Ultrasonic Communication Systems for Data Transmission

Boyang Wang and Jafar Saniie

ECASP Research Laboratory (http://ecasp.ece.iit.edu)
Department of Electrical and Computer Engineering
Illinois Institute of Technology, Chicago IL, U.S.A.

Sasan Bakhtiari and Alexander Heifetz

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

***Abstract*—Ultrasonic signals are widely used in the field of medical imaging and industrial nondestructive testing. Ultrasonic wave can propagate through solid, liquid or gas media and consequently can be used as the carrier of the information for communications. In this paper, we examine the feasibility of using the ultrasonic signal for communication in solid media. Characteristic of ultrasonic waves in the solid channel are studied and an FPGA based platform is designed for software-defined digital and packet communications. Experimental results are presented and analyzed to demonstrate the feasibility of using ultrasonic guided waves for digital communication in solid channels such as metal plates.**

***Keywords*—Ultrasonic Waves; Software Defined Digital Communication; I/Q Modulation; Packet Communication**

I. INTRODUCTION

The transmission of an ultrasonic signal in elastic solid is highly complex due to reflection, refraction, dispersion, scattering, attenuation and mode conversion [1] [2] [3]. Ultrasound is widely used in industrial and medical applications including nondestructive testing and medical imaging. In this paper, we present the feasibility of using ultrasonic waves as the carrier of information in elastic solid media such as metal plates and pipes. For this study, high-frequency analog devices and reconfigurable digital systems such as FPGA and ARM processors are integrated in order to realize a number of classical digital communication methods by means of ultrasound as the carrier of information.

Animals such as bats, frogs and dolphins have developed complex ultrasonic transmitters (generators) and receivers (sensors) for communications including target identification, localization, and sizing. As a viable alternative to electromagnetic waves, ultrasonic waves have numerous industrial applications for communications. Figure 1 shows a practical scenario for ultrasonic communication in the nuclear power plant. For safety reasons, the nuclear reactors are sealed with reinforced concrete and shield with only pipes goes in and out for water and steam exchange. For safe operation, it is crucial to monitor and control the operation of the nuclear reactor system in real-time. However, the containment and the shield block the electromagnetic wave for communication. A desirable solution is using ultrasonic transmitters and receivers on the water pipe for communications to monitor and control the operation of the sealed nuclear reactor. Ultrasonic communication can also be used in another environment such as underwater or underground [4] [5]. Another interesting application for ultrasonic communication is an ultrasonic sensor network designed to localize the relative position of every sensor node within the network. By knowing the transmitting and receiving delay between beacons (sensor nodes), one can compute the relative location of each node by using triangulation location algorithm. This method has already been applied to underwater device tracking and on land for robot tracking.

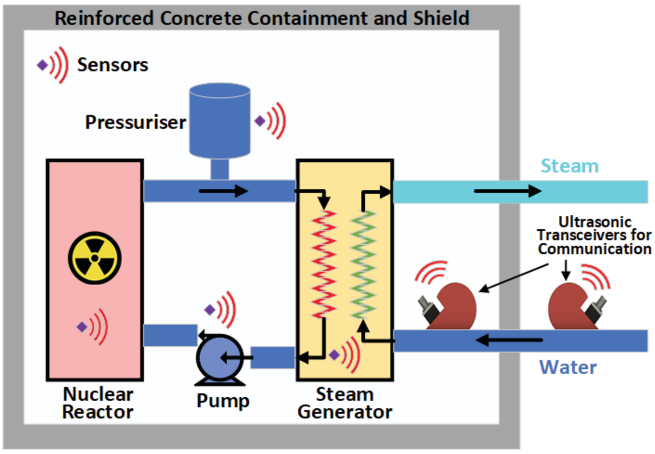


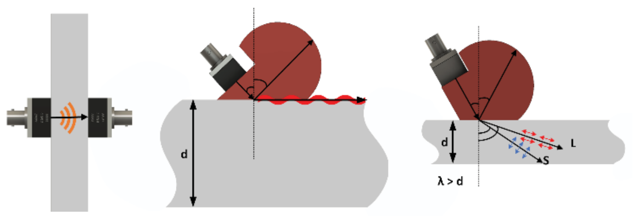
Figure 1. Ultrasonic communication system in a nuclear power plant

Section II presents the fundamentals of ultrasonic signal propagation in elastic solid channels. Unlike ultrasonic propagation in gas or liquid when only longitudinal wave is supported, both transversal and longitudinal waves exist in the solid material. In practice, ultrasonic signals traveling through elastic solid are suffered from absorption, scattering, refraction, reflection, and mode conversion. Section III presents the channel setup and test equipment used for communication experiments. Section IV shows the experimental results and overall system performance.

978-1-7281-0927-5/19/$31.00 ©2019 IEEE

II. Elastic Waves in Solid

Analyzing ultrasonic waves in the solid channel is much more difficult than it is in liquid and gas media since both longitudinal and transversal wave exists in the solid material while gas and liquid channel only support longitudinal waves. Depending on the test setup, multiple types of ultrasonic waves can be generated inside elastic solid channels. The bulk wave can be generated in infinite isotropic media and propagates without being interrupted by boundaries [6]. In practice, instead of infinite isotropic media, we consider the wave to be a bulk wave when the boundaries have no influence on the wave propagation as shown in Figure 2(a). The bulk waves can be used as a simple test case for studying ultrasonic communication in solids.



(a) (b) (c)

Figure 2. Ultrasonic wave modes in elastic solid for communication, (a) Bulk wave, (b) Surface wave, (c) Lamb wave

Other than a bulk wave, Rayleigh surface wave and shear waves can be generated when ultrasonic enters the solid materials with an oblique incident angle [6]. Rayleigh surface wave can propagate through the surface of a thick plate. It is generated when the incident angle is greater than the second critical angle as it is shown in Figure 2(b). Rayleigh surface wave is nondispersive. A lamb wave (also called plate wave) can be generated and propagate through a solid plate when the wavelength is larger than the thickness of the plate as it is shown in Figure 2(c). Lamb wave is a superposition of longitudinal and transversal waves when propagating through the channel. Both Rayleigh surface wave and plate waves have been studied thoroughly and proven to practical for nondestructive testing and communications. These wave modes can propagate through the materials over longer distance compare to bulk wave. So, it offers longer range communication when the ultrasonic signal is used as the carrier of information. Since different ultrasonic wave modes have their own characteristics, we can selectively generate necessary wave mode for communication purpose according to the specific situations.

Ultrasonic signal attenuates when traveling through the channel. Exact ultrasonic attenuation parameter is difficult to compute accurately. However, it is very important to address factors that will significantly affect the attenuation during the propagation of the signal in the channel. When traveling through the solid channel, ultrasonic signal suffers from energy loss for many reasons. One is the absorption losses. Absorption loss is caused by internal friction of the material and will convert ultrasonic energy into heat. It is typically proportional to the signal frequency. Another important factor of ultrasonic attenuation is caused by the microstructure scattering. Scattering losses are caused by the crystalline grains on the microstructural level of the metal. The grain scattering losses will also introduce a high-frequency bandlimited noise in the received signal. These two sources of attenuations are inevitable since they are caused by the materials themselves. Also, the imperfection of the material affects the propagation of the ultrasonic signal. However, it is almost impossible to model and analyze this type of attenuation. In the experiments, we polished the surface of the test materials in order to minimize this type of attenuation.

The ultrasonic signal propagates through a longer distance with lower frequency or greater wavelength. However, according to the communication theory, more information can be transmitted at a higher frequency with broader bandwidth. Designing an ultrasonic communication channel is a balance of propagation range, information transmission bit rate, and bit error rate.

III. Hardware Platform

Figure 3 shows the system diagram of the Software Defined Ultrasonic Communication (SDUC) platform that we designed for conducting experiments [7] [8]. The system has two ZYNQ System on Chip (SoC) based Digital Down Converter (DDC) and Digital Up Converter (DUC) that can be controlled by a computer using GNURadio. ZYNQ SoC is a Xilinx designed chip that contains two ARM processors and FPGA fabric on the same chip. This architecture allows users to place the algorithms that require heavy computations on the FPGA and control it through ARM processor [9] [10]. The Digital Up Converter (DUC) in the system is used to mount low-frequency baseband signal on the high-frequency carrier signal while Digital Down Converter (DDC) is to recover the baseband signal from the received signal. A Linux based operating system is running on the ARM processor taking care of data moving, communication with computer and control of the whole system. To improve the Signal-to-Noise Ratio (SNR) of the ultrasonic communication, a pre-amplifier for transmission and a Low Noise Amplifier (LNA) at receiver are used to amplify the transmitted signal and the received signal. An oscilloscope is used to monitor the transmitted and the received signal in real-time. The signal recorded by the oscilloscope will be used together with the baseband signal to analyze the performance of the communication system.

Ultrasonic communication systems can be modeled as a linear time-invariant (LTI) system that contains three functional blocks as is shown in Figure 4 [11]. The ultrasound generation and reception components represent the transfer function of the ultrasonic transducers when converting electronic signal to ultrasound energy and vice versa. The sensors used in the experiments are piezoelectric transducers. The sound propagation scattering component describes the propagation of the ultrasonic wave inside the material, and for this case is the Lamb wave or surface Rayleigh in the aluminum bar. Mode conversion, refraction, reflection, scattering, attenuation is the major contributor of this function. Also, the dimension of the channel and the digital system that generate and sample the signal will also affect the transfer function unavoidably.

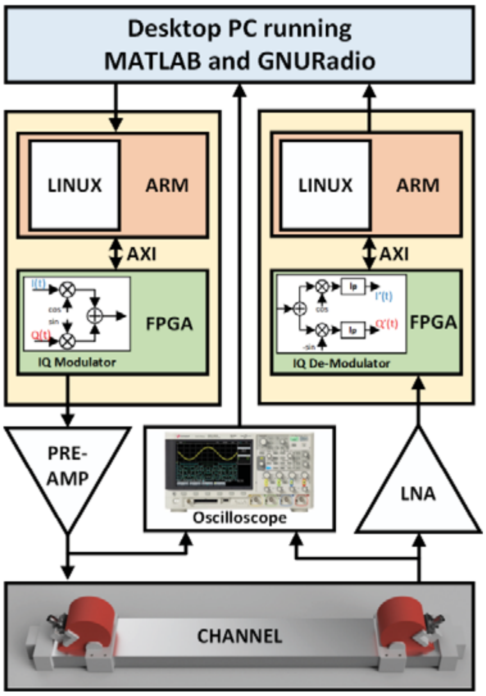


Figure 3. Software Defined Ultrasonic Communication (SDUC) system diagram

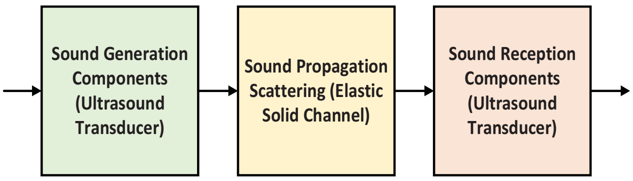


Figure 4. Ultrasonic communication system modeled as LTI system

IV. Ultrasonic Communication Experiments, Results and Discussion

Figure 5 shows the channel setup that we used to conduct ultrasonic communications. Two plexiglass angle wedges are used to guide the ultrasonic energy into the solid bar channel made of aluminum. The angled wedge can be switched to change the ultrasonic incidence angle. Gliders are used to adjust the distance between the transmitter and the receiver transducers. The surfaces between the wedge and the transducer, the wedge, and the aluminum bar are coupled with a very thin layer of ultrasonic coupling gel to enhance the sound transmission from one material to another.

Figure 5. Ultrasonic communication channel setup with plexiglass angle wedge

Figure 6 shows an example result using the SDUC platform when on-off keying (OOK) is applied to modulate the transmitted signal at the data rate of 12.5 kbps. The distance between the two transducers is adjusted to 50 cm. The incidence angle of the ultrasonic signal is set to 60 degrees so that the Rayleigh surface wave is generated during the transmission. The receiver recovers the transmitted message with a zero-bit error rate.

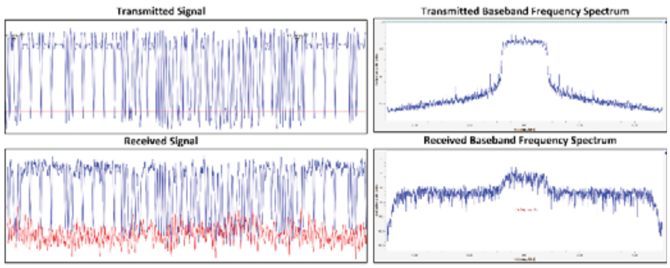


Figure 6. Ultrasonic communication test result Using OOK with a bit rate of 12.5 kbps

In the data transmission, the data is formatted into packets before sending out. Each packet contains a known header and the payload. The content of the information is contained in the payload. As shown in Figure 7, when the signal is received, it will be passed to a correlator to identify the pre-defined header in the received signal. After identifying the header, it will be removed to extract the payload information in the received signal. Also, when there are multiple ultrasonic transceivers sensor nodes in the channel, the header structure will also help to recognize the data transmitted from a different sensor node.

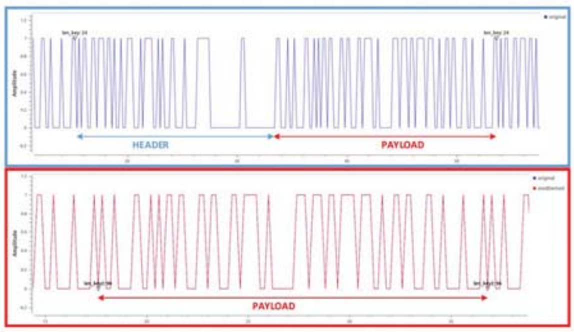


Figure 7. Header and payload separation in the received signal

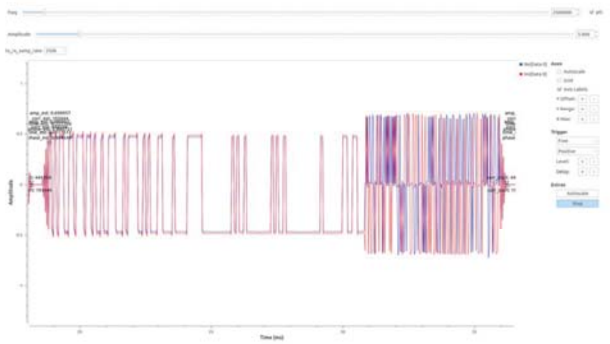


Figure 8. Received data with different modulation method in header and payload

To improve the data rate of the transmission, the header and payload can be modulated in two different methods. As shown in Figure 8, the header is modulated with BPSK because it has a smaller bit error rate (BER). The payload is encoded with QPSK since it has higher bandwidth. This arrangement increases the transmission rate and ensures the bit error rate at the same time. For further reducing the bit error rate, we use forward error correction (FEC) in the transmission. In the experiment, we encoded a message and send it through the ultrasonic channel. Two transducers are 50 centimeters from each other. The ultrasonic incidence angle is set to 60 degrees so that the signal generated in the aluminum bar is Rayleigh surface wave. Figure 9 shows the message decoded from the received signal and printed on the terminal.

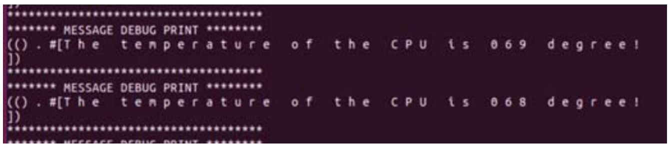


Figure 9. Message decoded from the received signal

IV. Conclusion

This paper presented the feasibility of using the ultrasonic signal for communications. The generation of multiple types of ultrasonic wave modes is introduced. The attenuation factor of the ultrasonic signal when propagating in elastic solid is discussed to address the issue of signal deterioration. The architecture of a Software Defined Ultrasonic Communication platform is introduced. The system consists of an FPGA based DUC and DDC for generating and receiving the modulated signal, two amplifiers to improve the SNR of the communication, oscilloscope for monitoring the high-frequency signal in the channel and a desktop computer for analyzing the signal and the overall control of the SUDC system. Experimental results clearly exhibit that the elastic solid can offer a robust channel for conducting communication using ultrasound.

References

[1] J. Saniie and D. T. Nagle, "Pattern recognition in the ultrasonic imaging of reverberant multilayered structures," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* vol. 36, pp. 80-92, 1989.

[2] J. Saniie, T. Wang and N. Bilgutay, "Statistical Evaluation of Backscattered Ultrasonic Grain Signals," *The Journal of the Acoustical Society of America,* vol. 84, p. 400, 1998.

[3] J. Saniie, "Ultrasonic signal processing : system identification and parameter estimation of reverberant and inhomogeneous targets," Ph.D Thesis, Purdue University, 1981.

[4] I. F. Akyildiz, Z. Sun and M. C. Vuran, "Signal propagation techniques for wireless underground communication networks," *Physical Communication,* vol. 2, pp. 167-183, 2009.

[5] G. Hattab, M. El-Tarhuni, M. Al-Ali, T. Joudeh and N. Qaddoumi, "An Underwater Wireless Sensor Network with Realistic Radio Frequency Path Loss Model," *International Journal of Distributed Sensor Networks,* 2013.

[6] N. C. J. David, Fundamentals and Applications of Ultrasonic Waves, CRC Press LLC, 2002.

[7] B. Wang and J. Saniie, "Software Defined Ultrasonic System for Communication through Solid Structures," in *IEEE International Conference on Electro Information Technology (EIT)*, 2018.

[8] B. Wang, J. Saniie, S. Bakhtiari and A. Heifetz, "Architecture of an ultrasonic experimental platform for information transmission through solids," in *2017 IEEE International Ultrasonics Symposium (IUS)*, 2017.

[9] B. Wang and J. Saniie, "Ultrasonic Signal Acquisition and Processing platform based on Zynq SoC," in *IEEE International Conference on Electro Information Technology (EIT)*, 2016 .

[10] B. Wang, P. Govindan and J. Saniie, "Performance analysis of system-on-chip architectures for ultrasonic data compression," in *IEEE International Ultrasonics Symposium (IUS)*, 2016.

[11] L. W. Schemrr. Jr, Fundamentals of Ultrasonic Non-Destructive Evaluation, A Modeling Approach, Second Edition, Switzerland: Springer International Publishing , 2016.