Analysis of Achievable Rates of Communication

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

Nuclear Science and Engineering Division

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

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1. Introduction

1.1 Background

Nuclear Science Engineering Division at Argonne has been developing a new method of transmitting information via elastic waves on pipes in a nuclear facility. Compared to traditional RF communications, acoustic communications allows for signal transmission across physical barriers, and better information security due to spatial confinement of the signal. Such communication system would take advantage of the existing piping infrastructure to transmit information in and out of containment building, as shown in Figure 1. Data of interest consists of sensor readings, sound, and images. This approach would provide a communication channel to the containment building under the conditions of total power outage following a severe accident.

Figure 1 - Proposed acoustic communication system at a nuclear facility would transmit information on steel pipes already in place for nuclear reactor operation (Argonne 2018).

1.2 Introduction

In this project, we are developing a wireless communication system for a nuclear facility, in which information is carried with elastic waves propagating on metallic pipes. Our project combines the fields of acoustics with communication technology. Because of limited bandwidth of ultrasonic transducers, on-off-keying (OOK) digital communication protocol was chosen for information transmission over an acoustic channel. Current work on the project is focused on investigating communication channel capacity (bit rate or duty cycle of the analog signal amplitude waveform), reliability (bit error rate) and energy efficiency (energy consumption per bit) of OOK. Design considerations of the OOK communication protocol are intimately connected to physical characteristics of the communication channel.

In general, communication data rate is proportional to carrier frequency. However, signal attenuation in the channel due to absorption is proportional to carrier frequency as well, so that carrier frequency cannot be increased indefinitely. Prior work demonstrated that pulse energy fades below detection threshold if the pulse temporal duration is smaller than some limit. Other factors adversely influencing communication bit rate studied more recently include mixture of modes and echoes. Longitudinal and shear waves have different propagation velocities in stainless steel, so that excitation of both modes can lead to bit errors. Excitation of shear waves only can be achieved with EMAT (electromagnetic acoustic transducers). Refracted shear waves can be excited with PZT (piezo-electric transducers) mounted on angled wedge, with an angle larger than the first critical angle. Echoes occur due to reflections of acoustic waves at discontinuities, such as pipe ends. Echoes are stronger at lower frequency, which suffers less attenuation from absorption losses in the channel. In addition, only round-trip echoes, re-scattered in the direction of the original signal, couple into the angled-wedge mounted PZT receiver. On the other hand, EMAT receiver is omnidirectional, and picks up echoes from every scattered in any direction towards the receiver. Thus, longer distance of echo propagation before coupling into receiver makes PZT-based channel more immune to echoes. Some aspects of the communication protocol affecting data bit rate include length of time required to achieve optimal performance with active control gain, and received analog signal decimation procedure.

This report describes implementation of amplitude shift keying (ASK) communication protocol using GNURadio software environment, and evaluation performance of communication channels based on PZT and EMAT transducers. Main achievements thus far include demonstration of transmission of sound and text files with PZT and EMAT across six-foot long nuclear grade stainless steel pipe, and demonstration of image transmission with PZT over the pipe. In the former example, 32KB image was transmitted at data rate of 2KB/s. Efforts are currently under way to further enhance data transmission rate.

2. Description of Software Defined Radio Protocol for Acoustic Communication on Pipes

2.1 Introduction

Data of interest for transmission on nuclear reactor pipes includes sensor readings, voice, and images. Transmission of images is most challenging because corruption of the header string might render the reconstructed image unreadable. We used the Software Defined Radio (SDR) 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.

For the physical transmission, we employed two ultrasonic PZT's on a six foot-long stainless steel pipe spaced at about five feet apart. The transducers were originally designed for nondestructive testing. A digital wave is generated by the GNURadio program, which is next converted into an analog wave by Red Pitaya electronic boards. This analog wave is sent to the PZT through an amplifier, which converts the electronic wave into an acoustic wave by vibrating PZT 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.

2.2 Modulation 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). Schematics of shift keying modulation techniques are displayed in Figure 2.

Figure 2 - Schematics of shift keying modulation techniques

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.

2.3 GNURadio Communication Protocol Implementation

In communication protocol implemented in SDR, 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.

Table 1. Example of header file

```
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
```

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.

To transmit this information, 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:

Table 2. ASCII to number conversion table

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		

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. GNURadio environment was used to develop and implement the communication protocol. Figure 3 below displays a flowgraph generated by GNURadio for ASK modulation with no convolutional code. Descriptions of various blocks functionalities are provided in tables below.

Figure 3 - ASK acoustic communication protocol flow chart created by GNURadio

Explanations of blocks functionalities before modulation, during modulation, and after modulation steps are provided in Tables 3, 4 and 5, respectively.

Table 3. Functionalities of blocks before signal modulation steps

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

Table 4. Functionalities of blocks during signal 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, scaled by the scale factor	Length of averaging window, number to divide by, max number of iterations in averaging	Sums the last N points, to be divided by the scaling 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 transducer 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 transducer	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 pitaya multiplies the square wave by (important as	Receives the data from the transducer	Acts as an analog (continuous) to digital (discrete) converter and

			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)		a fir filter
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 – input to output decimation rate (integer); audio_pass – audio low pass filter passband frequency (float); audio_stop – audio low pass filter stop frequency (float)	Demodulates the signal	Decimates the square wave
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)

Table 5. Functionalities of blocks after signal modulation steps

Block	Input	Output	Parameters	Actions	Purpose
Map	Float	Float	Map of values to send to	Maps incoming data to 0 or 1	Makes sure that data is 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 stream of characters	None	Input type: 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.		Saves the incoming file

2.4 Communication Protocol Testing and Analysis

To compare different data transmission techniques, a simple message was passed through the system and monitored in each GNURadio flowchart block. 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. Below is a representation of what occurs at each step in the process.

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”. Figure 4 below displays the raw data and each character labeled as a separate color.

Figure 4 – File source output (left) raw data, (right) data colored as individual bytes

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 in Figure 5 (raw data and data colored as bytes)

Figure 5 – Protocol formatter output (left) raw data, (right) data colored as individual bytes

Figure 6 below visualizes 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.

Figure 6 – Stream mux output (left) raw data, (right) data colored as individual bytes

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 in Figure 7. There are 15 bytes in total for the packet, meaning that we are now sending 120 samples through the system ($15 \times 8 = 120$).

Figure 7 – Bit value output (left) raw data, (right) data colored as individual bytes

Figure 8 below shows 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 $10101100 = (1 \times 2^7) + (0 \times 2^6) + (1 \times 2^5) + (0 \times 2^4) + (1 \times 2^3) + (1 \times 2^2) + (0 \times 2^1) + (0 \times 2^0) = 172$.

Figure 8 – First byte stream mux output (left) raw data, (right) data colored as individual bytes

Figure 9 below shows what happens to the information after the rational resampler and moving average block. Each bit is interpolated to create 600 bits after it, which is why the total number of samples goes from 120 in the figure with the data displayed as bits, to 72000 in the above figures ($120 \times 600 = 72000$). In both graphs, we can see how the signal is converted from digital to analog, transforming the latter into a square wave.

Figure 9 – Analog wave output (left) raw data, (right) data colored as individual bytes

Figure 10 below displays Fast Fourier Transform (FFT) digital calculation of the analog wave output spectrum. The bandwidth of the signal is less than 50KHz.

Figure 10 – FFT spectrum of analog wave output

Figure 11 below displays the data 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.

Figure 11 – Transmitted wave on pipe (left) raw data, (right) data colored as individual bytes

Figure 12 below displays FFT spectrum of the transmitted signal on pipe. Compared to the spectrum of the analog output signal in Figure 10, 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.

Figure 12 – FFT spectrum of transmitted wave of pipe

Figure 13 displays the received signal waveform before demodulation. The data is obtained from the oscilloscope, which is now 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.

Figure 13 – Received wave on pipe before demodulation (left) raw data, (right) data colored as individual bytes

Figure 14 displays the frequency spectrum of the received waveform before demodulation. Compared to the transmitted signal spectrum shown in Figure 12, we can see that the frequency response of the baseband is higher than the frequency response of the carrier frequency.

Figure 14 – FFT spectrum of received wave on pipe before demodulation

Figure 15 below displays of the first byte in the string of characters in the received signal in Figure 13. We see that after the shift keying has been switched to the off position, we still see some ringing from the waveform.

Figure 15 – First byte in received signal before demodulation

Figure 16 below is the received demodulated signal with Red Pitaya board, 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 boards.

Figure 16 – Received demodulated signal with Red Pitaya board

Figure 17 below displays FFT spectrum of the demodulated received signal, which should be matching that of the transmitted analog square wave in Figure 10. We can see that the frequency

roll off is similar to that of the transmitted information, however the frequency response is not as smooth as in the transmitted signal.

Figure 17 – FFT spectrum of demodulated signal received with Red Pitaya board

Figure 18 below provides a zoomed in version of the character transmission of the received signal from Red Pitaya board. If we compare this plot to the transmitted waveform in Figure 11, we can see that there is much more ringing in the received signal compared to the transmitted one. This result matches that of the frequency response, as we can see that the imbalanced frequency response makes the square waves less defined.

Figure 18 – Zoomed-in received signal from Red Pitaya board (left) raw data, (right) data colored as individual bytes

Figure 19 below displays a plot of the signal as it passes through the automatic gain control (AGC). We can see that this signal 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 between on and off states representing digital “0” and “1”

Figure 19 – Signal amplification with automatic gain control (AGC)

AGC is needed to compensation of demodulated signal amplitude reduction due to random phase difference in the received and reference waveforms. The average or peak output signal level is used to dynamically adjust the gain of the amplifiers, enabling the circuit to work satisfactorily with a greater range of input signal levels, so that we can set a proper up threshold for ‘1’ and down threshold for ‘0’. the AGC effectively reduces the amplitude if the signal is strong and raises it when it is weaker. Implements an automatic gain control with a single rate parameter for both attack and decay. The gain is updated by the equation

$$Gain = Gain + Rate * (Reference - abs(Input))$$

The equation is for each sample.

- Attack rate – how fast the AGC decreases the gain when a loud signal appears
- Decay rate – how fast the AGC increases the gain when the loud signal is gone
- Reference – This is the level the AGC will try to maintain

Figure 20 below displays the data of 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.

Figure 20 – Data of threshold block after demodulation

Figure 21 below displays information recovered from the threshold block after decimation. We see that the recovered information follows the same pattern as the transmitted bits.

Figure 21 – Data recovered after decimation (left) raw data, (right) data colored as individual bytes

The correlate access code removes the bits from the stream that follow originate from the protocol formatter, leaving the original information. Figure 22 below displays the resulting data bits

Figure 22 – Data recovered with correlated access code (left) raw data, (right) data colored as individual bytes

The repack bits block repacks the bits into bytes and stores the information into the file sink, successfully recovering the transmitted file. The data is displayed in Figure 23 below.

Figure 23 – Data from file sink input (left) raw data, (right) data colored as individual bytes

2.5 Comparison of Communication Protocols Performance

To quantify differences in performance of ASK and PSK communication protocols, we developed a Python script that transmitted a string of characters, similar to that of an image header file. Data was transmitted 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). Figure 24 displays bit error rate (BER) in header file transmission vs. signal to noise ratio (SNR) in units of dB.

Figure 24 – BER vs. SNR for ASK, ASK with CC, PSK, and PSK with CC schemes

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. The results are plotted in Figure 25 as BER vs carrier frequency. 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.

Figure 25 – BER vs. carrier frequency for different ASK and ASK with CC schemes

2.6 Conclusion

Overall, we can see the effect of each step in the GNURadio 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.

3. Demonstration of Information Transmission with Acoustic Communication System

Using the communication protocol described in Section 2, we have demonstrated data transmission over a communication channel consisting of two PZT's on six-foot long stainless steel pipe. As described in previous reports, the parameters of the pipe in this study closely resembles those of the chemical volume control system (CVCS) charging line pipe, which penetrates through the containment building wall in some common reactor designs.

3.1 Acoustic Transducer Frequency Selection

As discussed in Section 1, higher frequency of the carrier acoustic wave allows for transmitting information at high bit rate. As illustrated below, information is encoded with D/A into a square wave waveform with duty cycle. As an example, time-domain waveform with duty cycle of 100 μ s and its spectrum calculated with FFT are shown in Figure 26.

Figure 26 - Information-carrying waveform (left) time domain (right) frequency domain

The waveform is encoded as amplitude modulation of the carrier with acoustic frequency. Figure 27 shows amplitude modulated 2MHz carrier frequency and its FFT spectrum.

Figure 27 – Amplitude-modulated carrier waveform (left) time domain (right) frequency domain

Demodulation at the receiver occurs by multiplying received signal by a reference sinusoid with the same acoustic frequency. The signal after multiplication and its FFT spectrum are shown in Figure 28.

Figure 28 – Received signal multiplied by reference (left) time domain (right) frequency domain

Demodulation takes place by applying low-pass filter (LPF), shown as the box in the spectral plot, to remove carrier sidebands at $2f = 4\text{MHz}$. The spectrum of information-carrying square wave is close to DC. For higher-frequency amplitude modulation (AM) square wave, the baseband spectrum will increase. The spectral width of the LPF or the frequency of the carrier will determine the limit of AM duty cycle. Thus information bit rate is proportional to frequency of the carrier f .

At the same time, higher frequency results in larger absorption losses in the channel. A decrease in the plane harmonic wave amplitude as a result of its interaction with a medium takes place according to the Beer-Lambert law $e^{-\delta x}$, where x is the distance that the wave passes in the medium and δ is the damping coefficient. In what follows, the term “damping” will refer only to the wave amplitude decrease that is considered by an exponential multiplier, contrary to a decrease in the amplitude related to the wave front extension.

The damping factor consists of the coefficients of absorption δ_1 and dissipation δ_2 : $\delta = \delta_1 + \delta_2$. During absorption, a sound energy transforms to thermal, and during dissipation the energy remains sonic, but is emitted by a wave whose propagation is directional. Absorption is conditioned by ductility, elastic hysteresis (i.e., by a different elastic dependence during extension and compression), and heat conductivity.

The value of the dispersion coefficient in a medium is greatly affected by the correlation of the average size of heterogeneities and the average distance between heterogeneities with the elastic wavelength. In metals, the medium parameter that significantly affects the dispersion of crystals is the average size of a particle $\tilde{d}$. Then, total damping of stainless steel is calculated by the equation

$$\delta = Af + Bf^4\tilde{d}$$

Where A and B is the constant. The average size $\tilde{d}$ of stainless steel is 1.5 μm . Thus, the quadratic frequency term can be ignored, and attenuation in the channel is linearly proportional carrier frequency.

Commercially available PZT's are built for operation at a set of discrete frequency. In this study, considering tradeoffs between bit rate and attenuation, we have chosen PZT operating at 2MHz. Losses incurred due to attenuation in the channel were compensated with power amplifier (transmitter side) and low-noise amplifiers (receiver side).

3.2 Wedge Selection for PZT Refracted Shear Wave

As described in Section 1, physical realization of communication channel with PZT requires generation of single mode wave. This can be accomplished via generating a refracted shear wave with PZT mounted on angled wedge. Commercially available plastic wedges have 30°, 45° and 60° angles of incline. The first critical angle for plastic to stainless steel interface is approximately 29.5°, so that, in principle both 30°, 45° wedges are suitable. However, we have observed experimentally that using contoured 30° wedge results in generating in both longitudinal and shear waves in the pipe. The modes were inferred from calculated velocities of pulses (5790m/s and 3100m/s for longitudinal and shear wave velocities in stainless steel, respectively). Generation of longitudinal modes was possibly an artifact of relatively small radius of curvature of the pipe, such that parts of the wavefront were actually incident at the interface at angles smaller than the critical angle.

When using a 45° wedge without contouring, we have observed that only shear waves were generated in the pipe. At the same time, the amplitude of the refracted shear wave was slightly smaller than that of generated with a contoured wedge. This is consistent with prior findings indicating that larger surface area of contact between wedge and pipe are results in better coupling of elastic wave energy into the pipe at the expense of reducing signal clarity.

For verification that only shear wave is generated, signals were measured on a stainless steel plate and stainless steel pipe of similar thicknesses. The same set of wedges and transducers separated by the same distances were used for plate and pipe measurements. Figure 29 displays the schematics of the experimental arrangement. A pair of 2MHz PZT transducers separated by a distance of 165cm was used in this study. Transmitted pulses were of 200 μs time duration.

Comparison of time-domain signals transmitted on a plate and on a pipe are shown in Figure 30. Signal transmitted on a plate is shown in Figure 30(a), while those for transmission on a pipe are shown in Figures 30(b), (c) and (d). To validate COMSOL computer simulations predicting excitation of torsional waves on a pipe, receiver and transmitter at the ends of the pipe were aligned (Figure 30b), rotated by relative 90° angle (Figure 30c), and rotated by relative 180° angle (Figure 30d). The signal velocity obtained in all cases on plate and pipe was close to 3100m/s value, confirming that only shear wave modes were present in the channel. In addition, it appears that transmission is nearly insensitive to the relative angle between transmitter and receiver

transducers, which confirms prediction of torsional wave excitation on a pipe. Insensitivity to alignment between transmitter and receiver is advantageous for communication system robustness, since exact alignment would be difficult to perform in field conditions at a nuclear power plant.

Figure 29. Communication channels based refracted shear waves in stainless steel with PZT's on 45° angled wedge. The channels are stainless steel plate (top) and pipe (bottom)

Figure 30 - Time domain signals on plate and pipe: (a) transmission on plate, (b) transmission on pipe with transmitter and receiver aligned, (c) transmission on pipe with receiver and transmitter rotated by relative 90°, (d) transmission on a pipe with transmitter and receiver rotated by relative 180°

3.3 Demonstration Data Transmission with PZT-based Channel

Demonstration image, text and sound transmission on a CVCS-type pipe with baffle plates using Red Pitaya boards and GNURadio software was performed during the Digital Environment for Advanced Reactors Workshop at ANL on June 5. In the final demonstration, information transmission with 1.8MHz frequency shear wave at 2KB/s data rate across 5 feet distance on stainless steel pipe. Figure xx show schematic of data transmission architecture and the laboratory photograph. Demonstration included transmission of an image with ANL logo (32KB of memory of computer hard drive) at 2KB/s data rate. Schematics of the communication system setup for transmission of images and laboratory photograph of the setup are shown in Figure 31

Figure 31 - Schematics of communication system setup for image transmission on a pipe (top) and laboratory photograph of the setup (bottom)

An example of text file transmitted using the same communication setup is shown in Figure 32. The left panel displays the contents of transmitted file containing the string “Hello world!” The string is continuously transmitted. The right panel of the same figure contains multiple instances of the received string. Note that no errors can be observed in repeated transmission trials.

Figure 32 - Transmission of text (left) transmitted file, (b) received file

3.4 Preliminary Evaluation of Data Transmission with EMAT-based Channel

Shear-Horizontal (SH) wave is one of the plate waves which is well suited for ultrasonic communication. Advantages of SH wave is that they are not attenuated by water and less attenuated by the coating of the solids and it suffer little energy loss when propagate in the solids. If SH wave is obliquely incident on a free surface, there will be no mode conversion from SH wave to longitudinal wave or SV (shear vertical wave). Which means that the received signal is easy to analysis the multipath effect of the channel, as there is one certain type of SH wave modes exist. Generally, SH wave is generated by angle beam piezoelectric transducer and may suffer from the ambiguity in signal quality due to uncertainty in a coupling condition. However, an EMAT can selectively excite different kinds of SH waves requiring no direct contact with the samples. In addition, EMAT holds promise for ultrasonic signal generation in harsh environment (high temperature, radiation).

Since communication channel has finite length and EMAT transducer generate (receiver) signals in forward direction and backward direction, more reflections can be seen in the receiver side compared with PZT transducer. An experiment is setup to show the interference and reflection. The schematics of EMAT-based communication channel on a stainless-steel plate are shown in Figure 33. In order to see the see better reflection, the transmitter and receiver is set 30cm from the edge.

Figure 33 – Schematics of EMAT-based communication channel on a plate

A 100 μ s bit duration pulse is sent by transmitter, and Figure 34 shows the signal picked up by the receiver. We can see that the amplitude of signals of different frequencies and matches with

frequency response. The reflections from Group 1 are directly from 2 edges of steel plate and reflections from Group 2 are signals which next round reflection. SH waves are selected with different frequencies and they travel in different velocities. Group 1 signal travel 2 times long of steel plate arrives at Group 2. All these reflections will affect communication efficiency and bit error rate. We can see the attenuation is proportional frequency. It means that the lower frequency ultrasonic signal like 230kHz can propagation longer. However, the attenuation can restrain the Group 2 and later reflection signals. In this channel, we set transmitter and receiver next to the edge which can remove part of the group 1 reflection and set a longer bit duration to make the reflections overlap. Considering the power efficiency and less Group 2 reflection, we will choose around 400kHz as the carrier frequency.

Figure 34 – Signal reflections and interferences in EMAT-based channel

EMAT transmitter needs a large power excitation to generate ultrasonic signal. Any imbalance in the communication system cause the BNC cable, power wires and every other interconnection to become part of the transmitter and radiate. the interference can be seen in Figure 34 is at least 5 times larger than the ultrasonic signal. If the interference is not removed, the system can't communicate with ultrasonic signal. As a result, an impedance matching network is implemented in receiver side to improve the quality of received signal and isolated the RF interference.

Transfer efficiency between electric energy and sound energy with an EMAT is much lower than PZT. For the transmitter side, the impedance of EMAT is similar to the power amplifier. In the receiver side, there is large impedance mismatch between EMAT receiver ($140\ \Omega$ resistive) and

low-noise amplifier (100M Ω resistive), which will cause inefficient transfer the acoustic wave into electric energy. An INNERSPEC signal conditioning box (SCB) is implemented as the impedance matching. There is ground connector on the SCB and additional ground path is added for the receiver. Meanwhile, the steel plate channel has to be grounded. The interference is highly restrained and will not affect the ultrasonic communication.

4. Conclusions

This report provides recent results of software and hardware development of acoustics communication system on stainless steel pipes at a nuclear facility. Communication protocol was developed in GNURadio software defined radio (SDR) environment, with interface to Red Pitaya electronic boards. Transmission of images, text and sound was demonstrated using piezo-electric transducers (PZT) at 2KB/s data rate. Efforts are under way to increase data transmission rate of the communication system through algorithmic improvements in GNURadio protocol, and through optimization of hardware resources. Algorithmic improvements will include better design of automated gain controller to potentially reduce the time needed to compensate amplitude reduction of the demodulated signal. Other improvements under current study include design of decimation algorithm which tracks the rising and falling edges of the received pulse. Presently, the challenge in decimation is that the receiver is not synchronized with the transmitter. In case of hardware resource improvements, the tradeoff between transducer frequency and attenuation losses will be further investigated. In principle, losses in the channel can be compensated with low noise amplifier, so this additional constraint will be factored into design consideration. Also, attenuation in the channel could be potentially used to the benefit of communication system by suppressing echoes. Finally, custom geometry EMAT is under development to improve the efficiency of signal coupling into the pipe.

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