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Characterization of a 60GHz Reader and mmID System for High Fidelity Real-time Tracking With On-chip Processing

Marcus Chan, Ashley Goodnight, Aman Koul, Erin Ohm, Cynthia Wang,
Charles A. Lynch III, Manos M. Tentzeris
School of Electrical and Computer Engineering
Georgia Institute of Technology, Atlanta, Georgia, USA

***Abstract*—In this work, a $60\,\mathrm{GHz}$ real-time tracking system utilizing an ultra-low-cost and compact mmID-enabled system is characterized. The characterized system consists of an ultra-low-cost and compact Antenna on Package (AoP) FMCW radar and mmID tag. The system leverages the use of on-chip processing and high-fidelity ranging enabled through the mm-Wave radar module providing a probability of detection greater than 0.9 at $35\,\mathrm{cm}$ from the radar module and bounded average ranging error and standard deviation of $1.36\,\mathrm{cm}$ and $2.01\,\mathrm{cm}$, respectively. Additionally, the angular coverage of the mmID was characterized at $35\,\mathrm{cm}$ and displays an angular coverage of $\pm 15\,^{\circ}$ with a probability of detection greater than $80\,\%$. Finally, the authors present a multi-tag measurement with a maximum mmID displacement error of $1.5\,\mathrm{cm}$. Thus, the survey of the system provides a framework for a potential future system centered around tracking multiple mmIDs for wearable applications such as gait analysis.**

***Index Terms*—mm-Wave, mmID, tracking, IoT**

I. Introduction

With recent advances in wearable technology, motion tracking and gesture recognition have become an ever-present research area. Various applications including ubiquitous health monitoring and gait analysis could fundamentally improve the quality of modern healthcare [1]. Furthermore, advances in this area of research could improve the quality of life of an injured or a disabled patient by fine tracking the range of motion or providing a new input into the Human-Computer Interface systems of next-generation Internet of Things (IoT) systems. Promising solutions include the use of Radio Frequency Identification (RFID) systems, in which backscattering tags modulate incoming electromagnetic energy to be further processed by a tracking algorithm on the reader antenna connected to a radar [2]. Such technology also leaves room to utilize RFID tags as communication nodes as well. Currently, most RFID localization systems operate in the Ultra High Frequency (UHF) band, which is limited by its available bandwidth, as seen in a bounded $13\,\mathrm{cm}$ error [1]. UHF RFID localization has an inherent need for large receiving arrays for accurate Angle-of-Arrival (AoA) estimation due to the operational frequency being proportional to the geometric size of wireless components. In order to overcome the drawbacks of UHF systems, the authors propose a mm-Wave identification (mmID) tag and Frequency Modulated Continuous Wave (FMCW) radar reader system. The ultra-low power requirement, the small form factor which enables easy placement on the human body, and the ability to distinguish between phase noise at close proximity to the radar and the specific tagged location on the body make mmID tags a fantastic candidate for implementation in tracking technologies. These characteristics that highlight low-power, wearability, and compactness further suggest an independent and portable, yet capable system that can be easily integrated into mobile, non-bulky devices. To examine the efficacy of the proposed system the percentage of detected observations are presented for tags at different orientations and ranges. The remainder of the paper is structured as follows: In Section II, the real-time mmID ranging system is described in detail along with FMCW interrogation settings. In Section III, a survey of the probability of detection over 1D ranging, orientation of the mmID itself, and a demonstration of a multi-tag measurement is presented. Finally, in Section IV, the authors draw conclusions on the presented on-chip mmID-enabled localization system evaluation.

II. Real-time mmID Ranging System

The real-time mmID ranging system comprises of a miniaturized, semi-passive mm-Wave identification tag and a Texas Instruments (TI) Antenna-on-Package (AoP) radar module [3] as shown in Figure 1. Capitalizing on the capabilities of the mm-Wave regime, the system is theoretically designed for high-mobility and high-accuracy characteristics while maintaining affordability as the entire system would retail for $25 at scale. The stable, low-power tag encodes the 'ID' through modulating at a specific frequency, and is described in more detail in [3]. The radar module is characterized by its compact Antenna-on-Package form factor of $15\,\mathrm{mm}$ by $15\,\mathrm{mm}$, a maximum transmitted power of $10\,\mathrm{dB\,m}$, a $\pm\,120\,^{\circ}$ field of view for wide azimuthal and elevation coverage, and three transmit and four receive antennas. Only one transmit and one receive antenna were used for experimentation in this paper.

A. Design of Miniaturized mmID

The mmID consists of two primary systems: the RF front-end which enables signal transmission and the baseband circuitry which modulates the backscattered signal [3]. The fabricated tag can be seen in Figure 1. For the RF Front-end, the rectangular patch antenna is designed to operate over the intended 60-64 GHz operating frequency band with minimal

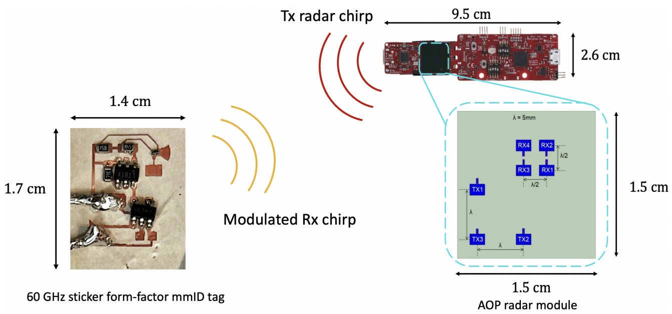

Fig. 1. FMCW radar and mmID tag system overview.

link loss (-10dB). Additionally, a switchable load isolates the backscattering signal from the tag's self-interference using amplitude modulation. For the baseband circuitry, the linear voltage regulator and voltage-controlled oscillator act jointly to generate the mmID tag's subcarrier frequency that encodes the localization information with low-power and high-stability characteristics. The fully-integrated mmID tag is fabricated with inkjet printing of a mask onto a copper cladded ceramic substrate. The unmasked surface is chemically etched and the remaining copper realizes the circuit design [4]. Such fabrication methods support a flexible tag design and the miniaturized form factor of $1.4\,\mathrm{cm}$ by $1.7\,\mathrm{cm}$ with the potential for reduction by optimizing packaging [3]. Note that the small tag size is made possible by the mm-Wave regime; higher frequencies correspond to smaller wavelengths, and thus a smaller separation of parts is needed for proper tag operation.

B. FMCW Radar Interrogation

The $60\,\mathrm{GHz}$ IWR6843AOPEVM FMCW radar module from Texas Instruments was used in the proposed reader system for its frequency capabilities and small AoP form factor. Chirp parameters were set according to values shown in Table I, and 512 samples were obtained per chirp. In order to enable debugging during development and testing, the MMWAVEICBOOST from TI was utilized, but the radar module can be flashed with the program binary to run standalone. Processing of the raw ADC values, including a fast-Fourier transform (FFT) was performed on-chip, and the range profile was received in real time via a UART connection. Based on the chirp parameters in Table I, the maximum total range, R_{max}, of the system is $26.785\,\mathrm{m}$ and defined by the expression

$$R_{max} = \frac{F_s c}{2 * S}, \tag{1}$$

where F_s, c, and S are the sampling rate in Hz, speed of light in $\frac{\mathrm{m}}{\mathrm{s}}$, and slope of the transmitting chirp waveform in $\frac{\mathrm{MHz}}{\mu s}$, respectively.

For a complex receiver, the resultant measured response of the mmID tag will appear in both the real and image band, displaying a positive spectral component at $f_{beat} + f_{mod}$ and a negative spectral component at $f_{beat} - f_{mod}$, where f_{beat} is the beat frequency of interest and f_{mod} is the modulation frequency of the tag as described in [3]. A peak-finding algorithm was written to detect the range bins corresponding to the beat

TABLE I
CHIRP PARAMETERS USED TO ACQUIRE THE REPORTED MEASUREMENTS.

Parameter	**Value**
Bandwidth	$3.50\,\mathrm{GHz}$
Slope	$70.00\,\mathrm{MHz}/\mu s$
Sampling Rate	$12.499\,\mathrm{MHz}$
Chirps per Frame	48
Chirp Periodicity	$438\,\mathrm{\mu s}$

frequency of the backscattering target by searching in windows in the positive and negative spectra for the highest peaks that are at least $6\,\mathrm{dB}$ above the mean signal magnitude within the window. Once the peaks were identified, the target range in the frequency domain could be determined by summing the ranges of the positive and negative peaks and dividing by 2. Thus, enabling a computationally efficient and range estimation algorithm for real-time tracking applications.

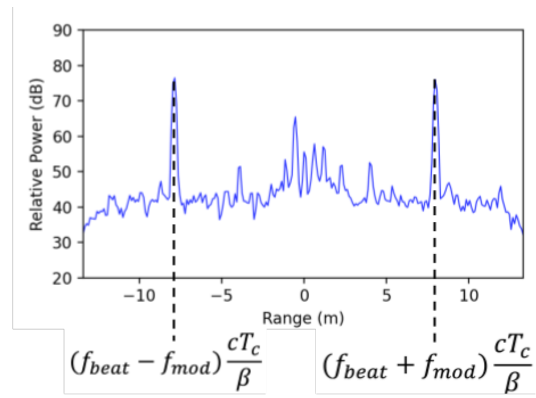

Fig. 2. Signal processing on the range profile after static clutter removal to estimate the range of the mmID tag. T_c is the chirp duration, β is the sweeping bandwidth, and c is the phase celerity of the electromagnetic wave.

III. EVALUATION OF THE REAL-TIME MMID RANGING SYSTEM

For the ranging coverage measurements, the tag was placed directly in front of the mmID reader at $0\,^{\circ}$ to be in boresight. As samples were collected, the tag was shifted farther from the interrogating ultra-low-cost FMCW radar. The system differentiates detected versus undetected points in the following manner. A point must lie within a windowed centered around the modulation frequency of the mmID. Furthermore, its amplitude must surpass a threshold $6\,\mathrm{dB}$ above the mean. Within the system, a false positive occurs when a detected point is offset a distance equal to or greater than one range bin from its known true range value. Accounting for both the false negatives and false positives, a probability of detection is calculated using the following equation.

$$P_{Detect} = \frac{Correct\ \#\ of\ Detections}{Total\ \#\ of\ Samples}, \tag{2}$$

While the tag requires line-of-sight interrogation, perfect angle orientation is not strictly necessary. In terms of gait analysis application of the real-time ranging system, characterizing the angular tolerance of the mmID is necessary as during the process of tracking human motion, misalignment is to be expected. Therefore, a characterization of the probability of detection versus the orientation is interrogated at a constant distance with greater than 85% probability of detection for this characterization.

A. Ranging Coverage of Current System

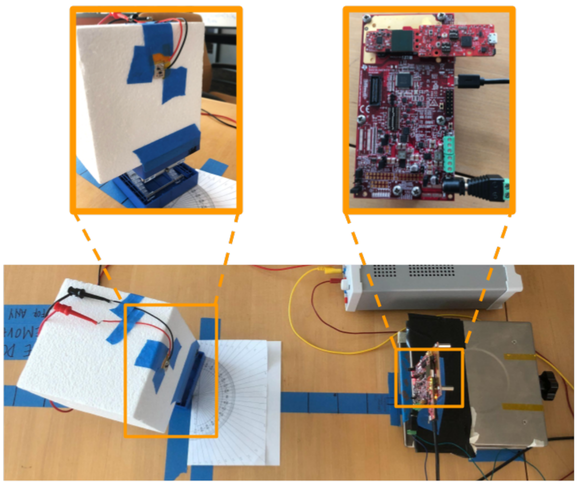

Fig. 3. Experimental setup for orientation measurements.

As aforementioned, the real-time mmID-enabled tracking system was characterized primarily in terms of probability of detection vs. range to determine the current system's range coverage. Figures 4-6 shows the measured range characteristics of the real-time mmID system. As displayed, the ranging data was collected over the range $5\,\mathrm{cm}$ to $90\,\mathrm{cm}$ in steps of $5\,\mathrm{cm}$. At each distance, 7000 observations were taken and probability of detection and ranging estimation was obtained. The experimental results indicate a very accurate ranging measurement with a maximum percent error of 0.20% and the average ranging error of detected mmID is bounded to $1.36\,\mathrm{cm}$, highlighting the accuracy of the real-time ranging system. The measured minimum and maximum probability of detection values were 0.9993 and 0.5366 at the distances $5\,\mathrm{cm}$ and $90\,\mathrm{cm}$ respectively. The intermediary data follows this decaying trend, demonstrated in Figure 4, with a steady dropoff in the probability of detection over range which is expected as the measured signal power of the mmID decays with range and with it the ability to detect the mmID. The decreasing trend of probability of detection versus range is best characterized by a one-term Gaussian fitted curve using the 'fit' function in Matlab. The fitted curve, valid for the $5\,\mathrm{cm}$ to $90\,\mathrm{cm}$ range, is shown in the equation below with the x term representing the range in centimeters.

$$P_{Detect} \approx e^{-(\frac{x+4.261}{108.4})^2} \tag{3}$$

To examine consistency, the standard deviation was determined from the data including false positive alarms. The standard deviation was bounded at the maximum range to less than $2.01\,\mathrm{cm}$, indicating overall stability and accuracy of the ranging estimation of the mmID.

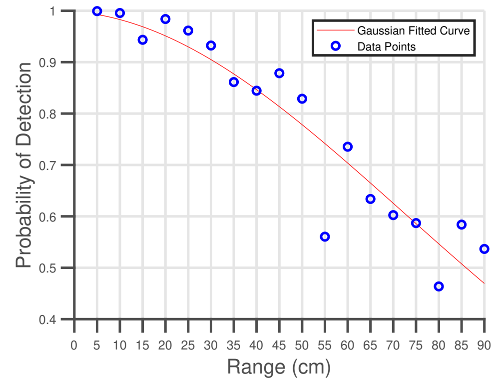

Fig. 4. Probability of detection of mmID vs. range.

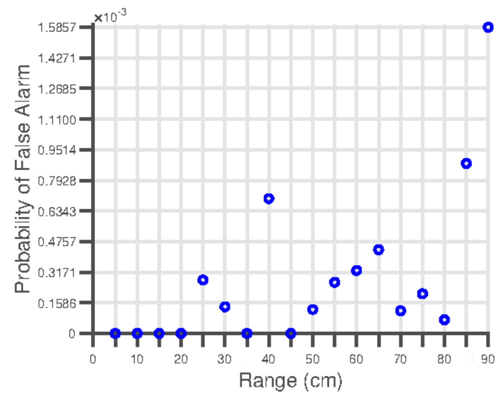

Fig. 5. Probability of false alarm of mmID vs. range.

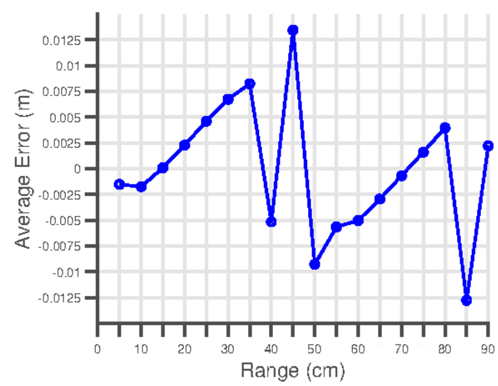

Fig. 6. Average error of detection vs. range.

B. Angular Coverage of mmID

Angular coverage of the mmID was measured from a range of $35\,\mathrm{cm}$ from the radar module. Based on ranging measurements, $35\,\mathrm{cm}$ is the farthest range that offers greater than 85% PoD and has relatively consistent measurements, with only a $1.13\,\mathrm{cm}$ standard deviation. Angular coverage measurements were taken at orientations $-30°$ to $30°$ from perpendicular, with a step size of $5°$, and a total of 7000 samples were taken at each orientation.

The experimental results indicate that the probability of detection remains above 75% at angles $\geq -15°$ and $\leq 10°$, and the probability of detection falls to 0 at angles $\leq -30°$ or $\geq 25°$. The PoD distribution for orientation is shifted towards the negative angles, due to the ICs being in close proximity to the antenna for compactness causing pattern to be skewed. As Figure 8 depicts, the probability of false alarm increases for farther orientations with 50-60% PoD, and drops for orientations with nearly zero PoD, as very few detections are observed at those orientations. Thus, for accurate tracking in a gait analysis, the system requires the mmID to be within $\pm 12.5°$ of perfect alignment.

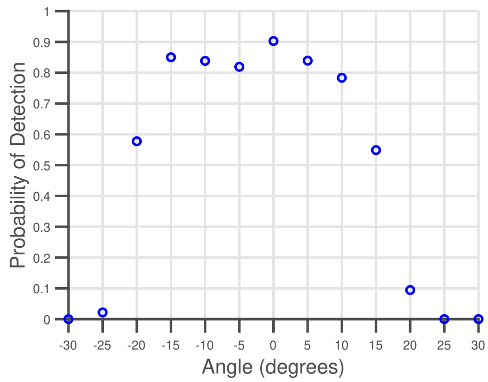

Fig. 7. Probability of detection of mmID vs. orientation.

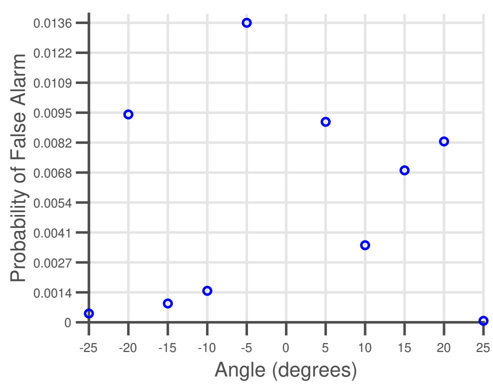

Fig. 8. Probability of false alarm of mmID vs. orientation.

C. Multi-tag Demonstration

In order to demonstrate the multi-tag capabilities of the proposed system, another identical tag was fabricated. As aforementioned, through frequency division, each mmID was given a unique modulation frequency. Thus, a proof-of-concept demonstration was conducted through positioning one mmID at $20\,\mathrm{cm}$ from the radar and displacing the second mmID from a range of $-10\,\mathrm{cm}$ to $10\,\mathrm{cm}$ away from the first mmID tag in steps of $5\,\mathrm{cm}$. Utilizing the same signal processing framework, the estimated range of each mmID recorded and the average displacement between the two mmIDs was calculated. The results form this multi-tag experiment can be viewed in Figure 9. With a bounded average error of $1.5\,\mathrm{cm}$ this measurement highlights the accuracy of the proposed system and applicability towards fine-scale gesture recognition or gait analysis.

Fig. 9. Multi-tag estimated offset vs. true offset.

IV. Conclusion

In this work, the novel low-power, compact mmID radar tracking system is characterized for highly reliable, one-dimensional localization at varying tag orientations. Note that this ranging characterization highlights the capabilities of the mmID system's on-chip processing. With peak finding that is less processing-intensive, the mmID and standalone AoP radar module system components are able to have such small form factors while maintaining high performance. Range is found to be detectable up to $90\,\mathrm{cm}$, and at an offset of up to approximately $20\,°$ at $35\,\mathrm{cm}$. At high probability of detection ranges, the standard deviation of measurements does not exceed $2\,\mathrm{cm}$ which is less than a range bin; with a maximal average ranging error of $1.36\,\mathrm{cm}$, the system shows reliable accuracy at-distance. Lastly, a multi-tag demonstration was presented and with a maximum average mmID displacement error of $1.5\,\mathrm{cm}$, the proposed system displays great potential for fine-scale gesture recognition or gait analysis applications. Following 1D ranging, the mmID radar system will be characterized for Angle of Arrival (AoA) and velocity measurements for 3D tracking. From this work's investigation and demonstration of the system's reliability and potential, further development of the system and its capabilities could encourage prevalent adoption and implementation of mm-Wave backscattering tracking systems for wearable or common-day applications.

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