

Ultrasonic Wireless Communication Through Metal Barriers

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Abstract: Ultrasound can be used as a carrier to realize wireless communication to and from a metal-enclosed space, which has the characteristics such as immunity to the electromagnetic shielding effect and non-destructive penetration of metal obstacles. This paper firstly reviews the previous studies in the field of ultrasonic wireless communication through metal barriers, and summarizes their achievements and the existing problems. Secondly, an overview of the research methods involved in studying the characteristic of acoustic-electric channel is presented, and the principles are introduced for the actual measurement method, equivalent circuit method, ABCD parameter method, finite element analysis method and time-domain finite difference method. Then, an overview of the communication algorithms are presented such as orthogonal frequency division multiplexing (OFDM), single-carrier frequency domain equalization and multiple input multiple output OFDM. Finally, the potential future study are proposed in light of the trend of development and unsolved problems.

Keywords: Wireless communication; ultrasound; piezoelectric transducers; metal barriers

1 Introduction

In industrial and civil activities, data transmission across both sides of metal materials is inevitable, such as the transmission of data between an environmental data acquisition system outside a ship and the control system inside, acquisition of the key parameters in a nuclear reactor, information communication to and from flying vehicles such as spaceship and airplane, and data transmission between the inside and outside of a high-pressure oxygen tank [1-53]. Currently, this process is widely realized through wire communication using cables going through punched metal materials and connecting to the internal and external communication devices [1-5]. However, by this means the fluid-tightness and completeness of the metal body are lost and the maintenance cost is greatly increased. If wireless communication is adopted instead, these problems can be avoided effectively. However, the existence of electromagnetic shielding effect prevents the transmission of electromagnetic waves through metal barriers, so the traditional technology of electromagnetic wave based wireless communication cannot be applied.

Ultrasound, as a kind of mechanical wave, can effectively penetrate metal; therefore, ultrasound can be used as a carrier and different information can be represented by the amplitude, phase or frequency of the carrier, so as to realize wireless communication to and from a metal-enclosed space. This process is inseparable from the transformation between electric signals and acoustic signals, which can be effectively realized by piezoelectric devices. Using the positive piezoelectric effect, piezoelectric devices can effectively convert acoustic signals into electric signals; conversely, with the inverse piezoelectric effect, the electric signals can also be effectively converted into acoustic signals. This communication method can be called “ultrasonic wireless communication through metal barriers”, which has the characteristics such

as immunity to the electromagnetic shielding effect and non-destructive penetration of metal obstacles [6-29,47-51]. It has become an important subject for research and application.

In this paper, previous studies on ultrasonic wireless communication through metal barriers are reviewed, followed by an overview of the recent research progress on channel characteristic and communication algorithms. Finally, areas of the potential further research are recommended.

2 Historical Review

In 1997, in the patent applied by Connor et al., ultrasound was first proposed as a means of penetrating metal walls for the transmission of power and data [1]. The proposed method used piezoelectric transducers attached to both sides of the wall and circuits for signal generation and capture in the transmission of data and power. However, neither theoretical analysis nor experimental results was provided in the patent. In 2000, Hobart et al. designed an acoustical modulation unit to achieve data transmission on both sides of a ship body⁴. This is the earliest research report on ultrasonic wireless communication through metal barriers. Since then, theoretical and applied research on this subject has started.

Since 2006, the research group led by Saulnier at Rensselaer Polytechnic Institute (RPI), US has mainly studied the channel characteristic and algorithms for the use of ultrasound to realize data communication and power transmission between both sides of a metal, and currently they are still active in this field [6-29]. This research group conducted the following in-depth studies: starting from channel modeling [9,10,13,14,23,26], the channel characteristic was analyzed for ultrasonic wireless communication through metal barriers [9-18,20-29]; the high-speed communication technologies in the single input single output (SISO) [6-15,18,20-27] and multiple input multiple output (MIMO) [16,17,28,29] cases were investigated; and feasibility studies were carried out on simultaneous wireless communication and power transmission through metal barriers [8,10-15,18,20-22,24,27]. In recent years, their research has mainly focused on the applications [20] and the expansion of application scenarios [19].

Since 2007, the research group led by Primerano at Drexel University, US has studied the algorithms for high-speed ultrasonic wireless communication through metal barriers [30-35]. Based on the finite difference time-domain simulation of the channels [32], a multipath transmission model of the channel was constructed [31,32], and a pre-distortion filter was designed on the transmitter side of the system to cope with the multipath fading and to suppress the inter-symbol interference [30]. However, this method requires off-line identification of system parameters, which brings great inconvenience and limits the range of application. After then, this group introduced the orthogonal frequency division multiplexing (OFDM) into the ultrasonic wireless communication system to resist the multipath effect, and obtained good results [32-34]. In the aspects of application, this group envisaged that on the walls of each room in a large vessel, repeaters should be installed, which constitute an ultrasonic wireless communication system, so that all the rooms can be covered by communication signals and full coverage of wireless communication can be realized [32,35].

Since 2011, the research group led by Yang at the Institute of acoustics, Chinese Academy of Sciences has carried out in-depth studies on the systems for ultrasonic wireless communication and power transmission through metal barriers [47-51]. They introduced the technology of single-carrier frequency-domain equalization (SC-FDE) into this field [47], studied adaptive algorithms to different transmission rates for ultrasonic wireless communication through metal barriers, and built a real system to validate the algorithm [48-50].

The parameters of the representative systems developed so far for ultrasonic wireless communication through metal barriers are shown in Tab. 1. In most studies steel plates were selected as metal barriers because in practical applications. As for the center frequency of transducer, the higher the center frequency is, the larger the available bandwidth is; however, a transducer with center frequency below 10 MHz is often used in most studies. This is because larger ultrasonic frequency will lead to more serious attenuation in the metal barrier, and thus lower signal-to-noise ratio (SNR) when the transmitting power is limited, deteriorating reliability of communication. In the aspect of communication modulation method, the earlier

studies focused on relatively simple approaches such as the phase shift keying (PSK), amplitude shift keying (ASK), frequency shift keying (FSK) and pulse amplitude modulation (PAM), and the acquired rates of transmission were low. With the introduction of the OFDM, SC-FDE and MIMO-OFDM, the communication rate has been greatly improved.

Table 1: Parameters of existing systems

Author	Barrier material	Center frequency of transducer	Modulation method	Transmission rate
Murphy [6]	Steel	1 MHz	PSK	5 kbps
Saulnier [7]	Steel	1 MHz	ASK	500 bps
Shoudy [8]	Steel	1 MHz	ASK	55 kbps
Kluge [37]	Aluminum	3 MHz	ASK	1 kbps
Primerano [32]	Steel	6.8 MHz	OFDM	30 Mbps
Moss [42,43]	Aluminum	1 MHz	PAM	115 kbps
Hosman [36]	Steel	40 kHz	FSK	360 bps
Lawry [18]	Steel	4 MHz	OFDM	17.37 Mbps
Ashdown [17]	Steel	4 MHz	MIMO-OFDM	700 Mbps
Wanuga [34]	Steel	6 MHz	OFDM	15 Mbps
Yu [47]	Steel	500 kHz	SC-FDE	1.3 Mbps
Tian [52]	Steel	1.14 Hz	ASK	10 bps

3 Characteristic of the Acoustic-Electric Channel

A common system for ultrasonic wireless communication through metal barriers has a sandwiched multi-layer composite structure, in which piezoelectric transducers are closely stuck at opposite positions, normal to both sides of a metal barrier [6,7,12-18,26,28-52]. As shown in Fig. 1, when the source data is processed on the left side of the metal barrier, a modulated electric signal is generated. This signal excites a piezoelectric transducer to produce an acoustic signal, which is then transmitted to the right side through the metal barrier. On the right side of the metal barrier, another piezoelectric transducer receives the acoustic signal and converts it into an electric signal. After a series of inverse processing, the transmitted data is obtained. In the earlier studies, three other types of structure also existed: the reflective, double hop and hybrid structures [6-8], but with the progress of research, the sandwiched structure dominates because more piezoelectric transducers are required in the other structures and the interaction of acoustic waves emitted by multiple transducers in the metal barrier causes more complex distribution of sound field and high communication rate is more difficult to obtain.

Ultrasonic wireless communication through metal barriers is also a kind of wireless communication. In wireless communication, channel characteristic is a fundamental and important topic because channel is the connection carrier between the transmitter and the receiver. The characteristic of the channel will determine the alteration of signal after it has been transmitted through the channel, and this alteration will affect modulation and demodulation, codec, channel estimation and equalization, and data synchronization. The methods commonly used to obtain channel characteristic include the actual measurement method and simulation analysis method.

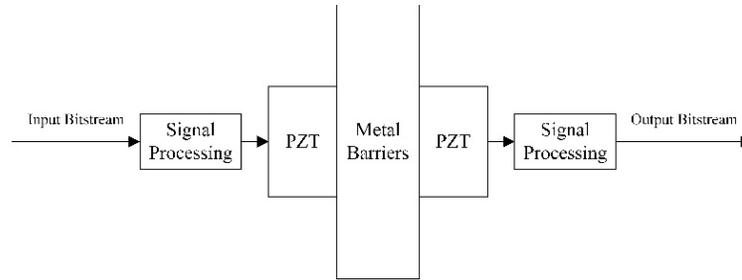


Figure 1: The sandwiched structure in an ultrasonic wireless communication system through metal barriers

The so-called actual measurement method is to connect a signal generator, oscilloscope, spectrum analyzer, vector network analyzer or other measuring instruments to the communication channel to be studied, send some special signals to the channel, receive and process the signals transmitted through the channel, and analyze the variations of signals after channel transmission to obtain the channel characteristic. However, in the actual measurement only one or several situations can be tested, and not all the situations can be traversed. For example, for the thickness of steel plate and the center frequency of transducer, the channel characteristic can only be measured under a certain number of parameters. It is more difficult to explore the channel characteristic in more general cases. For example, in [18] and [48], a vector network analyzer was used to measure the scattering matrix (S parameter) of the acoustic-electric channel under some specific conditions. The principle of measurement is to treat the system composed of a transmitter piezoelectric transducer, a metal barrier and a receiver piezoelectric transducer as a dual-port network. The vector network analyzer connected to the two ports sends a sweep signal within a certain frequency band and receives the signal processed by the dual-port network, and then the characteristic of the entire channel can be obtained based on the sent and received signals.

Fig. 2 shows the power transfer function and impulse response of an acoustic-electric channel obtained in an actual measurement. The measured acoustic-electric channel is composed of two piezoelectric transducers with center frequency at 4 MHz and a steel plate with thickness of 6.35 cm [18]. The figure shows that:

(1) Large deviation exists between the center frequency of the acoustic-electric channel and the center frequency of the piezoelectric transducers. The magnitude-frequency response of the channel has some fluctuations, and there is a peak at a certain frequency, displaying complex frequency selectivity. The channel gain varies greatly at different frequency points.

(2) The characteristic of multipath transmission is significant: The channel impulse response is composed of a number of distinct pulse signals, and the time intervals between two adjacent pulse signals are kept constant.

(3) Path loss is present, which is demonstrated by the decrease in the amplitude of the pulse signal (representing the channel impulse response) with the increase of time.

(4) The time delay is largely extended. The speed of acoustic wave is lower than that of electromagnetic wave, so the time delay is extended to microsecond, while that in electromagnetic wave communication is nanosecond. Hence improvement of transmission rate heavily relies on the progress made in channel estimation and equalization techniques.

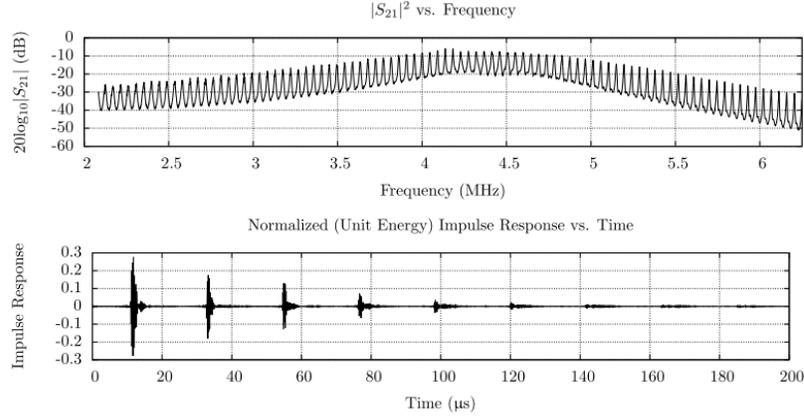


Figure 2: Measured characteristic of a communication channel (transducer center frequency at 4 MHz, 6.35-cm thick steel plate: [top] power transfer function ($|S_{21}|^2$) and [bottom] band-limited impulse response (2.08 MHz-6.25 MHz)

In the study of channel characteristic, the actual measurement method can only be carried out on a specific channel; and limited by the specific experimental conditions, it is difficult to traverse all cases to analyze the effects of key parameters on the channel characteristic. At this point, the simulation analysis method can be used to study the channel characteristic. The commonly used simulation methods include the equivalent circuit method [23,42], ABCD parameter method [13,14,26], finite element method [9,10] and time domain finite difference method [32], which are introduced in more details and compared as follows.

In the equivalent circuit method, electrical models are constructed corresponding to the specific devices in the channel that are combined in an appropriate way [23,42]. By adjusting the key parameters in the model, the overall performance of the channel is analyzed. Among the devices, piezoelectric transducers can be modeled with the methods, for example the Mason model, Leach-Puttmer's model and KLM (Krimholtz, Leedom, and Matthaei) model, while coupling agents and metal barrier can be modeled with the lossy transmission line method. Roa-Prada et al. constructed an equivalent circuit model for the acoustic-electric channel with the reflective structure using the Leach-Puttmer's model and the lossy transmission line method, and analyzed the characteristic of the channel [23].

In the ABCD parametric method, the acoustic-electric channel is regarded as a series of dual-port networks, and by analyzing the ABCD parameters of each internal dual-port network, the characteristic of the overall channel can be studied [14,26]. A semi-infinite elastic material can be regarded as a dual-port network shown in Fig. 3, in which the normal forces acting on the material surface are denoted by F_1 and F_2 and the particle velocities by v_1 and v_2 . They are related by the ABCD matrix:

$$\begin{bmatrix} F_1 \\ v_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} F_2 \\ v_2 \end{bmatrix} \quad (1)$$

Using the wave equation, the detailed expression of the ABCD matrix \mathbf{M} is obtained by:

$$\mathbf{M} = \begin{bmatrix} \cosh(\gamma d) & Z \sinh(\gamma d) \\ Z^{-1} \sinh(\gamma d) & \cosh(\gamma d) \end{bmatrix} \quad (2)$$

where γ is the complex propagation constant, d is the thickness of the material, and Z is the acoustic impedance of the material.

The overall channel can be represented by the ABCD matrix as:

$$\mathbf{M}_{CH} = \mathbf{M}_{P1} \mathbf{M}_{E1} \mathbf{M}_{C1} \mathbf{M}_{MB} \mathbf{M}_{C2} \mathbf{M}_{E2} \mathbf{M}_{P2} \quad (3)$$

where \mathbf{M}_{P1} , \mathbf{M}_{E1} , \mathbf{M}_{C1} , \mathbf{M}_{MB} , \mathbf{M}_{C2} , \mathbf{M}_{E2} and \mathbf{M}_{P2} represent the ABCD matrices of the transmitter-side piezoelectric transducer, transmitter-side electrode, transmitter-side Couplant, metal barrier, receiver-side Couplant, receiver-side electrode, receiver-side piezoelectric transducer, respectively. Lawry et al.

constructed a model of the overall acoustic-electric channel with the ABCD parametric method, and the estimates are consistent with the measured results [12,13].

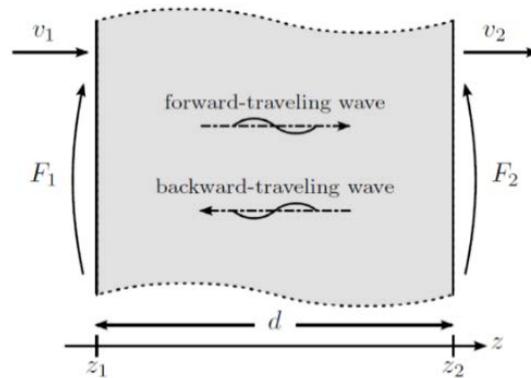


Figure 3: The dual-port network of a semi-infinite elastic material

The finite element analysis method can be used to obtain not only the distribution of sound field in each part of the channel, but also the influence of the variations of environmental parameters (such as the temperature) on the characteristic of the acoustic-electric channel [9,10]. Reference [9] mainly used the finite element method to analyze the characteristic of the acoustic-electric channel, with the influence of the asymmetry of the transducer-electrode surface considered. Fig. 4 shows the surface of a piezoelectric transducer: the white area is the electrode, which divides the transducer surface into three zones when the symmetry of the surface is broken. In the analysis, an insulating layer was added on to compensate for this asymmetry, based on which good results were obtained.

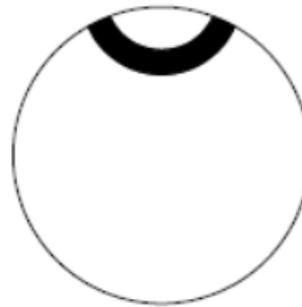


Figure 4: Transducer face asymmetry due to wrap electrode

With the time-domain finite difference method, the course of the propagation of sound waves in the channel can be observed, thus providing a visual demonstration of the details of acoustic phenomena such as reflection and transmission. Using this method, we can find out the causes of multipath signals and gain a visual understanding of the composition of multipath components. Primerano et al. used this method to analyze the characteristic of acoustic-electric channel [32]. However, in their model, the piezoelectric transducer and steel plate were regarded as fluids with different acoustic parameters. In fact, unlike fluids, both materials are solid in which not only compressional waves but also shear waves can propagate. Therefore, the model could only reflect the transmission of compressional waves in the channel, and the propagation of shear waves was not included, so the channel characteristic obtained was not accurate.

Comparison of the above simulation methods shows that the equivalent circuit method has the advantage that the channel can be seamlessly connected with the other circuits in the system, such as the

power supply circuits and matching circuits. Thus, it is more convenient to establish a model for the whole ultrasonic wireless communication system and conduct simulation analysis. The ABCD parametric method is used to model the channel in layers, so it is better suited to study the influences of the parameters belonging to each layer on the channel performance. The finite element analysis method can obtain the distribution of sound field in all parts of the channel, while the time-domain finite difference method can analyze the propagation of acoustic waves in the channel. In practical applications, these methods can be selected according to the actual need.

4 Algorithms for Ultrasonic Wireless Communication through Metal Barriers

The acoustic-electric channel has evident characteristic of multipath transmission, which will cause serious distortion after the transmission of signal, resulting in inter-symbol interference. Meanwhile, it is noted that large delay expansion will bring the inter-symbol interference covering several symbols, leading to the large multipath delay in the channel (usually several hundred microseconds). If the symbol rate is 5 MHz, the delay expansion of 20 μ s will cause 1 symbol to interfere with the subsequent 100 symbols. In this view, it is necessary to resort to certain methods to resist the effect of multipath effect. In the early stage, the research on algorithms for ultrasonic wireless communication through metal barriers mainly focused on a single carrier, and most did not include channel estimation and equalization algorithms, so the influence of multipath effect made it difficult to achieve higher rate. For example, references [7] and [8] mainly used amplitude modulation, reference [6] mainly used phase modulation, and reference [41] mainly used frequency modulation. With the single-carrier method, the communication rate was basically limited to the order of tens of kbps. In order to improve the communication rate, communication architectures effectively resisting the multipath effect are needed, and the representative algorithms include the OFDM algorithm, SC-FDE algorithm and MIMO-OFDM algorithm. These algorithms are introduced in the subsections.

4.1 The OFDM Algorithm

The basic idea of the OFDM algorithm is that the transmitter modulates the baseband signal on a series of orthogonal subcarriers, each of which has relatively flat frequency response; hence on the receiver side, only the amplitude and phase of each subcarrier need to be adjusted for equalization [13,32]. A typical OFDM-based ultrasonic wireless communication system is shown in Fig. 5. A suitable symbol encode method is adopted to modulate the binary bit stream to be transmitted. The encoded serial data stream is then divided into blocks, inserted into a training sequence, and sent to the inverse fast Fourier transform (IFFT) module before the baseband processing is completed when the IFFT output has gone through the serial-to-parallel conversion and added with the cyclic prefix (CP). Next after the up-conversion, the signal is sent to the channel and transmitted to the receiving terminal, where after the down-conversion, the signal is recovered to the baseband. In the process of down conversion, there may be inconsistency in the frequency and phase between the local carrier at the receiving terminal and the carrier in the received signal, so it is necessary to estimate and correct the carrier frequency offset through sequence training. At the same time, frame synchronization and symbol synchronization are also completed through sequence training, so as to find the block arrival time and the decision time before the completion of channel estimation. After then, the CP is removed from the serial data stream of the data block and sent to the fast Fourier transform (FFT) module in parallel. Finally, the calculated results go through the parallel-to-serial conversion, and equalization of the channel is achieved by means of a certain equalization method, and then the binary bit stream is recovered by decoding.

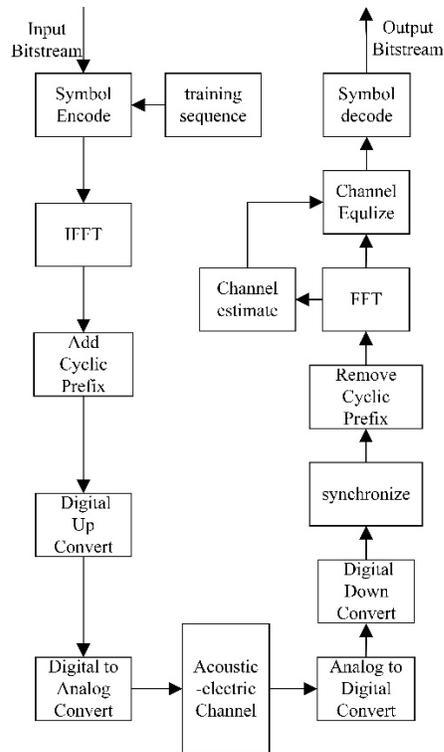


Figure 5: The architecture of the OFDM-based ultrasonic wireless communication system through metal barriers

Both Lawry et al. and Primerano et al. have studied the OFDM-based algorithms for ultrasonic wireless communication through metal barriers. Lawry et al. used the OFDM and a pair of piezoelectric transducers with center frequency of about 4 MHz to penetrate a 6.35-cm thick steel plate, and the communication rate of 17.37 Mbps is obtained [18]. Primerano et al. combined the OFDM technology with the bit-loading and power-loading technology to reduce the effect of frequency sag in the channel on the bit error rate (BER) performance [32]. These studies focused on such algorithms as the codec, modulation and demodulation, and equalization algorithms, but did not consider synchronization algorithms sufficiently. For a practical OFDM-based system for ultrasonic wireless communication through metal barriers, carrier synchronization, frame synchronization and symbol synchronization are all important: the OFDM system is sensitive to the carrier frequency offset, and the absence of suitable carrier synchronization algorithm will lead to a significant increase in the BER; frame synchronization and symbol synchronization are the basis of symbol detection, so they are inevitable for a digital communication system with block transmission. Therefore, it is necessary to study the synchronization algorithms for ultrasonic wireless communication through metal barriers.

4.2 The SC-FDE Algorithm

The SC-FDE algorithm originates from the following basic idea: on the transmitter side, a single carrier is modulated, and on the receiver side, with the aid of the fast Fourier transform and the inverse transform, the frequency-domain equalization is accomplished to resist the effect of multipath effect. Compared with the time-domain equalization, the SC-FDE algorithm uses block processing and the fast Fourier transform is introduced to lower the computational complexity to an acceptable degree [47-51].

The typical architecture of an SC-FDE system is shown in Fig. 6. On the transmitter side, a suitable symbol encoding method is adopted to modulate the binary bit stream to be transmitted. The modulated serial data stream is divided into blocks and inserted into a training sequence named unique word (UW)

before the completion of the baseband processing, and then sent to the acoustic-electric channel after the up-conversion. The received signal is then converted down to the baseband on the receiver side, and packet detection is performed to find the frame header for each frame. After the parallel-to-serial conversion, each block of data is sent to the FFT, and the channel parameters are estimated in the frequency domain. After the equalization processing, the results are converted into the time domain after the IFFT operation. Finally, the decision and decoding are performed to recover the final results into binary bit streams.

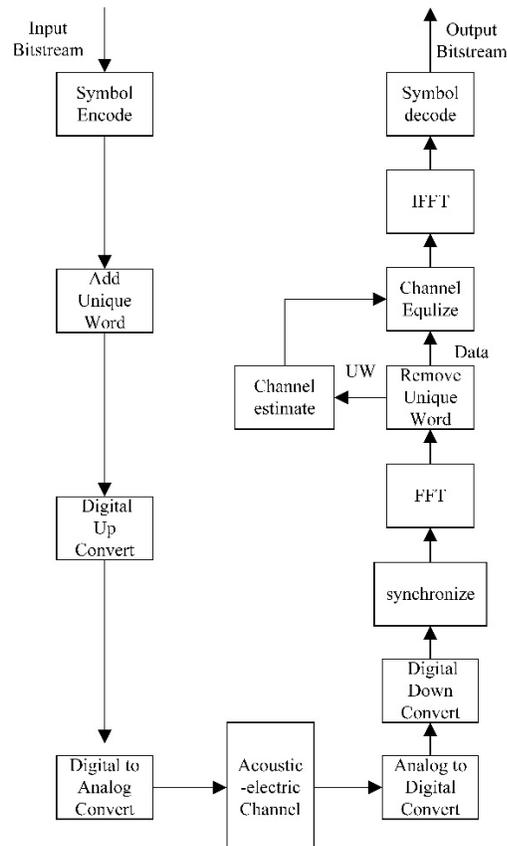


Figure 6: The architecture of the SC-FDE based ultrasonic wireless communication system through metal barriers

In 2014, the Noise and Vibration Lab, Institute of Acoustics, Chinese Academy of Sciences introduced the SC-FDE method to the field of ultrasonic wireless communication through metal barriers [47]. Compared with the OFDM, this method has such advantages as having low power peak and low sensitivity to the carrier frequency offset, and system complexity concentrated on the receiver side. It is expected to have more advantages than the OFDM-based ultrasonic wireless communication in some application scenarios. In 2015, based on the FPGA and DSP, the authors designed a prototype system for ultrasonic wireless communication through metal barriers using the SC-FDE algorithm, and data transmission were realized at 500 kbps data through 0~7 cm thick steel plates. The reliability of the algorithm was also verified [48].

4.3 The MIMO-OFDM Algorithm

According to the Shannon formula, an SISO system has a capacity limit which cannot be surpassed in communication. No matter what technology is adopted, the limit can only be approached infinitely, but cannot be broken through. With the MIMO technology, several independent parallel channels can be

generated in the space, i.e., spatial multiplexing can be realized, so as to increase the efficiency of spectrum usage without increasing the bandwidth of the system. With the aid of OFDM technology, the acoustic-electric channel with multipath transmission characteristics can be transformed into several flat subchannels at each sub carrier in the frequency domain, thereby reducing the influence of the multipath effect on system transmission [16,17,28,29]. If the MIMO technology is combined with the OFDM technology, the advantages of both are expected to give full play, i.e., both the resistance to the multipath effect and higher data transmission rate. The typical architecture of an MIMO-OFDM ultrasonic wireless communication system is shown in Fig. 7. On the transmitter side, the binary bit stream is separated into M paths after the multiplexer processing. The signal of each path is modulated and sent to the IFFT module, and the processed result are added with the CP and sent to the channel. After transmission through the channel, the cyclic prefix is removed from each path of signal received on the receiver side and the FFT processing is then followed. Finally, the signal is equalized according to the estimated channel transfer matrix, and the processed results are recovered by a demultiplexer into a binary bit stream.

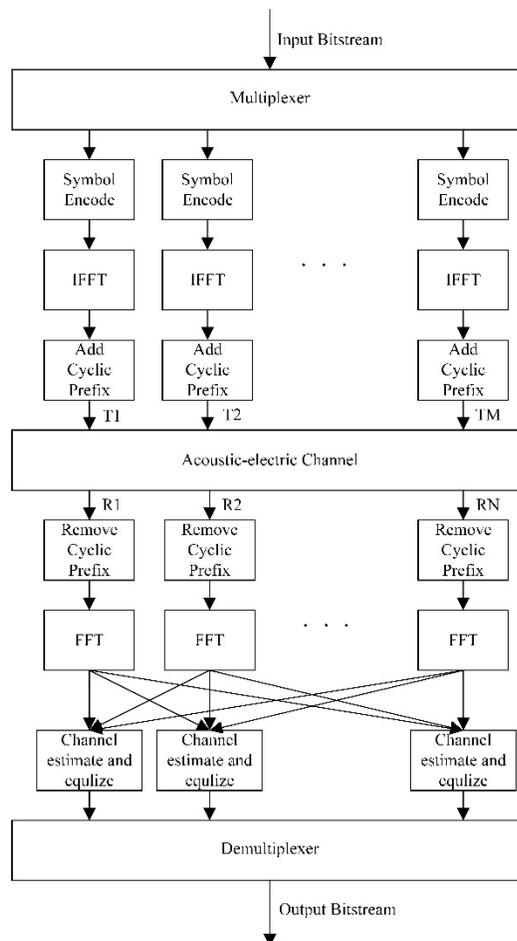


Figure 7: The architecture of the MIMO-OFDM ultrasonic wireless communication system through metal barriers

Since 2012, Ashdown et al. has used multiple piezoelectric transducers to form 2×2 and 7×7 MIMO systems, and tested and simulated the acoustic-electric channel of the 7×7 MIMO system, in which a theoretical communication rate of 700 Mbps can be achieved [16,17,28,29]. Their studies focused on the MIMO-OFDM signal detection algorithm, and proposed that the signal detection in a MIMO system for

ultrasonic wireless communication through metal barriers can be realized by means of such methods as eigen-mode transmission, zero forcing detection and minimum mean square error detection [17,29]. However, these studies did not sufficiently examine the channel estimation algorithms, which are particularly important to a MIMO system. The channel estimation algorithm is the first step in signal detection; without suitable channel estimation algorithm, signal detection cannot be carried out.

5 Discussion

Based on the results of previous studies, it is believed that the following research directions are worth further exploring in the field of ultrasonic wireless communication through metal barriers:

(1) As regards channel modeling, a model of the whole acoustic-electric channel is needed. For example, in practical applications, some coupling agents or adhesives are often applied between piezoelectric transducers and metal barriers, which need to be taken into account. In addition, most commonly used piezoelectric transducers have composite structures mainly consisting of three parts, including the backing, piezoelectric film and protective film. The backing and protective film are also suggested to be considered in channel modeling.

(2) As regards communication algorithms, most existing studies focused on the acoustic-electric channel with a certain configuration (some thickness of steel plate, or some coupling way), measured the channel characteristic, and then designed the algorithm architecture. Therefore, the designed algorithm is not universal; when the channel parameters change over the time, the algorithm cannot be adapted to the variation of channel. Hence, in future studies, the development of an algorithm is expected with a certain degree of adaptability to channel variations.

(3) There is less work on the MIMO-based ultrasonic wireless communication through metal barriers. Channel estimation and channel equalization based on the channel characteristic of a MIMO system for ultrasonic wireless communication through metal barriers need to be studied. The current research is mainly based on the MIMO-OFDM, and it is of particular interest to find out whether other forms of MIMO can achieve effective results.

(4) The time-domain impulse response of the acoustic-electric channel shows some sparsity. How to use this characteristic to improve the efficiency of channel estimation is a good research question.

(5) The acting of piezoelectric transducer on metal over long time may cause metal fatigue. When metal fatigue occurs, further study is needed on the variations of channel parameters.

(6) The study of a composite-type piezoelectric channel is required. In practical applications, the metal shell may not be a single layer structure, but a composite structure. In this circumstance, the problems associate with the channel characteristic and the communication algorithm need to be solved.

6 Conclusions

This paper first reviews the previous studies conducted by several representative research groups in the field of ultrasonic wireless communication through metal barriers, and summarizes their achievements and the existing problems. An overview of the research methods for the analysis of the characteristic of acoustic-electric channel is subsequently presented. The principles and application scenarios are introduced in more details for the actual measurement method, equivalent circuit method, ABCD parameter method, finite element analysis method and time-domain finite difference method. An overview of the algorithms for ultrasonic wireless communication through metal barriers are then presented. The OFDM, SC-FDE and MIMO-OFDE communication algorithms are introduced, which can effectively resist the multipath effect and obtain higher transmission rate. Finally, the potential directions of future study are proposed in light of the trend of development and unsolved problems in the field of ultrasonic wireless communication through metal barriers.

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