A High-Performance Communication Platform for Ultrasonic Applications

Boyang Wang and Jafar Saniie

Embedded Computing and Signal Processing Laboratory
Department of Electrical and Computer Engineering
Illinois Institute of Technology, Chicago, Illinois, U.S.A.

Sasan Bakhtiari and Alexander Heifetz

Nuclear Engineering Division
Argonne National Laboratory
Lemont, Illinois, U.S.A.

***Abstract* – Ultrasonic signals are used for communications in an environment when propagation of electromagnetic waves is not feasible. For example, ultrasonic signals are often used as the carrier information for underwater communication since such environments cause very high attenuation for electromagnetic waves. This paper presents two experimental system configurations for examining and characterizing the physical layer of ultrasonic communications. A modular system configuration and a Software Defined Ultrasonic Communication (SDUC) platform are separately researched and developed in order to demonstrate the capability and performance of these configurations. The modular system design is based on typical laboratory test equipment to study the behavior of ultrasonic propagation in the solid communication channels. The SDUC platform is developed based on the ZYNQ SoC to make the system more portable, energy efficient and reconfigurable. Experiments are conducted to evaluate the ultrasonic communication in solid channels with different modulation methods.**

Keywords – Ultrasonic Communication System, Software Defined Zynq-SoC, Analog and Digital Communications

I. Introduction

Using ultrasonic signals for communication is a desirable solution when RF electromagnetic (EM) waves are not penetrable in a channel. Most of the modern wireless communication systems are designed to use radio frequency electromagnetic waves as carriers of information. Studies shows that some environments such as underwater or underground have very high attenuation on the electromagnetic waves [1] [2]. The attenuation for the EM waves will be higher when the conductivity of the medium increases or the frequency of the EM signal increases [3]. Ultrasonic signals are elastic waves with frequencies above 20 kHz which is beyond the human hearing range. It is widely used in many industrial and medical applications such as nondestructive evaluation (NDE) and medical imaging, etc. Using ultrasonic signals for communications is challenging because of the complex propagation behavior of the ultrasonic signal in channels. When the ultrasonic signal travels in a solid channel, it attenuates, scatters, disperses and reverberates [4] [5] [6] [7]. This makes the received signal noisy and difficult for analysis and characterization. To study the complex behavior of the ultrasonic signal in a channel and to design robust ultrasonic communication systems, this paper presents two different system implementations methods and discusses various communication experiments conducted with these systems.

Section II presents the hardware system configuration and a software defined ultrasonic communication platform. During the initial phase of this study, an experimental system for ultrasonic communication was assembled with laboratory test equipment such as programmable Arbitrary Function Generator (AFG) and the programmable digital oscilloscope to allow users to fully control, capture, and analyze the generation and reception of information bearing signals. The Software Defined Ultrasonic Communication (SDUC) system is built with ZYNQ-SoC to achieve full-duplex communications with different modes of signal processing and modulations. The SDUC is fully reconfigurable and far more power efficient and portable compared to using laboratory test equipment. Section III of this paper presents experimental results using the developed systems. Different modulation methods and channel arrangements are used in these experiments. Results are presented and supported with analysis. Section IV concludes this paper.

II. Hardware Implementation Methods

To build a communication system that uses ultrasound as s carrier requires multiple components working together as a system. These components include processing system, digital and analog conversion, signal conditioning and ultrasonic transducer. The processing unit is the brain of the whole system, it controls all other components in the system and performs signal processing and analysis. Since the transducer needs electrical excitations, digital and analog conversions are required to generate and sample the electrical signal to and from the ultrasonic transducers. The ultrasonic transducer is used to covert the energy between the electrical signal and mechanical waves. Typical ultrasonic transducers are the piezoelectric (PZT) transducer, electromagnetic acoustic transducer (EMAT) and capacitive micromachined ultrasonic transducer (CMUT), etc. Between the digital and analog conversion and ultrasonic transducers, the signal conditioning circuit can be added to improve the signal-to-noise ratio (SNR) in the communication. A power amplifier on the transmitter side can increase the transmited energy to allow the acoustic wave to travel farther. A low noise amplifier (LNA) can be used on the receiver side to further increase the SNR at the receiver side.

Figure 1 shows the general system configuration for conducting ultrasonic communication experiments. The arrows in this figure are color coded to represent how signals travel through the system. The blue arrow represents the baseband signal that contains transmitted and received information. It is usually at a much lower frequency compared to the carrier signal.

An ultrasonic modulation block is used to up-convert the baseband signal to the desired ultrasonic frequency and demodulation block is used to recover the baseband information from the received signal.

There are generally two types of ultrasonic communication systems depending on where the modulation and demodulation are performed. One type of system is designed to use standard test and measurement equipment (computer, arbitrary function generator (AFG), digital oscilloscope, and ultrasonic transducers) for ultrasonic communication. The computer generates the modulated signal and send it to the buffer of AFG to be converted to an analog signal. The received signal is sampled by the digital oscilloscope and can be read by the computer. This type of system is usually not real-time because it requires high computation by the computer. The second type of system is software defined ultrasonic communication (SDUC) system. In the SDUC systems the in-phase and quadrature phase (IQ) modulation and demodulation are implemented in the hardware module using components such as FPGA, DSP, or ASIC. A computer can easily achieve sending and receiving messages to the hardware module in real-time. Each of these two types of system has its own advantages and disadvantages. In the following two subsections, an example of each type will be presented.

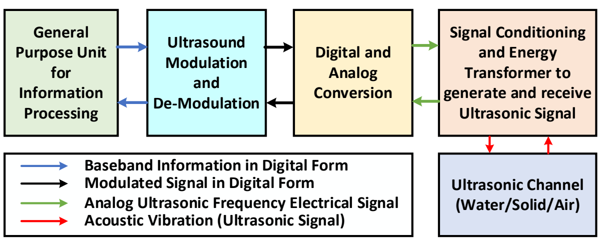

Figure 1. Block diagram for Ultrasonic Communications

A. Generic Ultrasonic Communication Platform

Figure 2 illustrates the system block diagram of a generic ultrasonic communication platform. As shown in this figure, the system consists of a personal computer (PC) as the main controller, a router for system connection, AFG (Agilent 33220A) for analog signal generation and digital oscilloscope (Keysight InfiniiVision MSOX2024X) for capturing and monitoring the received signal in the system. Baseband signal is modulated at the ultrasonic carrier frequency with the PC and transmitted to the buffer of AFG. On the PC, we can run MATLAB, LABVIEW or simply Python code for controlling and exchanging data with the AFG and the oscilloscope. As shown in Figure 2, A T-Shape connector is used to split the output of the AFG for monitoring the transmitted signal and comparing it with the received signal detected by the ultrasonic receiver transducer. The transmitting transducer converts the electrical energy to an elastic wave and sends it into the channel. Then, the receiving transducer senses the acoustic waves propagated through the channel. This received signal is sampled by the oscilloscope. The sampled data is buffered in the oscilloscope and can be read by the PC. The PC reads the sampled data and demodulate the received data to recover the baseband information.

In this type of system, the computationally demanding modulation and demodulation are processed with the PC offline. Also, the buffer structure on the AFG and oscilloscope do not allow real-time signal transmission and reception with this type of system configuration. The only advantage of using this type of system is that the transmitted signal is fully designed in advance. This allows us to generate and process signals conveniently. In practice, the standard laboratory equipment is more accurate and robust. Consequently, with this type of system, we can explore the feasibility and characteristic of using ultrasonic signals as a carrier for communication more efficiently.

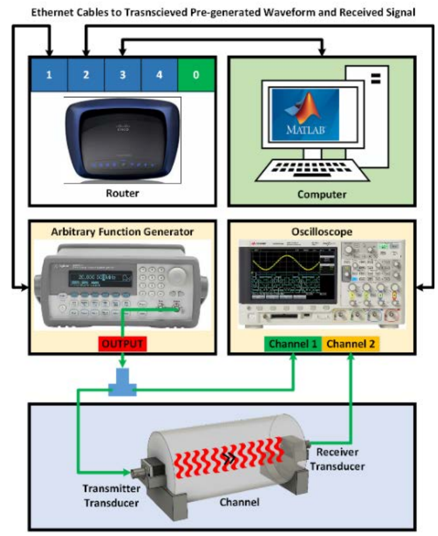

Figure 2. System Block Diagram of a Generic Ultrasonic Communication Platform

B. Software Defined Ultrasonic Communication Platform

Figure 3 shows the system block diagram of the SDUC platform. The SDUC system is developed based on a ZYNQ System-on-Chip (SoC) by incorporating the concept of a software defined radio. ZYNQ SoC consists of dual ARM processors and FPGA on the same chip, which makes it an ideal platform to build a digital communication system. In our previous work, a high-performance reconfigurable ultrasonic signal acquisition and processing platform has been built with ZYNQ SoC for ultrasonic non-destructive testing [8] [9]. The ARM processor will be the main controller of the system, it communicates with the host PC to exchange the transmitted and received baseband information. Digital Up Converter (DUC) and Digital Down Converter (DDC) are implemented on the FPGA fabric, which will handle the high frequency signals from and to the high frequency on board analog to digital converters (ADC) and digital to analog converters (DAC). Power amplifiers on the transmitting side and low noise amplifiers on the receiving side are used to condition the signal and to improve the SNR. A host PC is required in this system to generate and receive the baseband information. Low noise cables are used to transfer baseband information between the ZYNQ SoC ARM processor and the PC. On the host PC, an opensource software GNURadio is used to generate the baseband and process the received baseband signal. The combine realization of the software and the processing of the IQ modulator and demodulator on the FPGA allows testing and evaluating many modulation techniques in real-time. In the following section, three software-defined digital modulation examples are introduced and supported with experimental results. In the SDUC platform most of the heavy computations are done on the FPGA of the ZYNQ SoC. This arrangement offloads the computational demands for the on-chip ARM processor and the CPU of the host PC. Consequently, the SDUC platform makes it possible to realize a real-time full duplex communication system using ultrasonic signal as the carrier of information.

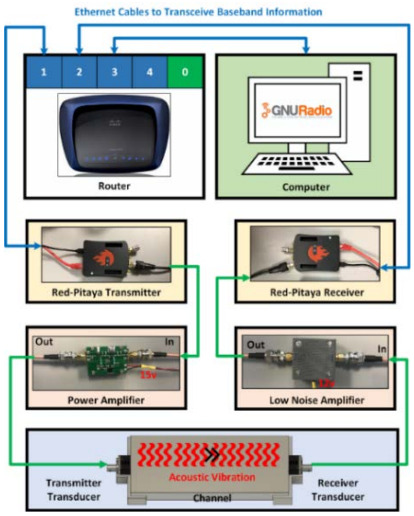

Figure 3. Software Defined Ultrasonic Communication Platform Block Diagram

III. Experiments and Results

To demonstrate the capability of the systems described in Section II, a simple test case of ultrasonic communication is created. As shown in Figure 4b, a pair of piezoelectric transducers with a carrier center frequency of 2.5 MHz (Figure 4a) is used in this test experiment. 3D printed fixtures are designed to attach transducers to both ends of an acrylic column (3 inch in diameter and 3 inch in length) which is used as the channel for experimentation. Figure 4c shows the frequency spectrum of the test configuration in 4b. The frequency spectrum of the combined transmitter-channel-receiver is obtained by sweeping the transmit frequency from 500 KHz to 4 MHz and record the received signal amplitude. This frequency response is acquired by using the experimental platform presented in Section II B.

Figure 5 shows the digital modulation and demodulation diagram of the SDUC system with GNURadio running on the host computer. In this diagram, the blue section is processed on the host PC, and the yellow section is running mainly on the FPGA of the ZYNQ SoC. The host PC will generate the baseband signal according to the data to be transmitted and the modulation method. Then, the generated baseband signal is sent to the ZYNQ-SoC to be modulated with the ultrasonic carrier frequency and converted to ultrasonic waves by the transmitting transducer. After the signal goes through the channel, it will be picked up by the receiver transducer. The baseband information will then be down converted from its carrier frequency using the IQ demodulation circuit on the receiver FPGA. This baseband information will be sent to the host computer to recover the transmitted information.

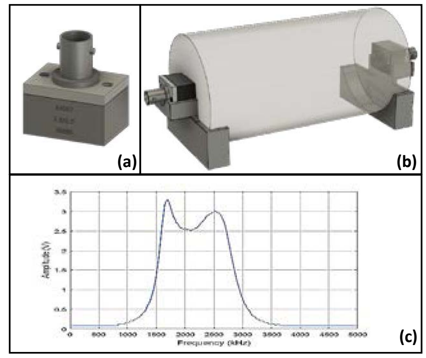

Figure 4. (a) 2.5 MHz Piezoelectric Transducer, (b) Test Configuration for Conducting Ultrasonic Communication, and (c) Frequency Response of the Combined Transducers and the Acrylic Channel.

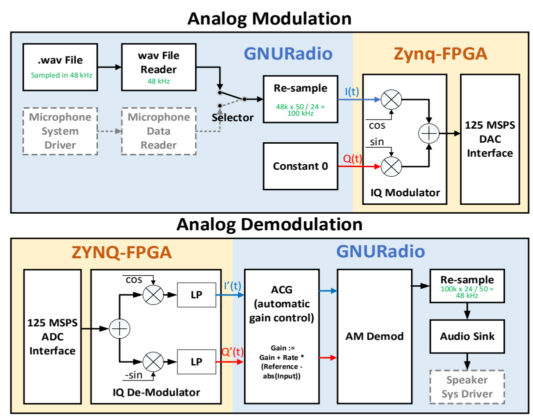

Figure 5. Modulation and Demodulation Blocks Within the SDUC Platform

Figure 6 shows the result of the on-off-keying (OOK) modulation. In this experiment, the signal is modulated with the SDUC system and the transmitted and received signal is probed by the oscilloscope at the sampling rate of 25 mega samples per second (MSPS). On the receiver side, the magnitude of the in-phase and quadrature components are computed to recover the transmitted information. The bit rate of this test is 612.5 kilo bit per second (KBPS) with zero bit error rate (BER).

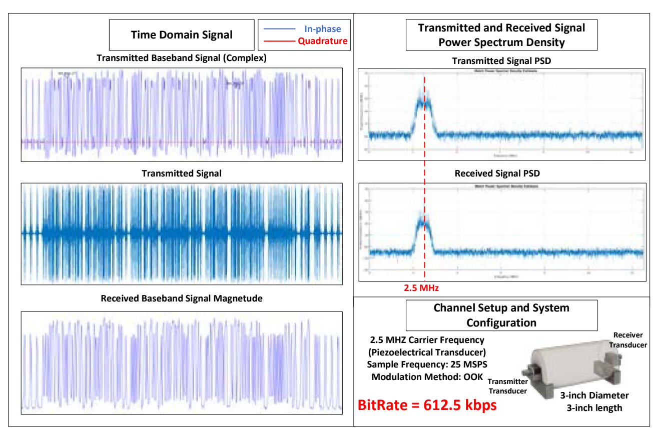

Figure 6. OOK Result with Bitrate of 612.5 KBPS

Figure 7 shows the result of the binary phase shift keying (BPSK) modulation method. The transmitted and received signal is probed by the oscilloscope at the sampling rate of 10 MSPS. The bit rate of this test is 612.5 KBPS without any error.

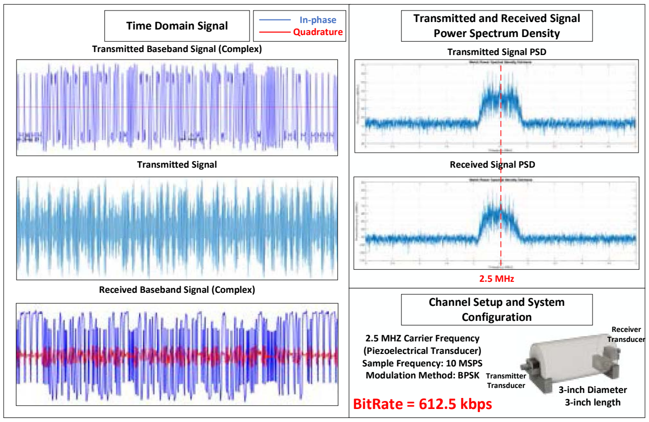

Figure 7. BPSK Result with Bitrate of 612.5 KBPS

Figure 8 shows the result of the quadrature phase shift keying (QPSK) modulation method. Each symbol of the transmission contains two-bit information. They are modulated separately to the in-phase and the quadrature phase components. The bit rate of this test is also 612.5 KBPS with zero error rate.

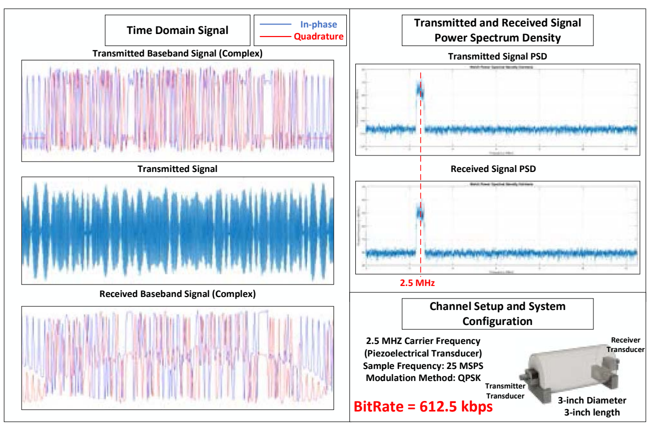

Figure 8. QPSK Result with Bitrate of 612.5 KBPS

These three results represent ideal test cases of OOK, BPSK, QPSK and they are presented to confirm the peak data rate performance of ultrasonic communication system. Additional experiments [10] [11] with different types of modulation, different channel geometries and different solid materials have been reported with limited data rate performance. Also, the data rates of ultrasonic communication system using EMAT transducers and channels made of metal plates and pipes are far from the peak performance [12].

IV. Conclusion

In conclusion, ultrasonic wave is a viable carrier signal in the communication system when electromagnetic wave is not applicable. Two types of system architectures are introduced to fit different objectives for conducting ultrasonic communication experiments. The generic system for ultrasonic communication is built with a general-purpose computer and laboratory test equipment. This type of system is designed for basic research concerned with the characteristic of the ultrasonic signal in the channel for communication applications. The software defined ultrasonic communication system is built with ZYNQ SoC. With the help of the FPGA on-chip, the SDUC can achieve full-duplex communication in real-time. This system setup is also more portable and energy efficient. Different modulation methods such as QPSK, BPSK and OOK are tested with the SDUC. The transmission bit rate is 612.5 KBPS and zero BER with the 2.5 MHz piezoelectric transducer through an acrylic block channel.

V. References

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