Multi-Tone FSK for Ultrasonic Communication

Thomas Hosman[†], Mark Yeary[†], John K. Antonio[*], and Brent Hobbs[*]
[†]School of Electrical and Computer Engineering
[*]School of Computer Science
University of Oklahoma
Norman, Oklahoma 73019

***Abstract*—Traditional radio frequency communication schemes are not capable of transmitting signals through metal enclosures. However, in some applications it is necessary to transmit information to/from devices located inside metal enclosures, e.g., a closed shipping container in transit. A conformal ultrasonic communication system based on multi-tone FSK (MFSK) has been developed and evaluated using steel corner posts from shipping containers as the communication medium. The communication system is configurable, consisting of two or more modules. A module is mounted to a metal surface and utilizes an inexpensive ultrasonic transducer to send and receive modulated signals through the metal channel. A module also makes use of an inexpensive DSP chip for modulating and demodulating MFSK signals. For the shipping container application, experiments were conducted that achieve data rates of approximately 800 bps. Experiments related to two scenarios for the shipping container application were investigated: (1) communicating through one container and (2) communication between stacked containers. For the second case, experiments were conducted with modules on two separate corner posts that are under compressive load.**

I. Introduction

A. Shipping Container Monitoring and Security

Much international shipping is carried in standardized containers, which can be transferred by ship, truck, or rail. It is of great importance to both shippers and security professionals to gather information about the contents, location, and environmental conditions within such containers. Shipping containers are typically either 20 or 40 feet long, 8 feet wide, and $8\frac{1}{2}$ feet tall. They are constructed with four structural steel corner posts terminated at the top and the bottom in cast steel corner blocks. Containers can be stacked in shipyards or on board ships, up to 12 high. When stacked, the weight of the containers and their cargo is carried by the continuous columns of corner posts at each corner of the stack. For structural and security reasons, the doors of a container must not be opened in transit, and holes may not be drilled through a container's walls. Closed shipping containers act as Faraday cages, which preclude the use of traditional radio frequency (RF) communication schemes for transmitting data through these metal structures. Ultrasound, however, presents a promising alternative. Steel is an excellent conduit of ultrasonic energy, and ultrasound transmission requires no compromise of the container's structural or security integrity.

A system that can reliably communicate through and among stacked shipping containers is described in the present paper. The conformal modules of this communication system establish two-way communication and are capable of participating in a relay network within a stack of containers. One type of unit is fixed and mounted inside a container. The other type of unit is portable (hand held) and is designed to be carried around a container ship or shipyard and put in contact with the outside of a container by an operator. Fixed units might go several months without the opportunity to charge/replace batteries, and thus are more power constrained than the portable units. The fixed units allow attachment of various environmental sensors and have facilities for storing data gathered from these sensors. They also have transmit and receive capabilities, as well as the ability to participate in a relay network. Portable units are not be as power constrained as fixed units, as they will be able to be charged on a regular basis. These units have the ability to gather information from a large number of containers, and store this data for later upload to a database. Furthermore, portable units have the ability to establish two-way communications with the fixed units.

B. Other Applications and Prior Research

Previous researchers have also investigated ultrasonic communication. A patent application [1] exists for an application involving sensor communication within an airframe; sensor communication along the surface of a single container is also mentioned. However, this prior research: (i) does not consider communication from within a container to outside a container; (ii) does not consider communication among stacked containers; (iii) does not consider two way communication; and (iv) did not proceed to the system prototyping stage.

Research was done at Oak Ridge National Laboratories in 1993 and further in 1999 regarding ultrasonic communications [2]. These researchers successfully built a demonstration system to communicate using ultrasound in air, and also carried out experiments in various types of pipes that might be found in a typical building water supply. The demonstration system built as part of this project consisted of three work boxes and a laptop running LabView Virtual Instruments at each end of the communication channel.

Other research on underwater communication with autonomous underwater vehicles (AUVs) was conducted at Florida Atlantic University in 1996 [3]. Their research involved using multi-tone frequency shift keying (MFSK) and differential phase shift keying (DPSK) to communicate in shallow water.

The most mature applications involving ultrasonics do not involve ultrasonic communications; they originate from the fields of non-destructive testing and medical imaging. In non-destructive testing, the propagation of high frequency (several MHz) ultrasound is transmitted through various materials for the detection of material discontinuities such as flaws or cracks [4]. In medical applications, ultrasonic reflections are the basis of forming images. Although there is an extensive body of data related to these types of applications, the high-frequency (and high-resolution) transducers designed to operate in these regimes are costly, and therefore may be impractical for the types of application domains where ultrasonic communications would be employed.

The remainder of the paper is organized as follows. Section II provides a characterization of the piezoelectric transducers utilized in this study. Section III describes MFSK and its role in the proposed ultrasonic communication system. The communication system design and current implementation details are provided in Section IV, followed by conclusions and future work plans in the final section.

II. Characterization of Ultrasonic Transducers

Piezoelectric materials expand and contract with applied voltages. Conversely, they produce a voltage in response to deformation. The electrical characteristics of a piezoelectric element resemble those of a capacitor. Piezoelectric elements are fast and precise in the realm of mechanical motion and motion detection. Because of the two way nature of the effect, piezoelectric elements can be used as both ultrasonic transmitters and receivers. A given transducer has one or more resonant frequencies depending on its design and construction. Ultrasound energy is much more efficiently transmitted and received by the transducer at these frequencies. A photograph of the transducers used in this study [5] is in Fig. 1.

By pulsing one transducer — with a receiving transducer clamped face-to-face — characterization of the transmission efficiency of a transducer pair was determined over a wide frequency spectrum. Data gathered in this way was used to produce the empirical frequency response curve of Fig. 2. From the figure, it is clear that the employed transducers exhibit two major regions of resonance. The first occurs around the manufacturer specified resonant frequency of the devices, at about 40 KHz [5]. The second occurs on a band beginning near 280 KHz and extending to approximately 330 KHz. This second band is well displaced from the nominal 40 KHz center frequency of the transducers and produces a better voltage response by a wide margin.

In addition to the effect that transmission frequency has on transmission efficiency, the overall transmission efficiency is also dependent upon the pressure with which the transducer is mounted to the opposing surface. As illustrated by Fig. 3, transmission efficiency is primarily an increasing function of the value of pressure applied in mounting the transducer to the surface. From the figure, observe that there is a reasonable range of pressures within which the transmission efficiency is relatively constant.

Two shipping container corner posts were acquired for demonstrating the communication system developed here. The

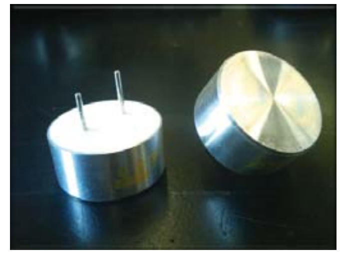

Fig. 1. Picture of employed transducers. The transducer face is slightly larger than the diameter of a quarter.

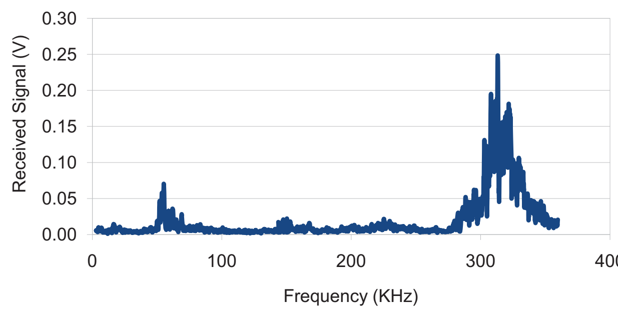

Fig. 2. Transmission efficiency versus frequency for a pair of transducers.

corner post setup is pictured in Fig. 4, which shows two corner posts laying horizontal on a support structure, and held in compression with a hand hoist and nylon strapping. Fig. 5 is an example of measurements taken using the experimental setup, which illustrates how received signal strength degrades as a function of distance between transmitting and receiving transducers.

Importantly for the shipping container application, it was discovered that ultrasonic signals can be transmitted from one corner post and received on a second corner post abutted to the first. Fig. 6 pictures the abutting interface of the corner blocks at the end of two corner posts.

III. Modulation Approach: Multi-tone FSK

MFSK, which is a generalization of FSK, is known to be well-suited for fading channels [6]. Ultrasonic signals transmitted through mediums such as steel or water are subjected to extreme fading effects. In the case of transmitting

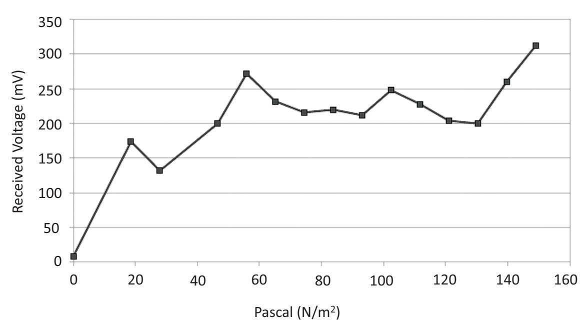

Fig. 3. Received signal versus transducer pressure. Transmitted signal at 296 KHz and 6 volts peak-to-peak.

Fig. 4. Corner post setup showing two corner posts held in compression with hand hoist and (yellow) nylon strapping. Shown in the picture are seven transducers mounted along the length of the corner posts.

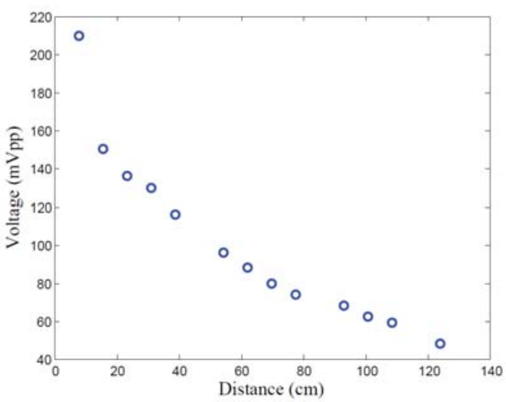

Fig. 5. Measured (received) voltages as a function of distance between transmission and receiving transducers along the length of a corner post.

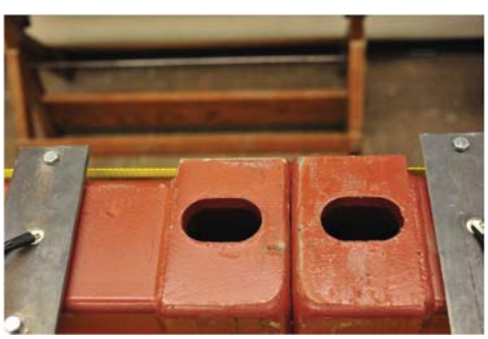

Fig. 6. Corner block interface of two abutting corner posts.

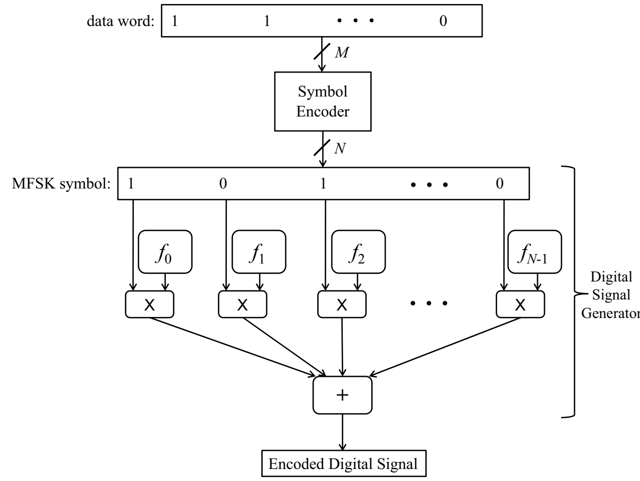

Fig. 7. MFSK encoding scheme.

ultrasound through a steel beam, fading is primarily due to two phenomenon: (1) multipath effects due to multiple reflections off of channel boundaries and (2) the effect of multiple Lamb waves traveling through the channel at different velocities [1].

Let N denote the set of tones available for defining symbols. Traditional FSK represents different symbols with individual sinusoidal tones. Thus, for a pool of N tones, FSK can encode at most N symbols. MFSK uses different combinations of multiple frequencies (summed tones) to encode symbols [6]. The MFSK scheme in which exactly Q tones are used at a time is known as Q-tone FSK, which can encode $\binom{N}{Q}$ symbols. On the transmission side, an M-bit data word is input to a symbol encoder module, which produces an N-bit symbol as shown in Fig. 7. For Q-tone FSK, exactly Q of these N bits are unity, which correspond to selected tones of the symbol.

In principle, an MFSK receiver employs a bank of matched filters with center frequencies tuned to each of the N tones. For the implementation described in the present paper, the received signal is digitized and an FFT performed on the receiver's DSP chip. The receiver thresholds the magnitude of the values from the FFT frequency bins associated with the N tones. If exactly Q tones exceed prescribed thresholds, then the corresponding symbol was detected. Otherwise, the receiver declares a transmission error.

In the system developed, experiments with $N = 16$ tones were conducted. Here, a select group of frequencies within a specific band was considered. The carrier frequencies were in the band of 280 to 320 KHz. These carrier frequencies, f_k are listed in Table I. Note that the spacing of the tones is not uniform across this range. These selected frequencies were determined experimentally by maximizing the frequency response through the channel.

A practical key to successfully realizing the FFT approach at the receiver was the design an implementation of an efficient digital sampling procedure based on the principle of undersampling. This approach enabled the sampling of the received signal to be at a rate of only 165 KHz, which is just

TABLE I
TRANSMISSION TONES

Tone Number	Frequency Value (KHz)
f_0	284.0
f_1	286.5
f_2	287.5
f_3	290.0
f_4	292.0
f_5	294.0
f_6	296.0
f_7	297.5
f_8	299.9
f_9	302.3
f_{10}	303.6
f_{11}	304.3
f_{12}	305.8
f_{13}	308.2
f_{14}	314.0
f_{15}	316.2

slightly over one-half the maximum tone frequency of 316.2 KHz. Had this undersampling procedure not been utilized, then an ADC sampling rate of around 3 MHz would have been required. Sampling at such a high rate is impractical for the envisioned applications that have severe cost and power constraints. By definition, "bandpass sampling" is a special form of undersampling that translates a high frequency bandpass signal to a baseband frequency [7]–[10]. Moreover, bandpass sampling is a "software defined radio" concept that provides a technique of reduced sampling speeds, which directly translates to reduced power consumption (as the authors have been able to demonstrate on other projects, i.e. [11]).

IV. SYSTEM DEVELOPMENT AND EVALUATION

Initial focus was on designing and constructing a receiver to receive and decode MFSK symbols from the steel beam. On the transmission side, an arbitrary signal generator, Tektronix 81150A, and an amplifier circuit were used to produce and transmit the MFSK symbols. The current receiver includes an amplifying and biasing circuit, the LM567 tone decoder, and a DSP chip. The amplifying and biasing circuit was used to amplify the received signal in order to utilize the full dynamic range of the DSP's on-board analog-to-digital converter (ADC). The circuit had a SNR of 27 dB and a gain of 600 v/v. This amplifies the signal from 5 mVpp to 3 Vpp on a 1.5 V bias.

The LM567 chip was chosen because it provides an easy and inexpensive way to detect the synchronization tone. Instead of the DSP constantly sampling and performing filtering to detect synchronization, the DSP is instead put into a low power wait state until the sync tone is detected by the LM567. This is a key in keeping the communication module as energy efficient as possible.

Using a DSP proved to be ideal because it is able to rapidly compute the spectrum of the received signal via the FFT. The Texas Instruments TMS320LF2407A DSP was chosen for this project, based on its low-cost aspects, features, and low-power consumption. The F2407A is a 16-bit fixed point DSP capable of operating at speeds up to 40 million instructions per second.

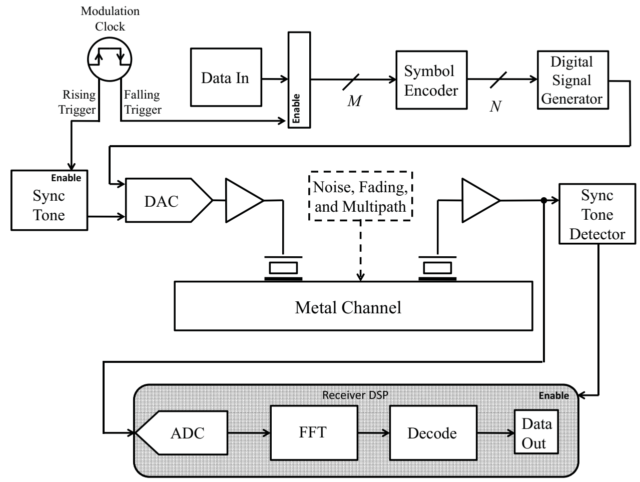

Fig. 8. System block diagram.

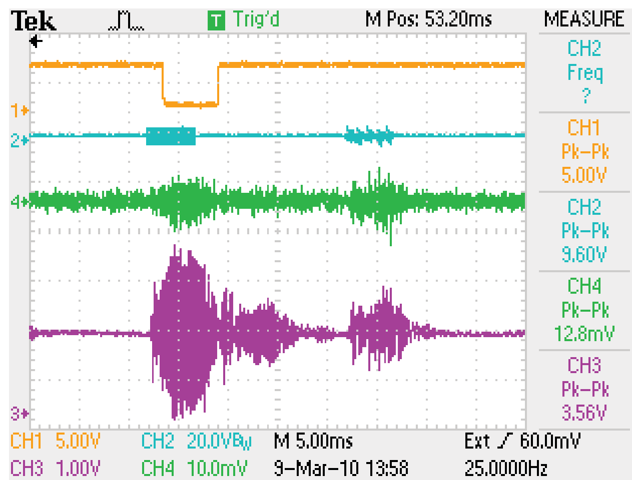

Fig. 9. Signals from top to bottom: LM567 output trigger; transmitted MFSK signal; received signal; and amplified signal. The first signal (on the left) is the sync tone; the second smaller signal is the MFSK waveform.

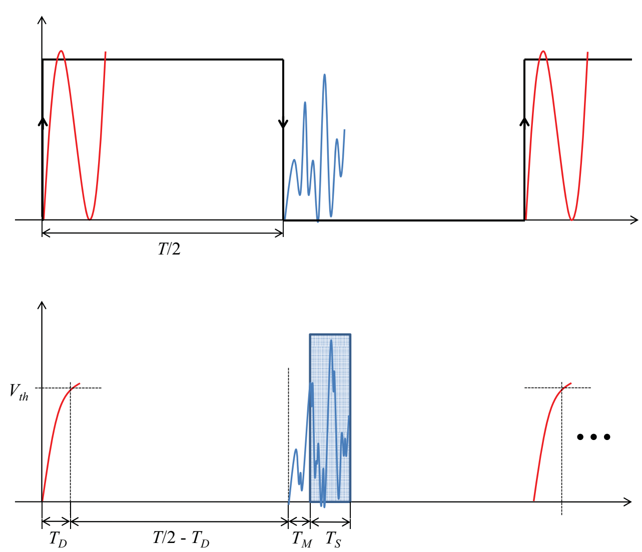

Fig. 10. Timing diagrams. Upper depicts transmission of the sync tone (red) and the signal (blue). Lower depicts detection and the sampling of the data.

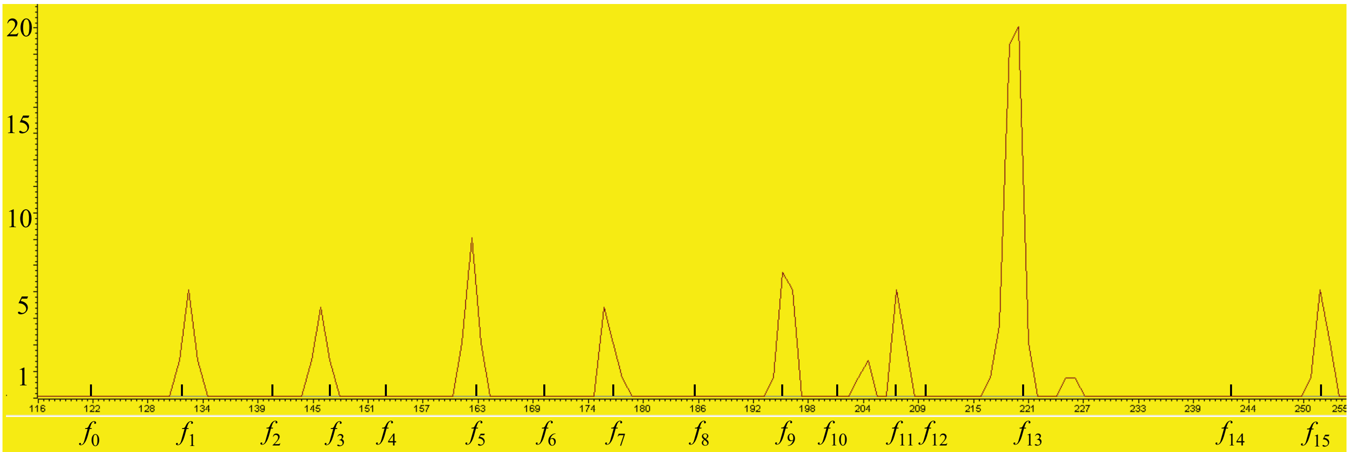

Fig. 11. FFT of received symbol 0xAAAA. Shown is the actual output of the real-time DSP, as taken from a screen capture of the memory contents. Annotations f_0 to f_{15} have been super-imposed on the graph.

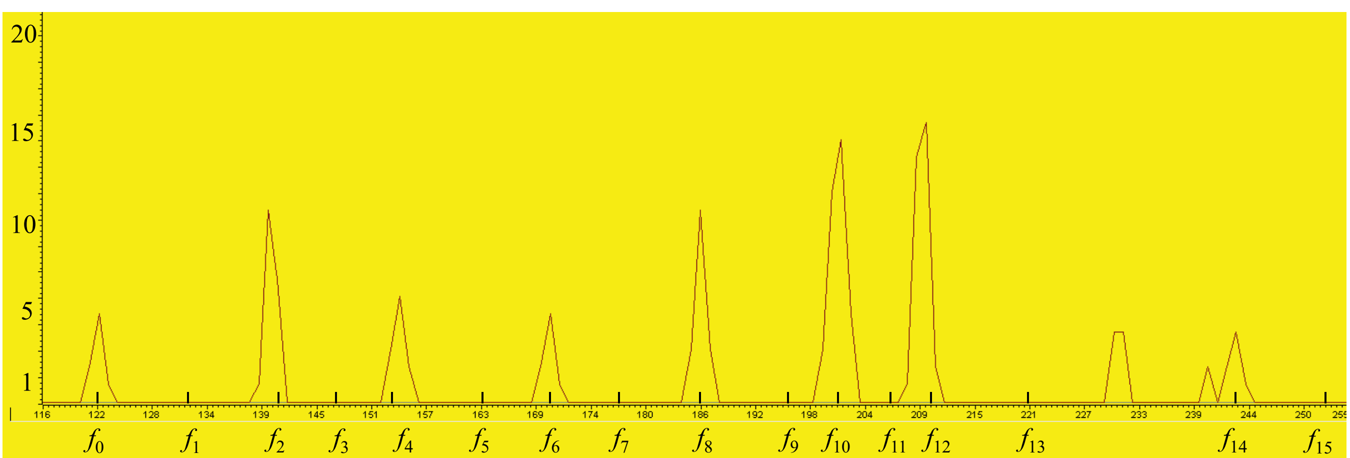

Fig. 12. FFT of received symbol 0x5555. Shown is the actual output of the real-time DSP, as taken from a screen capture of the memory contents. Annotations f_0 to f_{15} have been super-imposed on the graph.

The F2407A has an internal flash memory (32K), which allows for rapid prototyping and eliminated costly off-chip memory. This particular DSP chip also has an on board ADC with a 500 ns conversion time. This feature mitigated the need of an additional off board converter.

Fig. 8 shows the block diagram of our current system. The sync tone is sent at the beginning of a transmission cycle, which corresponds to the modulation clock rising to its high state. When the modulation clock falls to its low value at half the clock period, the MFSK symbol is transmitted. Fig. 9 shows actual scope traces of the transmission of the sync tone followed by the MFSK signal. As the MFSK signal travels down the channel, the signal degrades and fades but is eventually picked up by the receiving transducer. This signal was next amplified to 3Vpp and sent to a biasing circuit as well as the tone decoder.

Fig. 10 provides a detailed timing diagram showing how the sync tone (in red) is used to synchronize the receiver with the transmitted signal (in blue). When the sync tone is transmitted, the LM567 detects the tone after a (predictable) delay time of T_D. The value of T_D includes the time for the signal to propagate down the channel as well as trigger the LM567 chip. Once triggered, the LM567 pulls down a general purpose I/O (GPIO) on the F2407A. The GPIO wakes up the F2407A from its power-efficient mode and activates the necessary peripherals to start receiving processing the received ultrasonic signal. The F2407A waits for a specified time of $T/2 - T_D + T_M$, where T_M represents a safety margin to ensure the DSP takes samples near the center of the received signal pulse. The DSP samples at a rate of 165 KHz for a total sampling time of T_S, and collects 512 samples. The time interval in which sampling occurs is depicted by the blue shaded region in Fig. 10.

Once 512 samples are collected, a radix-2 FFT is performed on the samples. The magnitude of the FFT is then compared to a threshold at specific frequency bins corresponding to the frequency tones of the MFSK modulation. Figs. 11 and 12 show the FFT results of two example MFSK symbols. The hexadecimal representations of these symbols are 0xAAAA and 0x5555. Thus, these are examples of MFSK symbols for $N = 16$ and $Q = 8$ (refer to Section III). Although some extraneous frequencies are present (e.g., between f_{13} and f_{14} on both figures) they do not impact detection of the MFSK symbol, because detection is performed by thresholding *only* the frequency bins associated with the $N = 16$ MFSK tones.

V. Conclusion and Future Plans

This paper describes the design of an MFSK communication system based on ultrasonic signals transmitted through steel shipping container corner posts via conformally mounted low-cost transducers. We have demonstrated the ability to reliably encode and transmit a word of data that is encoded as an MFSK symbol. Experiments conducted show that inexpensive transducers are capable of both transmitting and receiving ultrasonic signals through steel with a relatively high signal-to-noise ratio and low transmit power. Our current system uses inexpensive parts to build a working receiver with a data rate of about 800 bps. Low-power aspects are further enhanced by leveraging software defined radio techniques to implement a bandpass sampling strategy. Currently, our data transmission is limited by how quickly the low-cost F2407A can preform an FFT. With an upgraded DSP chip, the potential to be able to receive data more quickly will be limited only by the inter-symbol interference (ISI) of the channel. Future research will evaluate and develop specific MFSK symbol encodings as well as communication protocols. A complete transmitter/receiver module will also be constructed that is capable of sensing and storing data from an array of sensors. For the shipping container application, experiments will be conducted on fully constructed containers.

Acknowledgment

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