$Q = \frac{f_C}{f_1 - f_2} = \frac{\text{center frequency}}{\text{3 dB bandwidth}}$$

This is because the low-power frequencies of the signal passing through the applied low-pass filter are strengthened after the noise increases. For this reason, the Q factor was kept between 2 and 3 as seen in figure 19. When calculating this range, f1 and f2 frequencies are tried to be taken in the appropriate range.

As a result, the image output is as in the figure. Here, an attempt was made to optimize all the parameters that affect the output. However, the error was always received because the peak did not occur in the 81st column at the most optimal level, as can be seen in Figure 20. This is because the low frequency components in the signal are reduced by the low pass filter effect added after the noise.

4. CONCLUSION

In conclusion, the implementation of RTL-SDR FM Demodulation & Image/Audio Receiver circuit was discussed. Two different demodulation techniques were compared. The difference between output signals and images of The Complex Delay Line Frequency Discriminator and The Complex Differentiation Discriminator was observed. It was found that more accurate results were obtained for both visual and audio with The Complex Delay Line Frequency Discriminator. Then noise was added to this model. A noise low pass filter was used to eliminate the noise. A frame error occurred while printing the received results.

REFERENCES

[1] *Product documentation*. NI. (n.d.). Retrieved May 27, 2022, from https://www.ni.com/docs/en-US/bundle/ni-usrp-20.5/page/usrphelp/ook.html

[2] Stewart, R. W., Barlee, K. W., Atkinson, D. S., & Crockett, L. H. (2015). *Software defined radio using Matlab' & Simulink' and the Rtl-Sdr*. Department of Electronic and Electrical Engineering, University of Strathclyde.