Ultrasonic Wireless Communication in Air using OFDM-OOK Modulation

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***Abstract*—A short-range multi-channel airborne ultrasonic data communication system using orthogonal frequency division multiplexing (OFDM) is described in this paper. An on-off keying (OOK) based OFDM modulation scheme was implemented successfully in the system by using a pair of commercially available air-coupled capacitive ultrasonic transducers. 56 orthogonal channels with a channel spacing of 1 kHz were transmitted in parallel, achieving a data transfer rate of 56 kbps with ultrasonic wireless synchronization. A simulation model developed in the work was able to predict ultrasonic signals accurately through the air channel. System performance was characterised by bit error rate (BER) testing over different transmission ranges. Error free decoding was achieved at distances up to 3 m.**

Keywords*— *air-coupled ultrasound; capacitive ultrasonic transducer; ultrasonic communication; wireless synchronization

I. Introduction

Ultrasound may be used for short-range wireless communication in air as an alternative to radio frequency (RF) based solutions. It has several advantages over RF in that ultrasonic transmissions are unregulated and interference free to most electronic devices. Ultrasonic signals in air also provide good privacy as they are difficult to intercept through solid barriers, thus increasing network security in an indoor environment. For example, a commercial ultrasonic system Shopkick [1] has been successfully used for a few years. Exclusive deals carried by ultrasonic signals sent from beacons installed in the partner stores are detected by customers' mobile phone microphones. Therefore, member users can only acquire electronic vouchers by physically walking into the stores. However, due to hardware restrictions of current mobile phone microphones, only token signals containing limited information can be transmitted. Previous work has achieved ultrasonic communication via single-channel modulation schemes including on-off keying (OOK), binary frequency shift keying (BFSK) and binary phase shift keying (BPSK) using prototype broad-band air-coupled ultrasonic transducers to produce data transfer rates of up to 83 kbps with a bandwidth efficiency of 0.41 bps/Hz over limited ranges [2]. A later study implemented quadrature modulation method using similar airborne ultrasonic transducers and achieved a bit rate of 200 kbps with an improved spectral efficiency of 0.57 bps/Hz over a distance of 1.2 m in air [3].

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In this work, a parallel-channel modulation method was investigated in both simulation and experiment. A pair of commercially available ultrasonic transducers with a nominal frequency of 50 kHz were used to achieve the highest data rate possible over longer distances within the available transmission bandwidth.

II. Modulation Scheme

The idea of a multi-carrier system is to use many carrier waves over different frequency channels within the available bandwidth instead of only one, and using each carrier wave for part of the message. In a traditional frequency division multiplexing (FDM) system, the sub-channels are non-orthogonal and separated by guard bands to prevent inter-channel interference [4], resulting low spectral efficiency. The orthogonal frequency division multiplexing (OFDM) scheme overlaps individual carriers, yet ensures the carriers are orthogonal. This method can significantly improve bandwidth efficiency. In the spectrum of a typical OFDM signal, the main lobe of each carrier lies on the nulls of the other carriers. Therefore, at each sub-carrier frequency, there is no interference introduced from any other adjacent sub-channels, and the inter-carrier guard bands are not required. To maintain the orthogonality, channels are separated at a spacing equal to the bit rate of the data message. Sub-carriers over each channel are then OOK modulated before being added together into a single waveform.

III. Experimental Set-up

The OFDM-OOK modulation scheme was investigated using an experimental set-up shown in Fig. 1. The transmitter and receiver are a pair of commercially available SensComp series 600 ultrasonic transducers [5], specially designed for operation in air at an ultrasonic frequency of 50 kHz with a beam angle of 15° at -6 dB. The data to be transmitted were encoded and modulated using MATLAB (MathWorks) on a PC before being sent to a TTi TGA12102 arbitrary waveform generator via a GPIB interface. The signal was then amplified by a Falco WMA-300 high voltage amplifier, and combined with a bias voltage of +200 V generated by a Delta Elektronika SM3004-D power supply. The receiver was connected to a Cooknell CA6/C charge amplifier powered by

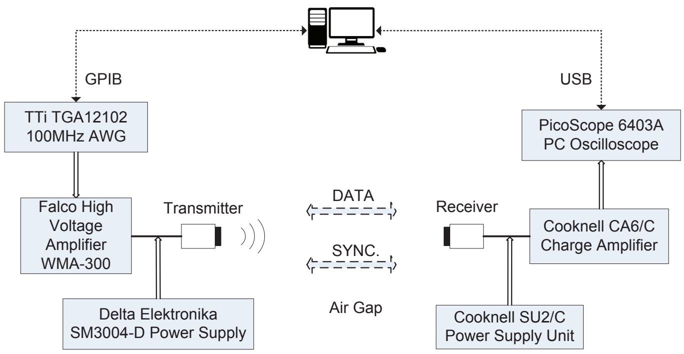

Fig. 1. Experimental set-up for a prototype ultrasonic communication system.

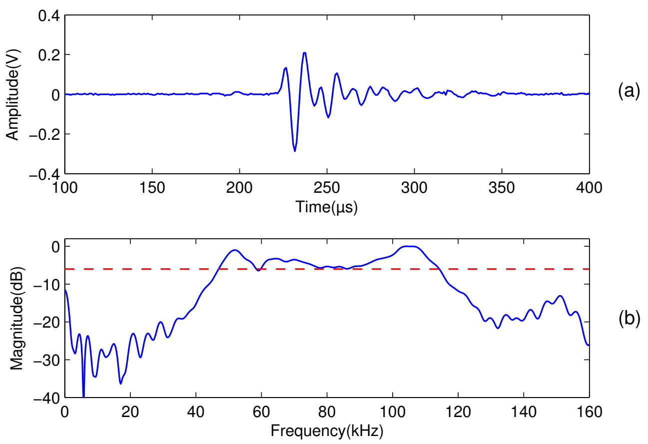

Fig. 2. System characteristics: (a) impulse response and (b) frequency response.

a Cooknell SU2/C power supply unit, and followed by a high performance PicoScope 6403A PC oscilloscope. After that, the received signal was then sent to the same PC through a USB interface for signal processing.

The system was characterised by both its impulse response and frequency response over 1 m as shown in Fig. 2(a) and (b). As can be seen from Fig. 2(b), the system has a prominent response across frequencies from 45 kHz to 115 kHz. In terms of 6-dB attenuation, the potential usable bandwidth is about 67 kHz.

IV. Simulation Method

The ultrasonic signal generated by a plane circular piston oscillator and transmitted across an air gap can be simulated using three filters: atmospheric absorption filter, beam spreading filter and transducer response filter.

A. Atmospheric absorption filter

Absorption of sound through the atmosphere is described by several mechanisms: shear viscosity, thermal conductivity, and molecular relaxation due to oxygen and nitrogen rotation and vibration [6]. A classical absorption component due to viscosity and heat conduction together with rotational absorption is a function of temperature, pressure and frequency, and can be expressed as:

$$\alpha_{cr} = 1.59 \times 10^{-10}(T/T_0)^{1/2} f^2/(P/P_0) \tag{1}$$

in dB/m. Here, P_0 is the standard atmospheric pressure, and P is the measured pressure. T_0 and T are standard atmospheric temperature and measured temperature respectively. f represents sound frequency. The vibrational attenuation constant for oxygen and nitrogen molecules can be written as:

$$\alpha_{vib,O,N} = f^2[1.11 \times 10^{-1}(T_0/T)^{5/2} \frac{e^{-2239.1/T}}{f_{r,O} + f^2/f_{r,O}}$$

$$+9.285 \times 10^{-1} \frac{e^{-3352/T}}{f_{r,N} + f^2/f_{r,N}}] \tag{2}$$

in dB/m, where

$$f_{r,O} = (P/P_0)(24 + 4.41 \times 10^4 h \frac{0.05 + h}{0.391 + h}), \tag{3}$$

$$f_{r,N} = (P/P_0)(T/T_0)^{-1/2}$$

$$\times\{9 + 350he^{-6.142[(T/T_0)^{-1/3}-1]}\}. \tag{4}$$

$f_{r,O}$ and $f_{r,N}$ are scaled relaxation frequencies for oxygen and nitrogen in Hertz, and h is the absolute humidity which is calculated as:

$$h = h_r(P_{sat}/P) \tag{5}$$

in percent, where h_r is the relative humidity for a given sample of moist air under pressure P and at a temperature T, and P_{sat} is the saturation vapour pressure of pure water at the same temperature T. The factors which contributed to the absorption coefficient in the simulation were set at $P = P_0 = 1$ atm, $T = T_0 = 293.15$ K (20°C), and $h_r = 70\%$.

B. Beam spreading filter

Due to diffraction effects, it is also necessary to consider the beam spread issue over different transmission distances. Depending on the range, different amounts of the transmitted energy will be intercepted by the receiver. The beam spread angle θ for a circular transducer can be approximated by [7]:

$$sin(\theta/2) = 1.22\lambda/D, \tag{6}$$

where λ is the ultrasonic wavelength and D is the aperture of the ultrasonic transducer. It is clear from equation (6) that ultrasonic beams are more diverged when transmitting a low frequency signal. Therefore, an identical receiver transducer with the same diameter as the transmitter transducer receives less energy from a low frequency signal than from a high frequency signal regardless of ultrasonic absorption in air. The received signal energy can then be calculated in terms of the ratio of the transducer radius and the beam spread radius.

C. Transducer response filter

For a typical capacitive transducer, the resonant frequency is a function of atmospheric pressure, density of the membrane, and the thickness of both the membrane and the air-gap [8], [9]. However, the accuracy of the theoretical prediction is affected by many factors. To simplify the simulation, an impulse signal was sent from the transmitter, and with the minimum separation of the receiver transducer, the transducer frequency response was then calculated based on the impulse signal captured by the receiver. According to SensComp data [5], the frequency responses are presented differently when the transducer is operated as a transmitter and a receiver. But in this work, an over-all transducer frequency response was used in the simulation. This system frequency response can then represent the transducer response over different frequencies without taking diffraction and absorption losses into account.

V. Results

To minimise the influence of both low frequency noise and high frequency absorption, channels ranging from 50 kHz to 105 kHz were used in the experiment. The duration of each bit was set to 1 ms so that the channel spacing was 1 kHz in order to maintain orthogonality. Therefore, 56 channels can be fitted within the available bandwidth, and the system transfer rate achieved was 56 kbps. A synchronization signal was added to the front for ultrasonic triggering of the oscilloscope. This removed the need for a hard-wired trigger. As can be seen in Fig. 3, the trigger impulse has an amplitude larger than the amplitudes of both the reference signal and data signal so that the oscilloscope could reliably trigger from a higher amplitude. The reference signal was generated with all '1's OOK modulated over each channel and placed before the data signal to help with decoding. Zeros were padded between each signal packet to avoid energy leaking and also help to distinguish different types of signals.

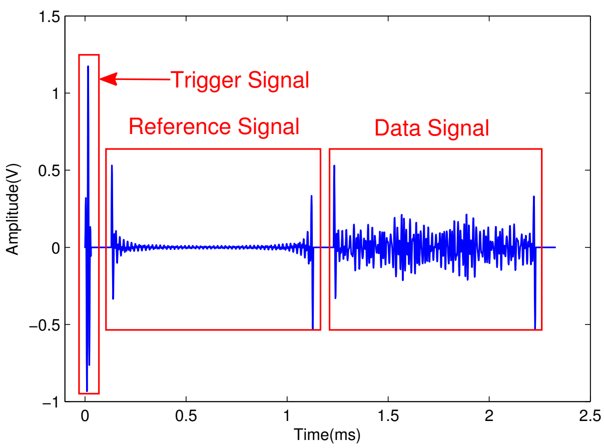

Fig. 3. Transmitted signal including trigger signal, reference signal and data signal.

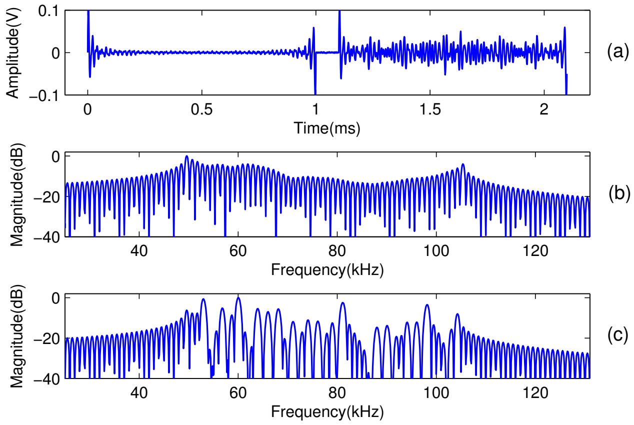

Fig. 4. Simulated OFDM signal: (a) time domain OFDM signal, (b) spectra of the reference signal and (c) spectra of the data signal.

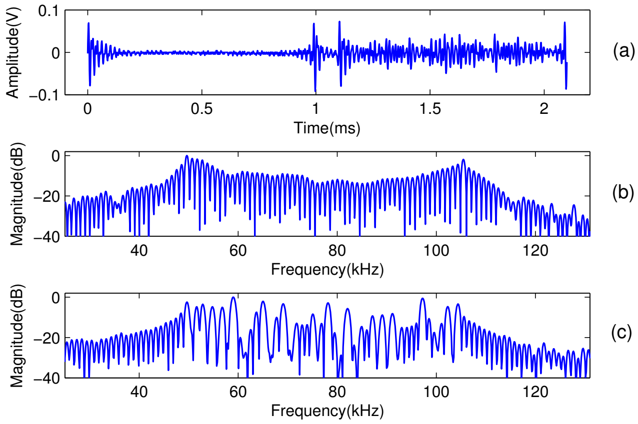

Fig. 5. Experimental OFDM signal: (a) time domain OFDM signal, (b) spectra of the reference signal and (c) spectra of the data signal.

The simulated OFDM signal and experimental OFDM signal are shown in Fig. 4(a) and Fig. 5(a) respectively. As can be seen, the simulated and experimental signal have a good agreement in the time domain. However, in the experimental signal, the energy leaking from the peaks at both the start and the end of the reference signal is obvious as the membrane keeps resonating when a high amplitude occurs. Additive white Gaussian noise (AWGN) was added to the simulation model to make it closer to the real conditions. The spectra of the simulated and experimental signal for both reference and data are also compared in Fig. 4 (b), (c) and Fig. 5 (b), (c) respectively. The side-lobes of the simulated reference signal spectra are higher when compared with those of the experimental reference signal spectra while the spectra of data signal are almost the same, as the peak to average power ratios (PAPR) of the data signal are relatively low. Over transmission distances ranging from from 1 m to 4 m with a step of 0.25 m, the root mean square (RMS) values of the experimental OFDM signal can be accurately predicted by the simulation model as Fig. 6 shows. It indicates that the model can be used to simulate other modulation schemes and predict received

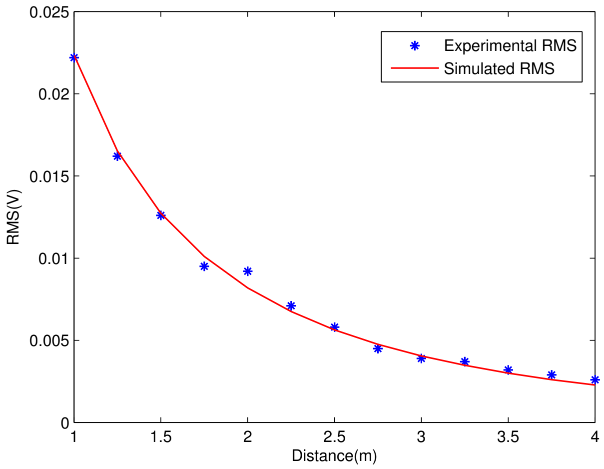

Fig. 6. Comparison of experimental OFDM signal RMS values with simulation over different ranges.

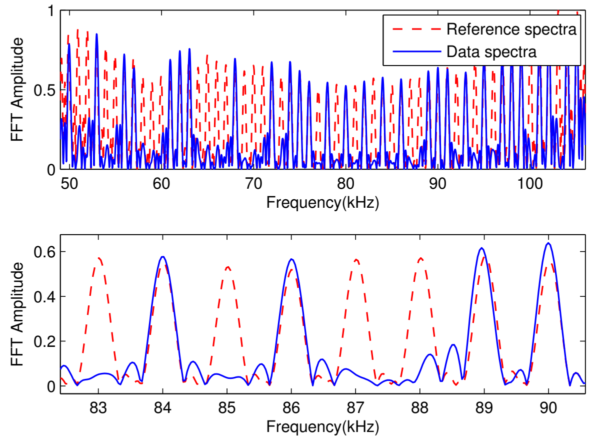

Fig. 7. Overlaid spectra of reference signal and data signal: (a) overlaid spectra over all frequency bands, and (b) a close-up view of the overlaid spectra.

signals through an air gap.

After the signals were captured by the oscilloscope and loaded to MATLAB, two spectra of reference signals and data signals were both normalised with respect to the maximum value of the reference spectra and overlaid as shown in Fig. 7 (a). A close-up view for spectra from 83 kHz to 90 kHz is presented in Fig. 7 (b). As can be seen, a comparison of the data spectra level with the reference spectra level over each channel produced a correct decoding result of '01010011'.

To further investigate the reliability of the system, it was necessary to look at the bit error rate (BER) of the OFDM-OOK modulation scheme over different ranges. Therefore, 800 packets of six 56-bit random binary streams were generated and transmitted continuously through the air channel. BER information was recorded over transducer separations of up to 4 m with an increment of 0.25 m. The process was repeated 10 times, and the results were then averaged. The system

TABLE I
BIT ERROR RATE AT DIFFERENT RANGES

Distance (m)	Bit error rate
3	0
3.25	6.7×10^{-6}
3.5	8.93×10^{-6}
3.75	5.36×10^{-5}
4	6.25×10^{-5}

produced error-free transmission up to 3 m. More details of errors at different ranges are shown in Table I. As can be seen, the system started to experience error decoding at a range of 3.25 m, and the BER increases rapidly beyond that range. At 4 m, the system reached a BER of 6.25×10^{-5}.

VI. CONCLUSION

This work has shown that short-range ultrasonic communication using an OFDM-OOK modulation scheme is practical in both simulation and experiment. By using a pair of commercially available air-coupled ultrasonic transducers with a nominal frequency of 50 kHz, the maximum data rate achieved was 56 kbps, with 56 parallel orthogonal channels being represented by 1 ms duration time signal. The simulation model developed in the work could precisely predict ultrasonic signals through an air gap. All results were based on multi-channel transmission within frequencies from 50 kHz to 105 kHz in terms of 6 dB bandwidth, and the spectral efficiency was 0.84 bps/Hz. System performance was analysed by BER tests over different transmission ranges. Error-free transmission over distances up to 3 m was achieved at 56 kbps. Future studies will focus on developing a full-duplex, two-way ultrasonic communication system, and effects such as reflection, diffraction and multi-path interference will also be taken into consideration.

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