Wireless Communication Using Ultrasound in Air with Parallel OOK Channels

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Abstract − The use of airborne ultrasonic transducers for wireless communication was demonstrated. The work used capacitive ultrasonic transducers to transmit coded binary signals through parallel air channels. On-Off Keying modulation was successfully implemented in the system. Within the limited bandwidth of the transducers, six channels were used at frequencies from 50 kHz to 110 kHz with a channel spacing of 12 kHz, allowing 8-bit packets to be transmitted simultaneously. Wireless handshaking was achieved using a simple synchronization signal in front of the information signal. A data rate of 60 kbps was achieved over a short distance and the system Bit Error Rate (BER) was analysed.

Keywords − Airborne ultrasonic transducer, Short-range wireless communications, OOK modulation, Bit Error Rate, Synchronization

I INTRODUCTION

Recently, the short-range wireless communications industry has been dominated by radio frequency (RF) systems, such as Zigbee, Bluetooth and Wi-Fi (Wireless Fidelity) [1]. However, the RF spectrum is already widely used, and the frequency band is in short supply. RF signals are also very easy to intercept using technologies such as Bluesniping [2] when considering security issues. Moreover, interference increases when many other electronic devices operate at the same frequency. Though infra-red (IR) technology is an alternative approach, it suffers from sunlight and artificial light interference [3][4]. As a means of wireless communication, an airborne ultrasonic system has several advantages. Physically, ultrasound signals cannot penetrate most solid surfaces as easily as RF signals can. Therefore, any indoor ultrasonic communication system will be difficult to intercept from outside the room, making the system inherently more secure. Furthermore, due to the slow propagation speed of sound in air, the location of a transceiver can be accurately tracked by ultrasonic positioning systems [5][6]. Nevertheless, the attenuation of sound travelling through air increases significantly at frequencies above 1 MHz [7]. Currently, the applications of such ultrasonic systems are restricted by the narrow bandwidth of transducers available that operate effectively in air. Previous works on airborne ultrasonic communication systems used broadband transducers and signals were synchronized by establishing a physical link between the transmitter and the receiver [3][4][8]. The objective for this work is to achieve the highest data rate possible using narrow band transducers with wireless ultrasonic synchronization.

II MODULATION TECHNIQUE

To produce a signal suitable for transmission over a wireless channel, an ultrasonic carrier wave is modulated by the information signal. One of the most commonly used modulation schemes is Amplitude Shift Keying (ASK) [9], in which the source sends a high amplitude carrier wave or a low amplitude carrier wave, depending on whether the information is logic ‘1’ or logic ‘0’. A further simplified version of ASK is On-Off Keying (OOK), in which the carrier wave is simply turned on or off. In order to increase the data rate, multiple carrier waves with different frequencies over different data channels may be combined together into a single signal, but the number of channels depends on the system bandwidth.

III Numerical Simulation

A simulation of the OOK modulation scheme was performed using MATLAB. For example, the binary representation of letter 'Q' is '01010001', and the duration of each bit was 0.1 ms, thus the bit rate was 10 kbps. For an OOK modulation, a carrier sine wave at frequency of 50 kHz and the binary digital signal were simply multiplied together to give a modulated OOK signal, as shown in Figure 1(a). Two factors were considered when simulating. One is additive white Gaussian noise (AWGN), the other is ultrasound attenuation in air. The attenuation can be approximated by the following expression [10]

$$A_{air} = 1.64 \cdot f^2 \cdot d \cdot 10^{-10} dB \quad (1)$$

where f is the operating frequency and d is the propagation distance.

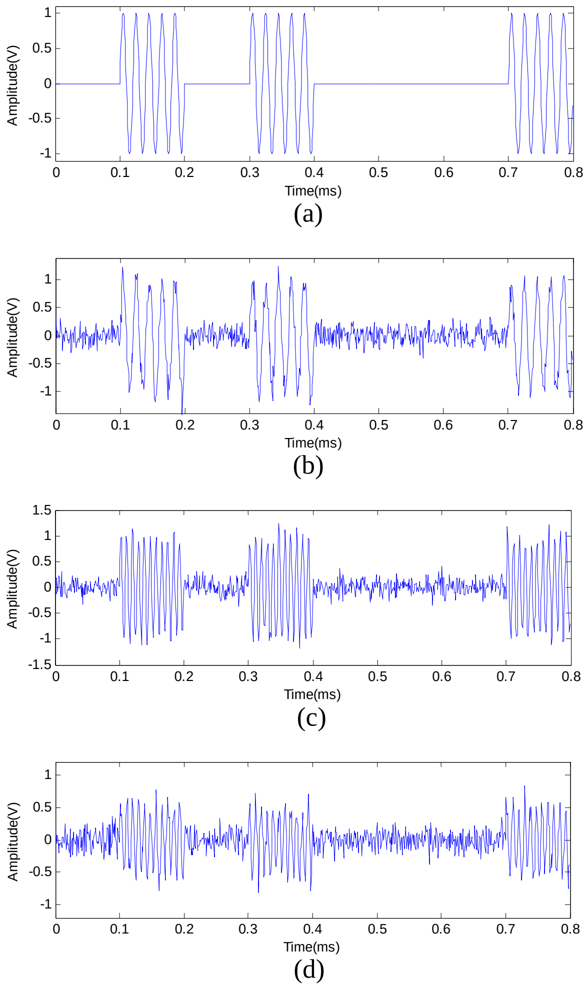


Figure 1(a) Modulated OOK signal, (b) OOK signal with AWGN and attenuation (50 kHz, 0.15 m), (c) OOK signal with AWGN and attenuation (110 kHz, 0.15 m), (d) OOK signal with AWGN and attenuation (110 kHz, 3 m)

Figure 1(b) shows the received OOK signal with AWGN and attenuation. The Signal-to-noise ratio (SNR) here is at an arbitrary level of 10 dB and the signal transmitted is at 50 kHz over 0.15 m. To make a comparison, signals transmitted at 110 kHz over 0.15 m and at 110 kHz over 3 m are illustrated in Figure 1(c) and Figure 1(d) respectively. As can be seen, attenuation increases significantly with the carrier frequency and the propagation distance. The SNR values of these two waveforms was calculated at 9.7 dB and 5.3 dB respectively.

Over a transmission distance of 0.6 m, six separate channels were assigned for each character transmitted at 12 kHz channel spacing from 50 kHz to 110 kHz. As an illustrative example, the characters 'QWERTY' were encoded and modulated using OOK. After that, six carrier signals were then combined together into a single waveform. The transmitted and the simulated received signals are shown in Figure 2(a) and Figure 2(b).

After the OOK signal was received, the signal was then bandpass filtered by a Butterworth filter to extract the channel representing letter 'Q' at 50 kHz. A zero-phase filter was implemented by processing input data in both forward and reverse directions. Figure 3(a) displays the result of the filtered signal, and the peaks can be visually identified which represent the bits at logic high. To decode the filtered signal, its envelope was calculated using the Hilbert transform [11]. Figure 3(b) shows the plotted envelope by taking its absolute value. The energy under the curve over each bit period was normalized and compared with a threshold value of 0.29, as Figure 3(c) shows. The threshold value was derived by trial and error. As can be seen, the difference between energies of '0's and '1's in each symbol period are large enough to deliver a correct decoding result.

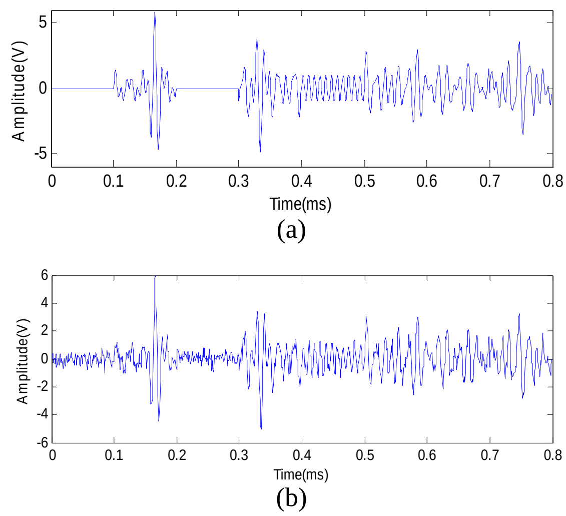


Figure 2(a) Combined waveform of 6-channel OOK modulation signals for characters 'QWERTY', (b) Simulated received multi-frequency 6-channel signal

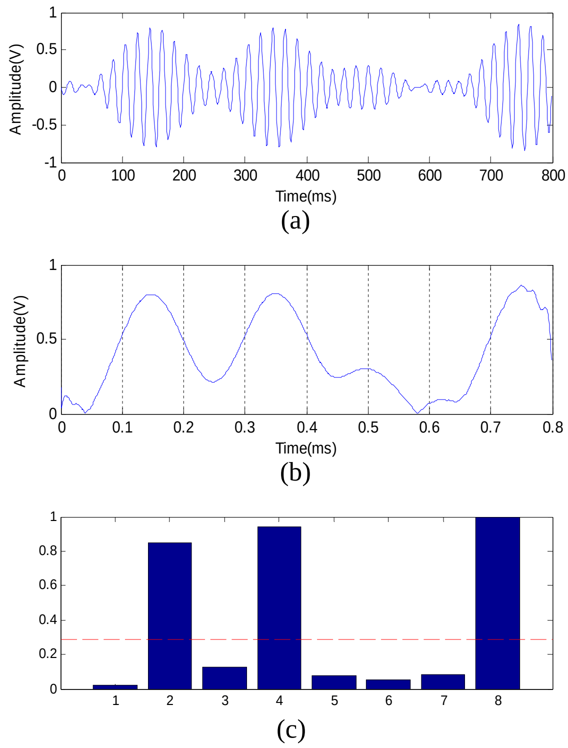


Figure 3(a) Filtered OOK signal, (b) Envelope of filtered signal, (c) Normalized energy plot under the curve of each bit duration

IV Apparatus and Experiment

The experimental system for testing ultrasonic communications in air is shown schematically in Figure 4. The data to be transmitted were encoded and modulated using MATLAB on a PC before being sent to a TTi TGA1244 Arbitrary Waveform Generator (AWG) using GPIB. The output signal of the AWG was then amplified by a factor of 10 using a transformer amplifier, and combined with a +100 V DC bias voltage generated by a HP 6205B Dual DC power supply. After that, the signal was sent to a SensComp series 600 ultrasonic transmitter [12]. This capacitive transducer is specifically intended for operation in air at an ultrasonic frequency of 50 kHz with a beam angle of 15° at -6 dB. Figure 5 illustrates the frequency response of the transducer used as a transmitter or a receiver as stated by the manufacturer. In addition, the overall system impulse response including the amplifier was tested and is shown in Figure 6. Therefore, data channels at frequencies from 50 kHz to 110 kHz were used in terms of -6 dB attenuation. The suggested DC bias voltage is 200 V and distance range is from 0.15 m to 10.7 m. The receiver transducer, initially placed 0.2 m away from the transmitter, was connected to a Cooknell CA6/C charge amplifier and then to a Tektronix TDS 210 digital oscilloscope for digitization. After that, the signal was then sent to the PC via GPIB for further signal processing.

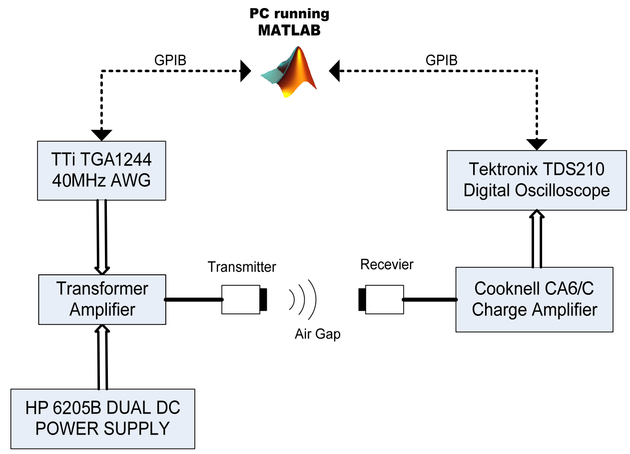


Figure 4. Schematic diagram of the experimental arrangement

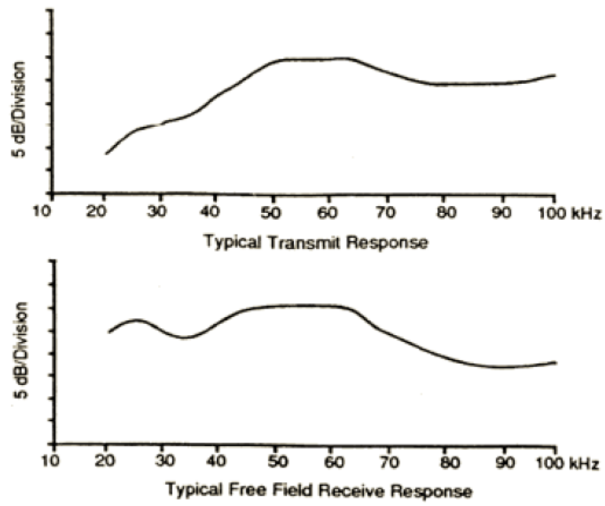


Figure 5. Transmit/Receive response of the ultrasonic transducer [12]

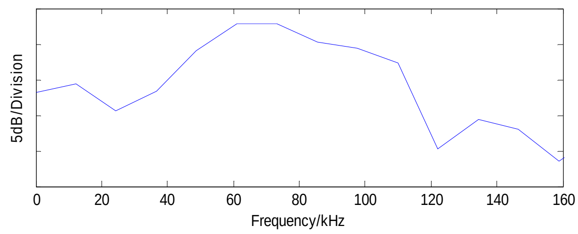


Figure 6. System frequency response

V Results

According to simulation, the binary representation of “QWERTY” for each ASCII character is shown in Table 1. The amplitude of each carrier wave was set to 5 V and then the six carrier signals representing ‘QWERTY’ were combined together into a single waveform as Figure 2(a) shows. Since MATLAB reads the waveform captured by the oscilloscope, a wireless synchronization signal was needed for successful demodulation. Therefore, an impulse with an amplitude slightly larger than the amplitude of information signal was added to the front of the signal. To reduce the influence of any energy leaking from the synchronization signal, zeros for a duration of 0.1 ms were padded between the synchronization signal and the information signal. Moreover, zeros were added for 0.5 ms after the information signal to separate one packet of signal from another. The final waveform transmitted through the channel is shown in Figure 7.

ASCII	BINARY	CHANNEL (kHz)
Q	01010001	50
W	01010111	62
E	01000101	74
R	01010010	86
T	01010100	98
Y	01011001	110

Table 1. ASCII character data representation for OOK

The signal waveform transmitted was correctly triggered by the oscilloscope to provide a display with the synchronised signal required for demodulation. The receiver transducer was set 0.6 m away from the transmitter and transmissions were in line-of-sight mode. Before demodulation, the redundant part of the signal including the trigger and padding was removed, as Figure 8 shows. The SNR of this waveform is about 12 dB.

Compared with the simulated waveform in Figure 2(b), the received waveform in Figure 8 is very close. To analyse the background noise, the trace of a received signal with no data was also captured as Figure 9(a) shows, with its frequency spectrum shown in Figure 9(b). As can be seen, there is background noise at 52 kHz, and with less at frequencies of 58 kHz and 80 kHz respectively. Therefore, the first, the second and the fourth channel will contain interference from ambient noise more than the other channels. The noise was from unknown electromagnetic sources, as the noise persisted even when the ultrasonic receiver aperture was physically blocked to prevent reception of any ultrasound. The received signal in Figure 8 was bandpass filtered to extract each signal over separated channels. The filtered signals on different channels corresponding to characters of 'QWERTY' are shown in Figure 10. Visually, the distinct amplitudes of '0's and '1's can be identified. The duration of each bit was 0.1 ms and as there were six parallel channels, the system data rate was 60 kbps.

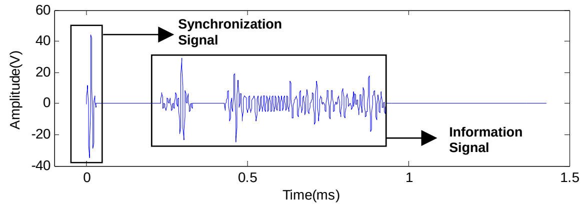


Figure 7. Signal waveform transmitted through the wireless channel

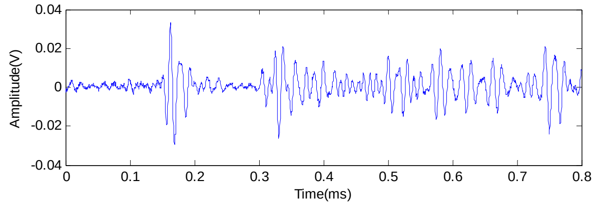
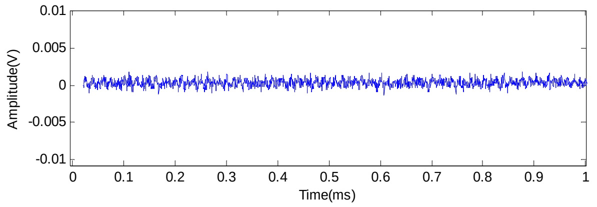
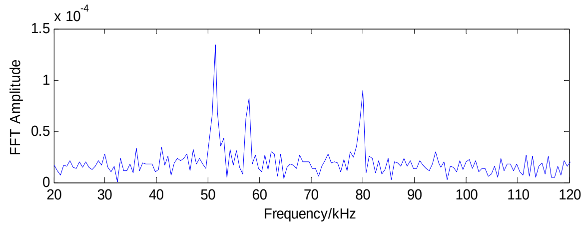


Figure 8. Received signal after redundant signal sections were removed



(a)

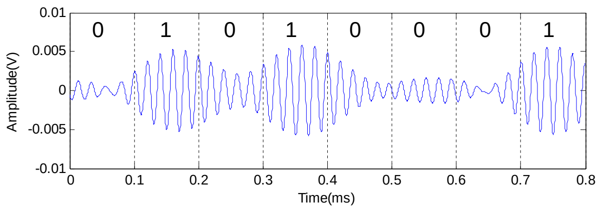


(b)

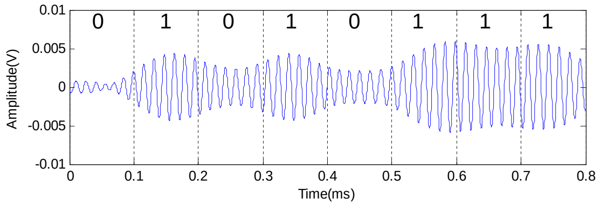
Figure 9(a). Background noise in time domain, (b) Frequency spectrum of background noise

VI Discussion

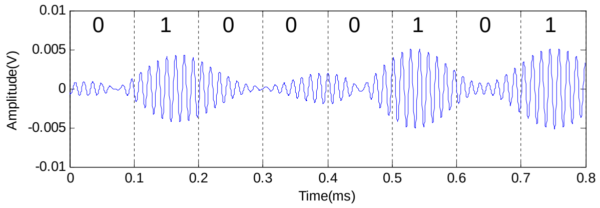
The results so far demonstrated that it was feasible to transmit binary data using an ultrasonic OOK modulation scheme over short range, using capacitive ultrasonic transducers with a limited bandwidth of only 60 kHz with wireless ultrasonic synchronization. However, as can be seen from Figure 10, when the modulation changes from '1' to '0' and vice versa, there is a delay in the response of the transducer, hence the maximum or the minimum of the modulated signal representing each bit is not usually in the centre of each bit period, leading to errors in the demodulation. These errors are greatest at the frequencies closest to the rated frequency response of the transducers. Additionally, the amplitude differences between '1's and '0's are also less significant at lower frequencies than that at higher frequencies. This is because the membrane of the transducer is more resonant near its rated operating



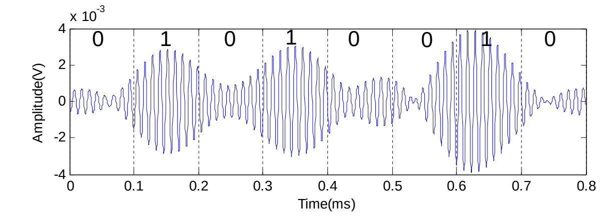
(a) ‘Q’ - Channel 1@50 kHz



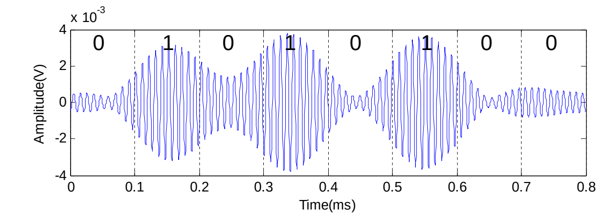
(b) ‘W’ – Channel 2@62 kHz



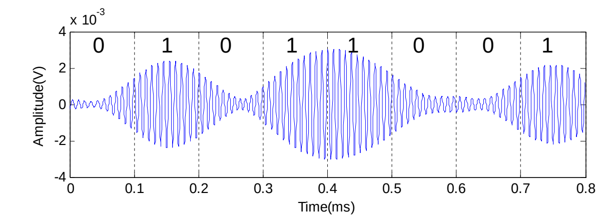
(c) ‘E’ – Channel 3@74 kHz



(d) ‘R’ – Channel 4@86 kHz



(e) ‘T’ – Channel 5@98 kHz



(f) ‘Y’ – Channel 6@110 kHz

Figure 10. Demodulation of different OOK channels

frequency than at higher frequencies. Therefore, it takes a longer time for the transducer to stop vibrating when changing from ‘1’ to ‘0’. Moreover, there is a significant signal at around 0.4 ms of the waveform in Figure 10(c). This is caused by inter-channel interference since the bit during this period in this channel should be ‘0’ but all the bits in adjacent channels are ‘1’s. It was also found that the transducer built up more energy when transmitting consecutive ‘1’s than single ‘1’s. This effect may increase the variation of the energies of ‘1’s, thus introducing incorrect demodulation. Consequently, it was necessary to test the bit error rate (BER) on each channel and over different distances to look at the overall system performance. 1200 packets of random 48-bit binary streams were generated, and the transducer separation was set at 0.2 m, 0.3 m, 0.45 m, 0.6 m, 0.75 m, 0.9 m, 1.05 m and 1.2 m respectively. The overall BER characterization as well as the BER on individual channels is shown in Figure11.

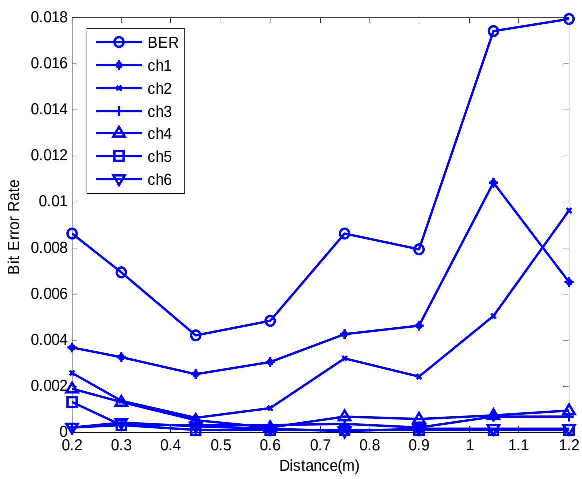


Figure11. Bit error rate over different transmission ranges

Figure 11 shows that the overall BER was higher at shorter ranges, and then reached a minimum at 0.45 m before rising rapidly again with longer distances. The reason for a higher BER at short ranges is the received signal is stronger when the two transducers are closer, leading to a stronger resonance of the receiver transducer. Therefore, there is more energy leaking from ‘1’s to ‘0’s, making the amplitude differences of ‘1’s and ‘0’s much smaller. As Figure 12(a) and Figure 12(b) illustrate, the amplitude difference between ‘1’s and ‘0’s is larger over 1.2 m than that over 0.2 m. The average amplitude ratios of ‘1’s and ‘0’s in Figure 12(a) and Figure 12(b) are 2.19 and 3.13 respectively. It indicates that a longer bit time should be used at lower frequencies, and the bit time could be slightly reduced at higher frequencies in order to keep the same data rate, while minimising BER.

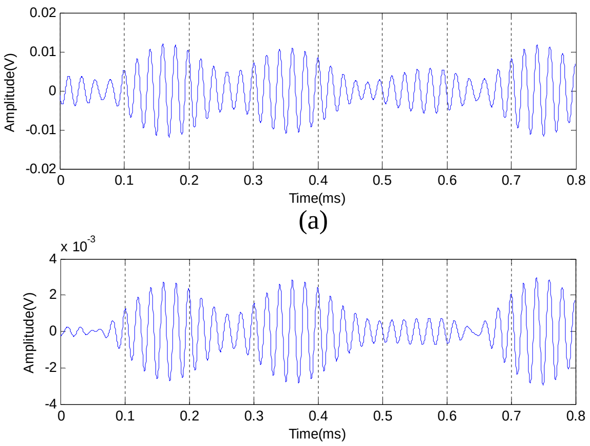


Figure 12(a) Extracted signal over a distance of 0.2 m, (b) Extracted signal over a distance of 1.2 m

The BER over different channels is also shown in Figure 11. As the curves show, most of the overall BER occurred on the first two channels. Accordingly, the percentage of errors distributed over each channel was calculated and is shown in Table 2. As can be seen, the errors decreased gradually as the channel frequency increased except for channel 4. Most errors occurred on channel 1, which is at 50 kHz, channel 2 at 62 kHz and channel 4 at 86 kHz. This may be attributed to the background noise which contains significant energy near those frequencies, as shown in Figure 9(b). Contrarily, the last channel at 110 kHz is the best channel with the lowest percentage of errors. This is because it is furthest away from the lower frequency noise, even though it suffers the most ultrasound attenuation. Moreover, it is found that channel 3 at 74 kHz has a lower bit error rate than its adjacent channels. This is possibly because there is a peak at around 70 kHz of the overall system frequency response, as shown in Figure 6.

Channel	CH1	CH2	CH3	CH4	CH5	CH6
Frequency (kHz)	50	62	74	86	98	110
Percentage of errors	49.8%	33.3%	3.7%	8.6%	2.8%	1.8%

Table 2. Error distribution

VII Conclusions and Future Work

The work proved that it was possible to transmit coded signals using ultrasound in air as the carrier signal with limited bandwidth ultrasonic transducers, the maximum system data rate achieved was up to 60 kbps when transmitting OOK modulated signals. Wireless synchronization was also achieved using a trigger signal in front of the information signal. However, other modulation schemes may be considered for further investigation to provide a lower bit error rate and longer transmission ranges. Future work will focus on using wider bandwidth transducers, other modulation schemes, and reduction of inter-channel interference. Moreover, the ultrasonic channel will be characterised in more detail.

Acknowledgements

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