Indoor Wireless Communication Using Airborne Ultrasound and OFDM Methods

Wentao Jiang and William M. D. Wright
School of Engineering - Electrical and Electronic Engineering
University College Cork, Cork, Ireland
Email: w.jiang@umail.ucc.ie, bill.wright@ucc.ie

Abstract—**Concerns still exist over the safety of prolonged exposure to radio frequency (RF) wireless transmissions and there are also potential data security issues due to remote signal interception techniques such as Bluesniping. Airborne ultrasound may be used as an alternative to RF for indoor wireless communication systems for securely transmitting data over short ranges, as signals are difficult to intercept from outside the room. A pair of off-the-shelf air-coupled capacitive ultrasonic transducers with a centre frequency of 50 kHz was used in the implementation of an indoor airborne wireless ultrasonic communication system. Binary phase-shift keying (BPSK), quadrature phase-shift keying (QPSK) and quadrature amplitude modulation (QAM) based orthogonal frequency division multiplexing (OFDM) modulation methods were successfully implemented using multiple orthogonal subchannels. The maximum system data rate of up to 180 kb/s was achieved using 16-QAM modulation with ultrasonic channels from 55 kHz to 99 kHz, over an error-free line-of-sight transmission distance of 6 m. The spectral efficiency achieved was 4 b/s/Hz. The transmission range with no measurable errors could be extended to 9 m and 11 m using QPSK and BPSK modulation schemes, respectively. The achieved data rates for the QPSK and BPSK schemes were 90 kb/s and 45 kb/s using the same bandwidth.**

Keywords*— *air-coupled ultrasound; capacitive ultrasonic transducers; multiple parallel channels; orthogonal frequency division multiplexing (OFDM); ultrasonic communication

I. INTRODUCTION

Radio frequency (RF) based wireless technologies have become prolific in the last few decades. The use of the RF spectrum is strictly regulated to prevent interference between different communication systems [1]. This partly constrains the system flexibility in allocating spectrum resources. In addition, due to the radiative and penetrative nature of RF communications, the signals can be easily intercepted remotely [2], therefore limiting their ability to provide a secure system to ensure confidentiality of information. Furthermore, RF transmissions are inappropriate in some circumstances where communication is required, such as inside intrinsically safe industrial environments. Long term exposure to RF radiation is also considered as a potential threat to public health as the World Health Organization classifies the emitted RF electromagnetic fields as a possible human carcinogen [3]. In 2015, the National Assembly in France passed a bill prohibiting the installation of Wi-Fi equipment in areas dedicated to the activities of children under 3 years of age [4].

Unlike RF communications, ultrasonic transmissions use unregulated frequency bands, and can be implemented in relatively simple and low-cost fashion. They may also be a good alternative to RF methods in circumstances where radio emission is prohibited. On the other hand, ultrasonic signals in air are highly localised and do not penetrate easily through solid materials, therefore eliminating unwanted external intervention. The medical experience of therapeutic and diagnostic ultrasound in the last few decades has shown that the use of ultrasound is harmless, as long as the overall acoustic output intensity is limited to safe levels, preventing hazardous bioeffects such as heating and cavitation in tissues [5]. Therefore, the use of ultrasonic technology in wireless communications can be considered as an alternative to RF systems for transmitting data more securely.

The use of ultrasonic waves as means of signal transmission in air has been investigated previously by several authors. Ultrasonic data was successfully transmitted and received across a 3-m distance through air at 31 kHz, with a system rate of 75 b/s in [6]. In [7], an indoor data communication system was developed by transmitting 40 kHz frequency-shift keying (FSK) modulated ultrasonic signals. The system achieved a functional range of 10 m with a data rate of 100 b/s. Later work has studied ultrasonic communications over a short distance of 0.5 m using multiple-channel amplitude-shift keying (ASK) and ON-OFF keying (OOK) modulations with a carrier frequency of 250 kHz [8]. In this work, a pair of laboratory-made prototype ultrasonic transducers was used, achieving a system transfer rate of 80 kb/s. In [9], the authors compared the performances of OOK, binary frequency-shift keying (BFSK) and binary phase-shift keying (BPSK) modulation schemes used for transmitting ultrasonic signals across an air gap. The maximum system bit rate used was 83 kb/s at a range up to 1.6 m without decoding errors. Another later study by the same authors has looked at the implementation of quadrature phase-shift keying (QPSK) modulation at a higher bit rate of 200 kb/s over 1.2 m [10]. Fig. 1 compares the above airborne ultrasonic data communication systems in terms of their data rates and attainable transmission ranges. As can be seen, the previous systems have suffered from either limited

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This work was supported by Science Foundation Ireland (SFI) Research Frontiers Programme grant number 11/RFP.1/ECE3119.

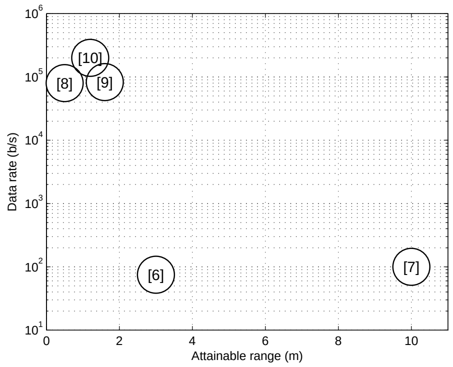

Fig. 1. Comparison of different airborne ultrasonic data communication systems and their data rates at attainable transmission ranges.

data rates or short transmission ranges. The aim of this work was to investigate more efficient and reliable airborne wireless ultrasonic communication methods using advanced orthogonal frequency division multiplexing (OFDM) modulation algorithms, achieving more practical transmission ranges in an indoor environment. In Section II, the implementation of the OFDM system including signal modulation, demodulation and synchronization technique is described. This is followed by the apparatus used and experimental layout of the work in Section III. Section IV and Section V give the experimental results and the conclusions, respectively.

II. SYSTEM DESCRIPTION

A. OFDM modulation and demodulation

OFDM is a multicarrier multiplexing method that distributes data over a number of equal-bandwidth narrow frequency channels. To maintain the orthogonality among all the subcarrier signals over the symbol duration T_s, the symbol rate $1/T_s$ was chosen to be equal to the separation f_d of the neighbouring subcarriers. The use of orthogonal subcarriers allows subchannel spectra to overlap, thus eliminating unnecessary guard bands and significantly increasing the spectral efficiency. A typical baseband OFDM signal, $s(t)$, can be expressed as the sum of N modulated subcarriers

$$s(t) = \sum_{k=0}^{N-1} s_k e^{j2\pi k f_d t} \Pi(t), \tag{1}$$

$$\Pi(t) = \begin{cases} 1, & 0 < t \leq T_s \\ 0, & otherwise. \end{cases} \tag{2}$$

Here s_k represents the OFDM symbol. Each transmitted symbol s_k is assigned with one of M possible signal states, and can be denoted as $s_k \in [s^{(1)}, s^{(2)}, ..., s^{(M)}]$. For example, $M = 4$, if QPSK modulation is applied. $\Pi(t)$ represents a rectangular pulse with a duration of T_s. This rectangular window in the time domain produces a sinc-shape spectrum in the frequency domain which makes the subcarriers heavily overlap each other without any interference.

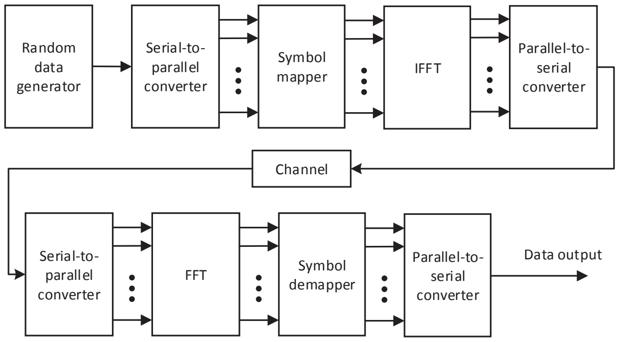

Fig. 2. Block diagram of OFDM modulation and demodulation.

The block diagram of OFDM modulation and demodulation is illustrated in Fig. 2. In practice, the encoded bits in series are mapped onto a modulation constellation producing complex values that represent the modulated subcarriers in parallel. The modulation and multiplexing can then be achieved digitally using an inverse fast Fourier transform (IFFT). The OFDM demodulation is virtually the inverse operation of the modulation. The fast Fourier transform (FFT) processing block transforms the OFDM symbols from the time domain to the frequency domain before demapping them to the according constellation patterns.

As OFDM is highly sensitive to frequency and phase noise, pilot symbols are added to the data packet. They are used to estimate the channel transfer function, and the inverse is applied to every subcarrier OFDM signal to compensate for the channel, so that OFDM can simplify the equalization process by turning the frequency-selective channel into a flat channel. During demodulation, the pilot subcarriers that were known by the receiver are used to correct the phase and amplitude of the received OFDM signals.

B. Time synchronization

Time synchronization is the first step before conducting demodulation and decoding at a receiver for any wireless communication system. Once an ultrasonic signal packet is detected, it is critically important for the receiver to identify the starting point of the arriving packet. A data-aided (DA) synchronization technique was used in this work. It is based on a known pilot signal being transmitted in front of the information data packets. As widely used in practical radar systems for range detection, a linear frequency modulation (LFM) signal whose frequency increases or decreases with time is used as the pilot for wireless synchronization [11]. By correlating the received signal with a known LFM signal through a matched-filter at the receiver, the highest peak of the matched-filtering output then indicates the first arrival of the transmitted signal.

III. APPARATUS AND EXPERIMENTAL LAYOUT

Most ultrasonic transducers used for airborne applications have a relatively narrow bandwidth to provide an acceptable data rate for wireless communications. There is a capacitive ultrasonic transducer [12] widely available commercially, originally designed by Polaroid as a range finder for autofocus

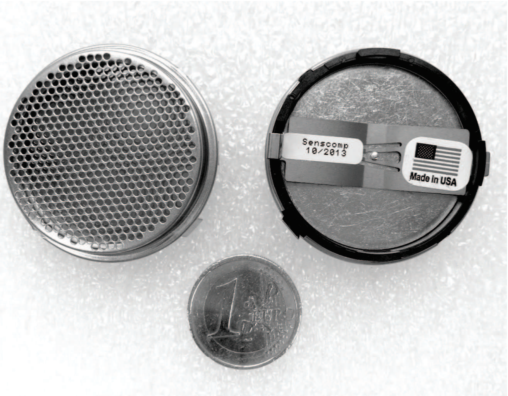

Fig. 3. SensComp series 600 environmental grade ultrasonic transducer.

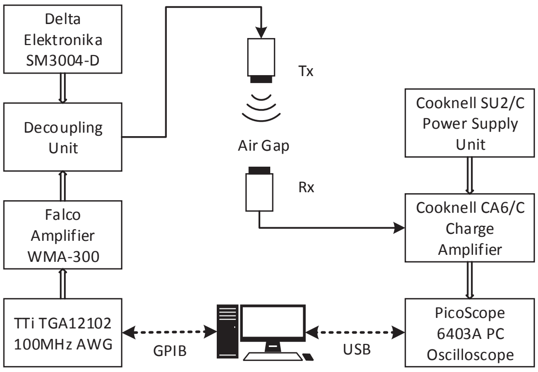

Fig. 4. Experimental setup for a prototype ultrasonic communication system.

cameras. The ultrasonic transducers used in this work, as shown in Fig. 3, are series 600 environmental grade with a prominent frequency of 50 kHz. These devices are composed of a gold foil coated polymer membrane and a rigid contoured aluminium backplate with an aperture size of 38.4 mm.

Fig. 4 illustrates the experimental setup of the ultrasonic communication system. The modulated data signal generated by a PC using MATLAB (The Math Works, Inc.) was uploaded to a TTi TGA 12102 arbitrary waveform generator (Thurlby Thandar Instruments Ltd.) through a GPIB interface before being amplified by a Falco WMA-300 amplifier (Falco Systems B.V.) and superimposed with a bias voltage of +200 V fed by a Delta Elektronika SM3004-D power supply (Delta Elektronika B.V.). The air-coupled ultrasonic signal was detected by a receiver transducer which connected to a Cooknell CA6/C charge amplifier (Cooknell Electronics Ltd.) with its SU2/C 100 V biasing unit. The voltage signal was then digitized by a PicoScope 6403A PC oscilloscope (Pico Technology), and sent back to the PC through a USB interface for the data analysis.

The system impulse response in the time domain and its corresponding frequency spectrum over a typical range of 2 m are shown in Fig. 5(a) and (b), respectively. As can be seen in Fig. 5(b), the spectrum peaks at about 50 kHz as expected with a dominant response extending to about 115 kHz. It indicates using data channels at ultrasonic frequencies from 46 kHz to 113 kHz is appropriate in terms of 6-dB bandwidth. The phase response of the system is nearly linear across the 6-dB bandwidth as shown in Fig. 5(c). It means that there is no phase distortion due to the time delay of frequencies relative to one another.

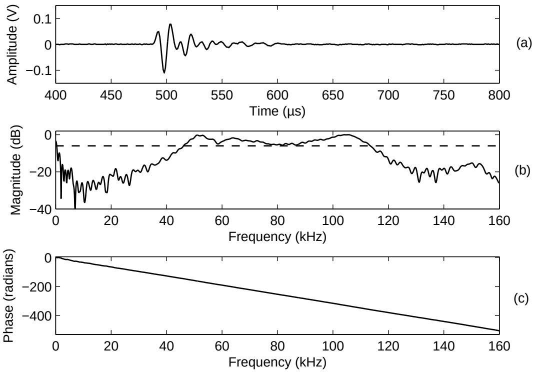

Fig. 5. System characteristics over 2 m: (a) impulse response; (b) frequency response; and (c) phase response.

TABLE I
PARAMETER SETTINGS OF THE OFDM SIGNAL

Parameters	**Settings**
Sampling rate	f_s = 10 MHz
Centre frequency	f_c = 77 kHz
Signal bandwidth	B = 45 kHz
OFDM symbol time	T_s = 1 ms
Subcarrier spacing	f_d = 1 kHz
Number of subcarriers	N = 45

IV. RESULTS

The experiment was carried out in an indoor laboratory with no detectable ultrasonic background noise. The centre normals of the transmitter and receiver transducers were laser aligned to provide a direct line-of-sight (LOS) transmission link. Parameter settings of the OFDM signal are listed in Table I. Three different baseband modulation methods, BPSK, QPSK and 16-QAM, were used to modulate the 45 subcarrier signals from 55 to 99 kHz, and their performances were evaluated and compared in the experiments. Note that Gray coding was used for generating both QPSK and 16-QAM symbols. This is to minimise the decoding error as every two adjacent symbols differs from each other by only one bit [13].

Initial separation of the transmitter and the receiver transducer was set at 1 m, and fed by different modulated signals with signal-to-noise ratios (SNRs) incremented in 1 dB steps from 5 dB to 18 dB. The resulting bit error rate (BER) characteristics in terms of SNR for the three modulation schemes are compared in Fig. 6. As expected, a gradual dropping of the BERs with the increase of SNR can be found from all three curves. Higher order modulation schemes have smaller noise margins, therefore requiring much larger SNRs to obtain the same level of BERs compared with low-order modulations. The bit errors of the OFDM signals using the

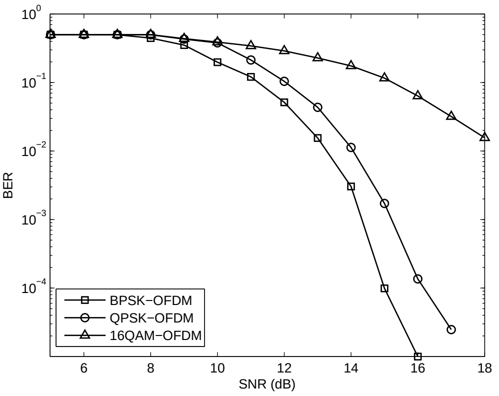

Fig. 6. BER performance of three different OFDM modulation schemes.

TABLE II
PERFORMANCES OF BPSK, QPSK AND 16-QAM MODULATIONS IN AN OFDM SYSTEM

	BPSK	QPSK	16-QAM
Error-free transmission range (m)	11	9	6
Overall system data rate (kb/s)	45	90	180
Bandwidth efficiency (b/s/Hz)	1	2	4

three modulation schemes were also measured experimentally with increased ranges. The maximum attainable transmission distances with no measurable errors as well as the achieved data rates for different modulation schemes are listed in Table II. As can be seen, the most reliable transmission link with no detected bit errors was up to 11 m using BPSK at a data rate of 45 kb/s. The error-free range was reduced to 6 m by using 16-QAM, however, at a largely increased system data rate of 180 kb/s. Table II also shows the corresponding bandwidth efficiencies for all three modulation schemes. As 16-QAM contains four bits for each transmitted symbol, the bandwidth utilization was four times more efficient than that of BPSK which uses only one bit per symbol.

To better visualise the received OFDM signal conditions before and after the phase noise correction and equalization, constellation diagrams of BPSK, QPSK and 16-QAM are given in Fig. 7. As can be seen from Fig. 7 (a) - (c), the signal constellations right after the demodulation process are completely corrupted as a significant amount of demapped symbols have drifted in both phase and amplitude. By analysing the received pilot signal which was previously known by the receiver, the phase and amplitude shifts due to the effect of the ultrasonic channel in air can then be compensated for before decoding. Fig. 7 (d) - (f) illustrate the three constellations after phase correction and channel equalisation. As can be seen, all constellations of BPSK, QPSK and 16-QAM are recovered and clustered around their target points.

V. CONCLUSION

As a highly efficient modulation scheme, OFDM has been investigated in this work for the implementation of an airborne ultrasonic communication system using off-the-shelf transducers. Baseband modulations used were BPSK, QPSK and 16-QAM, and their performances in terms of data rate, range and spectral efficiency were evaluated. The results have indicated that a 16-QAM modulation can be used to transmit ultrasonic signals in air at 180 kb/s over a range of 6 m in a LOS manner. It was also shown that the BPSK approach can provide the most reliable communication link up to 11 m at a reduced system transfer rate of 45 kb/s.

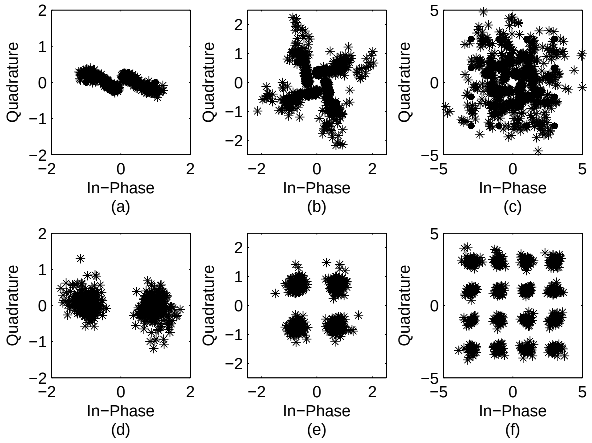

Fig. 7. Received OFDM constellations before (a) - (c) and after (d) - (f) phase noise correction and channel equalisation for BPSK, QPSK and 16QAM at 11 m, 9 m and 6 m, respectively.

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