Indoor Positioning Experiment Based on Phase Ranging with Bluetooth Low Energy (BLE)

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Abstract. In this paper, we propose and demonstrate an indoor positioning scheme based on phase ranging with Bluetooth low energy (BLE). It is to deal with the contradiction between the cost and accuracy of today's indoor positioning system. The experiment is based on BLE multi-carrier phase ranging, and the DA14695 BLE module from Dialog Semiconductor is selected as the experimental hardware module. The linearized pseudo range observation equation and least square estimation are used to construct a positioning platform to verify its positioning effect. The experimental results show that the indoor positioning method based on BLE phase-based ranging has high positioning accuracy, and in view of the low-power and low-cost advantages of BLE itself, it shows that this indoor positioning scheme is feasible and has further research value.

1. Introduction
In the field of indoor positioning, common indoor positioning systems include UWB positioning system, WLAN positioning system, Bluetooth Low Energy (BLE) positioning system, and 5G base station positioning system [1]. Ultra-wideband is a carrier-free communication technology that uses nanosecond non-sine wave narrow pulses to transmit data. UWB indoor positioning technology has the advantages of centimeter-level high accuracy and resistance to multipath fading, but the application of this technology in the market is still relatively limited. The most important reason is the high cost of UWB module equipment [2]. Although WLAN positioning technology [3] has advantages in equipment terminal deployment and low cost, it has weak time-varying characteristics and high power consumption. So it is not suitable for positioning scenarios that require equipment portability [4]. With the development and popularization of 5G technology in recent years, millimeter wave communication, as one of the key 5G technologies, can improve the accuracy of positioning TOA/TDOA measurements due to its high frequency and high bandwidth characteristics. However, since 5G positioning technology relies heavily on cellular networks, it only serves a single operational user and cannot serve cross-operational users. With the release of BLE, its low power consumption, low cost and long transmission distance characteristics have made it a standard for many IoT devices. The current BLE-based indoor positioning technologies are mainly based on Received Signal Strength Indication (RSSI), Arrival of angle (AOA), Time of Flight (TOF), Time Difference of Arrival (TDOA), etc. Multi-Carrier Phase Ranging (MCPR) [5] is a more mature and high accuracy way of ranging, so this paper develops secondary positioning based on the high accuracy ranging of MCPR.
In this paper, based on the multi-carrier phase ranging of BLE, we write the corresponding code to build the localization base station network and accomplish the localization purpose by linearizing the pseudo range observation equation. The fixed tag positioning is experimentally demonstrated and analyzed respectively. This experiment demonstrates and verifies the feasibility of the BLE indoor positioning scheme based on phase ranging, and analyzes the positioning accuracy and effect of the scheme.

The article is organized as follows: the first part introduces the BLE technology and the related experimental platform, the second part introduces the principle of phase ranging and positioning principles, the third part shows the experimental results of fixed tag in real situations and presents the analysis, and the fourth part states the conclusion and outlook.

2. Related works
Bluetooth (or IEEE 802.15.1) is regulated by physical and MAC layers for connecting different fixed or mobile wireless devices within a certain personal space. The reduction of BLE power consumption is mainly achieved through chip design and system design, while the power consumption of BLE chips mainly comes from dynamic operation power consumption and static sleep power consumption, which are affected by factors such as device activation, sleep time, and the efficiency of executing communication protocols and applications. These features of BLE are well suited for indoor positioning scenarios that require low power consumption, long transmission distances, and high portability.

The experimental hardware system first and foremost meets the Bluetooth transmitter with BLE technology and is able to achieve a more accurate point-to-point ranging function based on Bluetooth. The hardware module of this experimental system is the DA14696 module based on BLE version 5.2 developed by Dialog Semiconductor. The DA1469x family is the first mass-produced wireless MCU based on the Arm Cortex-M33 processor, providing enhanced processing power for compute-intensive applications such as high-end fitness trackers, advanced smart home devices and virtual reality game controllers. In addition, the wireless MCU family features a configurable MAC that helps manufacturers deploy proprietary 2.4GHz and the latest low-power Bluetooth protocols, opening up new application possibilities such as precise positioning for Real-time locating system (RTLS) and low-latency communication exchange for applications such as gaming.

![Figure 1. DA14695 module](image)

The DA14696 wireless ranging application obtains distance measurements by using tone switching, where the in-phase and quadrature outputs (IQ data) of the RF-ADC calculate the distance between two devices from the continuous wave signals received by the two devices. According to Dialog's documentation, theoretical ranging accuracy can reach sub-meter level. In view of the low power consumption, low cost and portability of BLE, it is worthwhile to further investigate the method of indoor positioning based on Bluetooth phase ranging.

3. Principle of phase ranging and positioning
Multi-carrier phase ranging (MCPR) is based on the condition that the transmitter and receiver are time-synchronized, and the transmitter and receiver will generate the same phase of the carrier at the same moment. In MCPR, two signals with different frequencies will experience different phase shifts after the same time. The transmitter first sends a signal of frequency f1, the transmitter locks its local oscillator
to that frequency, and then retransmits that signal back to the receiver. The transmitter and receiver respectively send continuous carrier signals $f_1$, $f_2$, and measure the phase difference $\theta_1$, $\theta_2$. It is calculated as follows [6]:

$$\theta_1 = 2\pi \cdot \left( \frac{2 \cdot d \cdot f_1}{c} + n \right)$$

(1)

$$\theta_2 = 2\pi \cdot \left( \frac{2 \cdot d \cdot f_2}{c} + n \right)$$

(2)

So according to equations (1) and (2), the distance between the two is

$$d = \frac{c \cdot \theta_2 - \theta_1}{4\pi \cdot f_2 - f_1}$$

(3)

We first solve the point localization problem by linearizing the pseudo range observation equation and the small squares analysis method. We summarize the development of the linearization procedure and the least squares method for the sake of completeness. We are inspired by the traditional satellite positioning method and apply this method to indoor positioning. First, we assume that we can take the actual observation as the sum of the model observation and the error term [7].

$$P_{\text{observed}} = P_{\text{model}} + \text{noise} = P(x, y, z, \tau) + v$$

(4)

Next, we extend the information about the model using the computation according to Taylor’s theorem, the temporary parameter values are $(x_0, y_0, z_0, \tau_0)$, and ignoring second-order and higher-order terms.

$$P(x, y, z, \tau) \approx P(x_0, y_0, z_0, \tau_0) + (x - x_0) \frac{\partial P}{\partial x} + (y - y_0) \frac{\partial P}{\partial y} + (z - z_0) \frac{\partial P}{\partial z} + (\tau - \tau_0) \frac{\partial P}{\partial \tau}$$

$$= P_{\text{computed}} + \frac{\partial P}{\partial x} \Delta x + \frac{\partial P}{\partial y} \Delta y + \frac{\partial P}{\partial z} \Delta z + \frac{\partial P}{\partial \tau} \Delta \tau$$

(5)

The partial derivatives in the above expressions also use temporary values $(x_0, y_0, z_0, \tau_0)$. The remaining observations are defined as actual observations and observations calculated using temporary parameter values:

$$\Delta P = P_{\text{observed}} - P_{\text{computed}}$$

$$\Delta P = \frac{\partial P}{\partial x} \Delta x + \frac{\partial P}{\partial y} \Delta y + \frac{\partial P}{\partial z} \Delta z + \frac{\partial P}{\partial \tau} \Delta \tau + v$$

(6)

This can be written out in matrix form as follows:

$$\Delta P = \begin{pmatrix} \frac{\partial P}{\partial x} & \frac{\partial P}{\partial y} & \frac{\partial P}{\partial z} & \frac{\partial P}{\partial \tau} \end{pmatrix} \begin{pmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta \tau \end{pmatrix} + v$$

(7)

We can obtain such an equation for each positioning base station. For $m$ positioning base stations, we generally can write this system of $m$ equations in matrix form as follows:
The equation is usually written using matrix notation as:

\[ \mathbf{b} = \mathbf{A}\mathbf{x} + \mathbf{v} \]  \hspace{1cm} (9)

It expresses the linear relationship between the residual observation value \( \mathbf{b} \) and the unknown correction of parameter \( \mathbf{x} \), where \( \mathbf{b} \) is the observation value minus the calculated observation value. The column matrix \( \mathbf{v} \) contains all the noise terms. We call the above matrix equation also the “linearized observation equation”. Based on the above principles, the positioning diagram is shown in the figure below:

4. Experimental results and analysis
The actual ranging experiments were conducted using DA14695 in the absence of obscurants. Since this experiment verifies the feasibility of BLE range-based localization, a short-range ranging accuracy experiment is conducted first. The distance range was tested from 0.5 m to 3.5 m. The test environment and test results are shown in Table 1 and Figure 3 below.

Table 1. Real Distance Measurement

| DA14695 Real Distance Measurement (Unobstructed situation) |
|-----------------|--------|--------|--------|--------|--------|--------|
| Real            | 0.50   | 1.00   | 1.50   | 2.00   | 2.50   | 3.00   | 3.50   |
| First test      | 0.40   | 1.00   | 1.30   | 2.00   | 2.40   | 2.90   | 3.40   |
| Second test     | 0.50   | 1.10   | 1.40   | 1.90   | 2.40   | 2.90   | 3.50   |
| Third test      | 0.50   | 0.90   | 1.50   | 1.90   | 2.50   | 3.00   | 3.50   |
| Avg             | 0.47   | 1.00   | 1.40   | 1.93   | 2.43   | 2.93   | 3.47   |
The actual test results from the above figure and the above table show that the DA14695 BLE module has a good ranging effect in the absence of obstructions, and the measured error is within 10 cm, which achieves sub-meter level ranging accuracy. Under the condition of sub-meter boundary-based ranging data, it is shown that it is possible to further construct positioning algorithms for indoor positioning experiments.

Experiment I: Indoor localization with fixed tag at the origin.

Experimental environment: In an empty experimental building, the actual environment is shown in Figure 4 below.

Experimental parameter setting: the tag is fixed at the origin position (0, 0) in our constructed Cartesian coordinates, and the tag height is set to 50 cm. The four base stations were placed at the four corners relative to the tags, and the base station heights were all set to 160 cm. Station 1 is placed at coordinates (-3, -3), Station 2 at coordinates (3, -3), Station 3 at coordinates (3, 3), and Station 4 at coordinates (-3, 3). After fixing the tag with the base station, the four distances data are collected and then the coordinates of the tag are experimentally output 60 times by the constructed positioning algorithm. A smoothing filter is used in the output to optimize the data.
Figure 7. Error dispersion at (0,0)

The experimental results in Figure 5 show that the output localization results of fixed tag are all around the actual position origin after smoothing filter processing, which achieves a better localization effect. Figure 6 shows the measured distance between each base station and the fixed tag, from which it can be obtained that excluding the error data set, the rest of the data are close to the actual 4.24 m. The degree of positioning dispersion can be visualized in Figure 7, from which it can be seen that the error in the X-axis is from 0 m to 0.1 m and the error in the Y-axis is from 0 m to 0.2 m. There are some errors in the data, which may be caused by the presence of certain wireless interference in the vicinity or the instability of the ranging data.

Experiment II: Under the same experimental environment as Experiment I, move the tag to the left at (-1.5, 0) and perform a positioning experiment.

Figure 8. Tag at (-1.5, 0)  Figure 9. Distance of stations from the tag at (-1.5,0)

Figure 10. Error dispersion at (-1.5,0)
As seen in Figure 8, the position positioned basically matches the actual position. Figure 9 shows the output of the distance data without smoothing filtering, the distance between base station 1 and base station 4 and the tag is $\sqrt{11.25}$ m approximately equal to 3.35 m, and the distance between base station 2 and base station 4 and the tag is $\sqrt{29.25}$ m approximately equal to 5.4 m. The degree of positioning dispersion can be visualized in Figure 10, from which it can be seen that the error in the X-axis is from 0 m to 0.25 m and the error in the Y-axis is from 0 m to 0.1 m. In summary, the localization scheme based on BLE ranging is better in the indoor environment for the case of fixed tag. In the case of tag movement, it has some localization effect, which shows the feasibility of this scheme.

5. Conclusion
In this paper, we introduce and demonstrate a BLE indoor positioning experiment based on phase ranging. We experimented and analysed the BLE with phase-based ranging positioning scheme with certain effect in indoor localization, and achieved better localization effect in the case of fixed tag. This paper presents a detailed formulation of the principle of implementing phase-based ranging for localization. Inspired by the satellite positioning principle, the point positioning problem is solved by linearizing the pseudo range observation equation and least squares estimation. The DA14695 BLE module is selected for secondary development, and the real positioning situation based on Bluetooth ranging data is experimented and demonstrated by constructing a ranging and positioning algorithm, and the experimental results show that this scheme has certain feasibility and further research significance and value. The next main task is to conduct experiments on positioning in the moving case and to optimize its positioning trajectory and accuracy.

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