# Communication using GNU Radio and Ultrasound Practical Application (GRCON 2024)

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**Abstract**

This research is based on using modulated ultrasound at high frequency in the audio band as a way to communicate between devices located in air, liquid, containers (such as shipping) and rail vehicles. It is an alternative solution to using a traditional radio system in places where RF does not propagate well such as enclosures, or structures that obstruct the radio signals.

The project was initially based on shipping containers that normally use 4G modems mounted on the outside of the containers as a way to communicate its ID along with environment data to the asset manager allowing cargo that may be sensitive to heat, humidity, vibration to be monitored. If the containers are stacked in rows adjacent to each other, the communication system can fail when the container in the middle cannot transmit a signal out of the stack or connect to the local mobile base station. Ad Hoc sensor networks can be created to allow audio communication to nodes (containers) located on the outside of the stack where that information would re-transmitted using the 4G modem that has a network connection.

Acoustic communication is also a great solution in water or other liquids where radio signals degrade quickly over short distances. The GNU radio FSK solution provided some excellent results for liquids and allowed me to leverage from this to using OFDM at a later phase in steel rail. This paper focuses on modulating data through water and other liquids.

The advances in software (GNU radio/Linux OS), D/A converters and micro-PCs that have fast processors allowing these devices to be sourced at reasonable cost, operate at low power along with a compact robust design makes them suitable for this type of application.

It is now possible to utilize these advances in software that could not have been possible 10 years ago.

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## 1.Introduction

The Ad Hoc shipping problem was investigated about 10 years ago by Prof Robin Braun (UTS) as part of a research project, it focused on networks and how links could be created between devices allowing these networks to be created

The problem is how do you create links between devices when radio is not a solution and wiring or other physical connection methods cannot be used. When containers are stacked, the metal of one container mates with the next, this creates pathways that audio waves can propagate through. Modulated sound waves can be used to create links between the devices and some of these devices can become nodes that can bridge an audio network with an RF network where they can be connected to the internet using a 4G modem.

The image above shows a cargo ship with containers stacked several rows high, container on the outside can

*Figure 1 Cargo Ship with stacked Containers*

connect to mobile networks, however containers on the inside have RF blocked, so any device using a radio signal will not work. Audio or sound energy is not blocked and moves through each container at approx. 6000m per second. Each column connects to the next column creating a path that audio can move from the inside to the outside of the stack.

Containers on a freight train is another example where communication using acoustic waves would have a benefit over the normal RF solution

*Figure 2 Freight Train with containers*

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## 2. RF Communications Advantages & Disadvantages

To answer this question, we need to understand RF communication and how it is impacted by the medium it passes through. Radio frequency communication has been with us for more than 100 years, it is a mature technology that is used in everyday applications such as blue tooth ear buds, mobile phone, Wifi and traditional radio communication systems. Radio propagates well in air and a vacuum; AM radio can be picked up in your car 100s of KM from the transmitter and your mobile phone will work when 5 to 10KM from the local base station

**Advantages**

- Long Range and Bandwidth
- Mature technology
- Well supported by Industry
- Lots of software application
- Made for personal and commercial use at reasonable cost
- Work well in air and a vacuum

**Disadvantages**

- Suffers from Interference
- Security
- Limited range (frequency and Power dependant)
- Significant attenuated when it passes through liquids and solids
- Spectrum is expensive for protected mission critical applications
- Multipath issues when used in a built-up area due to reflection

As an example, the range of a Wi-Fi or mobile phone signal in water can be as low as 1.8m, using Very Low Frequency (VLF is 3khz to 30khz) this can be extended to about 30m.

### 2.1. Acoustic Communications Advantages & Disadvantages

There is no real benefit using acoustic communication in air except for establishing a baseline. However, liquids and solids are a different matter where there is real advantages when compared to RF. Audio wave travel at 1500m/s in water and are not significantly attenuated with ranges from hundreds of meter to kilometre depending at the frequency and power used

In solids RF can be attenuated in a few centimetres with dense materials such as steel and rock. In building there are many penetrations that RF can pass through, windows, air ducts spaces around doors. However, in some apartment blocks and public building that uses a lot of steel and concrete, a distributed antenna system has to be used to allow people to connect to the mobile phone network

**Advantages of acoustics comms**

- Superior performance in liquid and solids
- Not restricted to line of sight
- Propagates long distances in water (can be 100s of km)
- Can be used to carry data
- No alternative without cables in the ocean

**Disadvantages of acoustic comms**

- Can not work in a vacuum (needs a medium)
- Signal speed dependant on the material it is passing through
- Limited bandwidth
- Not as well developed as RF
- Only required in Niche market
- Compares poorly to RF in Air
- Very limited App & Software compared to RF
- Expensive

RF communication with submarines and submersibles can be on VLF or ELF. The problem is this type of communication is one way and only good for text, there is just no bandwidth for data. The antenna size would be 10km for VLF and more than a 1000km for ELF, it is just not practical to be able to transmit from a submerged craft using RF in the ocean

### 2.2. What are Speeds & Wave lengths of each material

For acoustic communication the speed of the wave is not a constant and is determined by the type of medium that the sound way is propagating in

For the target speed of 40Khz the wavelength for each medium is as follows

- Air is 8.5mm at 343m/s
- Water is 37.05mm at 1482m/s
- Steel is 148.5mm at 5941m/s

One issue is that when sound energy travels from a low dense liquid to a higher density one the wavelength changes, this is also true for the air water boundary and water ground boundary.

At the boundary some of the energy will be reflected, more will propagate through, and you can have multipath issue's that can degrade your received signal making it hard to demodulate. These reflected signals can be managed and mitigated against by taking care in how the acoustic wave is directed using the appropriate audio level

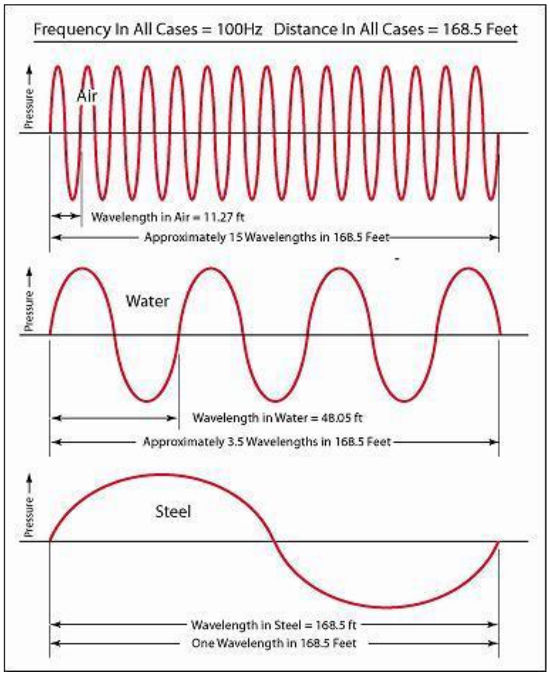



*Figure 3 Wavelength for Air, Water and Steel*

### 2.3.Wave types that can be expected in materials

Electromagnetic radio waves are traverse only, where acoustic wave can be Traverse or Longitudinal. This can be a source of interference and make the signal difficult to demodulate

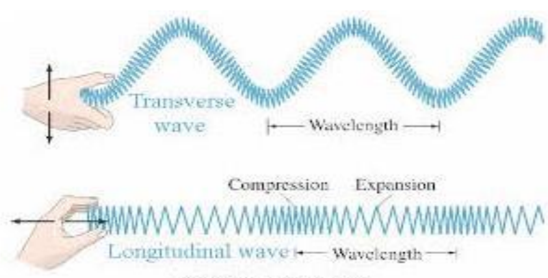



*Figure 3 Transverse and Longitudinal waves*

## 3. Different types of modulation

GNU radio can switch seamless from one modulation technique to another. There have been 5 modulation techniques used in the course of my project, this paper focuses on FSK for all tests

1. On Off Keying (OOK)
   - This is where the signal is switched on and off to correspond to the binary output
   - The amplitude value is 1
2. Amplitude Shift Keying (ASK)
   - In this test we are only looking at Binary Amplitude Shift Keying (BASK) using amplitude of 1
   - Proper ASK would use amplitude of 2 and 3 to represent all 4 values (00, 01, 10, 11)
   - BASK is the same as OOK
3. Frequency Shift Keying (FSK)
   - In this test we are only using Binary Frequency Shift keying (BFSK) that is two frequencies
   - The frequencies used are 39.5KHz and 40.5KHz for Space and Mark
   - The ultrasonic transducers filter out all signal below 39khz and above 41khz
   - The bandwidth available is 2 KHz
   - Proper FSK requires more bandwidth, 4 frequencies to represent 4 values (00, 01, 10, 11)
4. Phase Shift Keying (PSK)
   - In this test we are only using Binary Phase Shift keying (BPSK) that is two quadrants 0 and 180 degrees
   - The ultrasonic transducers filter out all signal below 39khz and above 41khz
   - The bandwidth available is 2 KHz
   - Proper QPSK requires more bandwidth, 4 frequencies to represent 4 values (00, 01, 10, 11)
   - Orthogonal Frequency Division Multiplexing (OFDM)
5. Orthogonal frequency-division multiplexing (OFDM)
   - This is a multi-carrier modulation system where data are transmitted as a combination of orthogonal narrowband signals known as subcarriers
   - This was used primarily in the later part of my research

### 3.1.Setting a base line for SNR in air

It was important to set a base line in the early part of the project for background noise, understand the signal to noise ratio and performance that could be expected. These tests were performed in air using a RP4 and Op amp

**Transmit values table**

| Raspberry Pi 4 TX Sound Card (Board No 1) and TX Op-Amp | | | | | |
|---|---|---|---|---|---|
| Distance | Transmit (dB) | Frequency (Hz) | Noise level (dB) | SNR (dB) (TX-Noise) | Comments |
| 10cm | 3 | 40000 | -120 | 123 | Very good signal level |
| | | | | | |

**Receive value table**

| Raspberry Pi 4 RX Sound Card (Board No 2) and RX Op-Amp | | | | | |
|---|---|---|---|---|---|
| Distance (cm) | Receive (dB) | Frequency (Hz) | Noise level (dB) | SNR (dB) (RX- Noise) | Comments |
| 10 | -12.18 | 40000 | -50 | 37.82 | Very good signal level |
| 20 | -12.36 | 39960 | -47 | 33.64 | Very good signal level |
| 30 | -11.91 | 39950 | -42 | 30.09 | Very good signal level |
| 40 | -11.72 | 39960 | -36 | 24.28 | Very good signal level |
| 50 | -11.67 | 39950 | -29 | 17.33 | Good signal level |
| 60 | -11.93 | 39960 | -28.34 | 16.41 | Good signal level |
| 70 | -11.92 | 39950 | -28.31 | 16.39 | Good signal level |

*Figure 4 Signal to Noise Ratio table*

## 4.GNU Radio GRC software flowgraph design

The software flowgraph was one that was developed by Barry Duggan and made available on the Wiki tutorial. An improvement was made to the graph to include a pre and post amble that allowed a PC on the receive side to sync with the transmit and correlate the data stream in the receive block. The post and preamble bit are stripped from the saved file before it is opened.

### 4.1.TX GRC flowgraph Software

The TX FSK flowgraph take a file and outputs a modulated bit stream using a 40Khz carrier. The EPB:File Source to Tagged Stream block takes a file that is specified on the command line when the flow graph is run. This is an OOT (Out of Tree) modules that add a series of 1s and 0s before the file is converted to bit stream and at the end of the data giving a pre and post amble. This block also assigns a length and tags to it before it is passed through the *Stream CRC32* block, and the output is split so the *Protocol Formatter* block can create header tag in a separate data stream.
The result is combined in the *Tagged Stream Mux* block and repacked in the *Repack Bits* block. The bit stream is passed through the *Repeat Interpolation* block, *Multiply Const* block *Add Const* block before arriving at the *Interpolating FIR Filter* block, interpolation is a process of increasing the sampling rate and available bandwidth

The *Voltage Controlled Oscillator* block (VCO) produces a sinusoid of frequency based on the amplitude of the input. This modulated signal is fed to the *Audio Sink* block as a float

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 air or liquid

### 4.2.RX GRC flowgraph software

The RX FSK flowgraph received a modulated electrical signal from the Audio source block, the sound waves are converted back to a signal by the receive transducer, this signal is amplified by the audio device when required so a signal level higher than background noise is received
The Frequency Translating Finite Impulse Response Filter block performs a frequency translation on the signal and simultaneously down samples the signal via a decimating FIR filter. The main use of this block is an effective channelizer, to pull out a narrowband portion of a wideband signal, without that narrowband portion having to be centred in frequency. Channelization in this manner is particularly useful for Software Defined Radios (SDRs) that capture a wide bandwidth via a very high sampling rate, yet the desired signal only occupies a narrow slice of bandwidth
A squelch block sets a min signal level to remove unwanted noise, this is followed by a *Quadrature Demod*, *Decimating FIR filter*, *Multiply Const*, *Automatic Gain Control* before being passed into the *Symbol Sync* block. This block performs the timing synchronization needed so that the signal is sampled at exactly the right moment in time, which is when each symbol/pulse is at its maximum value
The output is passed into a binary slicer that provides a digital signal to the *Correlate Access Code -Tag Stream* block, this block examines input for specified access code, one bit at a time. This block searches for the given access code by slicing the soft decision symbol inputs. Once found, it expects the following 32 samples to contain a header that includes the frame length (16 bits for the length, repeated), the output is repacked in the *Repack Bits* block before error check are preformed

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

BFSK is an ideal solution when you have limited bandwidth, you only need a few hundred hertz to separate the mark and space frequency. However, QFSK provide a faster data transfer rate but requires need a little more spectrum if it is available.

The transducers used in the project have a +/-1Khz from the centre frequency of 40Khz so it is safer to used BFSK. If time permits, it is hoped to do additional testing at a later stage that may allow a better modulation scheme to be utilised that will give improved data through put

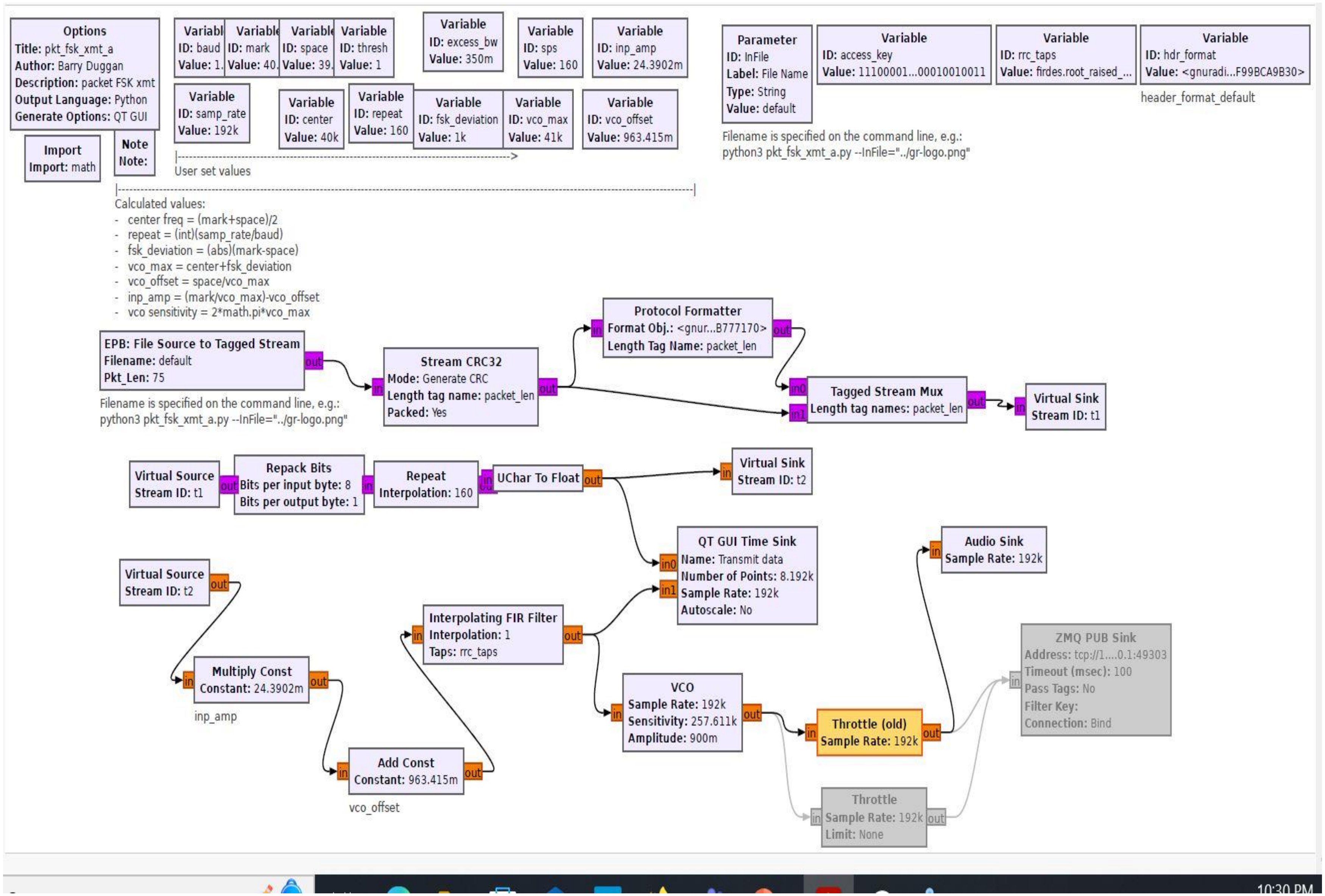



*Figure 5 TX BFSK Flowgraph*

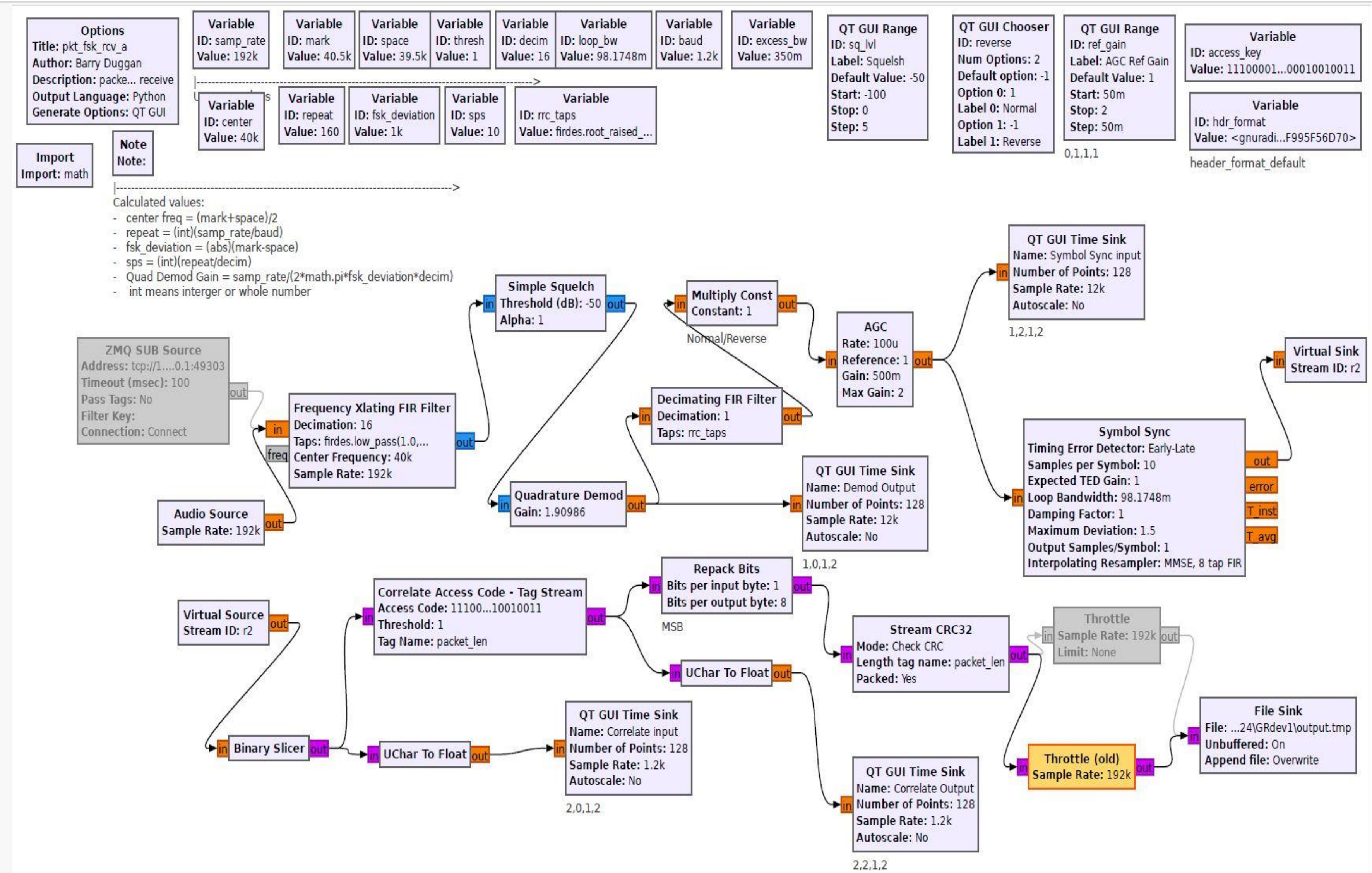



*Figure 6 RX OFDM Flowgraph*

### 4.4. Block diagram and description of test equipment

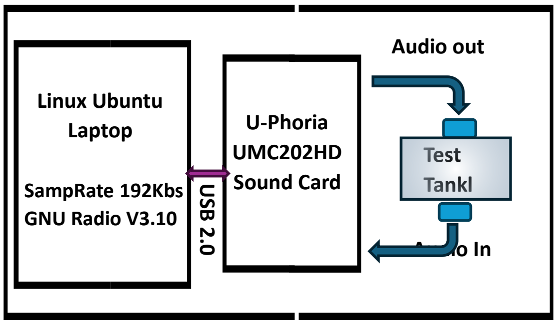



*Figure 7 Functional Block Diagram Test Equipment Layout*

Figure 11 shows a Functional Block Diagram (FBD) of the main component and their relationship to each other

An audio lead is soldered to the transducer mounted in the tank. The transducer has been glued to a penetration in the tank so no water or liquid can leak out. The mounting is done is such a way that the face is not fixed and has no glue attached to it. Another transducer was glued above it on the perpendicular face so tests across the air/liquid boundary could be made. The audio device used is a Behringer UMC202HD and connects to the Ubuntu laptop with a 2.0 USB lead and the laptop is running version 3.10 of GNU Radio companion. This configuration has been very stable, however when the port adaptor is connected for multi screens, the USB audio device has experienced lag and wave degradation after a period of time.

### 4.5. Tank used for testing in air and liquids

*Figure 8 Tank used to test liquids*

A suitable tank was created to test different solutions to understand the FSK modulation protocol using GNU radio and document the results

The first test was with no liquid in the tank, the image transfer did not go as expected initially because the acoustic wave was been reflected from the wall of the tank, a business card was folder over and placed in front of the receive sensor acting like a wave guide, this resolved the matter for this and all tests after including the one where liquid was used.  Gasoline was tested which is corrosive to the plastic tank and caused it to crack at the base. All tests after had a container placed under the tank in case of leakage

### 4.6.Transducer used (type and specifications)

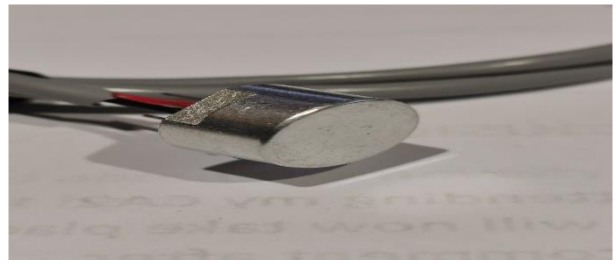


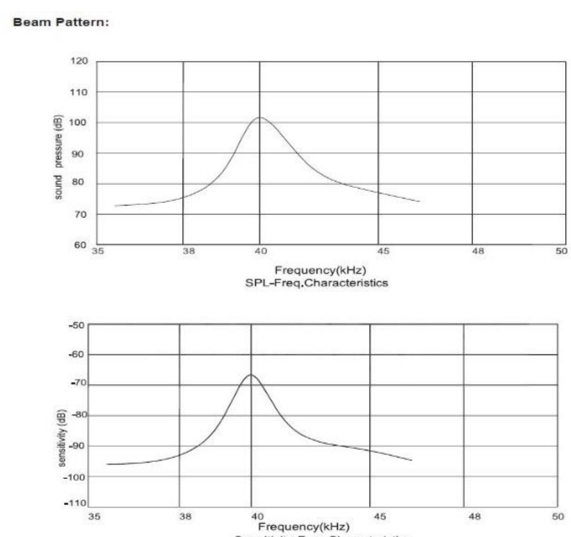
*Figure 9 40Khz Transducers*

Two types of transducers were purchased, they are Multicomp Pro 40Khz & 48Khz from Element 14.
I did have a selection of transducer from other suppliers but most of the time, the transducers shown were used.

*Figure 10 48Khz Transducer*

The feature for these transducer are as follows

- Waterproof and dual use
- Compact and light weight
- High sensitivity and sound pressure
- Less power consumption
- High reliability



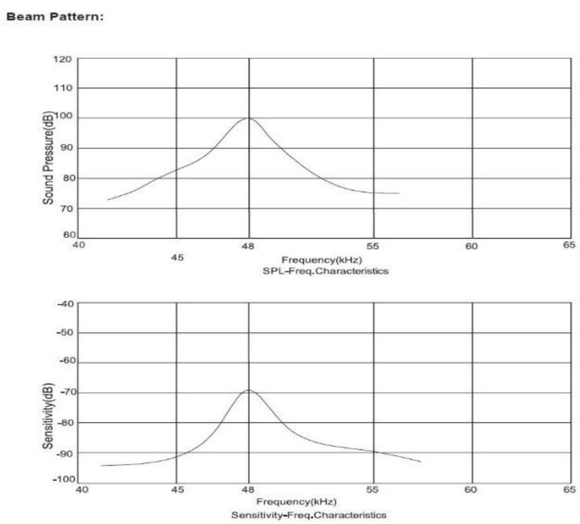



*Figure 11 Sound Pressure + Sensitivity 40Khz & 48Khz*

The graph above shows the sound pressure and sensitivity characteristic of both transducers. The best performance is within 1Khz of the centre frequency and the performance of the transducer drops off exponentially after this.

**Technical Terms:**

| No | Item | Specification |
|---|---|---|
| 1 | Part Number | MCUSD14A40S09RS |
| 2 | Construction | Water Proof |
| 3 | Using Method | Dual Use |
| 4 | Centre Frequency | 40 ± 1kKz |
| 5 | Sound Pressure Level (dB) | ≥90 (30cm/10V rms) |
| 6 | Sensitivity (dB) | ≥-75dB/V/μbar |
| 7 | Beam pattern | 110 × 50° |
| 8 | Capacitance (pF) | 2,500 ± 25% at1kHz |
| 9 | Operating Temperature Range | -40°C to 85°C |
| 10 | Storage Temperature Range | -40°C to 85°C |
| 11 | Allowable Input Voltage (Vp-p) | 160V |
| 12 | Housing Material | Aluminium |

**Technical Terms:**

| No | Item | Specification |
|---|---|---|
| 1 | Part Number | MCUSD17.5A48S11RS-30C |
| 2 | Construction | Water Proof |
| 3 | Using Method | Dual Use |
| 4 | Centre Frequency | 48 ± 1kKz |
| 5 | Sound Pressure Level (dB) | ≥90 (30cm/10V rms) |
| 6 | Sensitivity (dB) | ≥-75dB/V/μbar |
| 7 | Beam pattern | 110 × 50° |
| 8 | Capacitance (pF) | 1,800 ± 25% at1kHz |
| 9 | Operating Temperature Range | -40°C to 85°C |
| 10 | Storage Temerature Range | -40°C to 85°C |
| 11 | Allowable Input Voltage (Vp-p) | 160Vp-p |
| 12 | Housing Material | Aluminium |

*Figure 12 Transducer Specifications 40Khz & 48Khz*

The figure shown above give the specification of the transducers used for the tests with the BFSK flow graph

### 4.7. Graphs displayed during the test

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

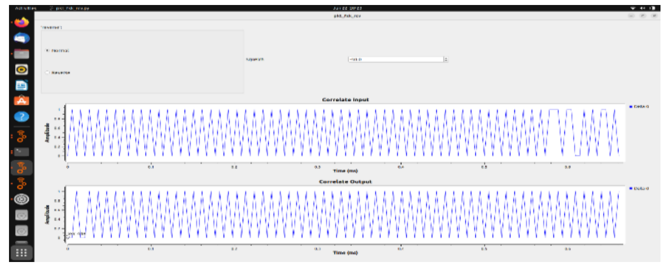


*Figure 13 BFSK Pre and Post amble flow graph 1*

In Figure 17 a preamble which is a series of 1 and 0 allows the receiver to sync with the Transmitter, the Correlate Access Code-Tag Stream block is then able to strip the tags off the bit stream outputting the bits in the correct sequence.

If correlation does not occur the file sink will not build and stay as a file of zero bytes

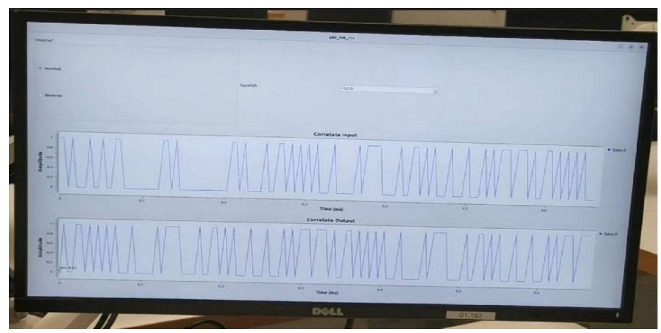


*Figure 14 BFSK data flow graph 2*

Figure 18 shows the normal data flow after correlation has occurred. A small image can take 7 to 10 minutes to be transmitted and demodulated at the receiver.

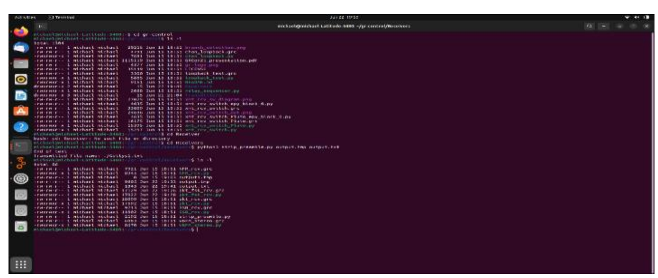


*Figure 15 Removing preamble in 1945 BFSK data flowgraph 2*

A post amble shows the file has been transmitted successfully, the pre and post able are removed using a phyton script from the command line specifying the target file. The file cannot be opened if this step is missed.

### 4.8. Text file Source and Received

The images shown below were used as source files to transfer to an empty target file.

The results were very good with high success rates

***Image of Giraffe and Chimpanzees shown below***

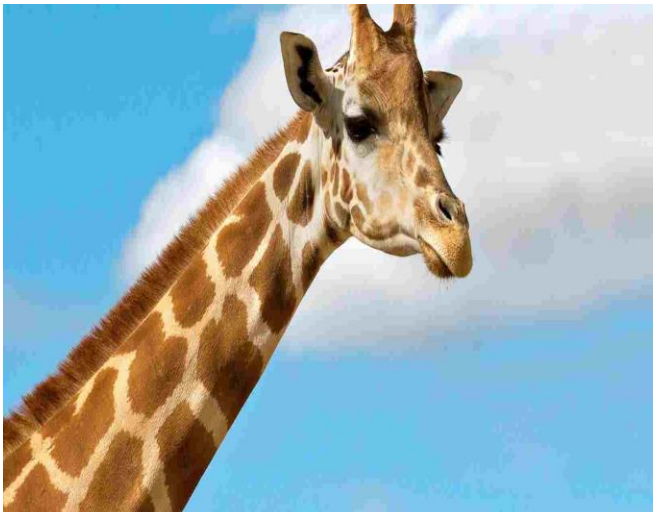


*Figure 16 Giraffe Source file*

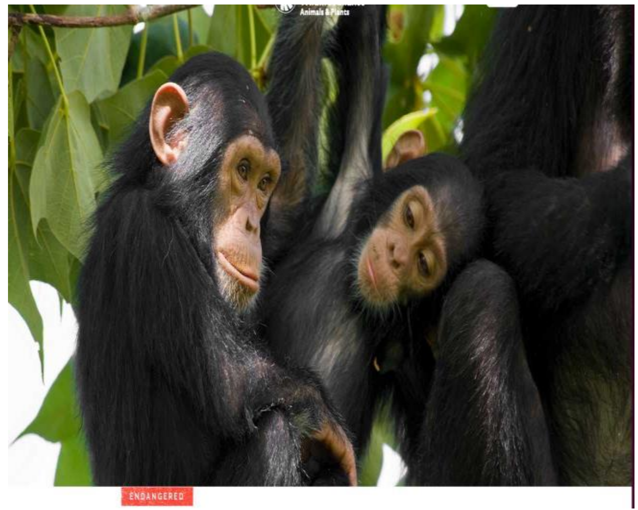



*Figure 18 Chimpanzees Source file*

***The Received file mirrored the source file***

If the transducer were moved during the transmission the received file sometime corrupted. However, in the majority of the tests the image was transmitted successfully. Text and audio files have also been sent.

*Figure 17 Giraffe received file where the transmission failed*

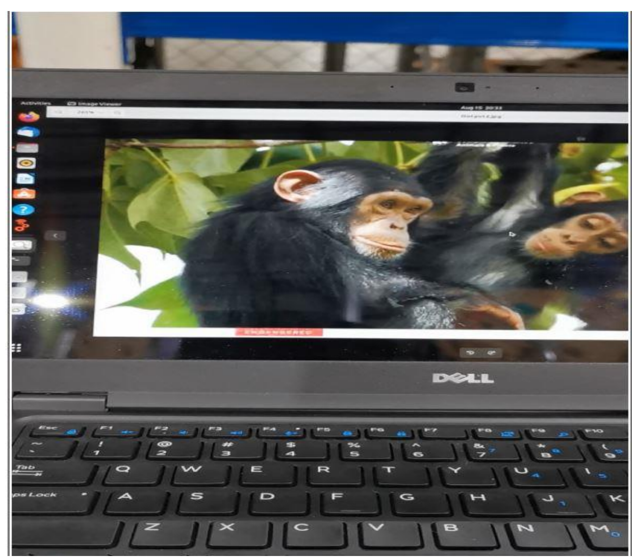


*Figure 19 Chimpanzees received file with no errors*

## 5. Demonstration Test Results

The following performance occurred during the FSK demonstration test case:

- If the transducer is moved during the test, the received data will be corrupted and the test will fail, care should be taken to confirm the baud rate is set as the same for TX/RX and the target file path is correct.
- Some types of files transmitted such as text and png increment in the receive showing the data is being captured and written to the target. However, for Jpeg files the target will only show the new size after the transmission has been complete, it will remain at zero until that time. The transmission can and does fail occasionally.
- The TX file may show transmission as completed but there will be data in the buffer, so it may take a few minutes for the data in the buffer to be transmitted

.

The test proved that this method works in practice within the scope of the demonstration testing, the implemented GNU Radio GRC FSK flowgraph can transmit and receive data through liquids such as water, diesel, orange juice, milk, etc when using FSK modulation protocol.

## 6. Improvements to software & hardware

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

- Research to identify transducer that have improved characteristics and performance
- Investigate when audio device become available with higher sampling rates than 192Khz
- 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 & 80Khz.
- 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 (images) through air and liquid using software defined radio, using an audio interface with appropriate sampling rate
- The transducers selected tapper off quickly when the frequency goes outside the ranges of +/- 1Khz, however as long as you stay near the centre frequency the transducer preform very well.
- The long-term goal is to sent images through steel rail; however, I have concluded that the transmission fails when using FSK and OFDM is a better solution to use in these applications
- Low density material such as wood and some clothing material work with FSK.
- They is many application for this research and I look forward to exploring them going forward

## References

Al-Obaisat, Y. and Braun, R., 2007, March. On wireless sensor networks: architectures, protocols, applications, and management.

Shribak, D., Heifetz, A. and Huang, X., 2018. Development of Software Defined Radio Protocol for Acoustic Communication on Pipes (No. ANL/NSE-18/3). Argonne National Lab.(ANL), Argonne, IL (United States).

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