IEICE Communications Express, Vol.13, No.8, 290–294

ComEX

Special Cluster in Emerging Communication Technologies in Conjunction with Main Topics of ICETC 2023

LETTER

Correction of round-trip time and selection of access points for estimating wireless LAN locations by multilateration

Yusuke Shida[1], **Satoru Aikawa**[1, a)], **and Shinichiro Yamamoto**[1]

Abstract This study explores an advanced method for indoor location estimation leveraging a wireless local area network (WLAN). The integration of round-trip time (RTT), as established by IEEE 802.11mc, has marked a significant advancement in WLANs. This enhancement is pivotal in refining indoor location estimations through multilateration (MLAT) techniques. The RTT, by providing more precise distance measurements between WLAN access points (APs) and users compared to the traditional received signal strength indicator, holds promise for improved accuracy. Nonetheless, in environments with numerous rooms, such as a multi-room floor, the efficacy of MLAT, even with RTT implementation, is not optimal. Addressing this challenge, our paper introduces and validates a novel approach for correcting RTT inaccuracies and a strategic method for selecting APs in MLAT scenarios.

Keywords: localization, RTT, multilateration, Wi-Fi
Classification: Navigation, guidance and control systems

1. Introduction

Our laboratory has focused on indoor location estimation techniques using the received signal strength indicator (RSSI), which measures the strength of radio waves received from WLAN access points (APs) [1]. With the widespread adoption of Wi-Fi devices, the cost of installing new APs has decreased significantly. However, RSSI is subject to fluctuations due to shadowing and multipath effects in the surrounding environment.

This paper discusses a multilateration (MLAT) method that employs round-trip time (RTT), which is less affected by shadowing and multipath than RSSI [2]. The standardization of IEEE 802.11mc was completed in 2016, but the adoption of Wi-Fi routers supporting it has only increased in recent years [3]. This paper anticipates an environment where RTT-capable APs are more prevalent, leading to situations where users can observe more APs than necessary for effective MLAT. Hence, we propose a method for selecting the most suitable APs for this purpose.

Furthermore, this paper, which extends a previous presentation at the IEICE ICETC 2023 [4], investigates the causes of incorrect RTT correction and proposes improvements.

[1] Graduate School of Engineering, University of Hyogo, 2167 Shosha, Himeji-city, Hyogo 671-2280, Japan
a) aikawa@eng.u-hyogo.ac.jp

DOI: 10.23919/comex.2024TCL0002
Received January 9, 2024
Accepted February 2, 2024
Publicized March 12, 2024
Copyedited August 1, 2024

2. Indoor location estimation

2.1 Multilateration (MLAT)

This subsection elaborates on the location-estimation method using RSSI-based MLAT. Initially, it calculates the distances between three or more APs and a user terminal based on the RSSI. The process involves plotting a circle for each AP, with the radius being the estimated distance to the user. The estimated user location is determined by the intersection of these circles (refer to Fig. 1). However, due to environmental factors like shadowing and multipath effects, these circles often do not intersect at a single point. To address this, the following procedure is employed:

First, the three APs with the highest RSSIs are selected from the observed set. Let x_1, x_2, and x_3 and y_1, y_2, and y_3 represent the x and y coordinates, respectively, of these APs. Let the distances between the APs and the user terminal be R_1, R_2, and R_3 and (x, y) be the user's position. The distances R_1, R_2, and R_3 are calculated from the RSSIs using Eq. (1), where f represents the frequency and N and L are environmental constants:

$$R = 10^{\frac{L-RSSI-20\log_{10} f}{N}}. \quad (1)$$

Next, the circle equations for each AP are formulated as follows:

$$(x - x_1)^2 + (y - y_1)^2 = R_1^2, \quad (2)$$
$$(x - x_2)^2 + (y - y_2)^2 = R_2^2, \quad (3)$$
$$(x - x_3)^2 + (y - y_3)^2 = R_3^2, \quad (4)$$

By subtracting equations (2) from (3) and (2) from (4), we derive equations (5) and (6) respectively:

$$2(-x_1 + x_2)x + 2(y_1 - y_2)y = -x_1^2 + x_2^2 + y_1^2 - y_2^2 + R_1^2 - R_2^2 \text{ and} \quad (5)$$

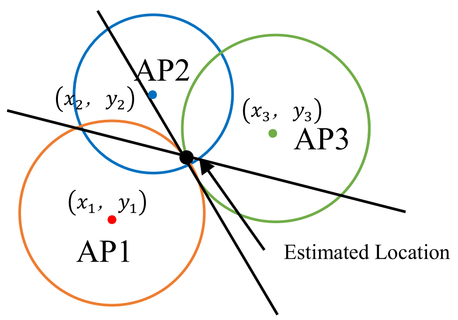


Fig. 1 Location estimation by the multilateration method

$$2(-x_1+x_3)x+2(y_1-y_3)y=-x_1^2+x_3^2+y_1^2-y_3^2+R_1^2-R_3^2 \quad (6)$$

Each of these equations represents a straight line (Fig. 1), and the user's location is estimated at the centroid of their intersection [5].

It is crucial for the MLAT service provider to know the locations of the APs in advance. This becomes challenging when numerous APs are present, the cost of identifying their locations is substantial, or their exact locations are unknown due to being on private premises. However, MLAT has the distinct advantage that it does not require prior many data measurement, which is necessary for the Finger Print method [1]. Therefore, MLAT is superior to the Finger Print method in terms of the cost of installing.

The accuracy of AP-user distance estimation using RSSI can be compromised by several issues. First, obstacles and walls can attenuate the RSSI signal. Second, distance estimations based on RSSI are susceptible to multipath effects. In contrast, distance estimations derived from RTT are less affected by multipath and other factors [6], leading to more accurate location estimation.

In MLAT, the user position is estimated from the AP-user distance calculated using RTT. Consequently, correcting RTT is expected to directly enhance the accuracy of MLAT estimations.

When implementing MLAT, selecting suitable APs for location estimation is pivotal. In scenarios where more than four APs are observable, the simplest selection method is choosing the AP with the highest RSSI or lowest RTT, likely the closest to the user. However, APs selected in this manner may not be optimally positioned for MLAT. Thus, this paper proposes a method for selecting APs that are more suitable for MLAT, aiming to improve its accuracy.

2.2 Nelder–Mead method

The Nelder–Mead method is a derivative-free optimization algorithm [7]. This method involves moving an n-dimensional simplex, composed of n + 1 vertices, to find the point where the objective function is minimized. The strategy for moving the simplex adapts based on specific conditions. In position estimation, the user's location can be estimated by setting the objective function $f(X,Y)$ as shown in Eq. (7), where x_i, y_i, X, Y, and R_i are shown in Fig. 2. This method is further explored in Section 3.2.

$$f(X,Y) = \sum_{i=1}^{3} \left| \sqrt{(x_i - X)^2 + (y_i - Y)^2} - R_i \right|. \quad (7)$$

2.3 RTT

RTT is the time difference between the transmission and reception of a radio wave, essentially the time taken for the radio wave to travel to the user terminal and back. To calculate the distance d between the AP and the user terminal, RTT is multiplied by the propagation speed c of the radio wave [3].

The signal exchange between the AP and terminal occurs at specific times: t_1 (first transmittance by the AP), t_2 (signal reception by the user terminal), t_3 (signal transmission from the user terminal), and t_4 (signal reception by the AP). As

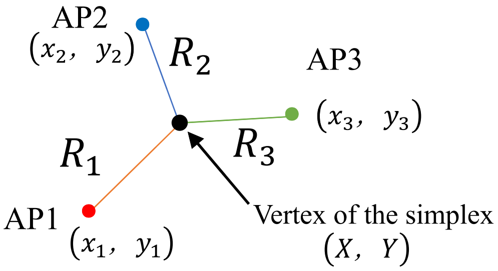


Fig. 2 Nelder-Mead method in localization

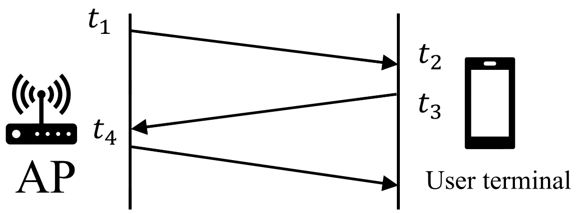


Fig. 3 Illustration of the RTT

shown in Fig. 3, $t_4 - t_1$ indicates represents the total RTT and $t_3 - t_2$ indicates the processing time at the terminal. Thus, the average time taken for the signal to travel from the AP to the user terminal is 1/2 $\{(t_4 - t_1) - (t_3 - t_2)\}$. Consequently, the distance d is calculated as:

$$d = \frac{1}{2}\{(t_4 - t_1) - (t_3 - t_2)\} \times c \quad (8)$$

3. Proposed method

3.1 Correction of RTT

RTT can measure the distance d between the AP and the user terminal more accurately than before. However, RTT also has errors, which adversely affect user location estimation in MLAT method. Therefore, we proposed a correction method for RTT [4], focusing on the fact that two types of information from radio waves in IEEE802.11mc or later: RTT and RSSI.

The RTT correction method proposed focuses on the RTT correction formula changing with each number of walls, and first determines the number of walls and then corrects the RTT with a suitable correction formula.The RTT correction formula is obtained by measuring the relationship between the actual distance and RTT in prior to the measurement and using the least-squares method. The actual correction formula obtained is the straight line shown by the red line in Fig. 4, which shows that the correction formula differs depending on the number of walls. The method for estimating the number of walls is based on the fact that the relationship between RTT and RSSI changes with the number of walls, as shown in Figure 5. The number of walls can be estimated from the RTT and RSSI obtained using Fig. 5.

1. Obtain the assumed RSSI value x from the RSSI–RTT relationship in Fig. 5.

2. Similarly, obtain the assumed RSSI value y from the RSSI–RTT relationship in Fig. 5.

3. Estimate the presence or absence of a wall by calculating the difference between x or y and the measured RSSI.

Previous RTT correction had a group of datas that were

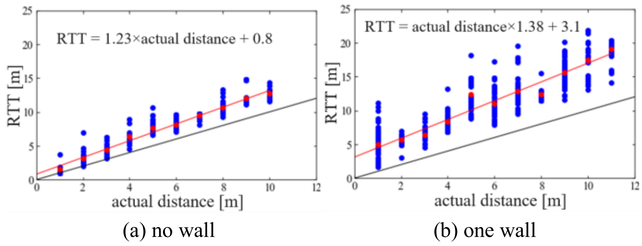


Fig. 4 Relationship between RTT and RSSI and correction formula

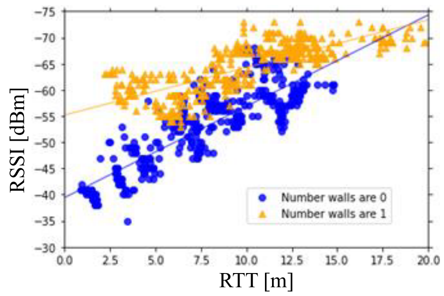


Fig. 5 Relationship between RTT and RSSI for each number of walls

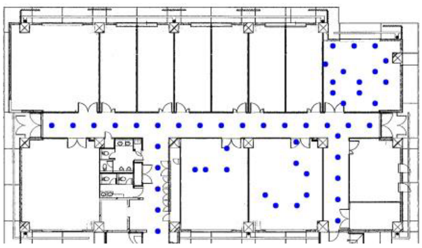


Fig. 6 Environment for experimental validation

clearly incorrect. We thought that the RTT correction formula, especially in the case of two or more walls, was the cause of the error, and we considered ways to improve it.

The previous correction formula was obtained by measuring the relationship between the actual distance and RTT in advance, for which 220 data were measured. We then tested whether this hypothesis is correct by increasing the number of data. In the verification, 9455 data were collected in the same environment as in Fig. 6 to obtain the correction equation. The blue dots in Fig. 6 are the measured locations.

3.2 Selecting APs in MLAT

As noted in Section 2.1, when the number of observed APs exceeds the required number for measurement, it becomes necessary to select the most appropriate APs for use. We propose and compare the accuracies of the following three AP selection methods:

Method 1.1: Selecting the APs with the smallest RTT
Method 1.2: Selecting APs with large angular variance
Method 1.3: Selecting APs such that they are not aligned in a straight line

Method 1.1, the simplest approach, selects APs with the smallest RTT, implying proximity to the user.

Method 1.2, as illustrated in Fig. 7, calculates the angular dispersion of APs around the user's location. It selects the

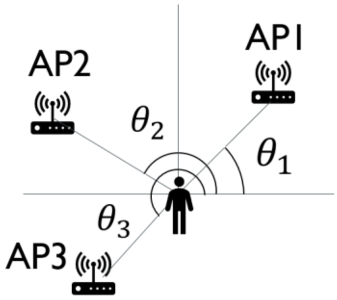


Fig. 7 Angular dispersion in Method 1.2

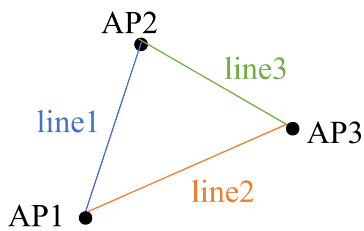


Fig. 8 Three lines made by APs in Method 1.3

AP combination with the greatest angular variance, derived using Equation 9 from angles θ_1, θ_2, and θ_3. However, this method faces the limitation of an unknown user position at the time of AP selection. While we use the user's location as the center in subsequent validations, we anticipate that employing a previous estimation result for actual position estimation will yield a close approximation.

$$\text{Angular dispersion} = 1 - \sqrt{\left(\frac{\sum_{i=1}^{3} \cos\theta_i}{3}\right)^2 + \left(\frac{\sum_{i=1}^{3} \sin\theta_i}{3}\right)^2} \tag{9}$$

Method 1.3 addresses the issue of increased maximum error when APs are aligned linearly. Find the slope of each of the three lines line1, line2, and line3 made by APs as shown in Fig. 8, find their cosine similarity, and select a combination of APs that is close to zero. We tested these methods in MLAT and compared their accuracies. The data used was gathered in the environment depicted in Fig. 6.

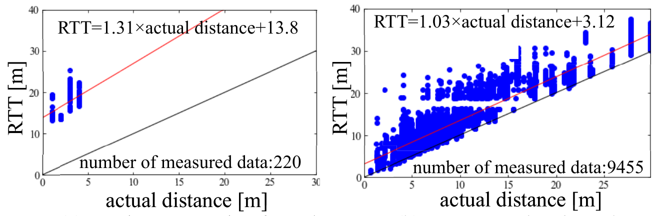
Similar to MLAT, the Nelder–Mead method estimates user location based on AP locations and AP-user distances. This section investigates whether the AP selection method based on angular variance is effective for location estimation using the Nelder–Mead method. The AP selection methods are:

Method 2.1: Selecting APs with the smallest RTT
Method 2.2: Selecting APs with large angular variance
Method 2.3: Selecting all

4. Verification

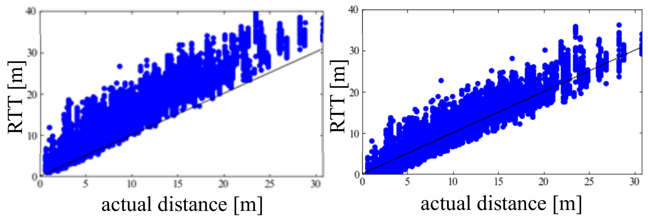
4.1 Correction of RTT

As described in section 3.1, the improvement of the correction formula is verified by actually correcting the RTT by increasing the number of data to obtain the correction formula. Figure 9(a) shows the previous correction formula and the data used to obtain it, and Fig. 9(b) shows the new correction formula and the data used to obtain it. Furthermore,



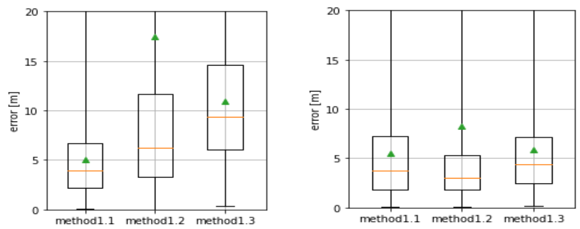
(a) previous correction formula (b) new correction formula

Fig. 9 Correction formula



(b) previous correction formula (c) new correction formula

Fig. 10 Result of RTT correction



(a) before RTT correction (b) after RTT correction

Fig. 11 Accuracy comparison of AP selection methods in MLAT

Fig. 10(a) shows the result before correction and Fig. 10(b) shows the result with the new correction formula. The black line in each figure is an ideal straight line.

Figure 10 demonstrates that the reliability of the correction formula improved with the expanded dataset. However, one challenge is the cost associated with gathering extensive data, which seems disproportionate to the accuracy gains achieved. Future work should aim to alleviate this problem by integrating feedback from actual user position estimation into the correction equation, and also consider flexible methods of determining the correction equation by setting parameters other than the number of wall sheets.

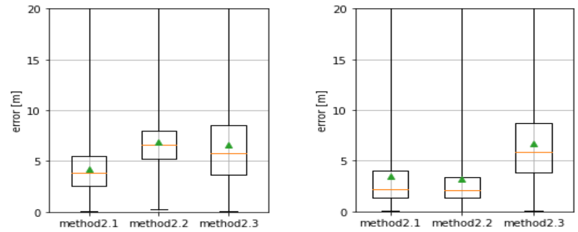
4.2 Selecting APs in MLAT

We compared methods 1.1-1.3 described in section 3.1 with the MLAT results. Figure 11(a) indicates that Method 1 produced the best results among the proposed methods. This is attributed to Methods 1.2 and 1.3 selecting APs distant from the user, resulting in larger errors.

We then evaluated accuracy using data with RTT correction, as presented in Fig. 11(b). This showed an overall improvement in accuracy, with Method 1.2 outperforming Method 1.1. This result suggests that the reduced accuracy of Methods 1.2 and 1.3 in Fig. 11(a) was due to RTT errors.

Thus, it was determined that MLAT accuracy can be improved by combining RTT correction with the AP selection method.

Next, a similar comparison of methods 2.1-2.3 was performed for the Nelder-Mead method. The validation results, shown in Fig. 12(a) before RTT correction and in Fig. 12(b) after correction, reveal that Method 1 yielded the best results in the case of Nelder-Mead method. Conversely, Fig. 12 demonstrates an overall accuracy improvement and the effectiveness of Method 2. These findings validate the efficacy of the AP selection method, incorporating RTT correction and angular variance, for single-position estimation using the Nelder–Mead method.



(a) before RTT correction (b) after RTT correction

Fig. 12 Accuracy comparison of AP selection methods in Nelder-Mead method

5. Conclusion

This paper focused on enhancing the accuracy of MLAT by proposing and evaluating an AP selection method for MLAT and discussing advancements in RTT correction.

Regarding RTT correction, our investigation clarified the reasons behind previous correction failures and introduced a new approach for calculating the correction formula. However, this method incurs substantial implementation costs prior to RTT correction, which presents a challenge for future optimization.

For the AP selection method, we established that the accuracy of user position estimation improved significantly when applying angle variance combined with corrected RTT.

Acknowledgments

This work was supported by JSPS KAKENHI (Grant Number: 21K04065).

References

[1] S. Aikawa, S. Yamamoto, and M. Morimoto, "WLAN finger print localization using deep learning," The 2018 IEEE 7th Asia-Pacific Conference on Antennas and Propagation (APCAP), pp. 541–542, 2018. DOI: 10.1109/APCAP.2018.8538306

[2] G. Guo, R. Chen, F. Ye, X. Peng, Z. Liu, and Y. Pan, "Indoor smartphone localization: A hybrid WiFi RTT-RSS ranging approach," *IEEE Access*, vol. 7, pp. 176767–176781, 2019. DOI: 10.1109/ACCESS.2019.2957753

[3] IEEE Computer Society LAN/MAN Standards Committee, "IEEE Standard for Information Technology–Telecommunications and Information Exchange Between Systems–Local and Metropolitan Area Networks–Specific Requirements–Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," IEEE STD 802.11-2020 (Revision of IEEE Std 802.11-2016), IE, pp. 2272–2277, 2021.

[4] Y. Shida, S. Aikawa, and S. Yamamoto, "Correction of RTT using the RSSI for estimating Wireless LAN locations," Proc. of ICETC2023, P1-21, Dec. 2023.

[5] O.S. Oguejiofor, A.N. Aniedu, H.C. Ejiofor, and A.U. Okolibe, "Tri-

Lateration based localization algorithm for wireless sensor network," IJISME, vol. 1, no. 10, 2319-6386, 2013.

[6] X. Feng, K.A. Nguyen, and Z. Luo. "An analysis of the properties and the performance of WiFi RTT for indoor positioning in non-line-of-sight environments," Paper presented at 17th International Conference on Location Based Services, Munich, Germany.

[7] J.A. Nelder and R. Mead, "A simplex method for function minimization," *The Computer Journal*, vol. 7, no. 4, pp. 308–313, 1965. DOI: 10.1093/COMJNL/8.1.27