Using GNU Radio in a Multipath Environment Practical Application (GRCON 2024)

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Abstract

Having used GNU Radio for several years, it has many worthy applications. One such use has been propagating data using ultrasound in a variety of material such as air, water and steel. The modulation protocol used to date has been binary FSK (some ASK/PSK have also been used), however these protocols do not handle multipath well. For this application we would look to use OFDM, however OFDM is normally used in a broadband application, where many subcarriers can be created, using it in an application that has limited bandwidth can be challenging. The bandwidth I have available with standard transducers is less than 1 kilohertz, as such the scaling and management of the subcarriers can be difficult. Sound waves travelling in solids can be made up of transverse and longitudinal waves, the sensors receiving this mixed signal must be able to filter out the unwanted signal so the modulated data can be extracted with the minimum number of errors. In liquids and air, shields can be employed on the receiving sensor to limit the unwanted signal picked up by the transducer, however in solids this is not possible. My objective is to modulate data in steel rail using GNU radio at a data rate that has useful and practical application. This paper explores these issues and how GNU radio can be employed to create duplex channels in ultrasound that can be used for data communications.

1.Introduction

Radio communication is an established mature technology that has been with use for more than 100 years, it has been improved in an iterative process from AM to the variety of transmission protocols we have today. However, radio works best in air (or open space), with unobstructed direct line of sight between the transmitter and the receiver, the receiver gets a signal that may be attenuated with some loss over distance, however it's a clean signal that the radio receiver demodulated and out put the base band.

Unfortunately, in real life, it is not so simple, in a county setting you may have hills and valleys where there is good coverage on the top of the hill but no connection in the valley, if there is a cliff for the radio waves to bounce off, you may have a reflected signal and main signal causing very poor TV/Radio reception. The TV images would be ghosted, and the reception would range from loss of signal to an image like the one shown below

Figure 1 Analogue TV Ghosting

In an urban environment, there was a lot more obstacles for the signal to be reflected or refracted.
Modern apartments buildings including office blocks with metal or glass surfaces may have won the designer a reward for their creative structure, but the material used can make the multipath situation so much worse, the radio waves would be bounced many times, the reflected signal could in some instance be stronger than the direct line of sight modulated wave, it may not matter what protocol you using such as PAL/NTCS, the filters or directional orientation of the antenna when there is just too much interference.

The definition of multipath is as follows:

In radio communication, Multipath is the propagation phenomenon that results in radio signals reaching the receiving antenna by two or more paths"

From a personal viewpoint this the reception I grew up with when watching the 4 or 5 channels that were available in my area. Living at the foot of a hill with a quarry provided a great surface for signal to bounce off.

Figure 2 Analogue TV Ghosting 2

Proceedings of the 14th GNU Radio Conference.

2.Why is this important and what is my objective

Having come from a radio background, I understand the fundamentals in communications, the modulation protocols, the antenna systems, amplifiers, the older analogue or more modern digital radio systems and the application, be it voice or data or both.

Radio is HF, VHF, UHF, SHF, etc but not used in the low frequency audio band (30hz to 300Khz), the wavelength for modulated signal at 40KHz signal is 7500m, this prevent most entities from having the means to create an antenna, unless you are a very big organisation like government or military with access to resources

When I started my doctoral degree, the objective was to modulate sound waves in substances such as air, water and solids, the sound wavelength for these materials is not a constant, it is tied to the substance and its structure.

While radio is great in air, it is not good in water and has a poor performance in solids. Ultrasound is great substitute for radio in these materials.

2.1.What is the difference between EM and sound waves

1. Electromagnetic radio waves are traverse only, have a constant speed and will work in a vacuum such as space.
2. Sound waves need a medium to travel through, will not work in space, can be transverse or longitude waves, can be reflected or refracted at the boundary of the substance with a second substance

The objective is to use sound waves to modulate data in substance where a radio system is not the best solution, this allow communications links to be established and useful data exchanged.

In gases like air, narrow band discrete channels using sound waves work very well, there is little or no multipath issues, however when the material is liquid or solid, the interference from reflected sound wave will cause the channel to fail.

The reach my objective to modulate data in solids, I have to resolve the multipath soundwave interference; this has been achieved using a software solution available in GNU radio.

2.2.Challenges with multipath in dense materials

The problem is sound waves bounce in the liquid or solid when it meets the material boundary, some energy escapes to the next substance, more is reflected back reinforcing and cancelling the energy in the sound wave. Solutions used in EM radio to resolve multipath issues can be applied to sound waves, these methods will be presented in this paper

2.3.Purpose behind using ultrasound for communications

My doctoral degree research project at the University of Technology Sydney revolved around creating Ad Hoc shipping networks between nodes and devices that were in close proximity to each other but in an environment where normal EM radio communication would be ineffective

The original suggestion was to allowing shipping containers that were stacked to form Ad Hoc Networks by creating communication link between the devices using ultrasound and GNU radio.
Stacked containers on the inside could not communicate using there 4G LTE modem because the RF could not propagate through the containers that were adjacent, above and below them. However, soundwave could propagate from the container on the inside to the container that would act like a node on the outside, thus creating a link to the outside world allowing sensor data to be relayed about the environment of precious cargo in the container, so the owner could respond if there was a failure that would result in the loss of the cargo if no action was taken.

Figure 3 Stacked Shipping Containers

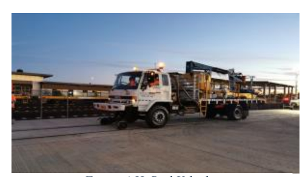

Figure 4 Hi Rail Vehicle

My proposal was a rail application where road rail vehicle would communicate through the rail track with each other and the wayside using this method.
Road rail vehicles have metal rail wheels that allow sound waves to propagate into the track where the signal can be read by a device connected to the rail track web.
Vehicles that are located a few meters away on the road outside the fence are not connected because they are not in contact with the track, logs plus sensor data for vehicle moments along with environment condition in rail tunnels and cuttings can be captured.

3.Converting electrical energy to sound energy

Sound energy is mechanical in natural causing the molecules of a substance to vibrate at a certain frequency and intensity. Energy cannot be created or destroyed, but transformed from one type to another, as such we must convert electrical energy to a mechanical wave. There are many ways to do this, speakers, transducers, microphones, the latter used to convert sound waves back to electrical energy.
The simplest method is a speaker, it has a magnet, coil, diaphragm and chassis, the electrical energy audio signal from the sound card makes the voice coil (an electromagnetic magnet), this moves inside the permanent magnets in response to the attraction or repulsion of the electromagnets force. The cone and surrounding membrane vibrate the air propagating the acoustic wave at the desired frequency and volume.

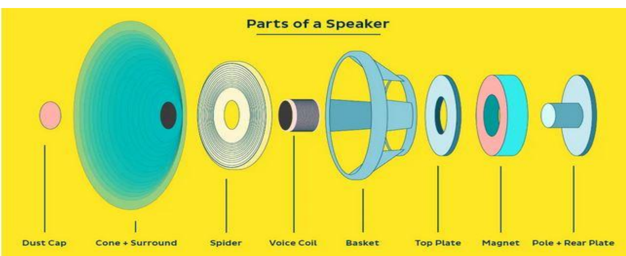

Figure 5 Speaker Components

This works in the opposite direction too for converting mechanical sound wave back to electrical energy. They have an operating frequency range, sound wave pressure and impedance that should match the sound card.

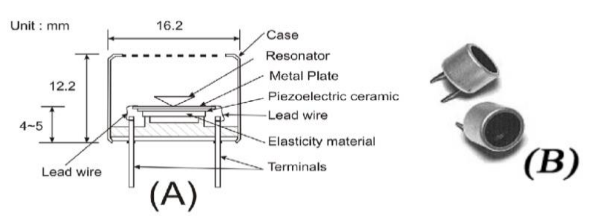

Figure 6 Transducer Components

Transducer work in a similar way with an enclosed metal plate/coil and are designed to operate at higher frequencies

The diagram shows the components of a piezoelectric ceramic transducer, typically one terminal is connected to the chassis and used as ground.

Human voice is one type of mechanical energy that is converted to another type of energy (sound) by means of muscles in your larynx oscillating pressurised air from your lungs

3.1.Sound card, GNU radio and Ubuntu

The method to convert the electrical energy to mechanical energy using ultrasonic transducer. There are many different varieties with choices of beam angle, range, construction, voltages and frequency. I have selected the 40KHz and 48Khz range because it is a frequency that I can be sampled at more than twice this range.

The bandwidth available is typically 1Khz with a centre frequency that may be plus/minus the labelled value. A signal generator, resistors, hook up leads can be used with an oscilloscope to find the centre, if you are using transducers that are 500hz above or below the centre value, your results may be wrong or generating a lot of errors

The Nyquist theorem states that a signal with the bandwidth B can be completely reconstructed if 2B samples per second are used.

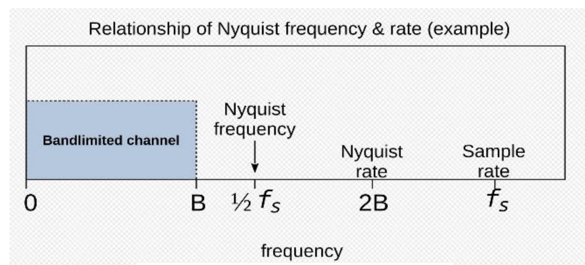

Figure 7 Nyquist Graph

I have tested many sound cards and the best one to date has been the Behringer that can sample at 192khz. This means you can have 2 channels allowing one for TX and the other for RX. There are many Chinese manufactured audio interfaces that claim to sample at this rate and higher but fail when tested.

Figure 8 Behringer Audio Interface

I have used GNU Radio version 10 on a laptop running Ubuntu, the sampling rate had to be set in the root directory, changed from 44.1Khz to 192Khz, the changed sampling rate can make some application that use audio crash or generate poor quality audio because they are not configured to operate at this samp rate.

Radioconda is a great way to run and test software in simulation mode on a windows laptop, it supports GNU Radio companion and has allowed for fine tuning flowgraphs before testing it on the target Linux ubuntu box.

4.GNU Radio GRC software flowgraph design

The software flowgraph was one that Qasim Chaudari updated from another source and made available for a tutorial I attended. I modified this to suit my requirements, I am not the original author of this flowgraph and have no knowledge who is

4.1.TX GRC flowgraph Software

The TX OFDM flowgraph uses a *File Source* block to select an image or text file from the desktop or a local directory, this bloc converts the information to a bit stream where the *Stream to Tagged Stream* block assigns a length and tags to it. A *Stream CRC32* block is used to perform a cyclic redundancy check, and the output is split so the *Protocol Formatter* block can create header tag in a separate data stream.

The result is *Header Bits* on one stream and *Payload Bits* on a second, two symbols are added to the *Header Bits* stream and four symbols are added to the *Payload Bits* stream where they are recombined back on to a *Tagged Stream to Mux* block that is now called the *Pre-OFDM stream*

The *OFDM Carrier Allocation* block connects to the *Fast Fourier Transformer* and *OFDM Cyclic Prefixer* block. This time signal stream is run through a Tag Gate block to stop tags from propagating, the output is fed into the *Interpolating FIR filter* block and is outputted as a complex signal that needs to be converted to a float for the *Audio Sink* block. We now have a new problem because a float only accepts a real signal, there is no input on a float block that the IM from the *Complex to Float* block can be tied to.

The novel solution is to combine the *Baseband I* and *Baseband Q* streams through a *Signal Source*, *Multiplier* and *Adder* block so we can get a modulated output that is a *Float* and not a *Complex* stream.

The sound cards digital to analogue converter creates the real wave output that use a sampling rate of 192KHz. There audio interface sound device has amplification that can help increase the signal so it has a level high enough so the transducer can convert it to sound energy that propagate into the steel rail

4.2.RX GRC flowgraph software

The RX OFDM flowgraph receives the modulated signal through the Audio Source block from the transducers where it is combined with a signal source and fed into a Float to Complex block
The signal passes through the timing /frame synchronization (*Schmidi & Cox OFDM synch*) block. Two outputs are available on this block, frequency offset and Detect that connect to the *Header/Payload Demux* Block using In and Trigger connection respectively. This block Demultiplexes the Headers and Payloads streams.

An FFT (Fast Fourier Transformer) converts the time domain to frequency domain for the header and a second FFT block convert the Payload stream from time domain to frequency domain.

The *OFDM Frame Equaliser* and *OFDM Serializer* blocks follow on the Payload stream providing an output that is the called the Payload IQ

The *Constellation Decoder* block decodes constellation symbols so our data stream can be fed back into our *Repack Bits* block. This combines the demodulated bits into bytes.

The *Stream CRC32* block does the reverse of what it did in the TX flowgraph, verifies the cycle redundancy checks

The data stream can be finally fed into the *File Sink* block where it will write to a text or image file in the same order it was read in the file source.

4.3. Overview of process & bandwidth consideration

The TX & RX flowgraph for OFDM is complex and requires many more steps than a simpler solution like FSK or PSK. The main benefit is OFDM ability to tolerate interference from degraded signal caused by multiple paths

OFDM is a broadband solution and bandwidth may not be available because of hardware limitations such as only have access to standard transducer with 1Khz max bandwidth
Fortunately, the transducer I used had a 4Khz bandwidth range, they are not an item that is readily available and would need to be ordered well in advance

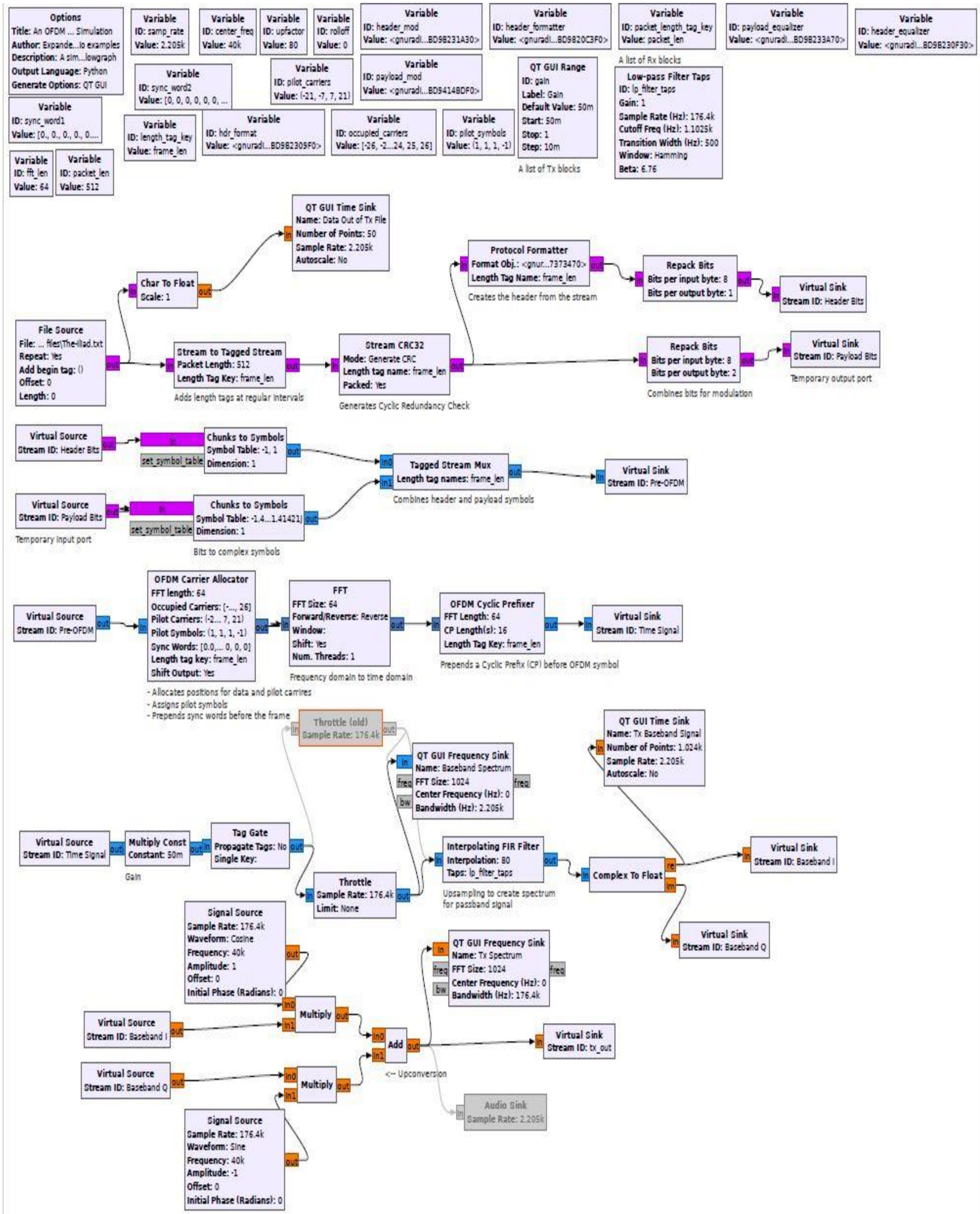

Figure 9 TX OFDM Flowgraph

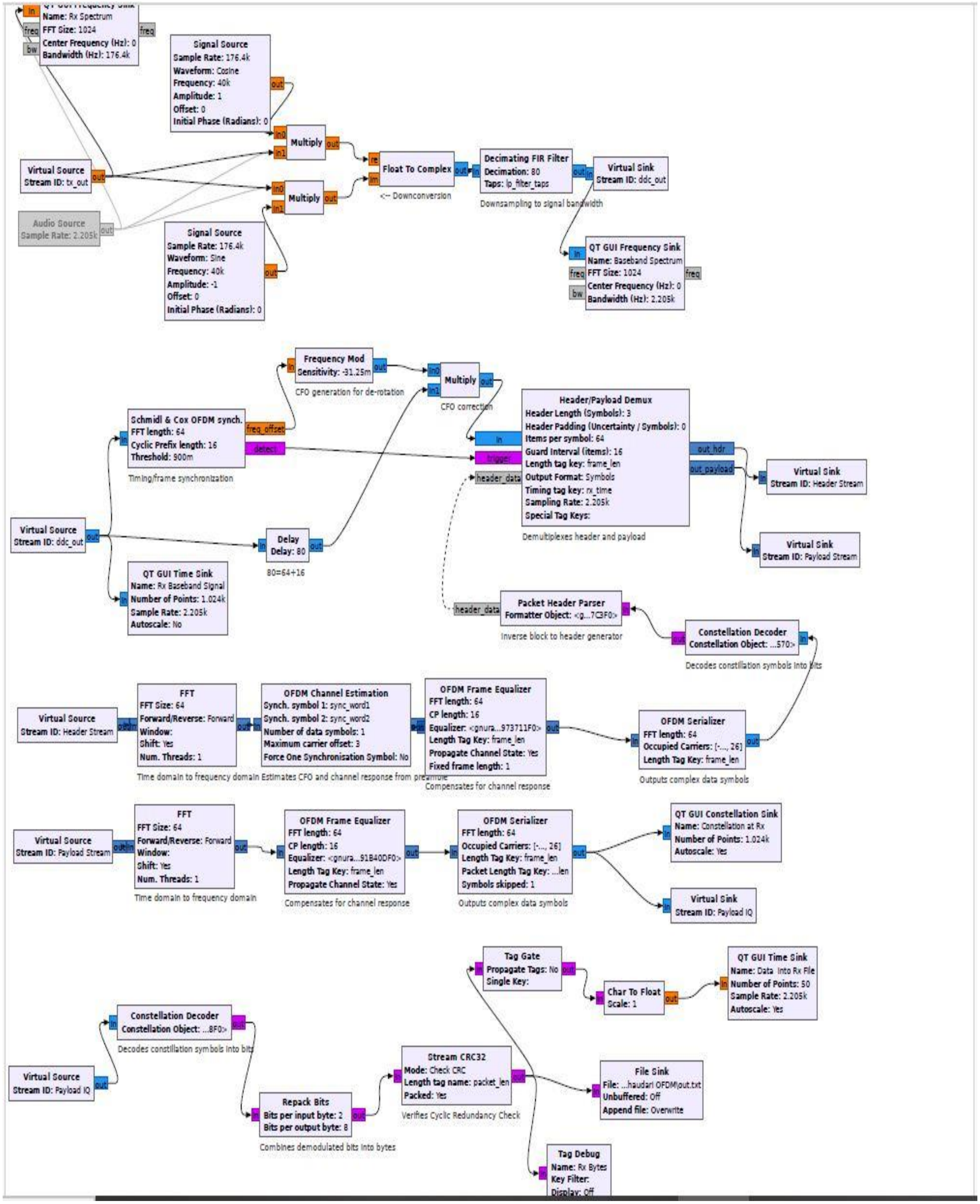

Figure 10 RX OFDM Flowgraph

4.4. Block diagram and description of test equipment

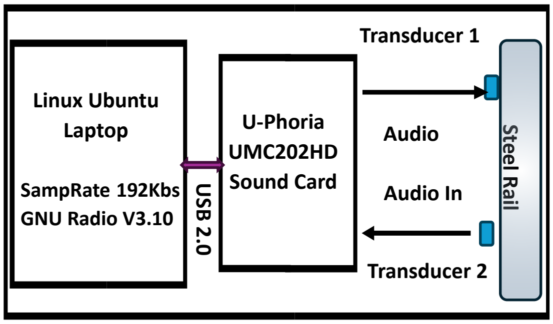

Figure 11 Functional Block Diagram Test Equipment Layout

Figure 11 shows a Functional Block Diagram (FBD) of the main component and their relationship to each other
An audio lead has been soldered to the transducer and they are attached to the rail using Blu Tack. Previous attachment methods required the sensors to be glued so they would not move if there were any vibrations. Another method that is available is mounting the transducer in a caddie with magnets located on either side of it. These caddies can be created using 3D printing and I have already designed a suitable solution for this attachment

4.5. Steel rail (60KG) used for testing

Figure 12 Steel Rail 60KG used in Sydney Trains network

The steel used in the test is shown in Fig 12, this is the same type of rail used in the Sydney Trains network. A variety of rolling stock is accommodated by this type of rail, such as Waratah, Oscar, Tangara along with metro and freight trains This is the same type of rail used in the initial tests when we tested the distance that tone could propagate and be detected. There is an expectation that we can in a properly configured system have a range of at least 50m using this equipment type and configuration

4.6.Transducer used (type and specifications)

Figure 13 400EP25U Transducers

Figure 14 400EP25U transducers

The transducer selected were a Prowave 400EP250, however this transducer type is no longer made, and the equivalent replacement is the 400EP25U

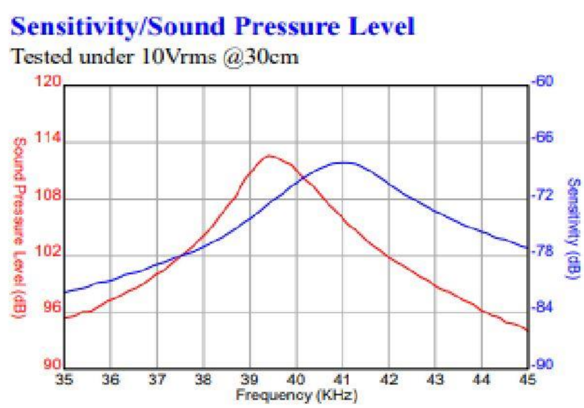

Figure 15 Sound Pressure + Sensitivity v 1

The graph above shows the sound pressure and sensitivity versus the frequency. It is interesting to note that the sensitivity stays above -80 dB from 38Khz to 42KHz which is the ranges required by the flowgraph

4 Specification

(rated at temperature 25±3℃, 45 to 60% RH, unless otherwise noted)

	Items	Specification	Remarks
4-1	Center Frequency	40.0KHz	±1.0KHz
4-2	Sound Pressure Level	110dB (min)	at resonant frequency ; 0dB re 0.0002μbar per 10Vrms at 30cm 10Vrms sine wave input detail see attached Figure 1
4-3	Sensitivity	-72dB (min)	at resonant frequency; 0dB re 1Volt/μbar detail see attached Figure 2
4-4	Bandwidth	2.5KHz (min)	-6dB (Figure Of Merit)
4-5	Capacitance	2700pF	±20%, measured at 1KHz
4-6	Total Beam Angle	30° (TYP.)	-6dB main beam
4-7	Max. Driving Voltage	100Vp-p	20 bursts maximum, 30ms repetition rate
4-8	Housing Material	Aluminum	
4-9	Operation Temperature	-30℃ to +70℃	
4-10	Storage Temperature	-40℃ to +80℃	

Figure 16 Transducer Specifications

The figure shown above give the specification of the transducer used for the tests with the OFDM flow graph

4.7. Graphs displayed during the test

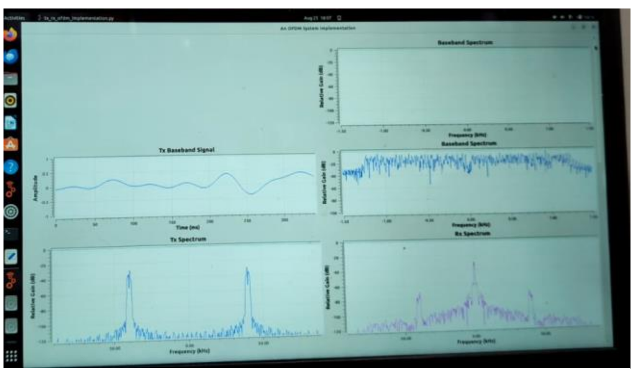

Figure 17 OFDM flow graph 1

Figure 18 OFDM flow graph 2 1

The flow graphs show the performance of the software defined radio when it is running

The centre frequency is approx. 40Khz, the constellation is showing there is data in the four quadrants and there is data on the stem graph showing that info is been written to the target file

The test lasted for about 3 minutes before the target was checked.

The source file was on repeat, so it did not have to run for too long to check the results which are shown on the following page

When the software is updated in the coming months, I will test between two computers, this will require a pre and post amble for the receiver to sync with the Transmit PC.

At a later point in time the distance between the transducers can be extended on rail track to determine what the range is before it is attenuated and can no longer be heard above the background noise

4.8. Text file Source and Target

The file shown below are the source and target text files. When compared the results are very good with low error rates

The Gettysburg was used as the source file

Gettysburg Address

Fourscore and seven years ago our fathers brought forth on this continent a new nation, conceived in liberty and dedicated to the proposition that all men are created equal.

Now we are engaged in a great civil war, testing whether that nation or any nation so conceived and so dedicated can long endure. We are met on a great battlefield of that war. We have come to dedicate a portion of that field as a final resting-place for those who here gave their lives that that nation might live. It is altogether fitting and proper that we should do this.

But in a larger sense, we cannot dedicate, we cannot consecrate, we cannot hallow this ground. The brave men, living and dead who struggled here have consecrated it far above our poor power to add or detract. The world will little note nor long remember what we say here, but it can never forget what they did here. It is for us the living rather to be dedicated here to the unfinished work which they who fought here have thus far so nobly advanced.

It is rather for us to be here dedicated to the great task remaining before us–that from these honored dead we take increased devotion to that cause for which they gave the last full measure of devotion–that we here highly resolve that these dead shall not have died in vain, that this nation under God shall have a new birth of freedom, and that government of the people, by the people, for the people shall not perish from the earth.

Line Break 1

Line Break 2

Line Break 3

The Target file mirrored the source file

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Line Break 1

Line Break 2

5. Demonstration Test Results

The following performance occurred during the OFDM demonstration test case:

- There was a short delay before the constellation graph showed the data in the 4 quadrant and the receiver started to receive data writing it to the target file.
- For simplicity the TX and RX flow graphs have been combined. This allowed me to go from simulation for testing the software to run the software and run the audio input/output.
- While the small text file worked well, larger files like images took a long time and did not display correctly

The test proved that this solution works in practice within the scope of the demonstration testing, the implemented GNU Radio GRC OFDM flowgraph can transmit and receive data through a material such as steel rail that failed when using FSK modulation protocol.

6. Improvements to software & hardware

Additional follow-on activities should include upgrading the software and Hardware solutions:

- Add a pre and post amble to the flow graph. This will allow the received to sync with the sender
- More control over the subchannels created in the OFDM, the block that manages this will need to be analysed to see how this can be achieved
- Upgrade to an audio interface device that has a higher sampling rate when it becomes available. A higher sampling rate may reduce the error rate and allow new ultrasonic channels at 60Khz & 80 Khz.
- Uses shielded cables for the transducer leads to limit the possibility of interference from test equipment and other sources of RF.
  PC/Server would prevent scalability of the design in this paper to additional GPP cores and higher data rates by just adding more Symbol Synchronizer and Costas Loop parallel chains.
- Preform a Bit Error Rate Test (BERT) to determine what the error rate is and how it can be improved.

7. Conclusions

- The objective has been met to modulate date (text) through a metal rail track using software defined radio, using an audio interface with appropriate sampling rate
- The transducers selected have approx. 3Khz before the performance tappers off. This allowed the flowgraph to use the full bandwidth with a 500 hertz band for transition at the low and high cut offs
- OFDM was a good modulation choice and gave results that showed it worked when FSK did not. Some bandwidth is required with this modulation protocol and picking the right transducer allowed this solution to be implemented
- When using separate computers, a preamble and post amble are required to allow the receiver to synchronise with the sender. I have discussed this with My Barry Duggan (GNU software developer) who will look at modifying the OOT block he developed for FSK to work with OFDM.

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Pakawat, P., Ameen, B., Imam, H.M., Braun, R. and Moulton, B., 2018. A Novel Software-Defined Networking Controller: the Distributed Active Information Model (DAIM). *International Journal of Electronics and Telecommunications*.

Biography

Michael Alldritt received a Master is Railway Signalling from Central Queensland University in 2015 and is pursuing a doctoral degree at University of Technology Sydney. I have worked in communication since I graduated from high school in the early 80s, I spent the first 20 years of my career working for telecommunication utilities and the next 20 working with Siemens on the Analogue Train Radio System used for mission critical communications in the Sydney Train rail network before it was replaced with DTRS. Currently employed on contract as a Technical Maintenance Plan Analyst with Sydney Trains in the Asset Management | Engineering & Maintenance