ACOUSTIC DATA TRANSMISSION IN AIR USING TRANSDUCER ARRAY

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Acoustic data transmission is an alternative method for wireless electromagnetic communication, especially in the presence of Faraday shielding. The existing airborne acoustic wireless systems are mainly focused on short-range applications where only the direct path travelled by waves from transmitter to receiver are taken into account. However, for some applications in rooms, there would be a certain distance between the transmitter and the receiver. Reverberation plays a significant role since the sound waves can be absorbed and reflected repeatedly at boundaries like walls, floors and ceilings, etc. A novel acoustic data transmission system for anti-reverberation applications is proposed. The single-carrier frequency domain equalization algorithm is used to reduce severe inter-symbol interferences caused by reverberation. A set of transducer array is proposed to enhance the signal to noise ratio. Experiments carried out in rooms of varying sizes and reverberation times demonstrate the effectiveness of the new system.

1. Introduction

Digital wireless communication in air is mostly dominated by wireless technologies that use electromagnetic telecommunications, such as wireless networking, portable electronic devices, etc. However, the validity are usually degraded by Faraday shielding effects. Acoustic data transmission provides a promising alternative to conventional electromagnetic telecommunication method. By using airborne ultrasound, location positioning or tracking [1] as well as consumer electronic device such as wireless computer keyboard [2] can be accomplished. It is also available for transmitting information though metal barriers by ultrasound waves without physical penetrations [3-5]. Audible sound waves can be utilized as carriers to send short messages, such as preauthentication information or steganography, or just for entertainment [6,7]. Existing airborne wireless systems are mainly focused on short-range applications, taking only direct-path components into account. In reverberant environment such as in rooms, sound waves can be absorbed and reflected repeatedly at boundaries like walls, floors and ceilings. Consequently, it is difficult to reconstruct transmitted information.

This paper presents a new acoustic data transmission method using single-carrier frequency domain equalization (SC-FDE) [8]. Serious inter-symbol interferences (ISI) caused by reverberation can be alleviated by combined digital communication algorithms. Compared with using conventional mono loudspeakers as transmitters, system performance can be further elevated by custom-designed transducer arrays. High intensity and directionality are achieved to enhance the signal to noise ratio, which make the system suitable for anti-reverberation applications. By different settings, each transducer array can be set to either as a transmitter or as a receiver, and the whole system can operate as a megaphone as well as an acoustic data transmission device.

The remainder of this paper is organized as follows. Section 2 describes communication algorithm of the acoustic data transmission system, followed by testing results in rooms using mono loudspeaker as transmitter. Comparing the system performance results of various frequencies and angles, custom-designed transducer arrays are designed and adopted in Section 3. Frequency response and directional response patterns of the proposed acoustic data transmission system are also tested. Section 4 presents the experimental results in rooms of varying sizes and reverberation times. The conclusion is drawn in Section 5.

2. System design

2.1 Digital modulation techniques

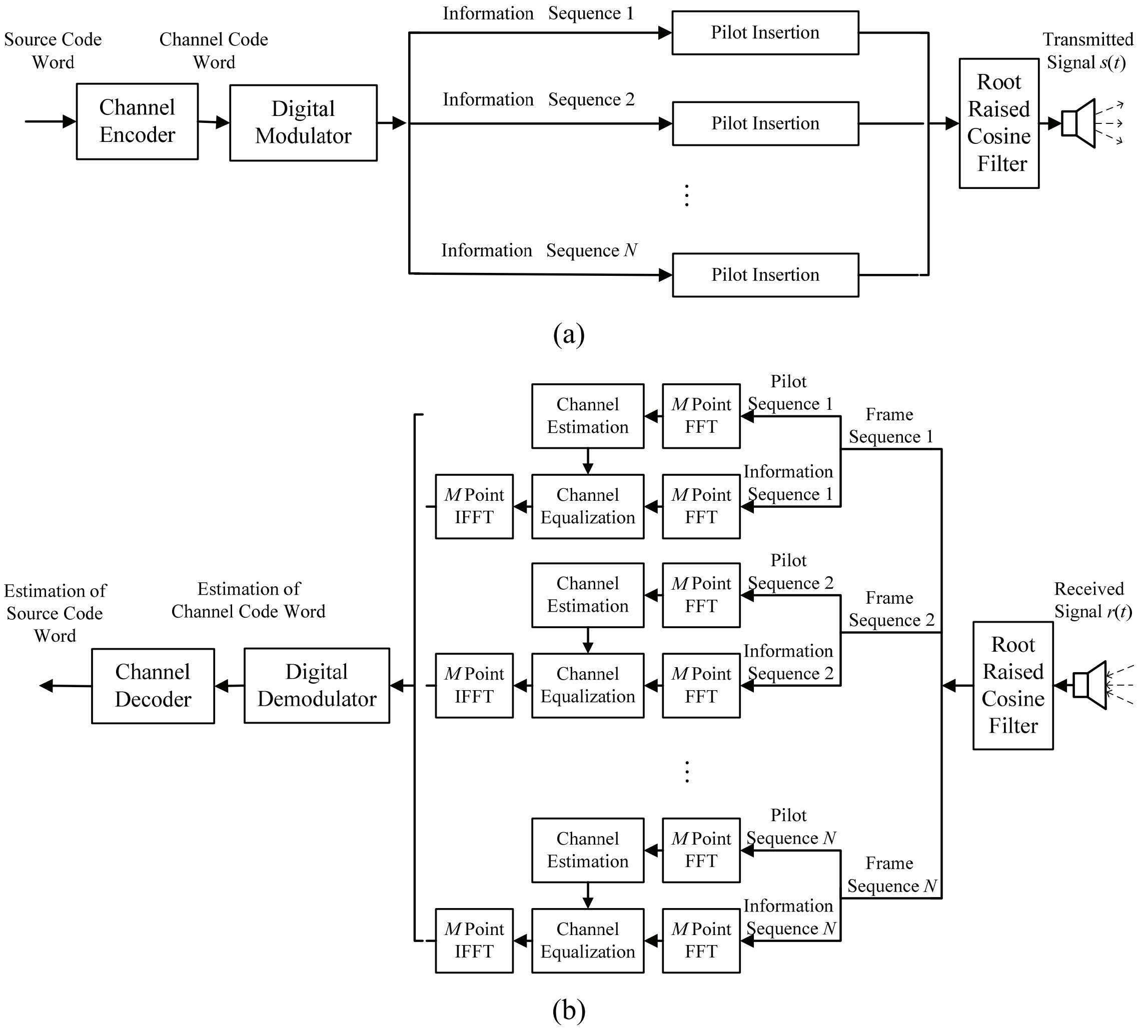


Figure 1. Diagram of the proposed acoustic data transmission system. (a) The transmitter. (b) The receiver.

The architecture of the proposed data transmission system is illustrated in Fig. 1. Modulated signals are separated as several frame blocks and encoded into $s(t)$. Amplified by the sending terminal, the sound waves including information are sent out in the air channel. In the receiver, sound waves are recorded and converted back to electric signals denoted as $r(t)$. One of the main factors restraining the bandwidth of the acoustic data transmission system in air is the presence of reverberant signals. These signals originating from the reflections at walls, floors or other obstacles usually lead to severe ISI. Moreover, complex air channel also limits the maximum transmission data rate of the system, and hence raises the probability of bit error. The problem encountered here bears a similarity to the traditional multipath phenomenon in broadband wireless communications. One conventional approach for ISI mitigation is to combine single-carrier modulation with time domain equalizations. However, the main bottleneck for the time domain solution is the high complexity. In the proposed system, the computational complexity using SC-FDE is reduced because channel equalization can be performed on every single short block with fast Fourier transform (FFT) operation. Channel distortion can also be tracked and equalized using pilot sequence each frame, respectively. Moreover, channel encoder, digital modulator, pulse shaping filter with matched ones in the receiver are also combined to form a more reliable algorithm for data transmission.

2.2 System performance using mono loudspeaker

Following the procedures mentioned above, we evaluated the effects of the acoustic data transmission system using YAMAHA mono loudspeaker (Type HS5) as the transmitter in a small rectangular room with dimensions of 5.00 m × 3.50 m × 2.50 m. Brüel & Kjaer (B&K) free-field microphone (Type 4189-A-021) was used as the receiver. The transmitter and the receiver were centered on the same axial line, and the volume was adjusted so that the normalized amplitude remained between 0.3 and 0.5. Bit error rate (BER) of 4-QAM, 16-QAM and 64-QAM modulation were tested for different symbol rates as shown in Fig. 2. Monte Carlo test with bitstream length above 10^5 bits was adopted in order to acquire reliable result. For M-ary QAM modulation, BER performance of the system is improved as M is decreased. However, bandwidth as well as symbol rate are declined. Consequently, reliable communication of BER less than 0.001 can be acquired when the symbol rate is less than 0.147 kbaud/s.

Directional response pattern was tested in an anechoic chamber. The free-field microphone mentioned above was used as the receiver and B&K PULSE Multi-Analyzer System (Type 3560C) was used for data analysis. The distance between the loudspeaker and the microphone was one meter. As illustrated in Fig. 3, the pattern is nearly omnidirectional in frequency range below 10 kHz, and getting weaker at higher frequencies.

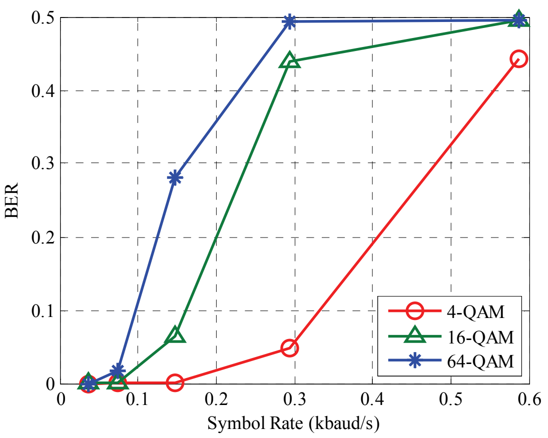


Figure 2. Relation between BER and symbol rate for M-ary QAM modulation using mono loudspeaker.

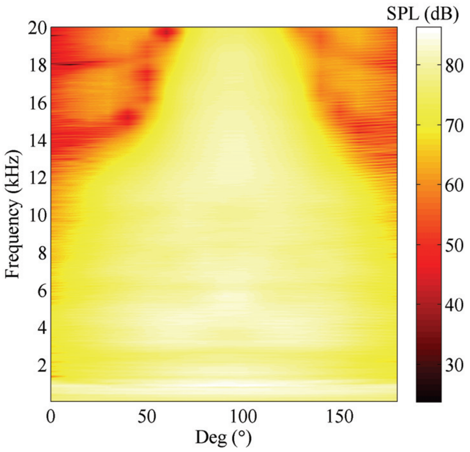


Figure 3. Directional response pattern of the mono loudspeaker.

To further investigate the relationship between acoustic data transmission performance and the acoustic characters of the loudspeaker, we evaluated the effects of various parameters associated with the transmitted signals. BER performance under 4-QAM modulation against carrier frequency is presented as Fig. 4. BER reaches the peak higher than 50% at 5 kHz and 7 kHz, so it is barely suitable for communication. Data transmission is not reliable at the frequency of 3 kHz and 8 kHz, since the BER exceed 0.001. The rests using carrier frequency in the range under 20 kHz are available for digital communication, and the BER is below 0.001. We also observed that the BER is much higher in the frequency range under 10 kHz, compared with that in higher frequencies. Considering the relationship between frequency and angle represented as Fig. 3, we made BER test against the angle between loudspeaker and the microphone. The results are shown as Fig. 5. These clearly indicate that the system acquires minimum BER when the loudspeaker points to the microphone, namely the angle is 90°. Performance descents as the angle deviates from 90°. The tolerable range is about 100° while using 10 kHz as carrier frequency, and it becomes narrower to about 60° while using 20 kHz as carrier frequency. It is coincide with the directional response pattern as in Fig. 3. As a consequence, the system performance would be optimized by using transducers with higher directivities. However, the effective transmission distance decays as the carrier frequencies are increased due to the impedance mismatch with air. Custom-designed transducer array which will be detailed in the following section are utilized to expand the transmission distance available compared with that using conventional mono loudspeaker and microphone.

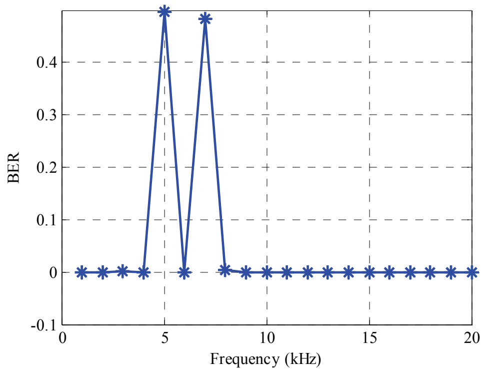


Figure 4. Relation between BER and carrier frequency for acoustic data transmission system using mono loudspeaker.

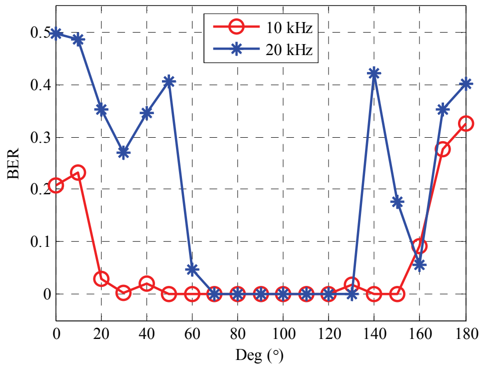


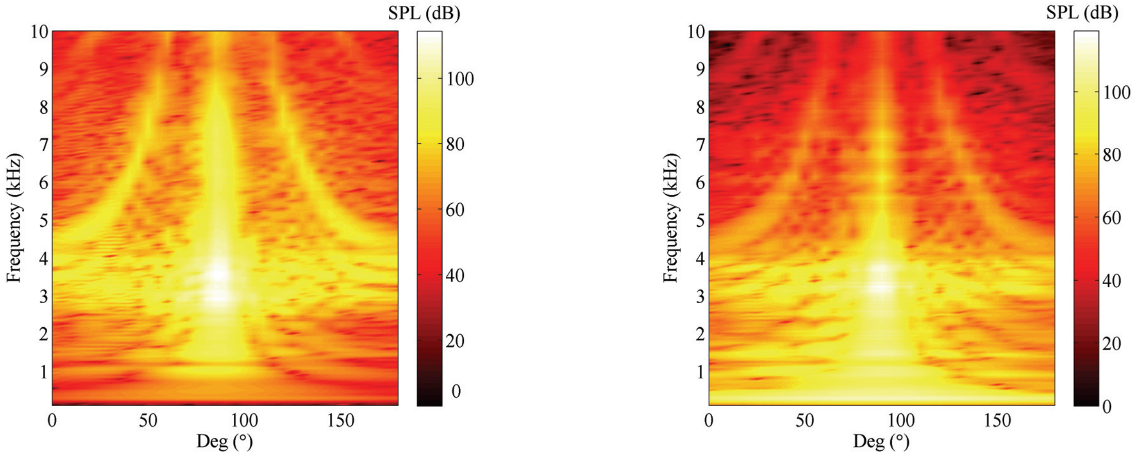
Figure 5. Relation between BER and angle for acoustic data transmission system using mono loudspeaker.

3. Custom-designed transducer array

The main conundrum limiting the performance of the acoustic data transmission system is the sound pressure level output for communication. To mitigate sound wave intensity attenuation against distance, forty-four horn loudspeakers are combined to form a custom-designed transducer array. Each of which consists of a horn with cross-sectional area increased exponentially.

Frequency response and directivity of the custom-designed transducer array as the transmitter and the receiver were tested in an anechoic chamber, respectively. Using the custom-designed transducer array as the transmitter, test was made following procedures similar as that mentioned in Section 2.2. To test the performance as receiver array, omni-directional loudspeaker combined with power amplifier was selected as the transmitter. B&K free-field microphone was also used as a receiver to calibrate frequency response of both the loudspeaker and the power amplifier. The distance between the transmitter and receiver was four meters. The array was rotated so that the SSR analysis data were recorded for every 5° ranging from 0° to 180°. Results in 90° represent for transmitter frequency response. Directional response patterns of the array for different frequencies ranging from 100 Hz to 10 kHz are shown in Fig. 6. Both the frequency responses of the transmitter and receiver array have a peak at around 4 kHz. It decays as the frequency is increased or decreased.

The quarter-power angle of the array becomes narrower in the frequency range below 5 kHz. The sidelobes appear to become more obvious at higher frequencies.

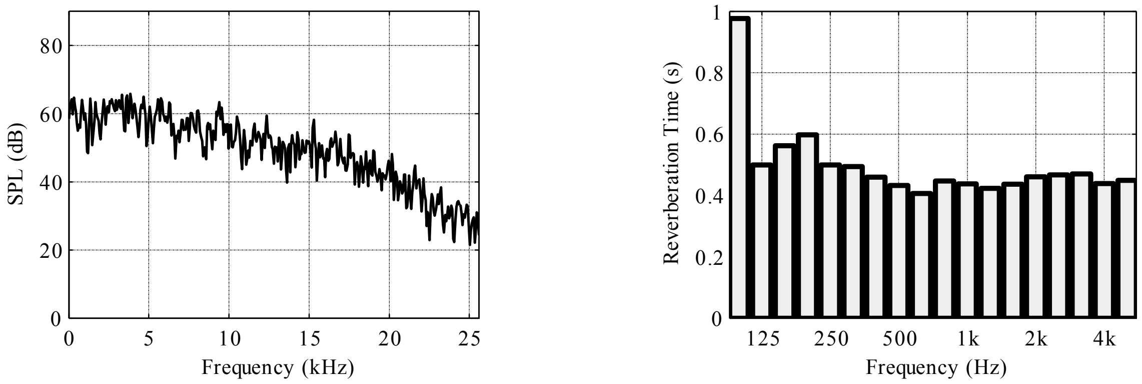


(a) (b)

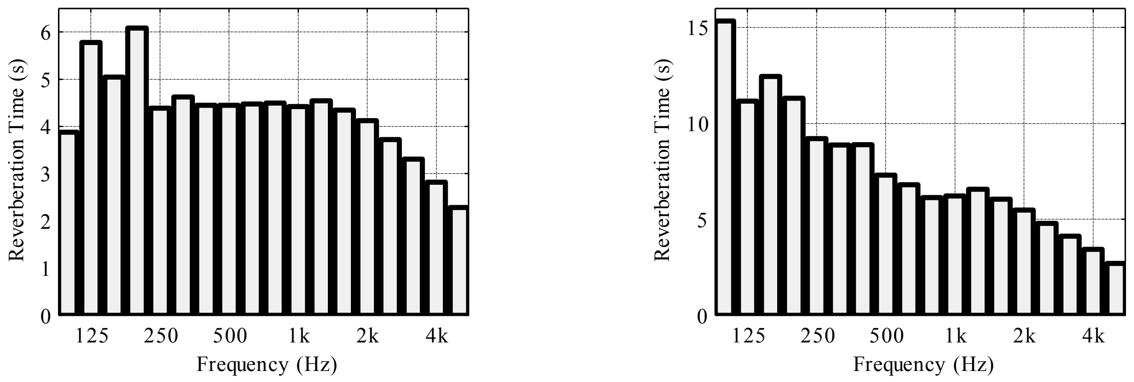
Figure 6. Directional response patterns of the acoustic data transmission system. (a) The transmitter. (b) The receiver.

4. Experiments and results

In this section, the system performances of the proposed acoustic data transmission system using custom-designed transducer arrays in three rooms with different reverberation times were evaluated. Reverberation time is defined as the time required for the sound in an enclosure to decay 60 dB from an initial steady-state level [9]. Steady-state source method was used for measuring reverberation decays. Signals were recorded by B&K microphone mounted on a tripod [10]. B&K PULSE Multi-Analyzer System and Pulse Labshop Software were utilized to calculate the reverberation time. The spectrum of the sound pressure level generated by the source in the small room mentioned above is shown as Fig. 7(a). Its value was around 60 dB and the use of ear protectors was necessary due to its loudness. Fig. 7(b) shows that the reverberation time in the test room mentioned in Section 2.2 was between 0.407 s and 0.976 s. Two reverberation chambers were also tested. The larger reverberation chamber with dimensions of 8.40 m×7.00 m×7.20 m had reverberation times ranged between 2.28 s and 6.08 s across the frequency range of interest. The smaller one with dimensions of 5.75 m×4.90 m×7.20 m had longer reverberation times ranged between 2.70 s and 15.30 s. They are illustrated in Fig. 7(c) and (d) below, respectively.



(a) (b)

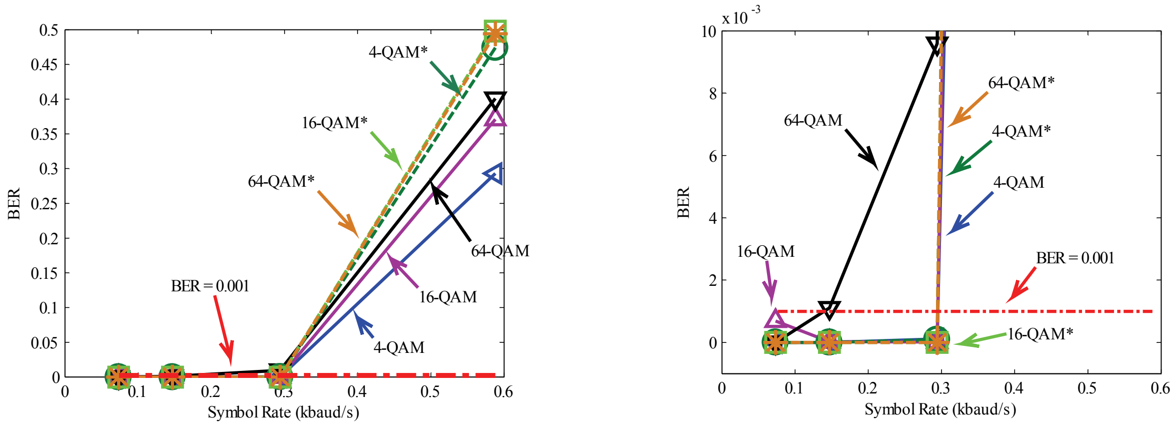


(c) (d)

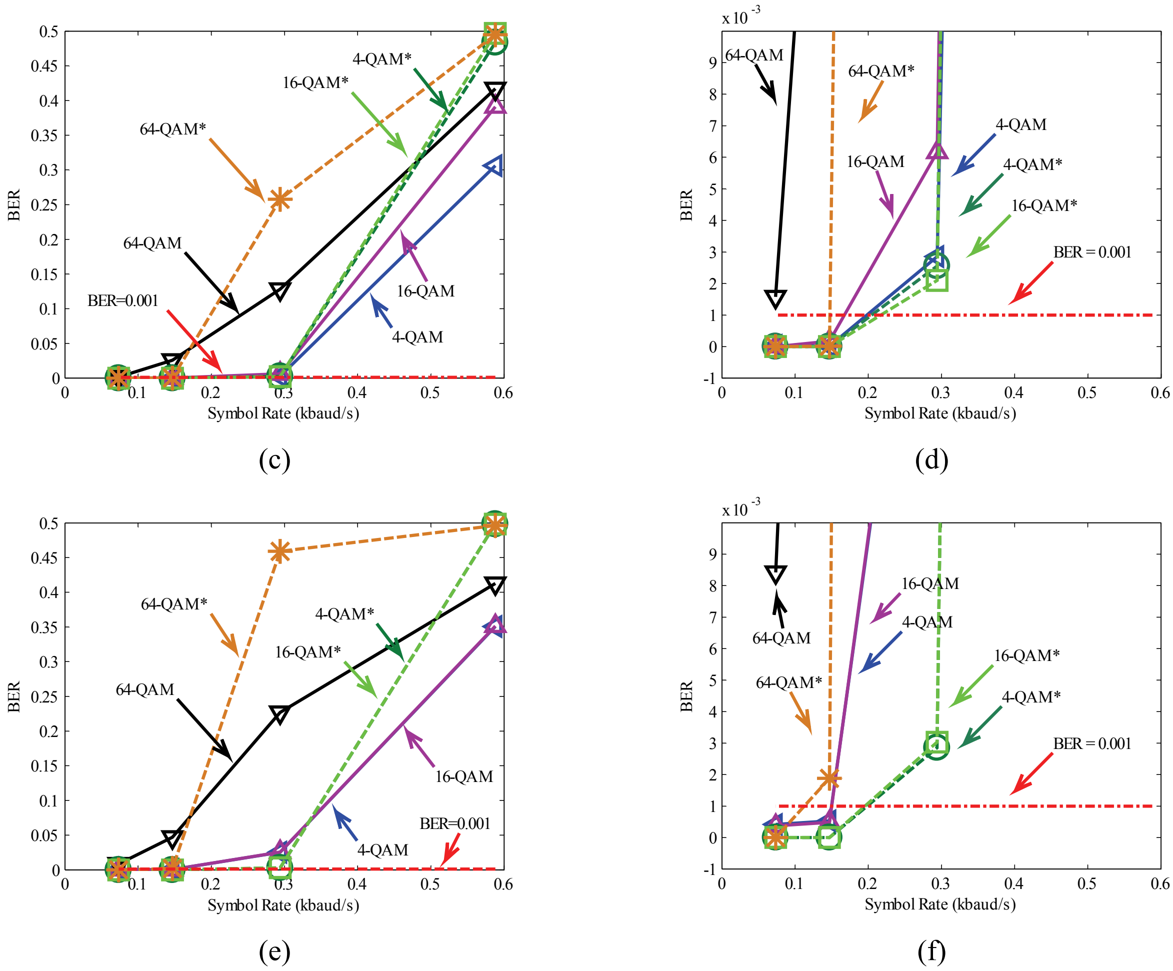
Figure 7. (a) Frequency response of the sound source used for reverberation time measurement. (b-d) Reverberation time test results of three different rooms. (b) The small room. (c) The larger reverberation chamber. (d) The smaller reverberation chamber.

BER of the acoustic data transmission system in these three rooms with different reverberation times were tested. Taking into account of the sampling rate as 44.1 kHz for the proposed system as well as the acoustic test results presented in Fig. 6, 4.41 kHz was chosen as the carrier frequency. BER of 4-QAM, 16-QAM and 64-QAM modulation were tested for different symbol rates as shown in Fig. 8. Results of the small room are shown in Fig. 8(a), and Fig. 8(b) shows a corresponding partial enlargement around a target BER constraint of 10^{-3}. Results of the two reverberation chambers are represented in Fig. 8(c)-(f). Fig. 8(d) and (f) shows partial enlargements of Fig. 8(c) and (e), respectively. BER will be reduced after adding channel coding, which is marked with superscript asterisk in Fig. 8.

The relationship between the reverberation time and optimal data rate is also demonstrated in Table 1. Compared with the BER results as illustrated in Fig. 2, the system performance improves markedly by using the custom-designed transducer arrays instead of conventional mono loudspeaker and microphone. The data rate can be increased to 1.764 kbps. As the reverberation time is increased, namely, comparing the results from the small room to the larger reverberation chamber, and further to that of the smaller reverberation chamber, both the noise resistance of the system and the data rate is reduced. Reliable data transmission can be achieved even in rooms with strong reverberation.



(a) (b)



(c) (d)

(e) (f)

Figure 8. Relation between bit error rate and symbol rate for 4-QAM, 16-QAM and 64-QAM modulation. (a and b) The small room. (c and d) The larger reverberation chamber. (e and f) The smaller reverberation chamber. The right figures are partial enlargements for the corresponding left ones, respectively. The superscript asterisk refers to test results with channel coding added. Red dashed line is reference line when BER equals 0.001.

Table 1. System performances in rooms with different reverberation times.

	Small Room	Larger Reverberation Chamber	Smaller Reverberation Chamber
Reverberation Time (s)	0.407 ~ 0.976	2.28 ~ 6.08	2.70 ~ 15.30
Optimal Modulation Method	64-QAM	64-QAM	16-QAM
Data Rate (kbps)	1.764	0.882	0.588

5. Conclusion

A new anti-reverberation acoustic data transmission in air is demonstrated in this paper. With single carrier frequency domain equalization algorithm and other digital modulation techniques combined together, severe inter-symbol interferences can be mitigated. System performance of the proposed algorithms in a small rectangular room using mono loudspeaker and microphone was tested. The result is limited by complicated mixed waves reflected from all boundaries. Considering the relationship between system performance and the testing characters of the mono loudspeaker, custom-designed transducer array is presented to replace both the loudspeaker and microphone. Experiments conducted in rooms with varying reverberation times show that the proposed system can achieve reliable data transmission under all these circumstances. It can resist reverberation effectively even in reverberation chambers with long reverberation times.

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