Angle of Arrival Localization for Single-Chip Micro Mote

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Abstract

The Single-Chip Micro Mote (SCμM) is a 2×3mm^2 single die, featuring a 2.4 GHz radio supporting IEEE 802.15.4 and Bluetooth Low Energy (BLE). Because of its small size, it is an ideal platform for tracking and localizing wild animal or insect. The existing localization method for SCμM is based on lighthouse laser, and uses the chip's built in light sensor. While this technique works, the chip needs to be less than 5 m from a lighthouse base station, and this type of localization can only be used indoors. We develop a localization method for SCμM based on the direction-finding feature of BLE 5.1. SCμM is flexible enough that we can, in software, add a Constant Tone Extension (CTE) portion to a BLE frame, which is key to use BLE's direction finding feature. With an antenna array and CTE, frequency offset can be estimated through the phase samples, assisting to improve the direction finding performance over SCμM. We built a prototype Angle of Arrival (AoA) localization system and achieves a median angle estimation error of ±5° inside of an anechoic chamber.

CCS Concepts

• **Networks** → *Location based services*; • **Hardware** → *Sensor applications and deployments.*

Keywords

Localization, SCμM, Angle of Arrival, BLE

1 Introduction

The Single-Chip Micro Mote (SCμM) is the first crystal-free mote-on-chip that can interoperate with off-the-shelf BLE and IEEE 802.15.4 radios. On a 2×3 mm^2 single die, SCμM integrates a 32-bit ARM Cortex-M0 core and a 2.4 GHz IEEE 802.15.4/BLE radio. The traditional crystal used in System-on-Chip (SoC) designs for clock generation is replaced by an internal oscillator circuit, allowing SCμM to operate with just an antenna and a power source. This innovation further reduces the size of IoT nodes, facilitating the development of compact tags for tracking applications, including warehouse management and wildlife tracking.

Alvarado *et al.* have developed a solution to localize SCμM chip; it is based on the lighthouse system, in which SCμM uses its built-in optical receiver to detecting a laser that a basestation periodically sweeps across a room [1]. This work achieving an RMS error of 7.25 mm in 2D, 11.2 mm in 3D. SCμM can calculate its own position [4]. The main limitations of light-house localization is that SCμM needs to be at most 5 m from a basestation, and that it doesn't work outside, as direct sunlight blinds the optical receiver.

The BLE 5.1 standard recently introduced a direction-finding feature, using AoA [5]. Each anchor node has an antenna array; its radio chip measures the phase offset of each antenna's received frame. By knowing the relative positions of the antennas, it determines the signal's angle of arrival. A central computation unit then determines the location of the mobile node through triangulation. In this system, SCμM is the mobile node. BLE AoA only works if the mobile node emits frames that have a Constant Tone Extension (CTE), a unmodulated and unwhitened tone for 16-160 μs inserted into the frame. SCμM can do this because its whitening is software-defined. Although SCμM's internal oscillator has frequency error without calibration, the frequency error can be estimated based on the CTE reference period and won't impact the performance of angle estimation. Compared to lighthouse localization, AoA localization consumes less energy, and as it can work outdoors, this technique is suitable for wildlife tracking.

2 BLE Angle of Arrival

If the transmitter is sufficiently far away, the signal arriving at the receiver can be treated as a plane wave [2] (Fig. 1, upper right). The angle of signal can be computed using (1), where Δ_ϕ, d, λ and θ represent the phase difference between two antennas, the distance between two antennas, the wave length of signal and the arrival angle of the signal, respectively.

$$\theta = arcsin(\frac{\Delta_\phi \lambda}{2\pi d}) \quad (1)$$

The BLE AoA receiver uses an RF switch to lower costs and energy consumption. It connects to an RF switch chip that allows sampling from one antenna at a time, resulting in discarded signals from others. To address this, BLE introduced the CTE packet field, enabling recovery of the full signal from each antenna using fewer samples.

The CTE structure, shown in the upper left corner of Fig. 1, consists of a sequence of unwhitened 1 bits following a standard BLE packet, with a length ranging from $16us$ to $160us$. After GFSK modulation, this produces a sinusoidal signal at a constant frequency. The CTE starts with a $4us$ guard period, followed by an $8us$ reference period, and then features alternating switch and sample slots, each lasting $1us$ in our experiment. During the reference period, I/Q

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samples are generated every $1us$, allowing the SoC to estimate the carrier frequency offset (CFO) from the slope of the black solid line from $4us$ to $12us$. The unstable I/Q samples during switching slot are discarded. The phase difference between antennas can then be measured by compensating one I/Q sample to another, as illustrated by the red dashed line and circle in Fig. 1.

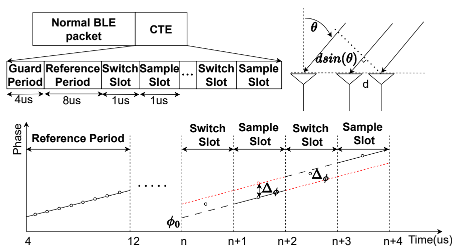

Figure 1: The structure of CTE and The phase difference between two antennas in BLE AoA system

3 SCμM AoA Localization Evaluation

3.1 Experiment Setup

To evaluate the AoA localization performance for the SCμM, a prototype is built using the SCμM, nRF5340-DK board, and a CHW antenna array. In system, the SCμM transmits a BLE packet with CTE, while the nRF5340-DK receives the packet. During the reception of the CTE portion, the RF switch mechanism is activated to generate I/Q samples from different antennas. All the I/Q samples are sent to a PC via serial communication, where the angle of arrival is calculated.

To reduce multipath interference, the experiment is conducted in an anechoic chamber, as shown in Fig. 2. The distance between the SCμM and the antenna array is set to $1m$, with both the SCμM and the antenna array positioned on two tripods, $1m$ above the ground. Below the antenna array, a tripod head with a dial gauge allows for rotating to different angles, simulating various angle of arrival scenarios. The antenna array is rotated from $-50°$ to $50°$ in $10°$ interval. At each position, 50 angle estimations are calculated, with beamforming and grid search algorithm [3] to improve the accuracy.

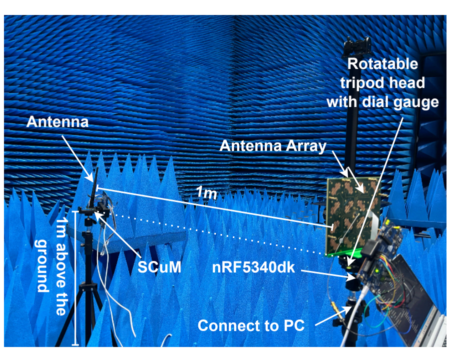

Figure 2: The SCμM AoA experiment setup

3.2 Results

Fig. 3 illustrates the angle estimation results. The boxplot displays the angle estimates at different positions, with the blue line representing the ground truth. The red dashed line and yellow dashed line indicate the $\pm 10°$ and $\pm 5°$ boundaries, respectively. At position $\pm 50°$, the estimated angle distribution shows significant errors compared to the true angle, indicating that the AoA localization for the SCμM has a limited effective range. Within the range of $-40°$ to $40°$, most estimated angle errors fall within the $\pm 10°$ boundary. When calculating the estimated angle at a given position multiple times, the median value remains within the $\pm 5°$ boundary, except at the positions of $\pm 40°$. Despite the limited effective range and some outliers, the main distribution and median provide valuable information for locating the SCμM.

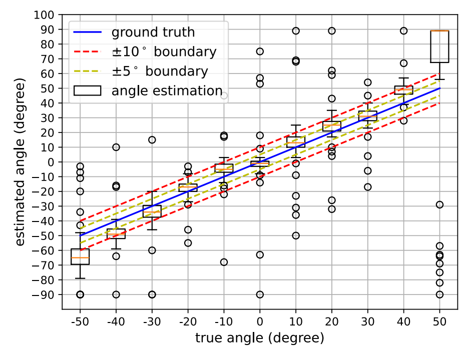

Figure 3: SCμM AoA estimation results in anechoic chamber

4 Conclusion

In this paper, we proposed a new localization method for SCμM, based on the direction-finding features of BLE 5.1. Compare to lighthouse localization, our method is energy efficient and suitable for outdoor environment. By modifying the whitening step on SCμM, we successfully use SCμM to transmit a BLE packet with CTE. The CFO of SCμM in each packet is estimated based on CTE so that it is possible to use AoA for SCμM localization while the frequency offset of SCμM is unstable. An AoA-based localization system for the SCμM is presented and tested in an anechoic chamber. The results indicate that the receiver accurately determines the direction of the SCμM within $\pm 40°$, with most angle errors under $10°$ and median errors under $5°$.

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