Multi-Channel Indoor Wireless Data Communication Using High-*k* Capacitive Ultrasonic Transducers in Air

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

***Abstract*—This work has demonstrated multi-channel wireless communication using a pair of broadband high-*k* capacitive ultrasonic transducers. Modulated ultrasound was used to carry digitally coded data signal over short distances using Amplitude Shift Keying (ASK) and On-Off Keying (OOK) modulation schemes. The over-all system data rate achieved was up to 420 kbps with ultrasonic wireless synchronization. Signal-to-Noise Ratio (SNR) and bit error rate (BER) characteristics were analysed and compared between different modulation schemes. It was shown that OOK can be used to transmit signals with higher power efficiency and lower BER than ASK.**

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

I. Introduction

Recently, there has been increased interest in the use of modulated airborne ultrasound for short-range wireless communication instead of the radio frequency (RF) band. Ultrasound has several advantages over RF in that it produces no interference with other electronic devices and is inherently secure in an indoor environment as the transmissions are difficult to intercept from outside the room, thus increasing indoor wireless network security and preventing long range eavesdropping techniques such as Bluesniping [1]. Previous works using ultrasound have used various modulation schemes to produce data rates of up to 200 kbps over distances of a few metres [2]–[4]. The main limitations of the ultrasonic techniques are due to a lack, until recently, of ultrasonic transducers that can operate efficiently in air with sufficient sensitivity and bandwidth, which has limited the channel capacity of the system.

A pair of broad-band air-coupled capacitive ultrasonic transducers, with metallized PET membranes and pitted silicon backplates coated with a high-*k* HfO_2 dielectric layer for enhanced performance [5], was used in a prototype wireless ultrasonic data communication system to transmit modulated signals through multiple parallel channels. The channel responses were tested to determine the available transmission bandwidth. Amplitude Shift Keying (ASK) and other modulation schemes were then implemented successfully using the multiple channels. The capacitive ultrasonic transducers had a usable bandwidth of up to 1 MHz, allowing many parallel data streams to be sent simultaneously over short distances. Unlike previous work, the system was completely wireless, with synchronization achieved by ultrasonic means instead of a hard-wired link.

This work was supported by Science Foundation Ireland (SFI) Research Frontiers Programme grant number 11/RFP/ECE3199, and NAP award 225 from the Tyndall National Institute, UCC.

II. Modulation Scheme

In order to transmit baseband signals using airborne ultrasound, a carrier wave operating at an ultrasonic frequency is changed based on the information signal to be transmitted. One of the oldest and simplest modulation schemes is Amplitude Shift Keying (ASK) [6]. In ASK, only the amplitude of the carrier is changed in response to the information signal and all other parameters are kept constant. Generally, a higher carrier amplitude and a lower carrier amplitude are switched over the symbol period to present bit '1's and '0's. On-Off Keying (OOK) is a special form of ASK, where one of the amplitudes is zero. Since wide-band ultrasonic transducers are used, multiple channels over different frequencies may be added together to give a single ultrasonic signal, thus increasing the band efficiency and data rate.

III. Numerical simulation

It is instructive to simulate ASK and OOK in a computer model before performing any experiments. The simulation of both modulation schemes used the ultrasonic band from 100 kHz to 835 kHz. Therefore, with 15 kHz intervals, 50 channels can be transmitted simultaneously. The data signal was encoded and modulated using MATLAB. The attenuation of ultrasound can be approximated by the following expression [7]:

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

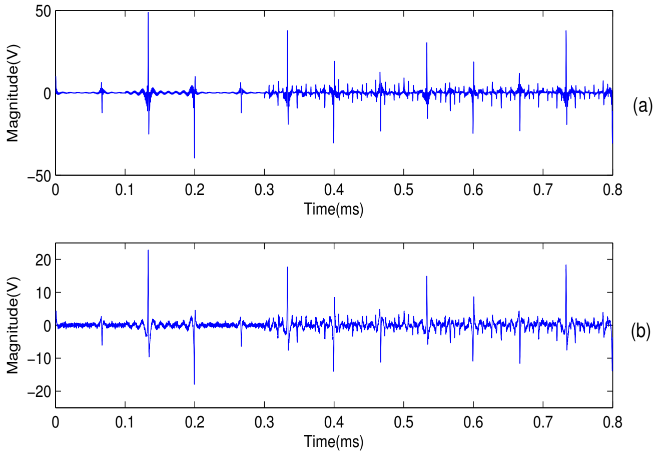

Fig. 1. ASK scheme:(a) Simulated signal and (b) simulated received signal.

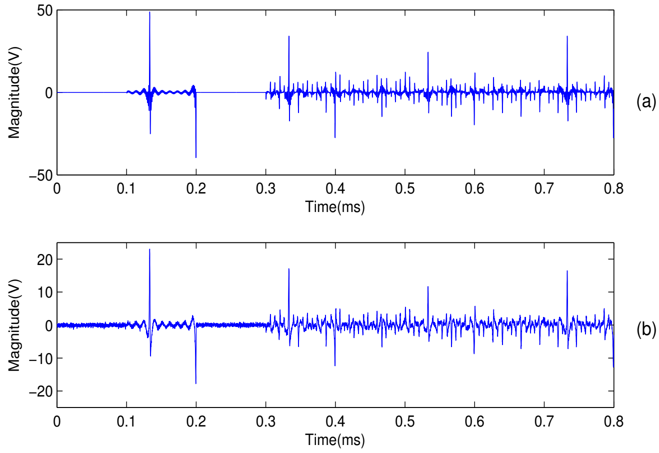

Fig. 2. OOK scheme:(a) Simulated signal and (b) simulated received signal.

where f is the operating frequency and d is the propagation distance. Two factors were considered when simulating. One is additive white Guassian noise (AWGN), the other is the attenuation of ultrasound in air. Fig.1(a) shows the modulated ASK signal before transmission. Fig.1(b) shows the simulated received signal with AWGN and attenuation. The Signal-to-Noise Ratio (SNR) for the received signal is at an arbitrary level of 20 dB and the separation of two transducers was 20 cm. Similar graphs for OOK simulation of the same data are shown in Fig.2.

After the received signal was generated, it was band-pass filtered by a Butterworth filter to extract different frequency channels. A zero-phase filter was implemented by processing the input data in both forward and reverse directions. The signal waveform of a filtered channel representing the letter 'Y' is illustrated in Fig. 3(a). Visually, the peaks of this signal can be identified to distinguish bits at logic high. The filtered signal was then envelope detected using the Hilbert transform [8]. Fig.3(b) shows the plotted envelope by taking its absolute value. After that, the energy under the curve over each bit period was normalized and compared with a threshold value as Fig.3 (c) shows. As can be seen, the differences between energies of '1's and '0's are large enough to deliver a correct decoding result.

IV. Experimental Method

Fig. 4 shows the experimental arrangement for testing different transmission methods using a pair of airborne capacitive ultrasonic transducers with high-k coated backplates. The data signal was encoded and modulated by MATLAB running on a PC before sending to a TTi TGA 12102 Arbitrary Waveform Generator using GPIB. The signal was then amplified using a Falco WMA-300 high voltage amplifier, and combined with a superimposed +100 V DC bias voltage generated by a HP 6205B power supply. The transmitter had a HfO_2 high-k layer with a thickness of 800 nm uniformly across the backplate, and covered by a 5 µm metallized PET membrane, assembled into a screened casing with a 10 mm diameter aperture.

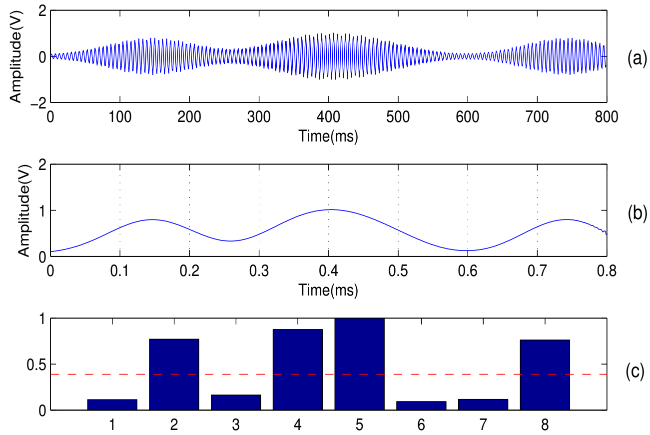

Fig. 3. Demodulation process.

The receiver, manufactured the same as the transmitter, was followed by a Cooknell CA6/C Charge Amplifier, and then connected to a Tektronix TDS210 Digital Oscilloscope for digitization. Afterwards, the captured signal was sent back to the same PC via GPIB for offline signal processing.

The system was characterised by its time domain impulse response and the corresponding frequency spectrum as shown in Fig. 5 (a) and (b) respectively. The experiment used the ultrasonic band from 120 kHz to 735 kHz.

V. Results

The ultrasonic communication system tested both ASK and OOK modulation schemes using multiple channels. The amplitude ratio of bit '1's and '0's was 0.25 for ASK. The 42 channels were modulated individually at the appropriate frequency and then added together in parallel to deliver a combined single waveform. A synchronization signal was then needed for triggering the oscilloscope correctly. The final signal output from MATLAB is shown in Fig. 6. As can be seen, an impulse with an amplitude slightly larger than the amplitude of the information signal was added to the front of

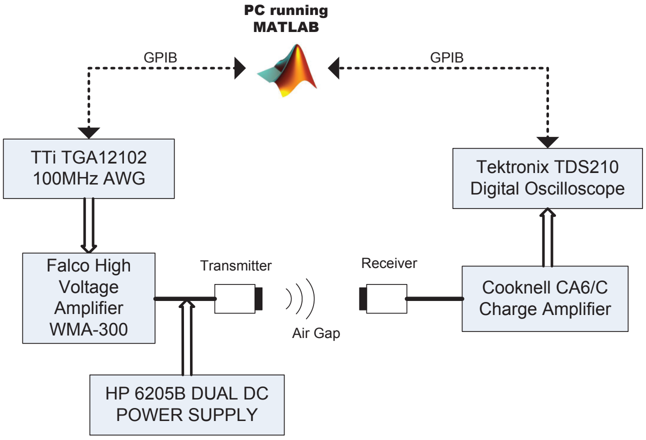

Fig. 4. Schematic diagram of the experimental arrangement.

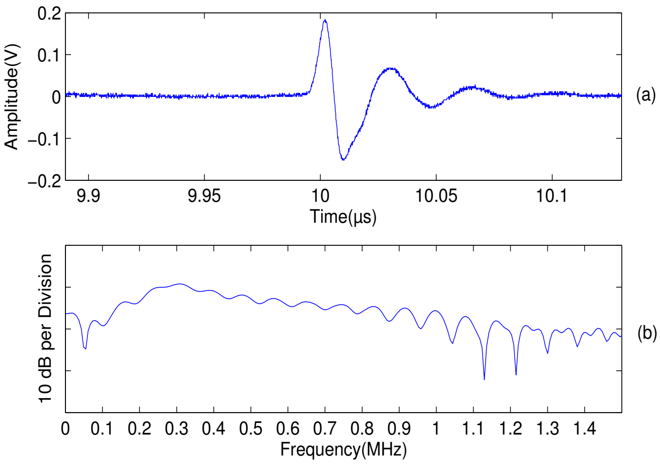

Fig. 5. Over-all system characteristics: (a) impulse response (b) frequency response.

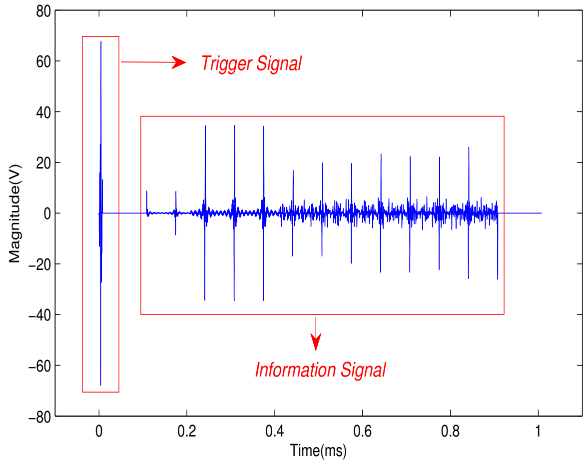

Fig. 6. Signal waveform transmitted through the wireless channel.

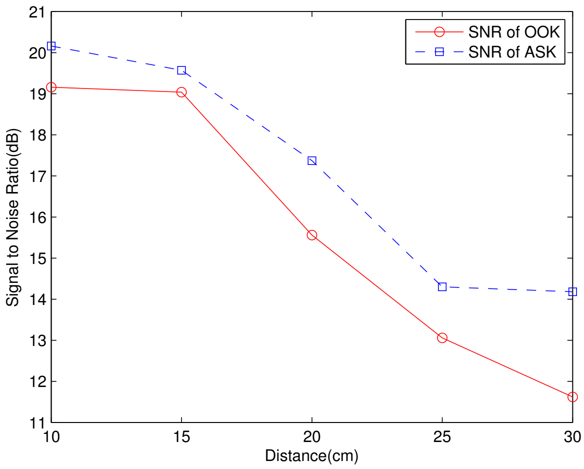

Fig. 7. Signal-to-noise ratio for ASK and OOK.

the signal. To prevent energy leaking from the trigger impulse, zeros for a duration of 0.1 ms were padded between the trigger signal and the information signal. In addition, zero padding for 0.1 ms was added after the information signal to separate one packet of data from another. The encoded signal was then amplified by a factor of 50 before being transmitted. The receiver transducer was set 20 cm away from the transmitter and the transmission was in line-of-sight mode. Before demodulation, the redundant part of the signal including the trigger signal and zero paddings captured by MATLAB from the oscilloscope were removed. The duration of each bit was 0.1 ms and as there were 42 channels transmitted simultaneously, the system data rate was 420 kbps.

Since SNR and bit error rate (BER) are two important parameters for data communication, it is essential to compare them for both ASK and OOK modulation schemes over different ranges. Thus, 1200 packets of 42-channel random binary bits were generated, modulated by ASK and OOK. The transmission ranges were from 10 cm to 30 cm in 5 cm increments. Fig.7 shows the SNR in dB against distance. The SNR of both modulation schemes decreased with distance as expected. OOK was shown to have better power efficiency than ASK. The BER results are shown in Fig.8. In general, ASK was more affected by noise since the amplitude differences for bit '1's and '0's were smaller than OOK. As a result, ASK had 0.64 % errors more than OOK on average. The reason for a higher BER at 10 cm than 15 cm for ASK is there are echoes reflected from the surface of the receiver and then bounced back to the receiver transducer again. It indicates a minimum range of using the current type of transducer housings, although these can be modified to reduce or eliminate these reflections. Again, because of the larger amplitude differences for bit '1's and '0's for OOK than ASK, OOK can suffer from the echoes more than ASK over short ranges. Moreover, high frequency channels have much more errors than low frequency channels over longer distances. As Fig.9 shows, for OOK, most errors occur on high frequency channels at 30 cm.

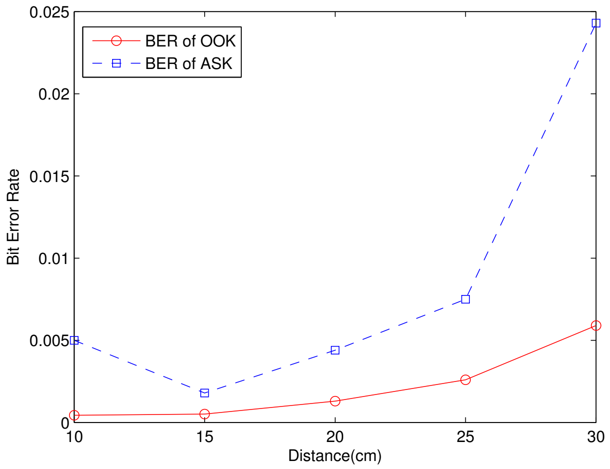

Fig. 8. Bit error rate for ASK and OOK.

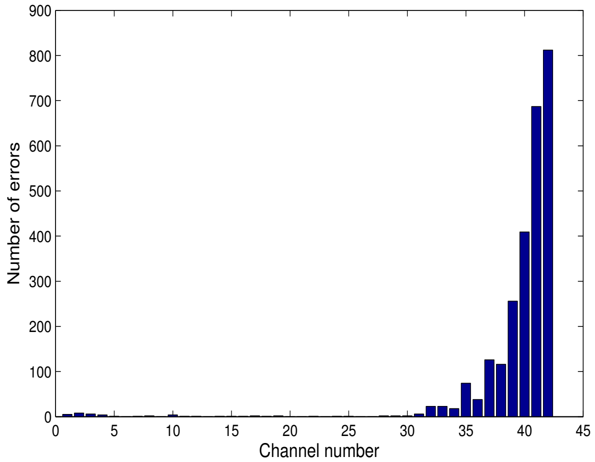

Fig. 9. Error distribution for OOK at 30 cm.

VI. Conclusion

This work shows that both modulation schemes (ASK and OOK) investigated for multi-channel data transmission over short distances using a pair of air-coupled capacitive ultrasonic transducers with high-k backplate coatings were possible. The system data rate achieved was up to 420 kbps. Wireless synchronization was used instead of a hard-wired link. System performance metrics including SNR and BER were analysed and compared between ASK and OOK. Future work will investigate other modulation schemes, and characterise channels in more detail.

References

[1] P. Mcfedries, "Bluetooth cavities," *Spectrum, IEEE*, vol. 42, no. 6, p. 88, 2005.

[2] C. Li, D. Hutchins, and R. Green, "Short-range ultrasonic digital communications in air," *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 55, no. 4, pp. 908–918, 2008.

[3] ——, "Short-range ultrasonic communications in air using quadrature modulation," *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 56, no. 10, pp. 2060–2072, 2009.

[4] W. M. D. Wright, O. Doyle, and C. T. Foley, "Multi-channel data transfer using air-coupled capacitive ultrasonic transducers," in *Ultrasonics Symposium, 2006. IEEE*, 2006, pp. 1805–1808.

[5] S. G. McSweeney and W. M. D. Wright, "HfO2 high-*k* dielectric layers in air-coupled capacitive ultrasonic transducers," in *Ultrasonics Symposium (IUS), 2011 IEEE International*, 2011, pp. 864–867.

[6] E. McCune, *Practical digital wireless signals*. Cambridge University Press, 2010.

[7] A. Turo, J. Salazar, J. Chavez, H. Kichou, T. Gomez, F. M. de Espinosa, and M. Garcia-Hernandez, "Ultra-low noise front-end electronics for air-coupled ultrasonic non-destructive evaluation," *{NDT} & E International*, vol. 36, no. 2, pp. 93 – 100, 2003. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0963869502000919

[8] Y. Shmaliy, *Continuous-time signals*. Springer, 2006.