Poster Abstract: Integrated Sensing and Communication between Daily Devices and mmWave Radars

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ABSTRACT

Millimeter wave (mmWave) radar has demonstrated excellent performance in object tracking and micro-displacement detection. Besides the powerful sensing function, this work brings the communication function, allowing daily devices to communicate with mmWave radars through vibrations. In this work, we present *VibBeat*, in which a daily device (*e.g.*, smartphone and smartwatch) sends messages by modulating vibrations, while a mmWave radar receives the messages by detecting and decoding the vibrations with reflected mmWave signals. By doing so, the device (user) can not only be passively sensed by a mmWave radar, but also actively send messages to the radar for a personalized response. We implement our system using a COTS mmWave radar and smartphones without any hardware modification. Experimental results show that *VibBeat* supports multiple object communication and achieves a communication range of up to 5*m*.

CCS CONCEPTS

• **Human-centered computing → Ubiquitous and mobile computing**.

KEYWORDS

mmWave communication, vibrations, ISAC

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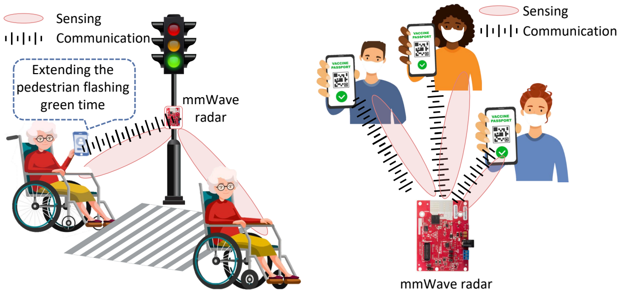
1 INTRODUCTION

Millimeter wave (mmWave) radars have emerged as a powerful sensor modality with unprecedented sensing resolution for all-weather conditions, widely deployed in robots, home appliances, vehicles, and road infrastructure. Recent works also show their excellent performance in detecting micro-vibration in industrial scenarios and vocal vibration for speech recognition. Motivated by these works, we ask a question: *is it possible for daily devices to communicate with mmWave radar through vibrations?*



(a) P2I Communication (b) Multiple Object Interaction

Figure 1: Application Scenarios of *VibBeat.*

This work tries to answer this question by presenting the design of *VibBeat*. In *VibBeat*, a daily device (*e.g.*, smartphone, smartwatch, and even small home appliances) acts as the transmitter, which leverages widely built-in vibration motors to send messages by modulating vibrations. At the same time, a mmWave radar as the receiver senses surrounding objects and decodes the messages embedded in the vibrations with mmWave signals. By doing so, we bring the communication function to COTS sensing-oriented mmWave radars. Thanks to precise spatial information (*i.e.*, range and angle of arrival of each object) from sensing, *VibBeat* can support multiple object communication, and each received message implicitly carries location information of the corresponding object.

VibBeat allows daily devices (users) to be sensed by and communicate with mmWave radars without link establishment before direct communication or any hardware modification on either side. We envision exciting applications can be enabled by *VibBeat*. For example, **1) Pedestrian-to-Infrastructure (P2I) communication.** In Fig. 1(a), after receiving the "crossing" message from an elderly's smartphone vibration, the traffic light can suitably extend the flashing green time and meanwhile track her movement. **2) Multiple object interaction.** In Fig. 1(b), mmWave radar can be deployed at the entrance of a venue to monitor visitors, while simultaneously checking their COVID-19 vaccine passports by decoding specific smartphone vibrations. **3) Gateway for traditional appliances without Internet connection.** mmWave radars can serve as Internet gateways for traditional appliances without communication modules (*e.g.*, hair trimmer and electric toothbrush) by receiving these vibration messages (*e.g.*, work mode and battery state) and relaying them to the Internet.

2 SYSTEM DESIGN

Fig. 2 illustrates the system overview of *VibBeat*.

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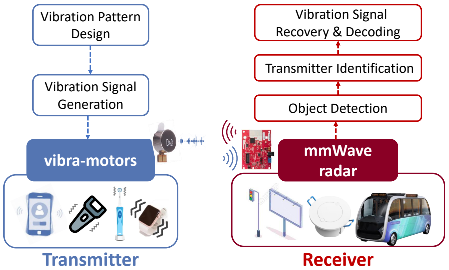


Figure 2: Overview of VibBeat.

2.1 Transmitter Design

We first design several different vibration patterns. Inspired by the widely-used Walsh code, we design a set of patterns with inter-pattern orthogonality. It means that the cross-correlation between any two patterns is minimized, so that we can differentiate vibration patterns and reduce matching errors. Specifically, we adopt OOK modulation and one symbol duration T_{sym} is divided into 2 smaller time slots T_{slot}. Data-1, data-0 are encoded into vibration modes "on-on" and "off-off", respectively. A specific delimiter modulated as "off-on-off" is used to separate different patterns. Typically, vibra-motor can be configured by a series of timing and amplitude pairs $\{\langle T_{vib}, A_{vib}\rangle\}$. For each pair, T_{vib} determines the vibration duration and A_{vib} determines the vibration amplitude. Thus, we can leverage different pairs to generate the expected vibration signals.

2.2 Receiver Design

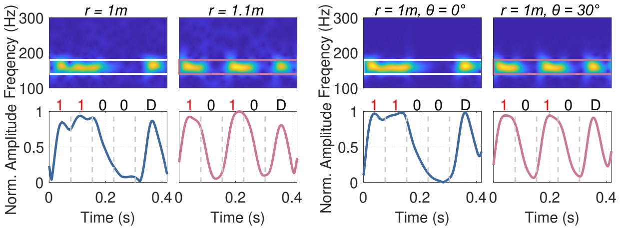
1) Object Detection. mmWave radar typically sends FMCW signals to sense objects. After being reflected by an object and mixed with Tx signals, we can obtain the Intermediate Frequency (IF) signal, whose frequency f_{IF} contains the object range information r. Then combining IF signals from multiple antennas, we can calculate each object's angle of arrival (AoA) θ [1, 2]. Thus, we can extract multiple candidate objects' location information, *i.e.*, range r and AoA θ.

2) Transmitter Identification. We next analyze the reflected signals from each candidate object to detect whether a candidate object is a real transmitter sending defined vibration patterns or interferences. When the object vibrates, it will produce a time-varying micro-displacement $\delta(t)$ that can be represented as $\delta(t) = A\cos(2\pi f_v t)$, where A is the vibration amplitude and f_v is the vibration frequency. Suppose the vibrating object locates in the initial range R_0 and AoA θ, the extracted phase values from the reflected signals corresponding to this object can be represented as:

$$\phi(t) = \frac{4\pi}{\lambda}(R_0 + \delta(t)) = \frac{4\pi}{\lambda}R_0 \; + \; \frac{4\pi}{\lambda}A\cos(2\pi f_v t) \qquad (1)$$

Ignoring the DC component, we name the second term as *vibration signal* $Y(t)$. Vibra-motors are typically set to operate on the resonant band for a better vibration effect (*e.g.*, $100Hz \sim 300Hz$ for smartphones). Thus, we can leverage a threshold in the expected frequency band to identify the vibration targets, *i.e.*, transmitters .

3) Vibration Signal Recovery and Decoding. After locating the transmitter, we can directly extract the vibration signal $Y(t)$ with a band pass filter. Then, we leverage a matched filter to detect the delimiter location and extract the vibration pattern signals before it. Next, we decode the vibration pattern signals by calculating the cross-correlations between the extracted vibration signals with the orthogonal pattern templates. The Walsh code corresponding to the highest correlation value is the decoding result.



(a) Different Ranges (b) Different Angles

Figure 3: Illustration of Multi-object Communication.

3 IMPLEMENTATION AND RESULTS

We build a prototype of *VibBeat* using the TI AWR1642 commodity mmWave radars (76 ~ 81GHz) and smartphones.

Multiple Object Communication. We simultaneously put two vibrating smartphones to demonstrate the capability of multi-object communication. Fig. 3(a) shows the extracted vibration patterns from different smartphones in different ranges, *i.e.*, "1100" and "1010", demonstrating that the objects can be separated in range. We further put these smartphones in the same range but in different directions relative to the radar. As shown in Fig. 3(b), the vibrations extracted from the same range and different beaming steering angles present different vibration patterns, implying the objects can be further separated in angle.

Communication Capacity. We adopt the OOK modulation to encode information. A higher vibration amplitude indicates a longer communication range. On the other hand, the vibra-motor takes a longer time to reach the target amplitude due to the inertia, resulting in a lower bit rate. There is a trade-off between communication range and transmission rate. In the experiment, we set the vibra-motor in a Samsung S9+ to a vibration time slot of $40ms$ with the highest vibration amplitude, its bit rate sending 4-bit data is $9.09bps$, and the maximum communication range reaches $5m$ in the line of sight between the smartphone and the mmWave radar. Moreover, the aggregated throughput on the receiver can be multiplied, since it supports concurrent reception from multiple transmitters.

4 CONCLUSION

In this work, we present *VibBeat*, which allows daily devices to communicate with mmWave radars through vibrations. *VibBeat* can support multiple object communication and achieve a communication range of up to $5m$. This system demonstrates the feasibility and practicality of building communication channels between daily vibrating devices and mmWave radars, which will open up a wide range of exciting applications.

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