

ADV DSP

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Advanced DSP

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Abstract

The purpose of this project is to produce and analyse Frequency Modulation (FM) communication using GNU Radio [1]. GNU Radio [1] is an open source radio development toolkit focused on designing radio architectures of Software Defined Radios (SDRs) using a flow-graph like Graphics User Interface (GUI) where individual blocks offer radio functionality (e.g. a low pass filter). The project is divided into two tasks with task 1 focusing on Narrow Band FM (NBFM) [2] and Frequency Hopping Spread Spectrum (FHSS) and analyse the effects of noise on both modulation schemes in the GNU radio software. Task 2 focuses on building a SDR receiver to capture real-world Radio Frequencies (RF) analysing the signal at the different stages of the receive architecture.



Introduction

Wide Band FM (WBFM) [2] and (NBFM) [2] are FM modulation techniques where wideband architectures are usually associated with a bandwidth of greater than 75KHz and provide a high signal to noise ratio (SNR). They are typically used for high quality audio applications where high fidelity is required. However, the requirement for more bandwidth makes them more expensive, power hungry and complex against other types such as NBFM [3]. WBFM is usually used in FM broadcasting and other commercial applications. NBFM is typically less than 5KHz of bandwidth with a lower SNR than WBFM but can still be used for audio applications. NBFM is more efficient than WBFM utilising less bandwidth, less complex and requires less power consumption [3]. The expense of audio quality, noise rejection and scope in terms of uses. This architecture is usually used for two way or amplitude communications.



When transmitting Over the Air (OTA) many parameters such as interference, multipath atmospheric conditions can disturb the signal quality and even deny successful reception [4]. Furthermore, there may be even parties which may wish to intentionally disturb a signal by emitting their own signal on the same frequencies. This is known as Jamming. Jamming can be very damaging to wireless communications as it is usually targeted and at higher powers than natural interference and so can be very troublesome. There are many forms of Jamming but the most popular include:

Type	Advantages	Disadvantages	Use Cases
Barrage – Jams wide range of Frequencies	Effective against multiple channels simultaneously	Inefficient, high power requirements	Against wide area communication
Sweep – Sweep across wide range of frequencies	Cover broad spectrum without high power requirements as barrage	Inefficient against specific frequencies	Wide area communication
Spot – Targets specific frequencies	Efficient – focused energy	Counteracted by frequency hopping	Military applications

Table 1: Types of jamming [4] [5]

The type of jamming being used in this project is spot/ narrow band jamming where Gaussian noise [6] is sent over a narrow frequency band against NBFM. This should effectively disrupt the NBFM communication as the energy is focused on the signal narrow band channel.

To mitigate against jammers the method Frequency Hopping Spread Spectrum (FHSS) was developed. FHSS works by rapidly alternating the frequency at which the channel is transmitted on according to a predefined pattern. By doing this a lot of the signal can be transmitted outside the jammers targeted frequencies. Both transmitter and receiver know the predefined frequencies and change accordingly. The rate at which the channel changes frequency is known as the hop rate [7]. Higher hop rates are more difficult to jam [7].

Background Research

Modern FM radio communications have focused on improving signal quality, expanding functionality and improving resilience against interference and/or jamming. Radio Data System (RDS) [8] is an example of expanding functionality whereby digital data such as song titles and traffic updates are transmitted alongside the usual analogue signal to improve listener experience. Furthermore, pure digital data transmissions in the form of Frequency Shift Keying (FSK) and Gaussian Frequency Shift Keying (GFSK) are used for the Bluetooth service for short range data transmissions for such applications of wireless speaker [9]. Here, the frequency shifts to a corresponding binary data value instead of an analogue tone.

As modern communication systems have become more matured so has ability to be robust and counteract against interference and jamming. Some systems utilise array antennas which allow the use of beamforming which can steer a beam so that the waves constructively interfere at the receiver. This increases the SNR at the receiver making it more robust against any jamming. Such techniques are usually used in military applications such as Radar and GPS [4].

Channel surfing is a similar technique to FHSS where a signal will change channel/frequency to avoid a jamming signal. However, instead of doing this to a pre-agreed pseudo-random procedure the channel surfing will dynamically switch to available channels. It is usually associated with Wireless Sensor Networks [4] which have multiple nodes.

Spatial retreat is a rudimentary anti-jamming technique which simply involves relocating the communications device in order to reduce the jammers effect. This could have limited success than more complex techniques [5].

In modern mobile communication networks such as 5G contain control channels which help maintain connection by communicating information such as BER, allocated bandwidth etc. If these are disrupted it severely affects the network connection. Control Channel Attack Prevention provides built-in contingencies such as channel randomisation, redundancy channels and encryption to make these control channels more robust against jammers [4].

Direct Sequence Spread Spectrum (DSSS) offers resilience by spreading the signal over a wide band and using a pseudo-random sequence encoded with the signal which the receiver can decode [5]. This makes it resistant to narrow band jamming due to the wide band characteristics of the signal. This technique is used in networks such as Wi-Fi [10].



Task 1a – NBFM Modulation & Demodulation

Figure 3 and 4 shows the transmitter and receiver of the NBFM showing a rather conventional radio architecture with a message signal multiplied with a carrier signal to produce FM. The Wav source file is multiplied with a constant value which will boost the signal by such factor if needed. A throttle block is then used in the workspace to control the number of samples being produced to control processing limitations [11]. The output of the throttle passes through a phase modulation block. For NBFM the modulation index must be less than 0.5 with 0.2 usually being selected. After this the signal is combined with a cosine carrier wave at 68KHz to generate the modulated signal. 68KHz carrier was selected as it was a frequency where a clean FM modulated signal was observed as well as a clean reception of the message. A low pass filter is then used to remove any unnecessary high frequency components from the summing of the two signals.

On the receive architecture seen in Figure 4 shows the modulated signal being a combined with the 68KHz- carrier signal which generates the sum and difference frequencies of the message signal. The low pass filter then rejects the high frequency summed signal and everything above 12KHz. 12KHz was selected as at this frequency almost all of the message would be recovered and it minimised the amount of noise on the message signal. The demodulated message signal is passed through a 'DC Blocker' block which removes the DC component of the signal.

$$s(t) = A_c \cos(2\pi f_c t) - A_c \sin(2\pi f_c t) 2\pi k_f \int m(t) dt$$

Figure1: NBFM formula

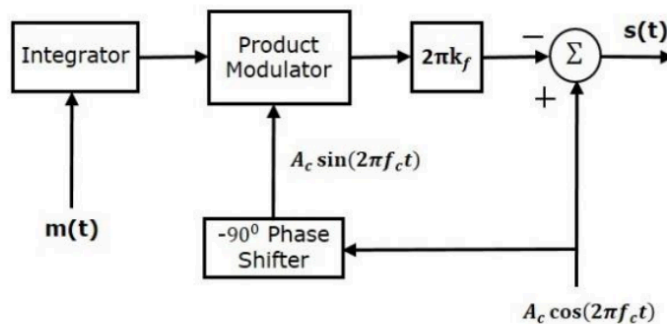


Figure 2: NBFM block diagram [2]

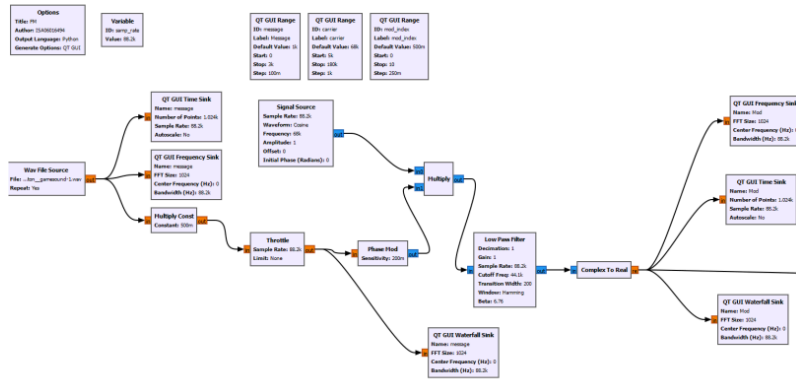


Figure 3: NBFM Transmitter [1]

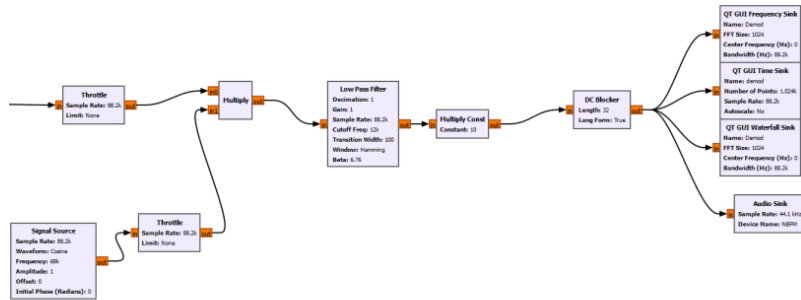


Figure 4: NBFM Receiver [1]



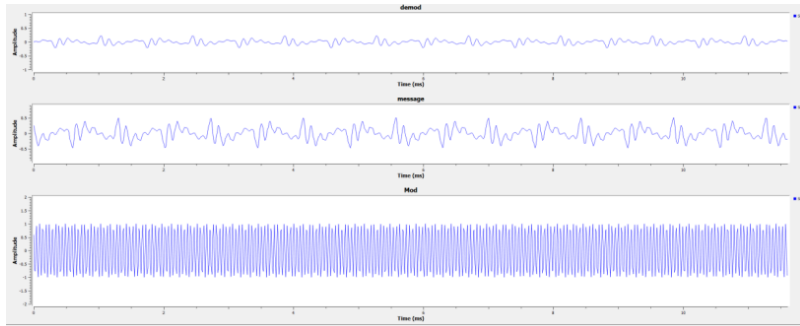


Figure 5: Demodulated, message and NBFM modulated signal in time domain [1].

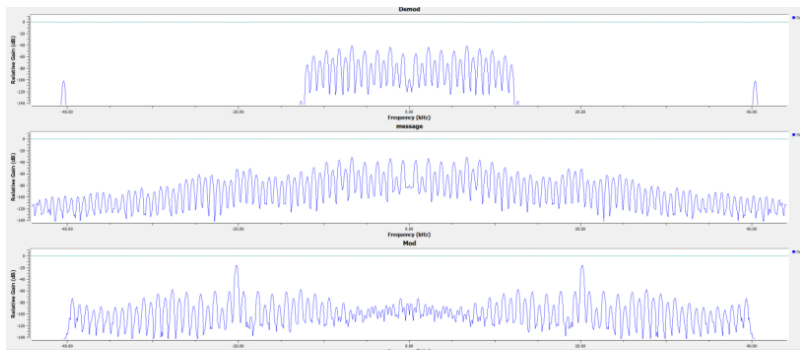


Figure 6: Demodulated, Message and NBFM Modulated signal in the frequency domain [1].

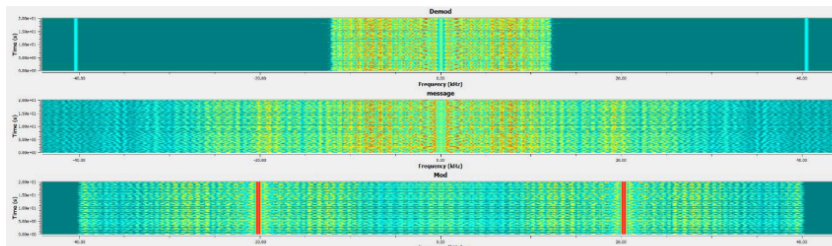


Figure 7: Demodulated, Message and NBFM signal displayed as a waterfall graph [1].

As mentioned above 68KHz carrier frequency was chosen as it proved to be an ideal frequency for NBFM and this can be seen in figure 5, where the modulated signal looks

clean with very little distortion which is then shown that the demodulated signal is coherent with the original message signal below it. Furthermore, figure 6 and 7 which shows the signals in the frequency domain show the message signal with a bandwidth of 20KHz bandwidth but the majority of the message is in 0-12KHz range. This is why on the demodulated signal the low pass filter rejected and frequency above 12KHz to help minimise interference on the low power aspect of the signal (from 12KHz- 19KHz). Both frequency and waterfall plots show the signal being cleanly transmitted especially in the demodulated waterfall where it looks very similar to the original message. This is further backed by the audio sink.

In the bottom waterfall of figure 8 showing the modulated signal shows the message signal in the sidebands surrounding the carrier at 20KHz. This carrier is shown at 20KHz and not 68KHz because Nyquist zones [3]. One Nyquist zone is $f_s/2$ [3] translating to $88.2/2 = 44.1\text{KHz}$ wide. This puts the wave into the second Nyquist zone where higher frequencies alias closer into the centre frequency (0 kHz). Because of this the 68KHz carrier is actual

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$$44.1\text{KHz} - (68\text{KHz} - 44.1\text{KHz}) = 20.2\text{KHz}.$$

Task 1b: NBFM Jammer

Task 1b involved adding a Jammer to disrupt the NBFM signal. RF jamming is the concept of purposely blocking/denying communication between a transmitter and receiver [4]. It is common technique used in electronic warfare [4]. This jammer was a simple noise jammer which transmitted Gaussian noise at the frequency of the modulated signal. Figure 13 shows the transmitter architecture, the same as figure 3, with the noise being added. Figure 9 shows the same NBFM receiver as figure 4. 68KHz is once again used as carrier's frequency. In this particular example the amplitude of the noise was 0.5.

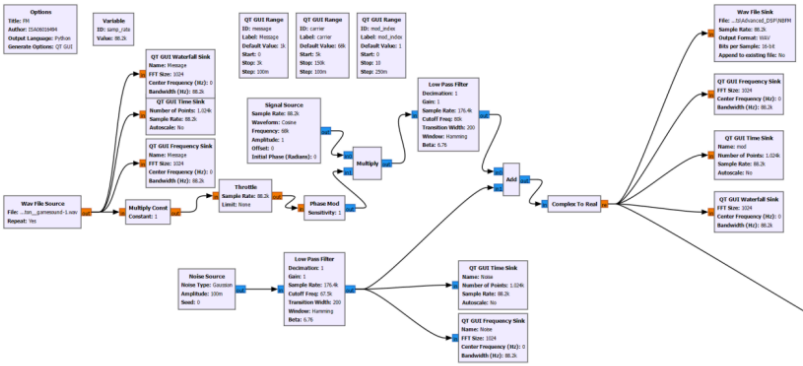


Figure 8: NBFM transmitter with Gaussian noise applied [1].



Figure 9: NBFM Receiver [1]

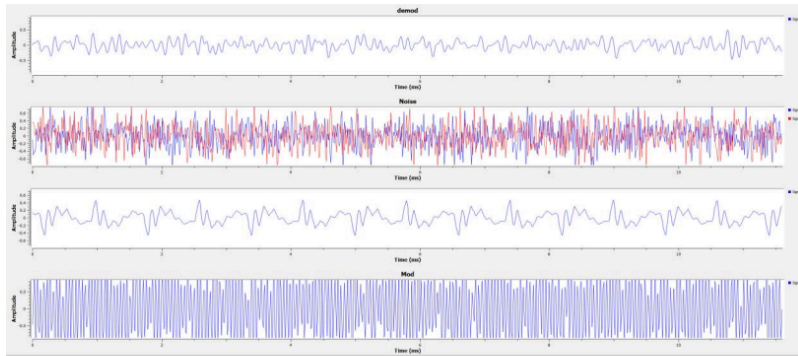


Figure 10: Demodulated, Noise, Message and NBFM with noise shown in the time domain [1].

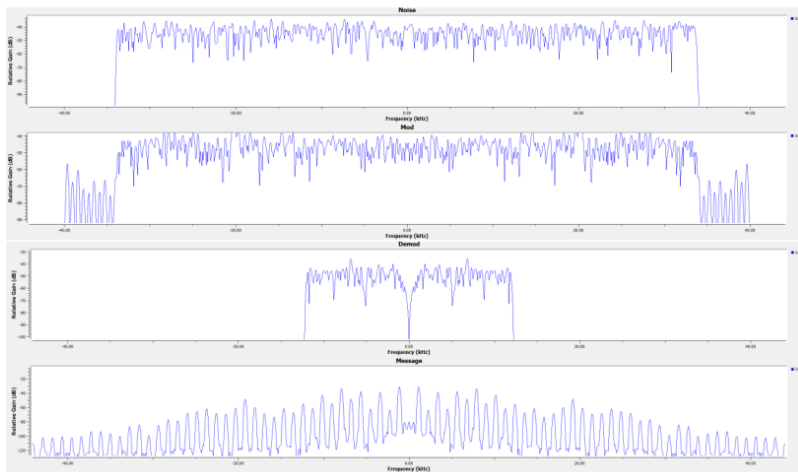


Figure 11: Demodulated, Noise, Message and NBFM with noise shown in the frequency domain [1].

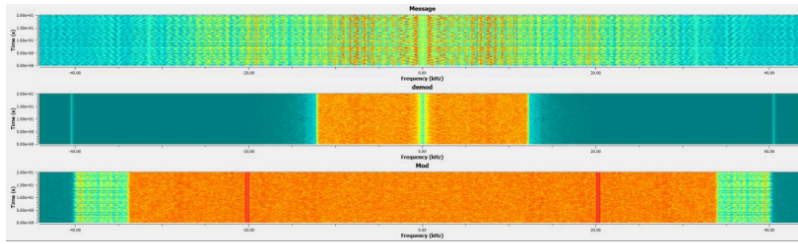


Figure 12: Waterfall plot of the Message, Demodulated and Noisy NBFM [1].

From figure 10 of the different signals in the time domain shows how the noise has distorted the modulated signal by the varying amplitude compared with figure 5 with the clean modulated signal. In the frequency domain plots from figure 11 the noise floor is a lot higher at around -40dBm a similar power to the modulated signal. This is seen further in figure 12 of the waterfall where the gaussian noise is very visibly masking the modulated signal, with only really the carrier being distinguishable. The demodulated signal also shows the noise masking the message signal compared with the clean original message above it. From the audio sink it can be determined that the signal is still being received however, it is very faint and the majority of the audio is the gaussian noise. Increasing the noise amplitude would increasingly hinder the ability of the modulated signal to be received. For this particular architecture if the amplitude of 2 the audio would be virtually incoherent and so could be said to be jammed.

As mentioned in the introduction a method to overcome jamming is to adopt the FHSS modulation technique. In GNU radio [1], 10 channels were set up with the different channel frequency being determined by multiplying the channel number by the carrier frequency.

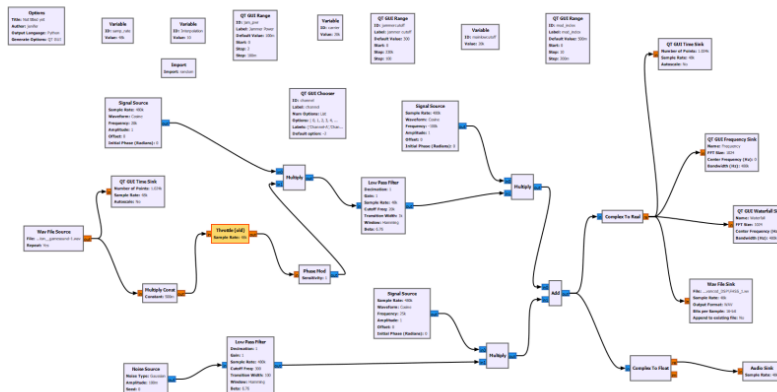
[illegible]

Figure 14: FHSS Receiver [1]

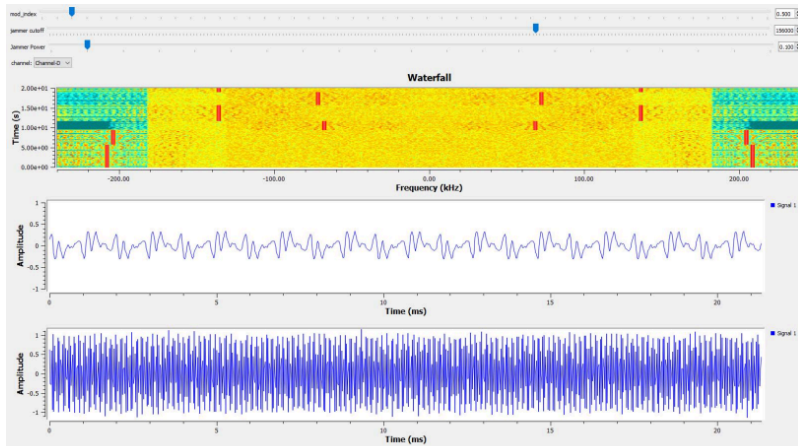


Figure 15: FHSS Transmitter with Jamming signal [1]

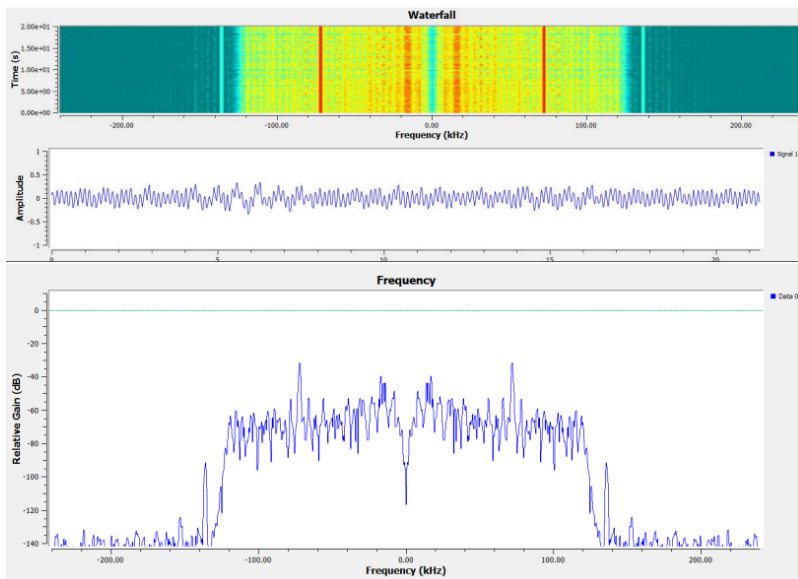


Figure 16: FHSS Receiver [1]

In the waterfall plot, figure 15, shows the varying channels of the carrier hopping from one frequency to another over time. The jammer frequency can also be seen as yellow colour (its power) with some of the channels being outside of this range. This shows how FHSS can get around a jammer emitting on a narrow band making it very effective here. The jammer can widen its bandwidth however, this makes it less efficient.  16

Jamming, which is the deliberate interference of wireless communication, is illegal under the Wireless Telegraphy Act 2006 [12] as it can create major problems which could disrupt services which are essential to people's lives and livelihoods. Jammers can disrupt essential services such as emergency services and healthcare which could cost lives. Furthermore, jamming interferes with individuals' private communications which could potentially be used to suppress freedom of speech. Jamming could also affect National security systems and economic systems.

Having robust modulation schemes such as FHSS  17 and other enhancements such as FER against jamming enables governments and business to have enhanced security. These enhancements also make these signals more robust against other natural occurrences of interference which in turn improves the reliability of the communication.  18 Because of this an increase in services can now be achieved wirelessly such as IP based protocol transmission for such protocols as Wi-Fi [10].

Task 2: RTL SDR Receiver

A RTL Software Defined Radio (SDR) is a radio which does a lot of signal processing in Register Transistor Logic (RTL) and are increasingly being used as they offer greater versatility being able to adopt multiple communication protocols, reduced cost compared to traditional radios and improved longevity due to the bulk of processing being RTL [R]. Still however, SDRs require some analogue components to initially sample the signal into a format readable by a FPGA or CPU. Figure 17 shows a basic receive architecture for a RTL SDR where the complex modulated signal $S(t)$ is received and split into its real $I(t)$ and imaginary $Q(t)$ components by the local oscillator with a 90 degree splitter which acquires the cosine and sine component. From this the high frequency product and any high frequency interferences rejected by the low pass filter (LPF) leaving only the low frequency component. This is then digitised by the Analogue Digital Converter (ADC) so that it can be digitally processed by the rest of the SDR [13].

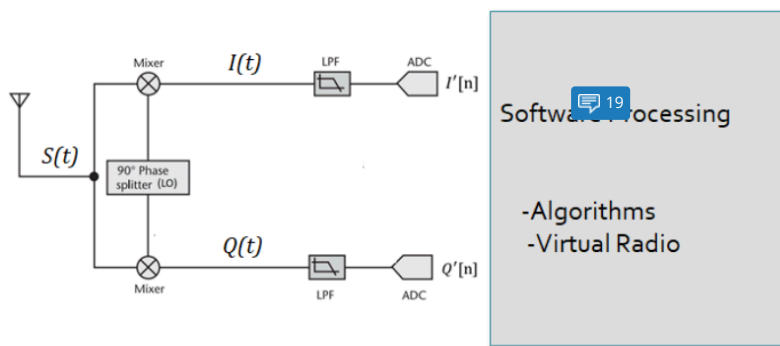


Figure 17: Basic schematic of a RTL SDR receiver architecture [13]

Figure 18 shows the RTL SDR in GNU Radio where a source block reads from a nooelec SDR [15] and the following blocks offer signal processing which is then implemented onto the SDR. From the flowchart after the source the signal goes to a 'Rational Resampler Block' [16] which modifies the sampling rate by a factor equal to the interpolation factor (12) divided by the decimation factor (5), which was $12/5 = 2.4$. This brings the sample rate down from 2.4MHz to 1MHz for the WBFM receiver block [17]. The low pass filter removes any high frequency components before processing of the WBFM. The WBFM demodulates the audio to a sample rate of 48KHz which is the sampling rate of the audio. This decimation is done by dividing the 'Quadrature Rate' by the 'Audio Decimation'. The WBFM block also includes some automatic signal processing such as filtering to help produce a clean received signal. Finally, it passes through another LPF to remove high frequency audio components and then multiplied by a constant which acts as a gain block used boost the signal if required before passing to the sinks.

The RTL SDR was tuned to 102.1MHz which was able to pick up the FM station Greatest Hits Radio cleanly [14]. Figure 19 shows a waterfall of the reception of this station being cleanly received in in the audio range. The frequency plots show the signal being quite weak, being down a -50dB, with the noise floor being about -80dB could explain why the signal had some very faint noise associated with it.

Ethically, whilst SDRs offer many opportunities for flexibility the ability to programme any type of receive/ transmit architecture can bring concerns to elements such as privacy, security and access to restricted bands etc. With regards to Privacy, SDRs can be programmed to decode private communications [18]. Also, SDRs could be set up as Jammer and more sophisticated Jammers. Easy access to licensed frequency bands could pose a problem for any sensitive communication types such military bands for military applications [4].

That being said SDRs offer many societal benefits such as cost effectiveness and flexibility. SDRs by nature can be configured and re-configured quickly so any design changes can be made easily and later on down the design process than could be done previously. Furthermore, because configuration is a lot easier, it could see a push in research and development in wireless communication such as 5G [4].

Conclusion

This task allowed for exposure and familiarisation of GNU Radio [1] which is a powerful SDR configuration tool. Having the flowchart like structure makes it very intuitive with little requirement for any coding experience or software knowledge to build radio architecture such as the NBFM. Having to build these digital architectures up enforced a lot of the DSP theory especially sampling and decimation and how using this to manipulate the signal can process it in such a way that it is readable. I think the prime example of this is in Task 2 where the sample rate was dropped from 2.4MHz initially to 48KHz for the audio sink.

The main findings from this project was being able to make a NBFM transceiver to successfully transmit and receive files in the GNU radio software. I was able to generate FHSS to overcome a jammer or noisy environments by successfully moving the carrier onto different frequencies some of which out of band of the jammer. Finally, I was able to build a RTL SDR WBFM architecture which configured a nooelec [15] SDR which was able to get a clean reception of the FM radio station Greatest Hits radio on 102.MHz [14].

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FINAL GRADE

GENERAL COMMENTS

73/100

Feedback on A4HEP Learning Objectives

B1: Demonstrates a good application of knowledge in problem-solving. You have successfully met the requirements for this learning outcome.

B2: Effectively analyses problems and reaches logical conclusions. You have successfully met the requirements for this learning outcome.

B3: Proper selection and application of computational and analytical techniques. You have successfully met the requirements for this learning outcome.

B6: Successfully applies a systems approach to problem-solving. You have successfully met the requirements for this learning outcome.

B8: Demonstrates strong ethical analysis and informed decision-making. You have successfully met the requirements for this learning outcome.

B12: Effectively applies laboratory and workshop skills in investigations. You have successfully met the requirements for this learning outcome.

PAGE 1

PAGE 2

PAGE 3



Comment 1

The overall objectives of this assignment are clearly explained



Comment 2 | Knowledge & Understanding (20)

The advantages of NBFM over WBFM are well articulated.



Comment 3 | Engagement with Lit (20)

The applications of Narrowband Frequency Modulation (NBFM) and Wideband Frequency Modulation (WBFM) are discussed.

PAGE 4



Comment 4 | Knowledge & Understanding (20)

The different types of jamming are presented effectively, which is commendable.



Comment 5 | Engagement with Lit (20)

The applications of anti-jamming techniques are mentioned, including channel surfing, which is well appreciated.

PAGE 5



Comment 6 | Engagement with Lit (20)

The research is thorough, with many citations supporting the applications of signal transmission in various fields.

PAGE 6



Comment 7 | Knowledge & Understanding (20)

It is commendable that basic blocks of NBFM are used to illustrate its concept.



Comment 8 | Knowledge & Understanding (20)

The processes carried out in these blocks are described.



Comment 9 | Knowledge & Understanding (20)

It would be beneficial to include a brief explanation alongside these expressions to clarify the working principles of the basic blocks.

PAGE 7



Comment 10 | Practical Skills (25)

The sink screenshots for NBFM are well captured and analysed.

PAGE 8



Comment 11 | Cognitive Skills (20)

Bandwidth considerations are explained, and noise-added blocks are appropriately demonstrated. It is also necessary to mention about the frequency deviation and modulation Index

PAGE 9



Comment 12 | Practical Skills (25)

The GNU Radio blocks are explained, with a brief overview of their functions and some assigned values.

PAGE 10



Comment 13 | Practical Skills (25)

The signal analysis is well-executed, with discussions on signal distortion, which is appreciable.

PAGE 11



Comment 14 | Cognitive Skills (20)

The effects of noise on the original signal are seen but needs more explanation.

PAGE 12

PAGE 13



Comment 15 | Practical Skills (25)

The signal are more realistic when no noise added to them and less performed with the increased noise power

PAGE 14

PAGE 15



Comment 16 | Cognitive Skills (20)

It would be helpful to include details on channel operations, such as identifying jammed channels and active channels during frequency hopping.



Comment 17 | Knowledge & Understanding (20)

The advantages of Frequency Hopping Spread Spectrum (FHSS) are clearly stated.



Comment 18 | Cognitive Skills (20)

The ethical considerations surrounding jamming are well addressed.

PAGE 16



Comment 19 | Cognitive Skills (20)

The architecture of Software-Defined Radio (SDR) is well captured, but it could be enhanced further by explaining the individual architecture blocks.

PAGE 17

PAGE 18



Comment 20 | Cognitive Skills (20)

The usage of decimation factors and resampler blocks is described.



Comment 21 | Cognitive Skills (20)

The selected frequency ranges are also specified. However, the use of complex mathematical systems is mentioned but not explained in relation to the SDR architecture, which should be addressed.



Comment 22 | Cognitive Skills (20)

Most of the blocks in the WBFM receiver are explained, which is commendable.



Comment 23 | Cognitive Skills (20)

The impacts of using SDR in licensed frequency bands without permission are stated.



Comment 24

Numerous citations and references are included. However, it would improve the report to elaborate on the technical concepts of FHSS.

**Comment 25** | **Transferable Skills (15)**

The document is well-structured and organized. More details on ethical considerations and some in-depth analysis would enhance its completeness.

GRADING FORM: ADSP_GRADING_TEMPLATE

MATT RUSSELL**72.60****ENGAGEMENT WITH LIT (20)**

Task 1: Demonstrate understanding of NBFM, jamming effects, and FHSS. Citations and research on related topics. Task 2: Show understanding of SDR receiver principles and signal representation. Evaluate research on SDR technology and related topics.



- Comprehensive understanding of topics with appropriate citations and research, though some areas could be enhanced.
- Good understanding of SDR principles with relevant research, though certain aspects in citations or depth could be improved.

15.3**KNOWLEDGE & UNDERSTANDING (20)**

Task 1 (i) Understanding NBFM, modulation, and demodulation. Exploring bandwidth, frequency deviation, and impact on signal quality. Task 1 (ii) Analysing jamming effects by studying noise sources and interference. Observing impact via frequency, time domain, and constellation diagrams. Task 1 (iii) Investigating FHSS to reduce interference and evaluating its effectiveness. Task 1 (iv) Comparing original, jammed, and FHSS signals. Studying Signal-to-Noise Ratio (SNR), clarity, and system efficiency. Task 1 (v) Understanding ethical issues in jamming. Discussing legal aspects and FHSS benefits for

security. Task 2 (i) Designing a WBFM receiver using RTL-SDR and GNU Radio. Studying block functions and sampling. Task 2 (ii) Visualising signals via waterfall plots, frequency sinks, and time-domain analysis. Studying SNR, stability, and filtering. Task 2 (iii) Evaluating privacy and interference issues. Analysing societal benefits like improved efficiency and technology.



- Strong knowledge of NBFM, with well-explained concepts, though additional depth could further enhance understanding.
- Good understanding of jammer effects, with scope for added depth.
- Sound knowledge of FHSS application, though certain areas in explanation could be refined.
- Basic understanding. Explanations are limited.
- Satisfactory understanding. Basic descriptions, but lacking clarity.
- Satisfactory understanding. Basic explanations of block functions and sink results are seen.
- Basic understanding. Explanations of signal analysis are limited. Constellation diagrams are missing.
- Satisfactory understanding. Basic descriptions, but lacking depth.

13.1

COGNITIVE SKILLS (20)

Task 1 (i) NBFM Modulation and Demodulation: Understands modulation, demodulation, bandwidth, and clarity. Task 1 (ii) Add a Jammer: Evaluates noise, interference, and signal impact in frequency, time, and constellation domains. Task 1 (iii) Implement FHSS for Anti-Jamming: Applies FHSS to reduce interference and compare signal stability. Task 1 (iv) Analysis and Comparison: Compares original, jammed, and FHSS signals using frequency and time-domain tools. Task 1 (v) Ethics and Impact: Assesses legal and societal effects of interference in secure communication. Task 2 (i) Setup and Design of WBFM Receiver: Designs WBFM receiver, focusing on setup, bandwidth, and stability. Task 2 (ii) Analysis and Visualisation: Examines signal analysis, error detection, and filtering techniques. Task 2 (iii) Ethics and Impact: Reviews interference impact and decision-making in WBFM technology.



- Basic setup with unclear reasoning.
- Satisfactory analysis, though some aspects could be refined.
- Basic implementation with unclear reasoning.
- Basic comparison with limited reasoning.
- Satisfactory discussion, limited depth.
- Displays satisfactory skills with limited clarity in receiver setup or signal demodulation.
- Basic analysis with limited depth in interpreting signal parameters.
- Satisfactory discussion with limited depth in ethical reasoning.

12

PRACTICAL SKILLS (25)

Task 1: Hands-on experience in transmitter and receiver setup, understanding signal bandwidth and frequency deviation. Implementing noise sources and analysing interference effects using frequency, time, waterfall, and constellation sinks. Applying FHSS techniques for anti-jamming and evaluating signal clarity through SNR analysis and stage comparisons. Developing an awareness of secure communication and legal implications. Task 2: Practical implementation of RTL-SDR receiver setup, signal representation, and processing. Understanding block functionality, decimation factors, and performing signal analysis using waterfall and frequency sinks. Visualising constellation diagrams and evaluating signal stability through SNR measurements. Comparing different demodulation stages for performance optimisation.



Task 1: Shows good practical skills in simulating NBFM and using FHSS for anti-jamming. Jammer introduction and signal analysis are effective, but minor gaps exist in explaining parameters like bandwidth and frequency deviation. Comparisons of signal stages are clear but need more depth. Task 2: Shows good practical skills with a well-configured RTL-SDR receiver and accurate signal representation. Signal analysis and visualisation are effective but lack some detail. Comparisons across stages are clear but need more depth.

19.7

TRANSFERABLE SKILLS (15)

Enhancing mathematical integration and simulation skills using GNU Radio and RTL-SDR. Developing ethical reasoning and effective communication for teamwork and professional interactions. Practising systematic reporting, structured problem-solving, and clear presentation skills.



Shows strong transferable skills with good application of GNU Radio tools and solid understanding of signal processing concepts. Minor gaps in analysis depth or documentation. Ethical considerations are discussed but need more detail.

12.5