Poster: Inaudible High-throughput Communication Through Acoustic Signals

Yang Bai*
WINLAB, Rutgers University
New Brunswick, NJ, USA
yang.bai.ece@rutgers.edu

Jian Liu*
WINLAB, Rutgers University
New Brunswick, NJ, USA
jianliu@winlab.rutgers.edu

Yingying Chen
WINLAB, Rutgers University
New Brunswick, NJ, USA
yingche@scarletmail.rutgers.edu

Li Lu
Shanghai Jiao Tong University
Shanghai, China
luli_jtu@sjtu.edu.cn

Jiadi Yu
Shanghai Jiao Tong University
Shanghai, China
jiadiyu@sjtu.edu.cn

ABSTRACT

In recent decades, countless efforts have been put into the research and development of short-range wireless communication, which offers a convenient way for numerous applications (e.g., mobile payments, mobile advertisement). Regarding the design of acoustic communication, throughput and inaudibility are the most vital aspects, which greatly affect available applications that can be supported and their user experience. Existing studies on acoustic communication either use audible frequency band (e.g., $<20kHz$) to achieve a relatively high throughput or realize inaudibility using near-ultrasonic frequency band (e.g., 18-20kHz) which however can only achieve limited throughput. Leveraging the non-linearity of microphones, voice commands can be demodulated from the ultrasound signals, and further recognized by the speech recognition systems. In this poster, we design an acoustic communication system, which achieves high-throughput and inaudibility at the same time, and the highest throughput we achieve is over 17× higher than the state-of-the-art acoustic communication systems.

CCS CONCEPTS

• **Networks → Wireless access networks**; **Mobile ad hoc networks**.

KEYWORDS

Acoustic communication, inaudible, high-throughput

ACM Reference Format:
Yang Bai, Jian Liu, Yingying Chen, Li Lu, and Jiadi Yu. 2019. Poster: Inaudible High-throughput Communication Through Acoustic Signals. In *The 25th Annual International Conference on Mobile Computing and Networking (MobiCom '19), October 21–25, 2019, Los Cabos, Mexico.* ACM, New York, NY, USA, 3 pages. https://doi.org/10.1145/3300061.3343405

1 INTRODUCTION

Short-range wireless communication of mobile devices has become increasingly popular recently, which is targeted to support various mobile applications and services, such as mobile advertisement, mobile payment, and device pairing, etc. Different from traditional approaches (e.g., NFC, QR codes and Bluetooth), acoustic communication builds on the inbuilt microphone and speaker of the devices, without the requirement for user intervention. Because of these benefits and ever-growing market demands, many companies (e.g., Verifone [1]) have started developing acoustic communication techniques for many applications (e.g., highly-secure proximity payments, customer engagement services).

In an effective and reliable acoustic communication system, high-throughput (i.e., high-speed) and inaudibility are the two key metrics affecting the possible applications being supported and their user experiences. Dolphin Attack [2] shows the feasibility of launching inaudible-voice-command attacks on speech recognition systems (e.g., Apple Siri, Google Now).In particular, regular voice commands are modulated on ultrasound carriers to achieve inaudibility. Current state-of-the-art audio hardware on mobile devices usually supports up to 48kHz sampling rate, thus the upper frequency in the communication frequency band is 24kHz according to Nyquist theorem. In order to achieve inaudible communication, existing efforts use near-ultrasound frequency band

---

*Both authors contributed equally to this research.

MobiCom '19, October 21–25, 2019, Los Cabos, Mexico

ACM ISBN 978-1-4503-6169-9/19/10…$15.00
https://doi.org/10.1145/3300061.3343405

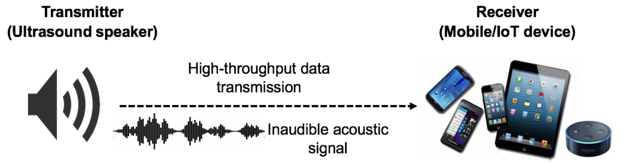


Figure 1: Inaudible acoustic communication with off-the-shelf mobile devices.

(i.e., approximately 18-20kHz) [3–5]. However, using this limited near-ultrasound frequency bandwidth cannot achieve satisfactory high throughput.

This poster proposes the first acoustic communication system, which can achieve inaudibility and high-throughput simultaneously by using the non-linearity of microphones. As shown in Figure 1, an ultrasound speaker transmits acoustic signals modulated on an ultrasound frequency carrier (e.g., >40kHz). Relying on the non-linearity of microphones, a nearby mobile or IoT device could pick up the signals of the entire audio frequency band (i.e., 0-24kHz) that are modulated onto this ultrasound frequency carrier to receive data.

Our contributions are summarized as follows:

- To the best of our knowledge, we develop the first high-throughput inaudible acoustic communication system, which is applicable to general mobile devices. The achieved throughput (i.e., as high as 47.49$kbps$) is over 17× higher than existing acoustic communication solutions.
- In order to maximize the throughput while keeping inaudibility, we theoretically model the non-linearity of the device's inbuilt microphone and innovatively use OFDM multiplexing technique together with the non-linearity model to transmit data over multiple narrow-band channels in an ultrasound frequency band.
- We propose a residual-signal elimination scheme, which elaborately modifies the analog OFDM symbol waveform, to mitigate the effect caused by the unrelated residual signals produced by AM.

2 SYSTEM DESIGN

2.1 Non-linearity of Microphone

Due to the limited sampling rate (i.e., 48kHz) of the microphone in mobile devices, the devices can only record the acoustic signals within a specific frequency range (i.e., < 24kHz). However, when receiving an ultrasound signal, the pre-amplifier of the microphone exhibits *non-linearity* in the ultrasound frequency range, which is feasible to make the ultrasound signal become recordable by the inbuilt microphones.

Specifically, the non-linearity of microphones can be modeled theoretically. Assume that the microphone receives an acoustic signal s_{in}. After the sound is picked up and amplified by the microphone's transducer and pre-amplifier, the recorded signal s_{out} can be represented as:

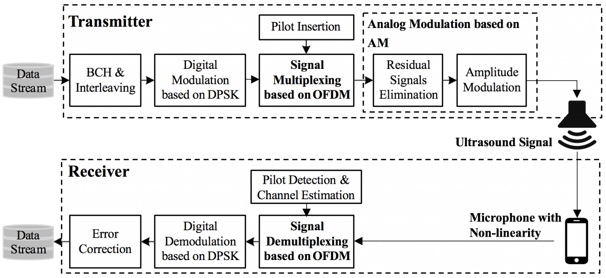


Figure 2: Architecture of the proposed work.

$$\begin{aligned} s_{out} = &\ A_1 s_{in} + \sum_{i=2}^{\infty} \delta(f) A_i s_{in}^i \\ \approx &\ A_1 s_{in} + \delta(f) A_2 s_{in}^2, \end{aligned} \tag{1}$$

where A_i is the energy gain for the ith order term and $\delta(f)$ is an indicator function. Although the non-linear output is an infinite power series, the value of A_i decreases with the increase of i and the third and higher order terms are extremely small. Thus we only consider the linear and quadratic terms. The indicator function $\delta(f)$ is defined as:

$$\delta(f) = \begin{cases} 0, & f < f_0 \\ 1, & otherwise, \end{cases} \tag{2}$$

where f_0 is the critical frequency of the non-linearity. We empirically find the critical frequency $f_0 \approx 18kHz$ in the most commercial mobile devices. The quadratic term of Equation 1 exhibits the non-linearity of microphones. The non-linearity of microphones provides the feasibility of utilizing ultrasound for communication. We are thus motivated to explore how to use such microphone's non-linearity to achieve high-throughput inaudible communication rather than using the limited near-ultrasound frequency band.

2.2 System Overview

To achieve high-throughput and inaudibility of the acoustic communication simultaneously, the design of our system mainly involves the following challenges, which are achieving high-throughput and inaudible communication for general mobile devices and the robust communication under various environmental factors. To overcome these challenges, the architecture of the system is shown in Figure 2, which consists of two parts, i.e., transmitter and receiver.

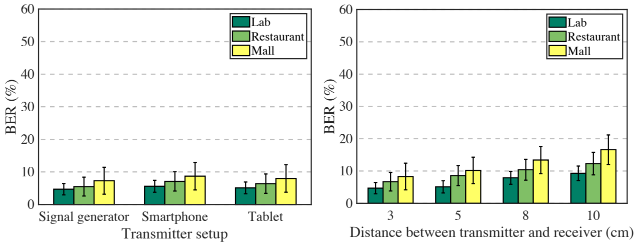
Transmitter Design. The transmitter is responsible to modulate data bits to an ultrasound signal for the high-throughput and inaudible acoustic communication. The data bits are first encoded with BCH error correction code and further re-ordered through an interleaving technique to reduce the unpredicted errors during the signal propagation. Then, the encoded data is converted to phase values through the digital modulation technique, i.e., differential phase shift keying (DPSK). To fully utilize the scarce frequency band for communication, the OFDM technique is further applied to modulate the phase values to multiple subcarriers for concurrent data transmission. During the OFDM, a pilot is inserted in OFDM signals for channel estimation so as to eliminate the impact of multipath effect on the received signals. After that, the OFDM symbol waveform $s(t)$ is modified to $s_e(t) = \sqrt{(s(t) + 1)} - 1$ for eliminating the unrelated residual signals, which are generated through AM under the non-linearity of microphones. Then the modified OFDM symbol waveform $s_e(t)$ is modulated onto the ultrasound carrier through AM for inaudible communication.

Receiver Design. The receiver in our system is a commercial mobile/IoT device (e.g., a smartphone) with an inbuilt microphone, which records and demodulates the received ultrasound signal to receive data. Taking advantage of the modeled non-linearity of microphone, the receiver can demodulate the received ultrasound signals to obtain the OFDM symbol waveform. After that, the receiver performs the demultiplexing on the recorded OFDM waveform to extract the phase values. Additionally, the pre-inserted pilot in the OFDM signals is used for channel estimation to eliminate the interference of multipath effect. Further, the extracted phase values are mapped into the digital data bits through DPSK demodulation. Finally, the receiver performs error correction on the digital data bits with the pre-inserted BCH code and the interleaving matrix to mitigate the unpredicted errors.

3 PRELIMINARY EVALUATION

To evaluate the performance of the system, we implement three settings of the transmitter to meet various application requirements. In the transmitting side, we use an Avisoft ultrasonic dynamic speaker Vifa and a portable ultrasound power amplifier to transmit ultrasound signals. In the receiver side, we use commercial off-the-shelf mobile devices (i.e., a Galaxy S6, a Galaxy Note 4, and a Samsung Tab P7510) as receivers to evaluate the system. Unless otherwise mentioned, the operation bandwidth for OFDM subcarriers is 8.06-$23.53kHz$, the digital modulation scheme is 16DPSK, the carrier frequency f_c for AM is $48kHz$ and error correction is based on $(63, 45)$-BCH code. The distance between the ultrasound speaker and the receiver (i.e., smartphone) is $3cm$, which is natural and appropriate for a short-range communication application.

Environments and Transmitter Settings. We evaluate the BER of the system under different environments and transmitter settings, as shown in Figure 3(a). It can be observed that the average BER of the system under the three settings in the quiet lab are all less than 6% with the standard derivation less than 2%. Moreover, all three transmitter settings achieve a comparable performance (i.e., BER difference is less than 1%), indicating that the system can use various device as the signal source at the transmitter end.



(a)

(b)

Figure 3: BER of the system under different (a) transmitter settings and environments (b) distances between transmitter and receiver (Throughput = $34.13kbps$).

Transmitter-Receiver Distances and Environments. We also evaluate the impact of distance between the transmitter and receiver on the system. Figure 3(b) shows BER of the system under different distances and environments. We observe that the BER of our system slightly increases as the distance increases. In the quiet lab environment, the average BER is around 5% with a standard deviation less than 2% under a distance between the transmitter and receiver less than $8cm$, which is a natural and appropriate distance for the short-range communication application. This result indicates that the system can achieve high throughput with an acceptable BER for almost all the short-range applications.

ACKNOWLEDGMENTS

This work is supported in part by the NSF grants CNS1801630, CNS1820624, CNS1814590 and Army Research Office W911NF-18-1-0221.

REFERENCES

[1] Verifone. Verifone.com. [Online]. Available: https://www.verifone.com/en/us, 2019.

[2] Guoming Zhang, Chen Yan, Xiaoyu Ji, Tianchen Zhang, Taimin Zhang, and Wenyuan Xu. Dolphinattack: Inaudible voice commands. In *Proc. ACM CCS*, pages 103–117, Dallas, TX, USA, 2017.

[3] Hyewon Lee, Tae Hyun Kim, Jun Won Choi, and Sunghyun Choi. Chirp signal-based aerial acoustic communication for smart devices. In *Proc. IEEE INFOCOM*, pages 2407–2415, Hong Kong, China, 2015.

[4] Soonwon Ka, Tae Hyun Kim, Jae Yeol Ha, Sun Hong Lim, Su Cheol Shin, Jun Won Choi, Chulyoung Kwak, and Sunghyun Choi. Near-ultrasound communication for tv's 2nd screen services. In *Proc. ACM Mobicom*, pages 42–54, New York, NY, USA, 2016.

[5] G Enrico Santagati and Tommaso Melodia. A software-defined ultrasonic networking framework for wearable devices. *IEEE/ACM Transactions on Networking*, 25(2):960–973, 2017.