Development of Software Defined Radio Protocol for Acoustic Communication on Pipes

*Transmission of Information by Acoustic Communication along Metal Pathways
in Nuclear Facilities*

Nuclear Science and Engineering Division

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Development of Software Defined Radio Protocol for Acoustic Communication on Pipes

Transmission of Information by Acoustic Communication Along Metal Pathways in Nuclear Facilities

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1. Introduction

Nuclear Science Engineering Division at Argonne has been developing a new method of transmitting information via acoustic waves on pipes in a nuclear facility. This method provides the capability to communicate information from within the containment building under the conditions of total power outage following a severe accident. Compared to traditional RF communications, acoustic communications allows for signal transmission across thick concrete barriers, and better information security due to spatial confinement of the signal. Data of interest consists of sensor readings, voice, and images. Transmission of images is most challenging because corruption of the header string might render the reconstructed image unreadable.

In order to achieve this task, we used the Software Defined Radio tool GNURadio, which allowed us to build a communication protocol to transmit data effectively. We created a python tool to compare different modulation and front error correction techniques used to transferring header files. The goal of this task was to successfully transmit the header file of a .ppm (Portable Pixel Map) image because any corruption in this data renders the image useless.

We first consider introduce the theoretical background of the physical communication system, modulation technique and data transmission protocol in Section I. Section II considers the specific experimental setup employed, emphasizing the implemented protocol. Following that, Section III outlines the function of each step in the GNURadio program and how the improvements to the system were quantified. Section IV analyses the results of the trials and highlights further potential improvements to the overall communication system.

2. Background

Our project combines the fields of acoustics with communication technology. It consists of three main layers: Physical Transmission, Modulation and Data Protocol.

Physical Transmission

Image 1: Reactor Layout with attached technology (from “Realizing a Pipe Dream,” <https://www.anl.gov/articles/realizing-pipe-dream>)

The overall challenge that this project aims to overcome is to maintain communication with a nuclear reactor reaction core in case of a meltdown, which is isolated by a few meters of

concrete to protect against radiation. However, there are steam pipes penetrating this confinement shell. This pipe will form the channel for our communication system.

For the physical transmission, we employed two ultrasonic acoustic wave transducers on six foot steel pipe spaced at about five feet apart. The transducers were originally designed for nondestructive testing. On the physical layer, a digital wave is generated by the GNURadio program, which is next converted into an analog wave by Red Pitaya. This analog wave is sent to the transducer through an amplifier, which converts it into an acoustic wave by vibrating a crystal at a certain frequency. This vibration passes through the pipe in the form of a shear mechanical wave and vibrates the transducer on the other end of the pipe, generating an electrical wave, which is converted back into a digital wave by Red Pitaya.

Modulation

Image 2: Shift Keying Techniques

Digital modulation is the process sending a binary signal inside of a different signal that can be easily transmitted over a physical channel. In our case, we chose to employ binary Amplitude Shift Keying (ASK) and binary Phase Shift Keying (PSK).

In ASK, a 1 is represented as a high amplitude, and a 0 is represented by a low amplitude. In PSK, a 1 is represented by a 180 degree phase shift on the carrier frequency, and a 0 is represented by a 0 degree phase shift on the carrier frequency.

The binary waveform is multiplied onto a carrier frequency, produced by the Red Pitaya, and transmitted through the pipe. On the receiving end, the signal is demodulated by multiplying again by the carrier frequency and passing the information through a low pass filter to recover the original signal.

These are the most simple forms of modulation available, and while more elaborate forms of Shift Keying exist that allow for more information to be encoded per key, we chose this technique due to the fact that the constellation symbols are maximally spread out, reducing the impact of noise on the channel compared to a setup that encodes more than one bit per symbol.

Protocol

Outside of being modulated and passing through the physical channel, the image data has to be processed in order to be successfully transmitted and recovered. As noted above, only a binary stream of information can be sent through the pipe. However, image data has a non-binary data structure and for that we have chosen to use a Portable Pixel Map (PPM) file as our primary image data structure for transmission.

```
P3      <- file type
4 4     <- dimensions in pixels
255     <- maximum pixel value (rgb is 0 to 255)
1 1 0
4 1 2
5 3 4
```

Table 1: Example of Header File

The PPM file type stores the image dimensions in the first three lines and the rest is the image itself as a matrix after that in the form of ASCII character. We will refer to these three lines as the “image header” and the rest as the “image payload”. The image header is critical to successful recovery of the image, as if there are any errors within the file, the computer will not be able to read the data effectively. The image payload, on the other hand, can contain more errors as a single error is less likely to make the file unreadable.

In order to transmit this information, this data structure has to be converted into binary, sent, and reassembled back into its original form. To accomplish this task, we first disassemble the file into a stream of ASCII characters, in the form of bytes (1 byte = 8 bits). A table of ASCII values is shown below:

ASCII value	Character	ASCII value	Character	ASCII value	Character
000	~@	043	+	086	V
001	~A	044	,	087	W
002	~B	045	-	088	X
003	~C	046	.	089	Y
004	~D	047	/	090	Z
005	~E	048	0	091	[
006	~F	049	1	092	\
007	~G	050	2	093	]
008	~H	051	3	094	^
009	~I	052	4	095	_
010	~J	053	5	096	`
011	~K	054	6	097	a
012	~L	055	7	098	b
013	~M	056	8	099	c
014	~N	057	9	100	d
015	~O	058	:	101	e
016	~P	059	;	102	f
017	~Q	060	<	103	g
018	~R	061	=	104	h
019	~S	062	>	105	i
020	~T	063	?	106	j
021	~U	064	@	107	k
022	~V	065	A	108	l
023	~W	066	B	109	m
024	~X	067	C	110	n
025	~Y	068	D	111	o
026	~Z	069	E	112	p
027	~[	070	F	113	q
028	~\	071	G	114	r
029	~]	072	H	115	s
030	^^	073	I	116	t
031	~-	074	J	117	u
032	[space]	075	K	118	v
033	!	076	L	119	w
034	"	077	M	120	x
035	#	078	N	121	y
036	\$	079	O	122	z
037	%	080	P	123	{
038	&	081	Q	124	
039	'	082	R	125	}
040	(	083	S	126	~
041	)	084	T	127	DEL
042	*	085	U		

Image 3: ASCII to number conversion table

These characters are then converted into a bit stream, a packet header is attached and is passed through the modulation methods mentioned earlier. After being demodulated, the bit stream is parse to remove the packet header, the bits are converted into their original bytes, and the file is reassembled.

When error correction is added, after the bytes are converted into bits they are multiplied by a convolution matrix, and once received, the bits are deconvoluted by an inverse matrix.

Overall, the protocol of the communication system was the primary focus of this project as reducing the number of errors in transmitting ensures that the communication system is reliable.

3. GNURadio implementation

In order to implement the communication protocol, GNURadio was used as a base. Below is a flowgraph generated by GNURadio for ASK modulation with no convolutional code, followed by an explanation of each step in the process.

Image 4: Flow Chart created by GNURadio of program used

4. Test and Analysis

In order to compare the different data transmission techniques, a simple message was pass through the system and monitored on as information was passed through the blocks. Below is a representation of what occurs at each step in the process. Below is the plot for ASK.

In this example, we send a file with characters “!s!” for demonstration purposes. We will follow the journey of a packet as it is transmitted through the system.

In the file source block, we see how file is being disassembled into three values: 33, 115, 33. The value of 33 corresponds to “!” and the value of 115 corresponds to “s”. Below is a diagram with each character labeled as a separate color.

The protocol formatter block creates a tagged stream of 1's and 0's that will be attached to the payload. In our case, we use the default preamble of '1010010011110010' and access code of '1010110011011101101001001110001011110010100011000010000011111100', which is displayed above as bytes.

Above we can see how the header file is combined with the payload. We first see the attached preamble in the form of bytes. The first 12 bytes are from the protocol formatter while the last 3 are from the file source. Specifically, we can see that bytes 12, 13, 14 match the file source.

Bit Value Output (colors are individual bytes, dots are individual bits)

We can now see how after the stream mux, we unpack the individual bytes into 8 bits each. The individual bytes are displayed above with colors corresponding to each byte. There are 15 bytes in total for the packet, meaning that we are now sending 120 samples through the system ($15 \times 8 = 120$)

Above is a zoomed in view of the first byte in the stream. We can see that it does in fact correspond to the character value of 172, since $10101100 = (1 \times 2^7) + (0 \times 2^6) + (1 \times 2^5) + (0 \times 2^4) + (1 \times 2^3) + (1 \times 2^2) + (0 \times 2^1) + (0 \times 2^0) = 172$.

The two above figures are taken from the oscilloscope at a sampling rate of 25 Ms/s, which is much higher than GNURadio's rate of 100 ks/s, which is why the number of samples for the same signals is 250 times higher than in GNURadio ($250 \times 100,000 = 25,000,000$). The individual bytes from the square wave are all translated into a signal with amplitude ranging from -0.3 to 0.3 volts. Note that in our setup we pass this signal into a 50 dB amplifier, the transducer actually feels a voltage of about 95 volts. We can see that Red Pitaya introduces ringing into the system on every on/off voltage high/low. This kind of behavior is why we chose to use binary ASK over quad ASK, since this kind of instability only lends itself to on or off keying.

Above is an FFT of the transmitted signal. Compared to the original signal, we see that the frequency response of the square wave is still seen on the lower end of the spectrum, and we can also clearly see the carrier frequency centered at 1.8 MHz. We can see that the frequency response of the carrier frequency is stronger than the frequency response of the base band.

Above we are again viewing oscilloscope data, which is this time connected to the output of the low noise amplifier placed after the receiving transducer. We can see that the signal, even with the use of two amplifiers, is attenuated by 10 and in addition, a DC offset of -0.075 volts is added to the signal. Compared to the transmitted signal, we can see more distortion along the peaks of the signal, as well as a much larger amount of noise around the DC offset.

Above is the frequency response of the received waveform. Compared to the transmitted waveform, we can see that the frequency response of the baseband is higher than the frequency response of the carrier frequency.

Above we can see the received transmission of the first byte in the string of characters. We see that after the shift keying has been switched to the off position, we still see some ringing from the waveform.

Above is the received signal from red pitaya, displaying the repeated string of characters. We see that at first the system produces information that cannot be decoded (Sample number <500000), but then proceeds to produce a waveform that is more stable. Since our sample rate is 100000 S/s, we can therefore conclude that the system has to transmit for 5 seconds before the information can be processed successfully. The overall shape of the incoming signal envelope has a sinusoidal shape, suggesting that there is a phase mismatch between the transmitting Red Pitaya and the receiving Red Pitaya. Below is an FFT of the received signal, which should match that of the transmitted square wave:

We can see that the frequency roll off is similar to that of the transmitted information, however the frequency response is much less smooth than before. Below we provide a zoomed in version of the character transmission:

If we compare this plot to the transmitted waveform, we can see that there is much more ringing in this signal compared to the transmitted. This result matches that of the frequency response, as we can see that the imbalanced frequency response makes the square waves less defined.

Above is a plot of the signal as that passes through the active gain control. We can see that it has the same shape as that of the signal that exits red pitaya, however the amplitude is increased. This is done to prepare the signal for the threshold section, which needs a greater difference in amplitude.

Above is a display of the threshold block after demodulation. We can see that the system can only begin to recognize the bits after a certain number of samples have passed, showing that the active gain control needs time to grow before being demodulated.

Above is received information from the threshold. We see that it follows the same pattern as the transmitted bits.

The correlate access code removes the bits from the stream that follow originate from the protocol formatter, leaving the original information.

The repack bits block repacks the bits into bytes and stores the information into the file sink, successfully recovering the transmitted file.

FEC simulation and testing

In order to quantitatively test which methods are best, we set up a python script that transmitted a string of characters, similar to that of an image header file, three times with different combinations of modulation and error correction. We then compared the number output by the file source against the input of the file sink to see how effectively the data was transmitted.

The Python code considers 4 combinations of communication channels: ASK (Amplitude Shift Keying), ASK with CC (with Convolutional front error Correction), PSK (Phase Shift Keying), PSK with CC. We ran a simulation channel that modified the SNR (Signal to Noise Ratio) by adding various voltages of AWGN (Additive White Gaussian Noise) and plotted whether or not the channel could transmit the header file of without error above.

Overall, we see that the most effective method of communication in simulation is PSK with CC, which was successful at transmitting at all SNR levels. PSK was also effective, with the bit error rate dropping sharply after 10 decibels. The CC technique appears to slightly increase the performance of ASK modulation.

However, due to experimental limitations, the analog to digital converter was not capable of effectively demodulating the signal transmitted through the pipe. Therefore, instead ASK and ASK with CC were tested. Interestingly, ASK either transmits perfectly or not at all at different frequencies while ASK with CC transmits at all frequencies, albeit with a high error rate. Both techniques work at 2 Mhz, which suggests that the communication system prefers higher frequencies.

4.Conclusion

Overall, we can see the effect of each step in the GURadio process for signal transmission. We see that passing the square wave through the communication channel leads to higher noise around the DC offset as well as a more jagged frequency response from the square wave. In order to further improve the system, we would have to lock the phase after the information is received from the Red Pitaya, as well as develop a system that helps reduce the number of samples the system needs to pass through the active gain loop before becoming decodable.

Appendix

Block	Input	Output	Parameters	Actions	Purpose
File Source	Text file containing information to be sent	Characters in the file in form of continuous stream of bytes	Output type: Whether the file is a stream of bytes, floats, ints, etc; Repeat: Whether the file will be infinitely repeated;		Opens the needed data file
Throttle	-	-	Sample Rate: Number of samples per second	Limits the flow of information to 32k samples/sec	Makes sure computer doesn't overheat
Stream to tagged stream	Continuous stream of characters	Continuous stream of characters with tagged	Packet Length: Controls how much data stored is per packet		Puts a marker on the start of a packet for the header generator to attach to
Protocol Formatter	Continuous tagged stream of characters	String of header characters	Formatter Obj: Sets the protocol formatter's key parameters: Preamble and Access Code, which are basically what the correlate access code will look for when assessing what is a packet	Creates a header for the packet	

Tagged Stream Mux	Two tagged streams	One tagged stream	Length tag names: Input the length of the data stream to which to attach the header	Combines the two data streams by putting input 1 in front of input 2	
Repack Bits	1 byte	8 bytes	Length tag name: Input the length of the data stream, Packet Alignment: How packets are aligned, Endianness MSB or LSB (which one comes first in stream)	Converts the stream of bytes into a stream of bits	Modulation techniques deal with bits and not bytes

Data Protocol during modulation steps

Block	Input	Output	Parameters	Actions	Purpose
Char to float	Character	Float	Scale: Ratio of Char value to Float value	Converts a character value of -128 to 127 (0 and 1 in this case as we are in BITS) to its numeric value	Numbers are sent through the channel, not characters
Rational Resampler	1 float	600 floats	Interpolation: How many samples to add to the stream	Creates a digital square wave out of single points	We use a square wave to transmit data
Moving Average	Input is a stream of floats	Output is the moving sum of the last N samples,	Length of averaging window, number to	Sums the last N points, to be divided by the scaling	

		scaled by the scale factor	divide by, max number of iterations in averaging	factor. This is	
Float to Complex	Float	Complex	Scale factor	Converts float to complex number (magnitude)	Succeeding blocks use complex numbers
Red Pitaya Sink	Complex	None	Address: IP address of red pitaya to connect to; Port: Connection port; Center frequency: Frequency by which the red pitaya multiplies the square wave by (important as this is the frequency at which the pzt oscillates); Sampling rate: Sampling rate of the red pitaya (basically we want this as high as possible to give the most accurate waveform)	Transmits the data to the pzt	Acts as a digital (discrete) to analog (continuous) converter and a fir filter
Red Pitaya Source	None	Complex	Address: IP address of red pitaya to connect to; Port: Connection port; Center frequency: Frequency by which the red	Receives the data from the pzt	Acts as an analog (continuous) to digital (discrete) converter and a fir filter

			pitaya multiplies the square wave by (important as this is the frequency at which the pzt oscillates); Sampling rate: Sampling rate of the red pitaya (basically we want this as high as possible to give the most accurate waveform)		
Low Pass Filter	Complex	Complex	Cutoff frequency: Frequency to attenuate	Attenuates above a threshold frequency	Removes high frequency noise as well as any carrier frequency to leave square wave
Active Gain Control (AGC)	Complex	Complex	The gain is updated by the equation: $\text{Gain} = \text{Gain} + \text{Rate} * (\text{Reference} - \text{abs}(\text{Input}))$; Max Gain: the automatic gain will not exceed this value. If set to 0 there is no max	Applies gain loop onto signal	Stabilizes the signal for demodulation
AM Demod	Complex	Float	Channel_rate – incoming sample rate of the AM baseband; audio_decim	Demodulates the signal	Decimates the square wave

				– input to output decimation rate (integer); audio_pass – audio low pass filter passband frequency (float); audio_stop – audio low pass filter stop frequency (float)		
Multiply Const	Float	Float	Number to multiply by	Multiplies by a constant	Fine tuning	
Add Const	Float	Float	Number to add	Adds a number	Fine tuning	
Threshold	Float (range of values)	Float (1 or 0)	Upper threshold, lower threshold	The output transitions from 0.0 to 1.0 when the input signal transitions from below to above the High level. The output transitions from 1.0 to 0.0 when the input signal transitions from above to below the Low level.	The threshold converts the stream of floats into binary (bits)	

Data Protocol after modulation steps

Block	Input	Output	Parameters	Actions	Purpose
Map	Float	Float	Map of values to	Maps incoming	Makes sure that data is

			send to	data to 0 or 1	mapped to bits
Repack Bits	8 bytes	1 byte	Length tag name: Input the length of the data stream, Packet Alignment: How packets are aligned, Endianness MSB or LSB (which one comes first in stream)	Converts the information from bits into bytes	Byte manipulation technique
Packed to Unpacked	1 byte	8 bytes	Endianness MSB or LSB (which one comes first in stream)	Converts the bytes into bits	The correlate access code deals with bits, not bytes
Correlate Access Code	Continuous stream of bits	Continuous stream of bits without header bits	Preamble and Access Code: What the correlate access code will look for when assessing what is a packet	Removes the header bits from the bit stream	The original data has no header bits, so we want to remove them
Repack Bits	8 bytes	1 byte	Length tag name: Input the length of the data stream, Packet Alignment: How packets are aligned, Endianness MSB or LSB (which one comes first in stream)	Converts the bits into bytes	Original data was stored as characters, not bits
File Sink	Continuous	None	Input type:		Saves the

stream of
characters

What kind of
information is
being written
to file;
Unbuffered:
Whether or
not the file is
being
buffered;
Append file:
Whether the
incoming
data
overwrites
the old file or
append it.

incoming file

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