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 AoA 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.

CCS CONCEPTS

• **Computer systems organization** → **Sensor networks**; **Embedded systems**; **Sensors and actuators**.

KEYWORDS

Ultra-low-power sensing; Self Localization; IoT; Embedded AI; Low-power antenna

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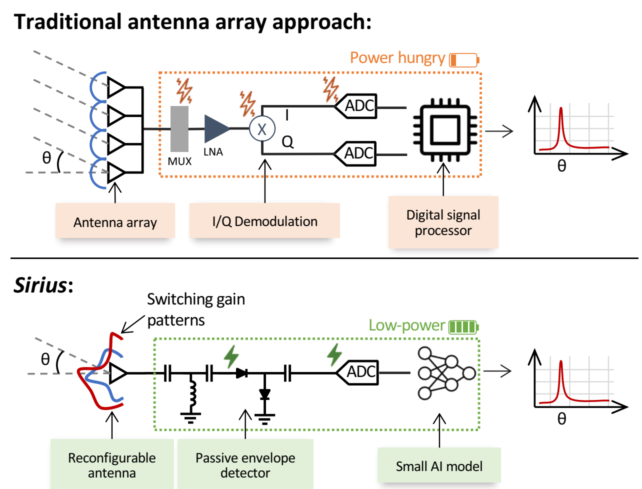

Figure 1: *Sirius*'s antenna beam pattern is dynamically switched to embed direction-specific signatures in the signal, allowing for unique angle-of-arrival mapping.

1 OVERVIEW

Miniaturized, low-power localization techniques have paved the way for long-term wildlife and climate monitoring over vast open areas. However, self-localization poses challenges for these nodes due to their size and power limitations. Conventional location sensors demand significant power and rely on distance and angle-of-arrival (AoA) features extracted from received signals. Triangulation with AoAs from two basic beacons can determine a node's position, but existing methods require complex, power-intensive hardware. Furthermore, spatial sampling necessitates an antenna array separated by at least half-wavelength, resulting in a power-consuming front end and larger antenna space requirements.

In this poster, we present *Sirius*, an ultra-low-power self-localization system that estimates angle-of-arrival (AoA) and triangulates its position using a single antenna, eliminating the need for anchor synchronization. Our "directional code embedding" method encodes a unique, direction-specific code into the incoming signal during reception and later extracts the AoA-specific code during post-processing. By subtly and consistently altering the signal amplitude, we create a transparent signature for

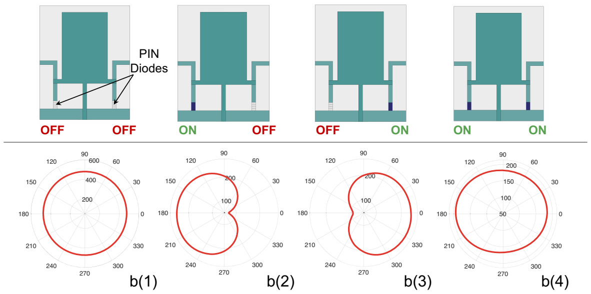

Figure 2: *Sirius* uses pin-diodes to switch the gain pattern of an antenna by connecting and disconnecting the conductive patches to the antenna.

regular communication, identifiable as a unique code through signal processing. This fluctuation, dependent on the AoA, reveals the AoA through the embedded code. We utilize the antenna's gain pattern for this purpose. Figure 1 shows the reconfigurable antenna that receives signals with various gain patterns, generating a gain value vector that uniquely corresponds to the signal's AoA.

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 [1, 2]. For a detailed system description and evaluation, please refer to our MobiSys 2023 paper [3].

2 INTUITION AND SYSTEM DESIGN

Our objective with *Sirius* is to enable self-localization on ultra-low-power nodes comprising passive envelope detectors. We embed a direction-specific code through subtle amplitude fluctuations in the received signal, allowing envelope detectors to sense changes without sampling the signal's phase. Figure 2 shows diverse gain patterns switched by connecting conductor patches using pin diodes.

AoA extraction: The amplitude of the received signal $y(\phi, t)$ is proportional to the gain of the antenna, $G(\phi)$, at a specific AoA 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 AoA. $[y_1(\phi,t)y_2(\phi,t)\ldots y_n(\phi,t)]$, here n is the number of unique gain patterns. The amplitudes of the array contain a unique signature of the AoA 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 codes in a lookup table to estimate the best AoA ϕ.

Asynchronous anchor identification: We developed an algorithm utilizing hardware non-linearity to associate

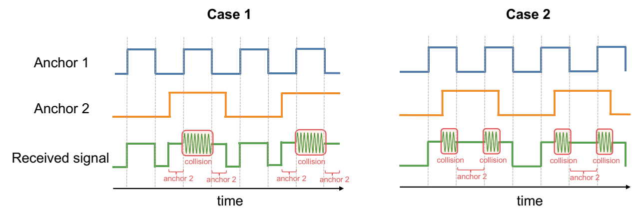

Figure 3: Interference of multiple signals creates a beat frequency that enables anchor identification.

asynchronous anchor signals with their respective time windows. Sinusoidal tones with frequencies f_1 and $f_2 = f_1 + \Delta f$ are transmitted from anchor1 and anchor2. The rectifier's non-linear nature produces a beat frequency component equal to Δf when signals from both anchors intersect. Figure 3 illustrates anchor signals with varying duty cycles, leading to non-interfering time windows for received signals. The first scenario positions anchor 2's window outside the collision windows, while the second places it inside.

3 PRELIMINARY EVALUATIONS

We evaluated *Sirius*'s performance in real-world settings by attaching the antenna to a microcontroller-operated programmable turntable. This setup allowed for precise antenna rotation, enabling the evaluation of AoA and location estimation across various outdoor environments. Fig. 4(a) displays the overall AoA estimation performance, including estimated angles and standard deviation error bars for each measurement. Fig. 4(b) presents the cumulative distribution function of overall error, revealing a median AoA error below 7 degrees. Our outdoor open-field experiments demonstrated a median localization error of 2.5 meters.

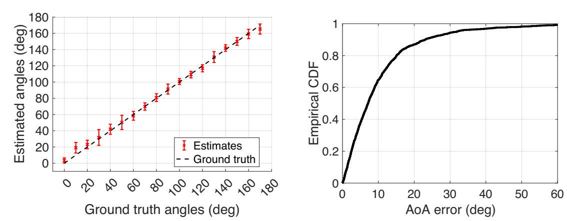

Figure 4: (a) *Sirius*'s overall AoA estimation accuracy, (b) Cumulative distribution function of AoA errors.

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