Demo: Long-Range Accurate Ranging of Millimeter-wave Retro-Reflective Tags in High Mobility

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ABSTRACT

In this paper, we demonstrate Adaptive Millimetro as an extension of Millimetro, an ultra-low power millimeter-wave (mmWave) retro-reflector presented in [1], for high mobility scenarios. Adaptive Millimetro makes use of automotive radars and enables communication with and accurate localization of roadside infrastructure over extended distances (i.e. >100m). Millimetro achieves this by designing ultra-low-power retro-reflective tags that operate in the mmWave frequency band and can be embedded in road signs, pavements, bicycles, or even the clothing of pedestrians. Millimetro addresses the severe path loss problem of mmWave signals by combining coding gain and retro-reflective antenna front-end to achieve long-range operation. However, highly mobile scenarios may still experience unreliable performance due to the Doppler effect changing the received signals. In this paper, we demonstrate a simple solution for robust localization in high mobility by implementing a Moving Target Indication (MTI) filter and an adaptive Kalman filter. We also present an augmented reality app, as an in-car AR platform, that uses Adaptive Millimetro's algorithms to estimate the tag positions and overlay a virtual box at the estimated locations.

ACM Reference Format:
Thomas Horton King, Elahe Soltanaghai, Akarsh Prabhakara, Artur Balanuta, Swarun Kumar, and Anthony Rowe. 2022. Demo: Long-Range Accurate Ranging of Millimeter-wave Retro-Reflective Tags in High Mobility. In *The 27th Annual International Conference on Mobile Computing and Networking CD-ROM (ACM MobiCom '21), March 27-April 1, 2022, New Orleans, LA, USA.* ACM, New York, NY, USA, 2 pages. https://doi.org/10.1145/3447993.3510592

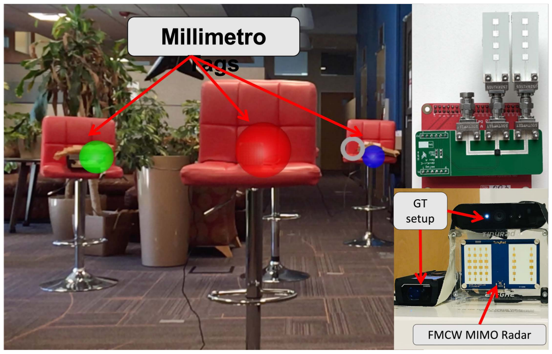

Figure 1: A snapshot of Adaptive Millimetro identifying multiple tags and visualizing the location with ARKit

1 INTRODUCTION

This paper presents a novel ultra-low-power radio platform for next-generation roadside infrastructure, which we argue is critical for enabling future autonomous driving, active safety, and in-car augmented reality (AR). Central to this vision is the role of next generation wireless technologies that can give vehicles the ability to improve their sense of location and situational awareness in harsh low-visibility environments where current sensors often fail. Millimetro designs markers that, when placed on roads, signs, or other vehicles, are able to support precise positioning and communication with fast moving vehicles. Radio technologies naturally offer significant advantages such as robustness to obstructions and poor weather. Unfortunately, existing ultra low-power radio technologies (e.g. RFID, LPWAN, etc) do not fit the tight latency and long range requirements critical in the vehicular context.

Millimeter-wave bands, already used in automotive contexts for collision avoidance, have the potential to fill this gap providing both high accuracy and low latency sensing and communication. Millimeter-wave advantage comes from the plethora of contiguous bandwidth and the ability to realize compact many-antenna arrays at high frequencies. We use the high spatial processing gain and highly directional transmissions offered by mmWave bands, and make them compatible with battery-free coded reflectors (tags) that can be uniquely identified and localized quickly from long distances. This enables an ultra-low-power and low-latency communication link with roadside infrastructure that, with the right architecture and signal processing techniques, can piggy-back on the already available radar hardware in cars.

The core challenge is that mmWave signals experience a severe path loss. Combined with the poor Radar Cross Section (RCS) of a small backscatter tag, it significantly limits the operating range. This

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ACM MobiCom '21, March 27-April 1, 2022, New Orleans, LA, USA

ACM ISBN 978-1-4503-8342-4/22/01.
https://doi.org/10.1145/3447993.3510592

can be accounted for by using a narrow beam with high-speed electronic steering, but this comes with its own challenges in multipath-rich urban environments. Millimetro addresses these challenges and breaks the traditional trade-off between *range*, *performance*, and *power* in mmWave sensing systems. Adaptive Millimetro's key innovation is the use of a passively retro-reflective antenna front-end that reflects signals directly back at their sources. This naturally boosts the operating range despite the severe path loss of mmWave bands. Adaptive Millimetro further improves tag detection by using a simple on-off keying modulation at the tag and frequency-based signal processing at the radar.

We demonstrate the operation of Millimetro in an AR application by visualizing the estimated location of tags in the AR app and continue tracking the object as the radar moves.

2 SYSTEM OVERVIEW

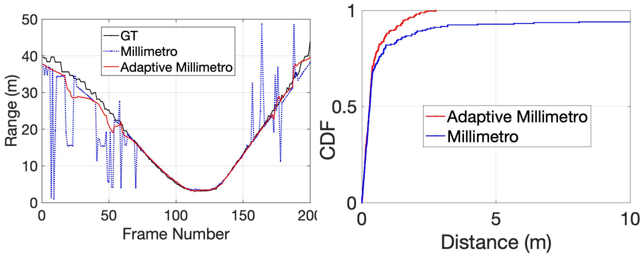
Adaptive Millimetro's system consists of three main parts:

Retro-directive tag design to mitigate SNR loss: Millimetro addresses the sever path loss of mmWave bands compared to sub-GHz frequencies by using a retro-reflective antenna structure. Given the mono-static setup of automotive radars, the tag only needs to reflect any signal arriving from any direction back toward its arrival direction. Millimetro achieves directivity by using Van Atta retro-reflective architectures [2], while keeping the tag passive (no need of phase shifter or high-power components for active beamforming).

Asynchronous tag-reader communication architecture: One of the challenges with large-scale mobile systems, such as autonomous vehicles, is the ability to *quickly* and *effectively* detect, localize, and identify tags across multiple readers simultaneously. To address this, Adaptive Millimetro uses a fully asynchronous tag-reader architecture, in which the tags and radars are operating independently without requiring any synchronization or coordination with each other. As opposed to the existing RFID tag-reader architecture where a medium access protocol is used to deal with concurrent tags and readers, in this design the tag constantly and continuously modulates any incident signal and the radars unilaterally process the received reflections to detect the existing tags.

Accurate tag identification and Localization: While the fully asynchronous tag-reader architecture provides the desired low latency, it brings up new challenges on tag detection robustness as the radar has no notion of tag operation status during scanning. Millimetro addresses this challenge by leveraging the tag modulation. The switching on and off behavior of the tag appears as a sinc function in the frequency domain and this can be easily detected by using template matching techniques without any syncronization required between the tag and the readers. While this approach is accurate (cm level) in static and low mobility scenarios, it is less effective in high mobility scenarios in which the received signal will inevitably contain certain noise artifacts and doppler effect. Therefore, fault conditions such as missing detection and false detection are more likely to occur in high mobility. To address these issues, we extend Millimetro with digital MTI filtering and an adaptive Kalman filter.

In high mobility scenarios, a background object with a large RCS can cause a false detection if its Doppler frequency overlaps with the Doppler frequencies of the matched filter used for tag identification. To overcome this, we implement an MTI filter which normalizes the received signal, identifies the frequency bin containing the highest total magnitude of reflections as being the velocity of the reader, and attenuates the received signals around the Doppler velocity of the reader. Because the tag's signal is constructed to appear across multiple Doppler frequencies (i.e. sinc function), this approach is robust to overlap between the signal waveform and other objects.



(a)

(b)

Figure 2: (a) Snapshot of Improved performance with Adaptive Millimetro in high mobility, (b) CDF of range errors

Another challenge of high mobility cases is that the radar can occasionally fail to detect a tag because of obstructions or limited Doppler bandwidth. To address this, an adaptive Kalman filter [3] is implemented to detect errors in tag localization and track tags. Using Mahalanobis distance [4], the measurement noise covariance matrix is tuned over time to match a dynamic, changing environment. Additionally, if a measurement differs significantly from the filter state, it is used to update the covariance but not the state estimate, allowing the tag to be tracked through detection errors (Fig. 2).

3 DEMO SETUP

We will demonstrate three aspects of Adaptive Millimetro as follows:

Tag Identification and Localization: We demo an AR app which localizes a tag using Adaptive Millimetro's algorithm and overlay a virtual box at the estimated location using the platform presented in [5]. A laptop processes Adaptive Millimetro's data and sends detected tag positions to a server, which then concurrently images it for all devices connected to an AR scene.

Tag Detection in Mobility: We show the robustness of our extend algorithm for mobile scenarios by either moving both the tag and the radar while visualizing the results with the AR app. The robustness of the Kalman filter under mobility is shown in Figure 2.

Tag Detection in the presence of obstacles: We demonstrate Adaptive Millimetro's performance in non-line-of-sight scenarios by obstructing the tag behind a non-metal obstacle and demonstrating how it affects the operating range.

REFERENCES

[1] E. Soltanaghaei, A. Prabhakara, A. Balanuta, M. Anderson, J. M. Rabaey, S. Kumar, and A. Rowe, "Millimetro: mmwave retro-reflective tags for accurate, long range localization," in *Proceedings of the 27th Annual International Conference on Mobile Computing and Networking*, pp. 69–82, 2021.
[2] L. C. Van Atta, "Electromagnetic reflector," Oct. 6 1959. US Patent 2,908,002.
[3] R. Mehra, "On the identification of variances and adaptive kalman filtering," *IEEE Transactions on Automatic Control*, vol. 15, no. 2, pp. 175–184, 1970.
[4] G. J. McLachlan, "Mahalanobis distance," *Resonance*, vol. 4, no. 6, pp. 20–26, 1999.
[5] N. Pereira, A. Rowe, M. Farb, I. Liang, E. Lu, and E. Riebling, "Arena: The augmented reality edge networking architecture," in *2021 International Symposium on Mixed and Augmented Reality (ISMAR)*, 2021.