Poster: Ultra-low-power Angle-of-Arrival estimation Using a Single Antenna

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ABSTRACT

In this poster, we present a new approach to low-power self-localization for IoT nodes called *Sirius*. With the rise of low-power sensor networks in precision farming, climate monitoring, and surveying, it has become increasingly critical to accurately and robustly localize low-power sensor nodes. However, traditional systems that rely on antenna arrays and time synchronization are too complex for low-power IoT nodes. To overcome this limitation, *Sirius* utilizes gain-pattern reconfigurable antennas with passive envelope detector-based radios to estimate angle-of-arrival. This is achieved by embedding direction-specific codes in the received signals, which carry angle-of-arrival information. Our prototype has demonstrated a median error of 7 degrees in angle-of-arrival estimation and 2.5 meters in localization, comparable to state-of-the-art antenna array-based systems. This new approach opens up exciting possibilities for low-power IoT nodes in various fields.

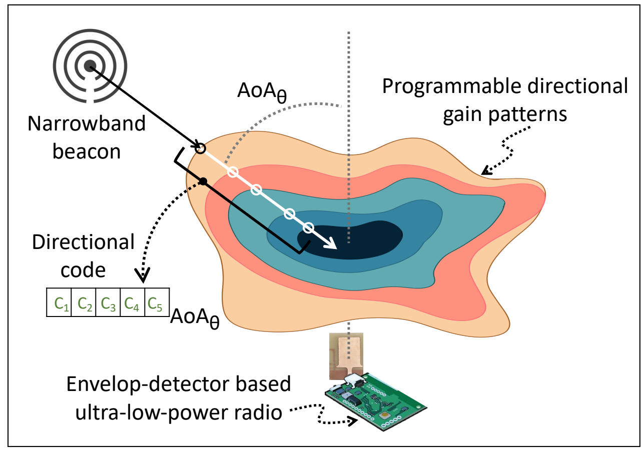

Figure 1: *Sirius*'s antenna beam pattern is switched to embed a direction-specific signature in the signal, allowing for unique angle-of-arrival mapping based on the vector of amplitudes.

1 OVERVIEW

The development of miniaturized and ultra-low-power localization techniques has created new opportunities for long-term monitoring and behavioral studies of wildlife and climate over large open fields. Sensor nodes that are only a few centimeters in size and a few grams in weight have the ability to self-localize and store data for several days, while intermittently transmitting the data to nearby gateways. However, self-localization is particularly difficult for small and low-power nodes. Traditional location sensors require a lot of power, while localization is based on the distance and angle-of-arrival (AoA) features extracted from the received signal. Triangulation using AoAs from two unsophisticated beacons can be enough for a node to find its position, but existing methods need complex and power-hungry hardware for AoA estimation. Spatial sampling needs an antenna array separated by at least a half-wavelength distance, which results in a power-hungry radio front end and a bigger space for low-frequency antennas.

In this poster, we present *Sirius*, an ultra-low-power self-localization system that uses a single antenna to estimate the AoA of incoming signals and triangulate its location without the need for synchronization with anchors. Our approach, called "directional code embedding", embeds a unique direction-specific code to the incoming signal during the reception, and later post-processes the signal to recover the code specific to a particular AoA. By fluctuating the amplitude of the signal in a consistent and subtle manner, we can add a signature to the signal that remains transparent to regular communication and signal to decode but can be identified as a unique code by signal processing. This signal fluctuation can be a function of the AoA, which allows the embedded code to reveal the AoA. We leverage the antenna's gain pattern to achieve this. Figure 1 shows an overview of the system, where the reconfigurable antenna receives the signal with various gain patterns to generate a vector of gain values that uniquely maps to the AoA of the signal.

This work aims to simplify spatial sensing on resource-constrained devices by reducing hardware complexity and treating it as a computation and inference problem. It is a significant step towards a broader vision of edge device sensing. For a detailed system description and evaluation, please refer to our MobiSys 2023 paper [1].

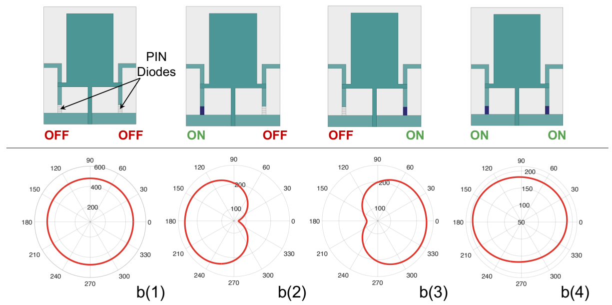

Figure 2: *Sirius* uses pin-diodes to switch the gain pattern of an antenna, allowing for changes to the shape of the gain pattern by connecting and disconnecting a conductive patch to the antenna.

2 INTUITION AND SYSTEM DESIGN

Our goal with *Sirius* is to enable localization on ultra-low-power nodes comprising passive envelope detectors. The core idea is to embed a direction-specific code using subtle amplitude fluctuations in the received signal so that even the envelope detectors can sense these amplitude changes without requiring to sample the phase of the signal. We modify the antenna's gain value to incorporate direction-specific variations by using RF switches to connect and disconnect conductor patches to the antenna carefully. Figure 2 shows the gain pattern of an antenna that we configure using pin diodes to connect conductor patches to either side, allowing us to switch between unique gain patterns in real time.

AoA extraction: The amplitude of the received signal $y(\phi, t)$ is proportional to the gain of the antenna, $G(\phi)$, at a specific angle-of-arrival ϕ of the incoming signal $x(t)$. By using a reconfigurable antenna with multiple gain patterns, we obtain an array of sampled signals with unique gain values and the same angle-of-arrival. $[y_1(\phi, t)y_2(\phi, t)\dots y_n(\phi, t)]$, here n is the number of unique gain patterns. The amplitudes of the array contain a unique signature of the angle-of-arrival, but are dependent on the transmitted signal strength or the distance between the antennas. To solve this, we divide each element of the array by the first element, creating a signature that is independent of the transmitted signal. This signature code is then matched with a pre-learned signature in a lookup table to determine the angle-of-arrival ϕ.

Asynchronous anchor identification: We create an algorithm that utilizes the envelope detector-based receiver circuit's non-linear properties to label asynchronous anchor signals to their corresponding time windows. We use pure tones of frequency f_1 and $f_2 = f_1 + \Delta f$ transmitted from anchor1 and anchor2, respectively. The rectifier's non-linear property generates a beat frequency component equivalent to Δf when signals from both anchors collide. Figure 3 depicts two anchor signal designs with different duty cycles that result in time windows of received signals without interference. The first case shows anchor 2's window as the exterior neighbor of the collision windows, while the second case shows anchor 2's window as the interior neighbor of the collision window.

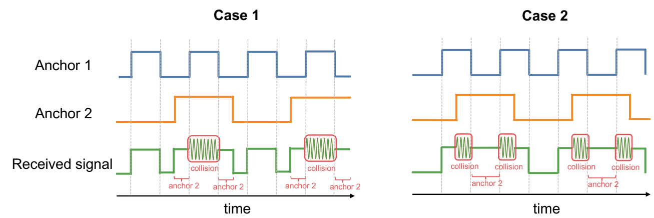

Figure 3: Interference of multiple signals creates a beat frequency that enables anchor identification.

3 PRELIMINARY EVALUATIONS

We evaluated the performance of *Sirius*'s 900MHz and 2400MHz prototypes in real-world scenarios by mounting the antenna on a programmable turntable controlled by a microcontroller and a stepper motor. The antenna's precise rotation was controlled to evaluate AoA estimation and location estimation in various outdoor locations and environments. The overall performance of AoA estimation is shown in Fig. 4(a), where the estimated angles at each measurement are displayed, along with standard deviation error bars. Fig. 4(b) shows the cumulative distribution function of the overall error, indicating that the median AoA error is less than 7 degrees. Our outdoor open-field experiments show that the median localization error is 2.5 meters.

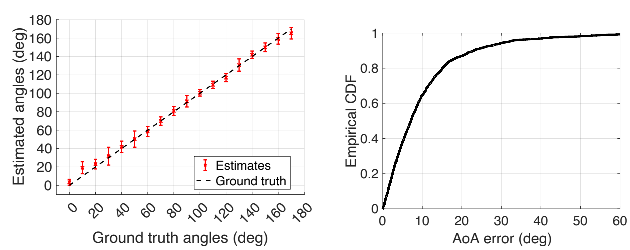

Figure 4: (a) *Sirius*'s overall AoA estimation accuracy, (b) Cumulative distribution function of AoA errors.

REFERENCES

[1] Nakul Garg and Nirupam Roy. Sirius: A self-localization system for resource-constrained iot sensors. In *The 21st Annual International Conference on Mobile Systems, Applications, and Services (MobiSys '23), June 18–June 22, 2023, Helsinki, FInland*. ACM.