Channel Estimation for Ultrasonic Communication using OFDM on Steel Pipe Channel

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***Abstract*— Ultrasonic communication through solid channels suffers from wave dispersion, attenuation, and multipath effect. It can be observed that the channel is frequency selective, and some frequencies will severely be attenuated as the distance between transmitter and receiver increases. Besides, when the pipes are used as the communication channels, the limited bandwidth and the adversarial reverberations are even worse. Orthogonal frequency division multiplexing (OFDM) has been widely used in modern wireless communication systems due to its robustness against frequency selectivity. The method can separate narrowband channels at different frequencies, which can reduce interference and crosstalk. In this study, we investigate the feasibility of using OFDM to realize intersymbol interference (ISI) mitigation through the steel pipe channel by using a reconfigurable FPGA-based SoC platform. Quadrature Phase Shift Keying (QPSK) modulation scheme and varied bitrates are selected to determine the feasible and reliable transmission rate. The communication bitrate exceeded 716 kbps without any error despite dispersion, intersymbol interference, and the multipath effect within the steel pipe channel.**

Keywords—Ultrasonic Communication, Steel pipe channel, OFDM Modulation

I. INTRODUCTION

Ultrasonic waves are used as an information carrier in ultrasonic communication across a solid channel where the transmission of radio-frequency (RF) or wired signal is inadequate [1][2]. Compared with liquid or biological tissue channels, the propagation of an ultrasonic wave through a solid channel is more complex [3][4]. Solid channels vary with shapes (e.g., bar, pipe, plate, or rectangular tube), and ultrasonic waves propagating through such channels are classified as longitudinal waves, surface waves, lamb waves, flexural waves, et al [5]. The channel frequency response is highly frequency-selective due to the multipath effect. Certain frequency bands are severely attenuated as the distance between the transmitter and receiver changes. When a pipe is used as the communication channel, the bandwidth limitation, multipath effect, and undesired conditions become more pronounced [6][7]. Previously, we investigated signal processing methods such as pulse shaping and the time-reversal to reduce reverberations (multipath effect), and consequently increase the bitrate [8][9][10].

Orthogonal frequency division multiplexing (OFDM) has been widely used in modern wireless communication systems due to the efficiency of bandwidth usage and robustness against frequency selectivity [11][12]. The OFDM method can separate narrowband channels at different frequencies, which can reduce channel distortion and intersymbol interference (ISI). Furthermore, the pilot signal, guard interval, and guard band in OFDM can be used for channel equalization and synchronization [13]. In this paper, we focus on the study of ultrasonic communication through steel pipes. An FPGA-based SoC platform is developed to test and analyze the OFDM performance of ultrasonic communication systems. An 88cm-long steel pipe is used as the communication channel. Two 2.5 MHz Piezoelectric transducers (PZT) with 60-degree oblique angle wedges are used as the ultrasonic transmitter and receiver. Quadrature Phase Shift Keying (QPSK) modulation scheme and varied bitrates are selected to examine the feasible and reliable transmission rate.

This paper is organized as follows. Section II presents the implementation of OFDM ultrasonic communication through pipe channels. Section III presents the steel pipe channel frequency band estimation. Section IV presents experimental results using OFDM for ultrasonic communication. Section V summarizes the key design issues for OFDM ultrasonic communications.

II. OFDM IN ULTRASONIC COMMUNICATION

Fig. 1 displays the encoding and decoding design flow of the OFDM method applied in ultrasonic communication. The OFDM transmitter utilizes different modulation in order to increase the data-carrying capacity of an OFDM symbol. For example, 64 quadrature amplitude modulation (QAM) maps 6 bits for one complex symbol. The symbols are transmitted at different frequency subcarriers using the inverse fast Fourier transform (IFFT) method. In each OFDM symbol block, the cyclic prefix is added to reduce the ISI. Then the modulated signal is fed to the PZT transducer by analog to digital converter (DAC). The PZT receiver is placed on the other end of the pipe channel and converts the signal into the digital domain by analog to digital converter (ADC). Time synchronization is achieved by removing the cyclic prefix. The OFDM symbol block is demodulated by using the FFT method. The complex symbol (in-phase and quadrature) is demapped according to the constellation.

III. STEEL PIPE CHANNEL ESTIMATION

Deployment of ultrasonic communication on a pipe channel could be more challenging due to the ultrasonic wave dispersion, attenuation, and multipath effect. In this section, we briefly discuss the potential challenges and solutions of using a metal pipe as the communication channel.

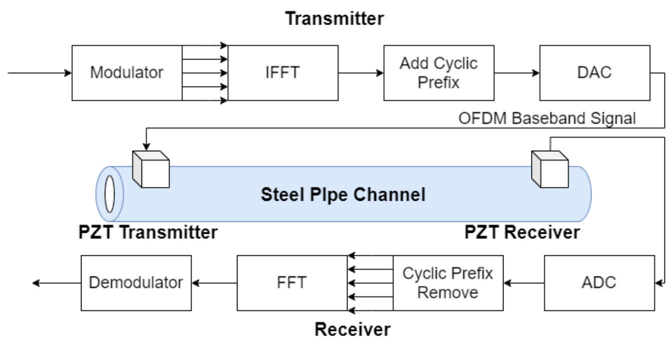

Fig. 1. OFDM design flow for ultrasonic communication

We implement a preliminary estimation of ultrasonic waves propagating through the Aluminum pipe channel using the ABAQUS/Explicit model. The Aluminum hollow pipe has a geometry size of 100 cm long, 14 cm outer diameters, and 1.5 cm thickness. The excitation wavelet frequency is 2.5 MHz and the simulation results are shown in Fig. 2. The pseudo-color map of displacement distribution depicts the amplitude of ultrasonic waves. The displacement of the wavefront in the hollow cylindrical structure travel in the circumferential and axial directions and its velocity is 5400 m/s. Simulation results reveal that multiple modes are generated which includes the longitudinal and torsional wave modes.

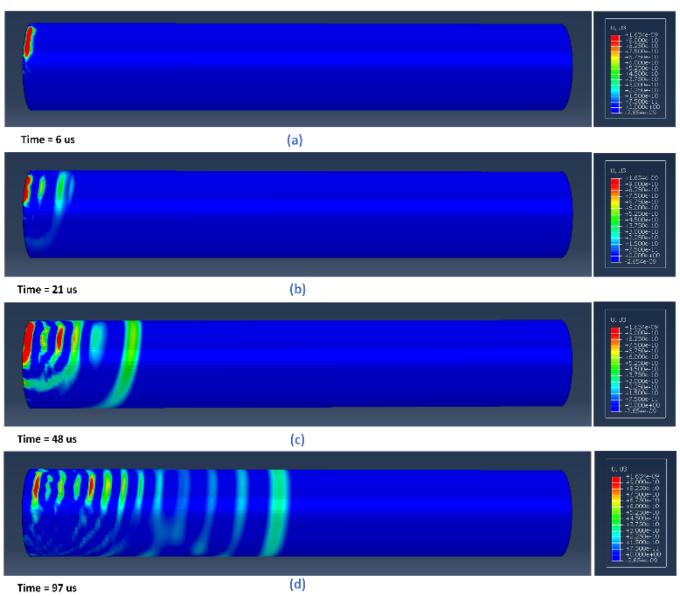

Fig. 2. Computer simulation of a 2.5 MHz ultrasonic wave propagating in the steel pipe channel. Ultrasonic wavefronts are visualized with a pseudo-color map of the displacement distribution at 6, 21, 48, and 97 μs.

The testbed for the pipe channel is shown in Fig. 3. The steel pipe communication channel has an 88cm length, 8.96cm outer

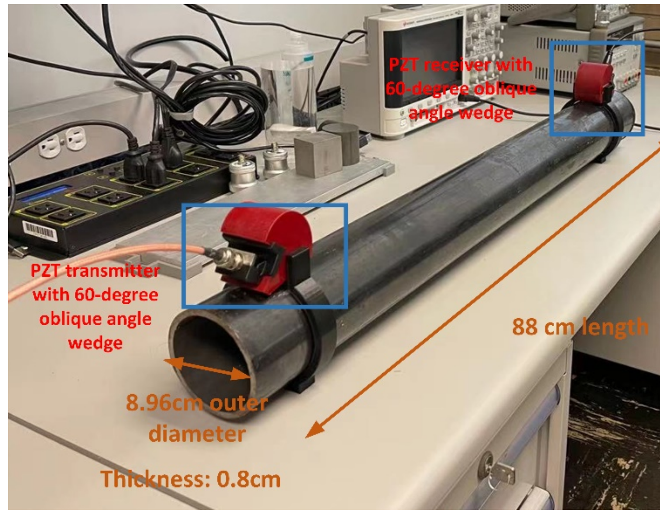

Fig. 3. Steel pipe channel for ultrasonic communication using OFDM

diameter, and 0.8cm thickness. Two 2.5 MHz PZT ultrasonic transducers with 60-degree oblique angle wedges are used as transmitter and receiver. The bitstream is transmitted/received using a reconfigurable FPGA-based system-on-chip (SoC) platform where the OFDM algorithm is installed.

We study the steel pipe channel frequency response for different distances between the transmitter and the receiver. As shown in Fig. 4, effective power spectra span from 1.5 to 3 MHz. The frequency range around 2.1 MHz is attenuated severely. Comparing the three-distance tests, the channel length of 30 cm displays the best SNR. As the distance increases, the overall SNR decreases. This observation implies that the SNR of ultrasonic communication is inversely proportional to the channel distance.

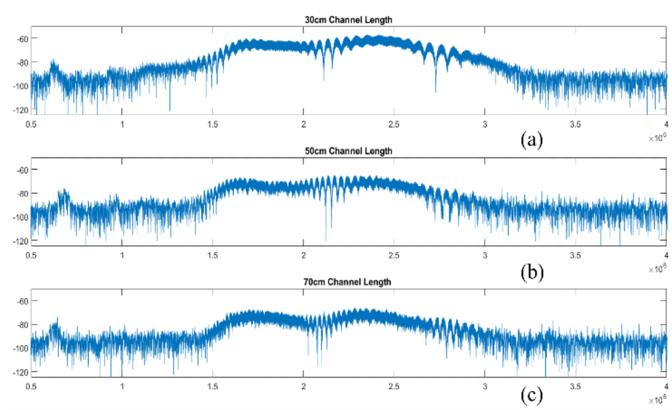

Fig. 4. Frequency response of different distance between transmitter and receiver: (a) 30cm, (b) 50cm, and (c) 70cm.

IV. EXPERIMENTAL TEST RESULTS

Several experiments were conducted to determine the feasible and reliable transmission rate using the QPSK modulation scheme where the distance between the transmitter and receiver is 30 cm. The symbol rates of the SoC platform are selected as 250k symbols per second (SPS) and 500kSPS. The experimental results are shown in Fig. 5. As the data rate increases, the constellation diagram becomes more scattered and prone to higher bit error rates. Nevertheless, the 500 kSPS symbol rate can still recover the transmitted bitstream. Considering the null subcarriers and cyclic prefixes used in the OFDM symbol, the efficiency of the symbol rate is 71.6%. Consequently, the communication bitrate exceeded 716 kbps when using QPSK modulation. Our experimental results confirm that OFDM ultrasonic communications through pipe channels provide practical bitrate without any error despite dispersion, ISI, and the multipath effect within the pipe channels.

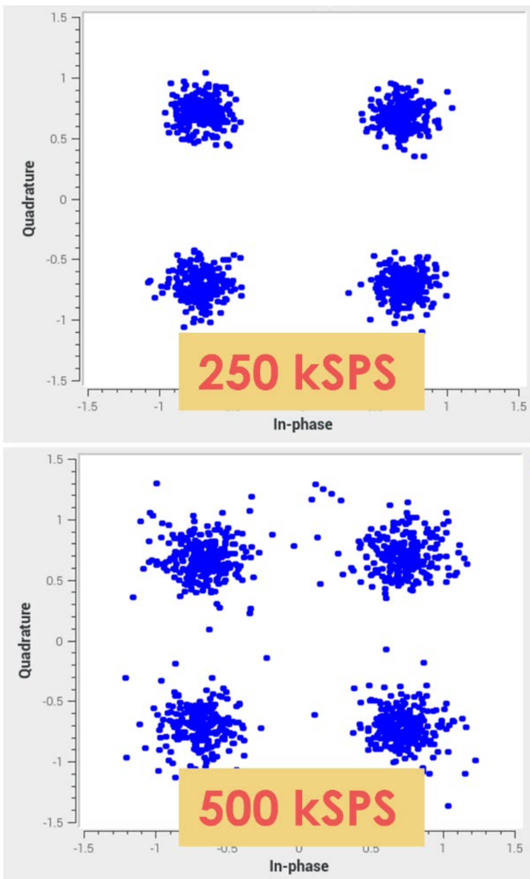

Fig. 5. OFDM constellation diagram using 250k and 500kSPS

V. Conclusion

In the paper, we examined the performance of the OFDM method used in the ultrasonic communication system. The ultrasonic wave simulation and the estimation of the frequency response of a steel pipe are examined. For this study, An FPGA-based SoC platform is developed to test and analyze the OFDM performance of ultrasonic communication through a steel pipe channel. The OFDM method can combat the bandwidth limitation and multipath effect. Multiple bitrates using QPSK modulation are examined. The experimental results confirm that ultrasonic communication using OFDM can achieve a 716 kbps bitrate with low BER across a 30cm channel length.

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