Exploiting Phase Difference of Arrival of V2X Signals for Pedestrian Positioning

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***Abstract*—Position information plays an important role in preventing pedestrian accidents by pedestrian-to-vehicle communication. But the computation of pedestrian position, based on GPS, may fail in urban canyons due to the obstruction of roadside building. This problem can be solved by using vehicles and roadside units as anchors for pedestrian positioning, where trilateration is used to compute pedestrian position based on distances to anchors. But the performance is degraded by multipath propagation and limited by the time resolution. To address this problem, in this paper, we investigate how phase information of OFDM signals in V2X communications varies with the propagation distance, and exploit the phase difference of arrival to estimate the distance difference. We study how to deal with the inter-symbol interference in OFDM symbols and combine multiple estimations of distance difference to improve the accuracy. Simulation evaluations by 3D ray-tracing confirm the effectiveness of the proposed method.**

***Index Terms*—Pedestrian positioning, V2X, OFDM, phase difference of arrival**

I. Introduction

Vehicles greatly facilitate our mobility but also have a bad impact—traffic accidents. Among the per-state fatalities[1] in traffic accidents, the number of pedestrian fatalities is the highest, and accounts for more than one-third in Japan [1]. Poor visibility without line of sight is an important cause of such traffic accidents, which cannot be solved by using sensors aboard vehicles such as camera, Radar and LiDAR. In order to detect pedestrians in blind spots of a vehicle (*e.g.*, behind a building), pedestrian-to-vehicle communication [2], notifying neighboring vehicles of pedestrian position, was proposed, but its effect largely depends on the accuracy of pedestrian position.

In outdoor environments, pedestrian position is usually computed by GNSS (Global Navigation Satellite System). But in urban canyons, the number of directly visible satellites may be insufficient for position computation, due to the shielding of roadside skyscrapers. In the future V2X (vehicle-to-everything) communication, either IEEE 802.11bd [3] in the progress of standardization or Cellular V2X [4] defined as a part of 5G specification by 3GPP will support the communication between vehicles and other things (including pedestrians). Vehicles periodically exchange position information to avoid traffic accidents [5], and can be used as anchors to compute pedestrian position [6], [7]. This is because a vehicle is equipped with more sensors than a pedestrian and is capable of high-accuracy RTK-GPS positioning [8], which ensures that a vehicle will have much higher positioning accuracy than a pedestrian. In order to promote 5G communication technologies, the Government of Japan has decided to open all traffic signal poles in the country for 5G base stations, which can potentially serve as road side units (RSU), and be used as anchors as well [9].

Generally, position computation can be performed in two modes. One is user-based positioning, and position is computed at pedestrian devices. Because a pedestrian device has to receive signals continuously, power consumption is a big burden. Another mode is network-based positioning, where a pedestrian device as a transmitter transmits packets periodically while nearby anchors as receivers help compute pedestrian position. In order to avoid the time synchronization between transmitter and receivers, time difference of arrival (TDoA) [10] or phase difference of arrival (PDoA) [11] can be used. In addition, PDoA usually provides higher measurement accuracy than TDoA [12]. But when exploiting phase information, previous methods use narrow-band signals and estimate the phase of each frequency successively, which is time consuming. Because it is difficult to find a method working well in all environments, it is suggested to select the most proper positioning method for NR V2X users, based on the accuracy of measurements [13].

In this paper, we focus on network-based positioning. We exploit OFDM signal in V2X communication to efficiently compute the phases of multiple frequencies, and on this basis estimate distance difference to anchors. We investigate the variation of PDoA with respect to distances, study the impact of modulation data, frequency synchronization error, inter-symbol interference (ISI) in OFDM symbols, and show that double phase difference can remove most error factors.

The contribution of this paper is three-fold, as follows.

- ISI may occur when OFDM signals at different anchors are sampled at the same time. We suggest adjusting the sampling time to solve this problem without affecting the estimation of distance difference.

[1]Statistics of traffic accident fatalities in 2020: Motor vehicle occupant (31.1%), Motorcycle rider (13.6%), Moped 1st class rider (5.0%), Pedal cyclist (14.8%), Pedestrian (35.3%)

- We show how the accuracy of distance difference changes with frequency difference and suggest combine multiple estimations of distance difference to improve the performance.
- We evaluate the accuracy of distance difference using 3D ray-tracing to emulate multipath-rich urban canyon environments.

Simulation results confirm that the proposed method helps to suppress noise and the impact of multipath propagation.

The rest of this paper is organized as follows: Sec. II reviews related work. Sec. III explains the relation between distance difference and PDoA. Sec. IV proposes how to use PDoA of OFDM signals to estimate the distance difference. Then, Sec. V presents the simulation evaluation results. Finally, Sec. VI concludes this paper.

II. Related work

When a model-based positioning method is used, pedestrian position usually is computed by trilateration. The pedestrian-anchor distances can be estimated by different methods, as follows:

(i) Signal-strength-based method. RSSI is a measurement of RF power at a receiver. The path-loss model indicating the attenuation of RSSI with respect to distance is often used to predict distance from RSSI, although its accuracy is greatly affected by the impact of shadowing and multipath fading.

In a wideband system, multipath signals and the direct wave arrive at a receiver at different timing, and it is possible to estimate the distance from the strength of the direct wave [6], [14], [15]. In this way, the pedestrian-anchor distance is more accurate than that by RSSI. But its performance is limited by time resolution when a reflected wave overlaps the direct one.

(ii) Time-based method. It is possible to measure the time-of-arrival (ToA) at a receiver. In order to avoid the synchronization between transmitter and receiver, time-of-flight is estimated by exchanging a sequence of messages containing ToA between a transmitter and a receiver, in FTM (fine time measurement) based method standardized in IEEE 802.11mc. This, however, causes a large delay in position computation [16] (and also much overhead). It is shown that FTM has a similar distance error behavior as that by RSSI in a multipath rich environment [17], and a correction is required for each pair of transmitter and receiver [18].

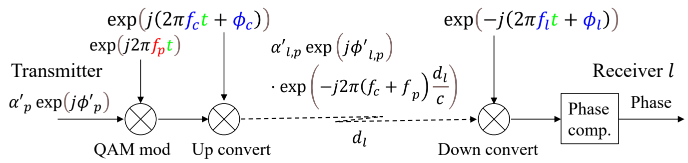
To avoid the synchronization between transmitters and receivers, another method is to compute the TDoA. In [19], a transmitter transmits an IEEE 802.11g signal, and ToA is estimated at the receiver side, using the long training sequence. Then, TDoA is used to compute the transmitter position.

(iii) Phase-based method. In order to measure the radio wave propagation distance more accurately, in the RFID field, the property that the phase increases linearly with the radio wave propagation distance is exploited [11], [20]. Each time one frequency is used and it takes time to switch frequencies and measure phase variation of each frequency successively. To further improve the accuracy, a combination of TDoA and PDoA is studied in [12].

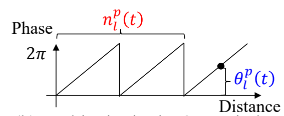
To improve the efficiency of measuring phases, in this paper, we focus on using OFDM signals to estimate the phases of multiple frequencies simultaneously, and discuss potential problems and solutions.

III. Estimation of Distance Difference by PDoA

This work assumes that a pedestrian device (as a transmitter) periodically broadcasts a signal to announce its presence to nearby vehicles (so as to avoid collision accidents). This signal is received by several anchors (RSUs or vehicles, as receivers) connected to a common server. By estimating the differences of distances from a pedestrian to anchors, pedestrian position can be computed at the server and sent to vehicles later.



(a) Signal transmission from a transmitter to receiver l



(b) Ambiguity in the 2π period

Fig. 1. Phase variation with distance in the wireless transmission.

Consider two frequencies f_p and f_q and two anchors l and m. At the pedestrian device, $\alpha'_p \exp(j\phi'_p)$ is used to modulate frequency f_p, and the resulting baseband signal is

$$\alpha'_p \exp(j\phi'_p) \cdot \exp(j2\pi f_p t). \tag{1}$$

As shown in Fig. 1, this signal is up converted using a carrier signal $\exp(j(2\pi f_c t + \phi_c))$, and the transmitted signal is

$$s(t) = \alpha'_p \cdot \exp(j(2\pi(f_c + f_p)t + \phi'_p + \phi_c)). \tag{2}$$

This signal is received by a receiver (anchor) l with a distance d_l away. The complex channel gain is $\alpha'_{l,p} \exp(j\phi'_{l,p}) \cdot \exp(-j2\pi(f_c + f_p)d_l/c)$, which includes a phase variation depending on propagation distance d_l and light speed c. $\alpha'_{l,p}$ represents the channel attenuation and $\phi'_{l,p}$ is an extra phase variation. The received signal is down-converted to the baseband, using a carrier signal $\exp(-j(2\pi f_l t + \phi_l))$, Then, the phase of the baseband signal corresponding to frequency f_p is

$$\begin{aligned} 2\pi(f_c + f_p - f_l)t - 2\pi(f_c + f_p)\frac{d_l}{c} + \phi_{l,p} - \phi_l \\ = n_l^p(t) \cdot 2\pi + \theta_l^p(t). \end{aligned} \tag{3}$$

Here $\theta_l^p(t) \in [0, 2\pi)$ is the measured phased while $n_l^p(t)$ is an integer representing the ambiguity of 2π periods. It is impossible to compute d_l from $\theta_l^p(t)$ without knowing $n_l^p(t)$.

The phase of frequency f_q, $\theta_l^q(t)$, can be computed in a similar way. Then, the phase difference, $\theta_l^{p,q}(t) = \theta_l^p(t) - \theta_l^q(t)$, is computed as

$$2\pi(f_p - f_q)t - 2\pi(f_p - f_q)\frac{d_l}{c} + (\phi_p^{'} - \phi_q^{'}) = n_l^{p,q}(t) \cdot 2\pi + \theta_l^{p,q}(t), \quad (4)$$

where $n_l^{p,q}(t) = n_l^p(t) - n_l^q(t)$. Here, the impacts of carrier frequency and initial phase (f_c, ϕ_c, f_l, ϕ_l) are canceled out. But d_l still depends on the phase of the modulation data ($\phi_p^{'}$, $\phi_q^{'}$) and the phase sampling time t.

When another receiver m, with a distance d_m away from the transmitter, receives the signal at the same time (Fig. 2), the phase difference at m, $\theta_m^{p,q}(t) = \theta_m^p(t) - \theta_m^q(t)$, is computed in a similar way. Then, the double phase difference, $\theta_{l,m}^{p,q}(t) = \theta_l^{p,q}(t) - \theta_m^{p,q}(t)$, is computed as

$$-2\pi(f_p - f_q)\frac{d_l - d_m}{c} = 2\pi \cdot n_{l,m}^{p,q}(t) + \theta_{l,m}^{p,q}(t), \quad (5)$$

where $n_{l,m}^{p,q}(t) = n_l^{p,q}(t) - n_m^{p,q}(t)$. Now the impacts of time t and modulation data are removed. Even though the two receivers (anchors) are not synchronized with the transmitter (pedestrian), the distance difference $d_l - d_m$ can be computed correctly, if $n_{l,m}^{p,q}(t)$ is somehow estimated. But it requires that the phase information is sampled simultaneously at the two receivers.

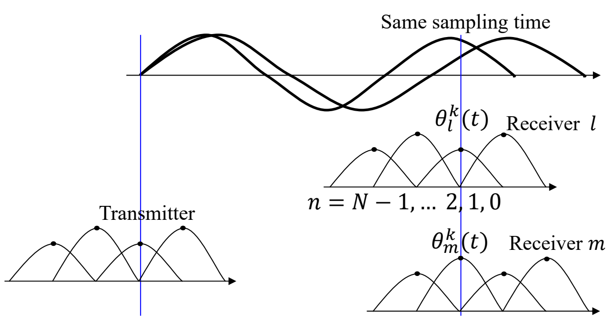


Fig. 2. A simple model for 2 frequencies and 2 receivers.

IV. Estimation of Distance Difference by OFDM

Many wireless signals, especially, V2X signals, are transmitted by OFDM, where N subcarriers (frequencies) are used at the same time. In addition, the frequency interval Δf and the sampling interval T_s are set as follows in order to maintain the orthogonality between the subcarriers.

$$f_k - f_0 = k \cdot \Delta f, k = 0, 1, \cdots, N-1,$$
$$t = nT_s, T_s = 1/(N \cdot \Delta f), n = 0, 1, \cdots, N-1. \quad (6)$$

When an OFDM signal is transmitted, a pulse shaping signal, $f(t)$, is used to prevent spectrum leakage outside the allocated bandwidth. Usually, at $t \neq nT_s$, $f(t)$ is not 0. Therefore, ISI occurs if the sampling time synchronization is not achieved.

As for the k-th subcarrier at the receiver l, assume its phase at the initial sample is $\theta_l^k(t)$. Then, the subsequent N samples, with an interval T_s, are

$$\alpha_{l,k} \exp(j(2\pi\frac{k \cdot n}{N} + \theta_l^k(t)))f(t - nT_s), \quad (7)$$
$$n = 0, 1, \cdots, N-1.$$

$f(t - nT_s)$ disappears if the sampling time is synchronized. After fast Fourier transform (FFT), the coefficient of the k-th subcarrier is

$$F_{l,k} = N\alpha_{l,k}\exp(j\theta_l^k(t)), \quad (8)$$

from which $\theta_l^k(t)$ is computed as

$$\theta_l^k(t) = \angle F_{l,k}. \quad (9)$$

A. Adjustment of sampling time

In order to correctly compute the distance difference, it is necessary for the two receivers l and m to sample their phases at the same time. However, it is not always possible to obtain samples at the time nT_s for both receivers, because the arrival times of the signal vary with the distances. E.g., as shown in Fig. 3, the receiver l can acquire samples at the times nT_s. But if the receiver m acquires samples at the same times, an ISI occurs. To solve this problem, the receiver m postpones the sampling time by Δt.

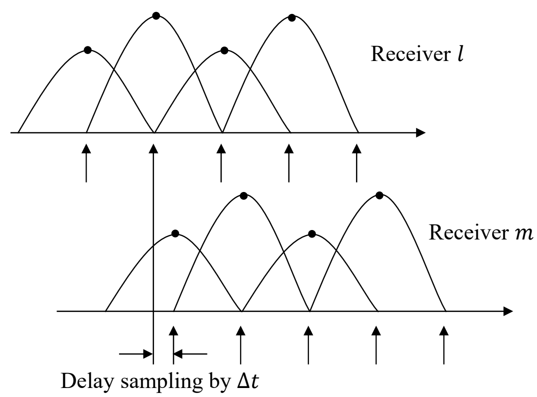


Fig. 3. Adjust sampling time at two receivers to avoid ISI.

The phase difference at m, $\theta_m^{p,q}(t + \Delta t)$, is expressed by

$$2\pi(f_p - f_q)(t + \Delta t) - 2\pi(f_p - f_q)\frac{d_m}{c} + (\phi_p^{'} - \phi_q^{'}) = n_m^{p,q}(t + \Delta t) \cdot 2\pi + \theta_m^{p,q}(t + \Delta t). \quad (10)$$

The double phase difference, $\theta_{l,m}^{p,q}(t, t + \Delta t) = \theta_l^{p,q}(t) - \theta_m^{p,q}(t + \Delta t)$ is computed from (4) and (10) as

$$-2\pi(f_p - f_q) \cdot \Delta t - 2\pi(f_p - f_q)\frac{d_l - d_m}{c} = 2\pi \cdot n_{l,m}^{p,q}(t, t + \Delta t) + \theta_{l,m}^{p,q}(t, t + \Delta t). \quad (11)$$

Despite the extra phase caused by Δt, the distance difference can be computed from $\theta_{l,m}^{p,q}(t, t + \Delta t)$ if the time delay Δt is known. This is possible by synchronizing the clock at two receivers. In this way, each receiver adjusts its own sampling time to avoid ISI, which does not affect the distance estimation.

B. Using multiple frequencies at two receivers

In (11), if p is fixed at 0 and q is changed from 1 to $N-1$, $N-1$ equations are obtained.

$$\begin{aligned} d_l - d_m &= -c \cdot \Delta t \\ -\tfrac{c}{f_p - f_q}&(n_{l,m}^{p,q}(t, t+\Delta t) + \tfrac{1}{2\pi}\theta_{l,m}^{p,q}(t, t+\Delta t)). \end{aligned} \quad (12)$$

$n_{l,m}^{p,q}(t, t+\Delta t), p = 0, q = 1, 2, \cdots, N-1$ are unknowns, and can be found by using the approximate distance estimated from channel state information. Then, an average of $d_l - d_m$ can be computed to improve its accuracy.

The distance difference estimated by the $N-1$ equations have different error properties. $n_{l,m}^{p,q}(t, t+\Delta t) + \frac{1}{2\pi}\theta_{l,m}^{p,q}(t, t+\Delta t)$ in the brackets have nearly the same variance. Then, the error in $d_l - d_m$ decreases with $\frac{c}{f_p - f_q}$, when q increases. Because p is fixed, this means a large difference in two frequencies will lead to a smaller error in the distance difference.

V. Simulation Evaluation

OFDM signals with 20MHz bandwith ($N = 64$ subcarriers) are used to evaluate the estimation accuracy of the distance difference from a pedestrian (transmitter) to two anchors (receivers). The sampling rate of an OFDM signal is 20MHz ($T_s = 50$ ns), and data is processed with a 1GHz clock in order to simulate both multipath propagation and ISI. The pulse shaping signal $f(t)$ uses raised cosine with a rolloff of 0.5. At the receiver side, a signal is down-sampled to 20MHz after time synchronization, from which phases per subcarrier is computed.

In the evaluation, first we consider a simple scenario composed of one transmitter and two receivers (anchors) in Fig. 2. The distance from the transmitter to the two receivers is set short enough so that $n_{l,m}^{p,q}$ equals 0. In the second scenario, we will evaluate the performance in a multipath-rich environment using 3D ray-tracing, assuming that $n_{l,m}^{p,q}$ is known in advance. The estimation and evaluation of $n_{l,m}^{p,q}$ is left as future work.

A. Effect of adjusting sampling time

First, the effect of adjusting sampling time on the distance difference is investigated. The delay of the direct wave from the transmitter to the receiver l is set to 100 ns, and that to the receiver m is increased from 50 ns to 100 ns, with a step size of 2ns. Here, it is assumed that there is no multipath signal and no noise at both receivers.

Fig. 4 shows how the error in the distance difference varies as the delay of the direct wave to the receiver m increases, without adjusting sampling time. The difference between p and q is set to 5, 10, 15, 20, 25, respectively. Since 50 ns and 100 ns are multiples of $T_s = 50$, the error is 0 at those points. As the delay to the receiver m increases, the error changes like a sine wave. This error is caused by ISI at receiver m. In addition, it can be seen that the larger the difference between p and q, the larger the maximal error.

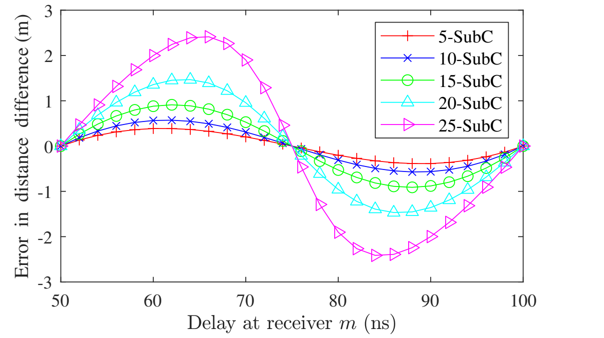


Fig. 4. Error in distance difference with respect to the delay to receiver m (without adjusting sampling time)

Fig. 5 shows the error in the distance difference after adjusting the sampling time at the receiver m. Now the error is almost 0, which confirms the effect of adjusting the sampling time.

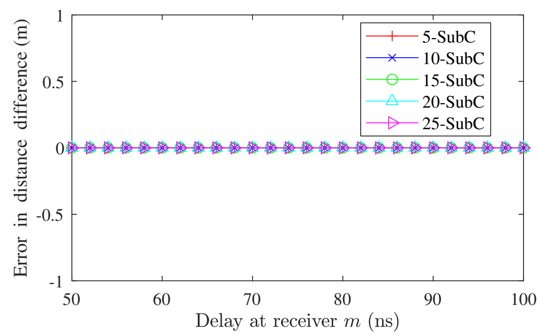


Fig. 5. Error in distance difference with respect to the delay to receiver m (with adjusting sampling time)

B. Impact of frequency distance

Next, the impact of frequency distance is investigated. The delays of the direct wave from the transmitter to the receiver l and the receiver m are set to 50 ns and 100 ns, respectively. The amplitude of the reflected wave to the receiver m is set to 0.3162 (in power, -10 dB) of the direct wave, and the extra delay of the reflected wave is increased from 2 ns to 100 ns at a step of 2 ns. Here, there is no noise at both receivers, and no reflected waves to the receiver l.

Fig. 6 shows the error in the distance difference when $p = 1$ is fixed and q is increased from 2 to 63. The extra delay of the reflected wave is set to 2 ns, 10 ns, 20 ns, 50 ns, and 100 ns at the receiver m. The larger q is, the smaller the error tends to be. Accordingly, it is preferred to use the estimation of distance difference at a large frequency difference. But other results at a small frequency difference also provide useful information.

C. Effect of combining multiple estimations

Here, the effect of combining multiple estimations is investigated. The delays of the direct wave from the transmitter to the receiver l and the receiver m are set to 50 ns and 70

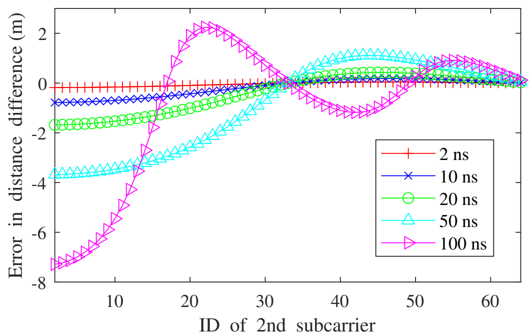


Fig. 6. Suppression of multipath signals by using two frequencies in estimating distance difference.

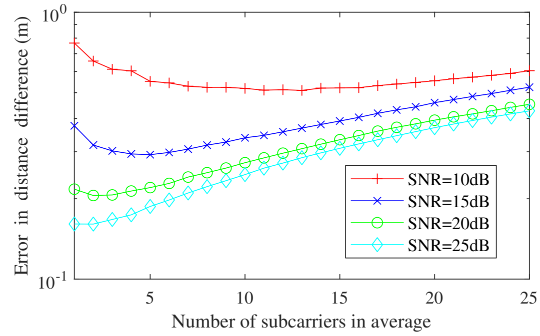


Fig. 8. Error in distance difference with respect to the number of subcarriers in average.

ns, respectively. The reflected waves to the two receivers have an extra delay, randomly drawn from the uniform distribution between 1 and 50 ns. Their amplitudes are random, uniform between 0 and 0.3162 of the direct wave, and their extra phase due to reflection are uniform between 0 and 2π. The signal-to-noise ratio (SNR) at the two receivers is assumed to be the same.

With one subcarrier fixed to $p = 1$, Fig. 7 shows how the error in distance difference changes with q, the other subcarrier. With the increase of q, the bandwidth increases and accordingly the error decreases at all SNR.

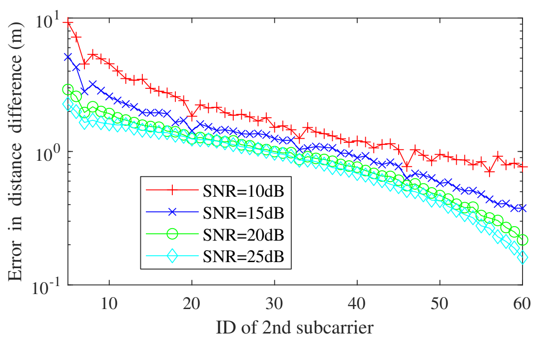


Fig. 7. Error in distance difference with respect to the 2nd subcarrier.

To get a good estimation of distance difference, we choose to compute the average of the results obtained by different q. Because large q leads to better performance, this average starts from $q = 60$, and includes a number of smaller subcarriers, e.g., 5-aver is the average where q varies from 60 to 56, and 10-aver is the average where q varies from 60 to 51.

Fig. 8 shows the error in the distance difference after the average computation, with respect to the number of subcarriers used in the average. It is clear that at each SNR, there is an optimal number of subcarriers, from which the average result reaches the minimal error. But this optimal number varies with SNR, being a large number (smoothing effect) at low SNR and a small number (using large q that lead to small errors) at high SNR. The optimal numbers of subcarriers used in the average are 13, 5, 2, 2 for SNR = 10 dB, 15 dB, 20 dB, and 25 dB, respectively.

D. Result in multipath-rich environment

The ray-tracing tool, RapLab[2], together with the 3D building map (Fig. 9) around Ginza, Tokyo, is used to simulate the multipath propagation in urban canyons. The maximum number of radio wave reflections/diffractions is set to 1. The time resolution is set to 1ns, i.e., two waves whose arriving times have a difference within 1ns will overlap together. The transmission power and noise power are fixed, and the received power depends on the pedestrian-anchor distance. For a comparison, here, distance estimation from RSSI is also computed, using the path-loss model. In the proposed method (PDoA), two anchors change per scene. The nearer one is l and the other is m.

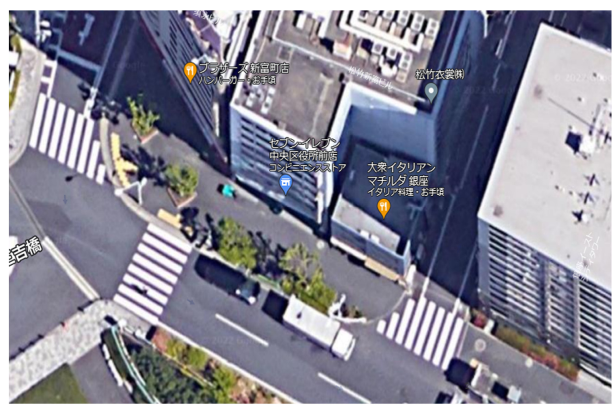


Fig. 9. 3D map used in ray-tracing simulation (Ginza, Tokyo).

Fig. 10 shows the result. Although it is hard to directly compare the error in distance difference with that in distance itself, it can be seen that using PDoA does reduce errors. Most errors in distance difference of PDoA is less than 1m, while the distance error of RSSI is usually much larger. The average error in distance to anchor l is 5.2m, and that to anchor m is 8.6m. In comparison, average error in distance difference is only 0.48m in PDoA.

[2]https://network2.kke.co.jp/wireless-products/raplab/

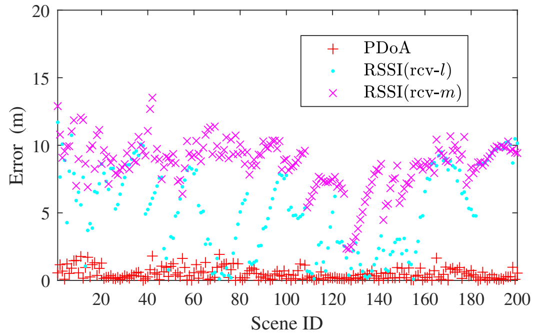


Fig. 10. Error in distance difference in the multipath-rich urban canyon environment.

VI. Conclusion

In order to achieve high accuracy pedestrian position, this paper has investigated a new method for estimating distance difference between a pedestrian and two anchors, using phase information that is more resistant to noise, compared with RSSI that depends on radio wave attenuation characteristics. By the double phase difference, error factors such as OFDM modulation data and carrier frequency variations can be mitigated, and ISI can be avoided by adjusting the sampling time. Furthermore, it is confirmed that multipath waves can be suppressed by using multiple frequencies at the same time, and the result in the multipath-rich environment is promising.

In the future, we will further investigate how to solve the ambiguity of the 2π period in the phase, study and evaluate the positioning method.

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