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Utilizing the Virtual Triangulation for Wireless Indoor Localization of Mobile Devices with Channel State Information

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Abstract

To locate an RF device or to enable target oriented communication services in wireless indoor environment, RF properties as RSSI and CSI have been widely adopted in the research and commercial societies. However, the complex indoor scenario makes the task to locate an RF device with fine-grained accuracy more difficult. This paper deals with a virtual triangulation utilization to estimate the length of Line of Sight (LoS) signal out of non LoS on receiving multipath signals from any dimension. Thus, it forms a virtual right angled triangle of the received signals. From the angles ratio, the propose method estimates the side corresponding to the reference LoS length. Eventually, it estimates the distance error between the measured reference LoS of the virtual triangle and the approximated LoS from the CSI. The error is utilized to provide a basement for more precise localization of an RF device.

Keywords: *CSI, Indoor Localization, RSSI, Triangulation*

1. Introduction

The Receive Signal Strength Index (RSSI) was the most prior localization metric for calculating localization [1]. RSSI fingerprint can be easily obtained from most off-the-shelf wireless network equipment, such as Wi-Fi or ZigBee enabled devices. It can be utilized for other applications as identification and security.

The localization methods are mostly divided into two stages: training and operation. In the traditional approaches, the training stage comprises a site-survey procedure which records the RSSI fingerprints (*e.g.*, Wi-Fi signal strengths from multiple Access Points (APs) at every possible location of an interested area). With the recorded RF fingerprint, the localization system constructs a fingerprint database (*e.g.*, radio map) in which each fingerprint is related to the corresponding locations. In the operation stage, when a user sends a location query with the current RSSI fingerprint, the localization algorithm retrieves the most closely matched fingerprint from the database to estimate an approximate distance of the RF device.

However, RSSI fingerprint based methods can provide meter-level indoor localization accuracy at the expense of explicit site-survey. Even, it suffers from dramatic performance degradation in complex situation due to RF signal behaviors. With the multipath fading propagation, RSSI based indoor localization suffers a great constraints with high estimation error. Although, some frontier works based on Channel State Information (CSI) shows that it is possible to localize an RF device with sub-meter level accuracy [2].

This paper presents a virtual triangulation utilization to estimate the Line-of-Sight (LoS) length in order to locate an RF device in a wireless indoor environment. The main idea of this work is to determine the localization error in order to adjust it to a precise location of an RF device. For this, the AP has to receive raw data of CSI of LoS and non LoS (NLoS) with the receiving angle information. Meanwhile, AP will form a virtual right angled triangle from the received angles of LoS and NLoS. As it is assumed that the

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distance of the obstacle of the reflected NLoS from the stationary AP is known, so that the side corresponding to the reference LoS can be estimated using the trigonometric geometry. Finally, the difference between two estimated LoS lengths will be adjusted, so that the distance error could be mitigated to achieve more precise localization.

2. Related Works

Recently, indoor localization based on RF properties has been the issue of active researches, and many approaches have made their appearance in the area of interest.

Reference [3] is an extensive work that can simplify the RF behaviors and determine the parameters of multiple received signals at AP. It shows that the techniques of RF property based location distinction are applicable in indoor localization scenario. Several approaches have been proposed based on RSSI for indoor localization. LiFs [4] was proposed a RSSI fingerprint based wireless indoor localization approach. In this work, the fingerprint database is built without the extensive site-survey with the average localization error 5.8 meters. LiFi [5] was proposed with the primary goal of distinguishing LoS from the NLoS components with the succession rate of 90.4% using the CSI. Applying the LoS length estimation on this distinguishable LoS from NLoS based on the CSI also has the meters level accuracy.

The randomness and the environmental complexity of wireless indoor scenario makes the localization task hurdle to measure the LoS distance of an RF device precisely. Even though, the RSSI or CSI can be utilized in order to measure the LoS distance of an RF device, it could not accomplish the desired outcomes of precise location. So that, it requires a reference distance in which it can compare with approximated distance of LoS from the RSSI or CSI. The variations of comparisons could be adjusted. Therefore, this work proposes a virtual triangulation based localization error correction method, where the sides of the triangle play a vital role in case of measuring reference LoS distance.

3. The Proposed Method

3.1. Overview

This work is based on the assumption of a wireless indoor scenario in the following Figure. 1. The illustrated indoor scenario is a part of the inside of a building where the rooms are equipped with the Wi-Fi APs. A mobile user or an RF device has needed to find out his location by sending the location query to the AP inside the building.

The proposed method consists of some procedural steps as shown in Figure. 2. This contains the operation phase to process the location query. This work assumes that, the AP is equipped with the Wi-Fi wireless link 5300 802.11n MIMO radios CSI tool in [6]. Corresponding to the location query from a user, AP receives the CSI raw data of LoS and NLoS of that query to form a virtual right angled triangle and estimates the reference LoS length corresponding to the side of that triangle.

Meanwhile, AP estimates the physical/approximate LoS length from the CSI data of the received LoS and compares that length with the reference LoS length. The difference in comparison is detected as an error and that requires to correction in order to precise the location of an RF device in wireless indoor scenario.

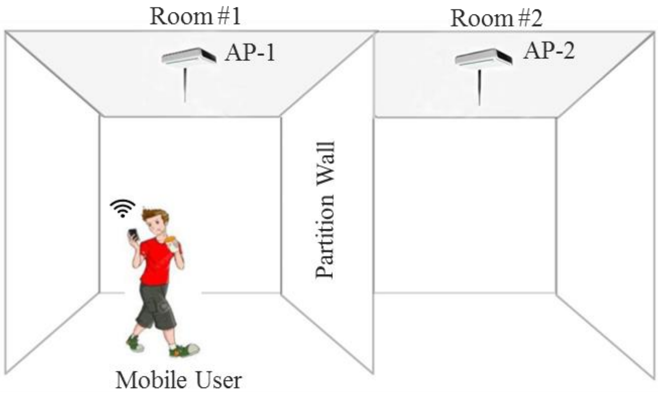

Figure 1. An Example of a Wireless Indoor Scenario

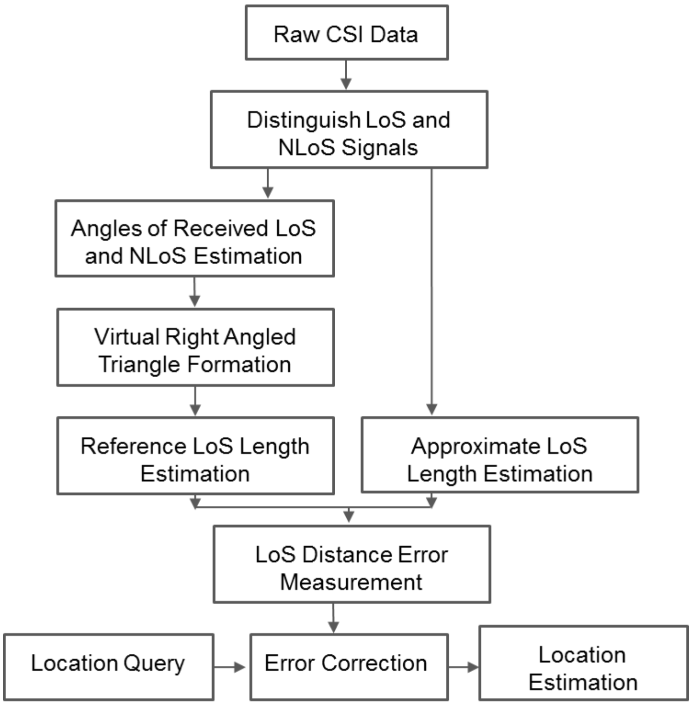

Figure 2. Procedures of the Proposed Method

3.2. Generalization

In general, when an RF signal emits from a transmitter (Tx) in any direction, the corresponding AP/Rx can receive the multiple propagated signals from different directions with different amplitudes of receiving angles $A(\theta)$. In the case, the direct signal that received at AP with less time/less-distance is called the LoS signal and the others are multipath components/signals caused of refraction, reflection, or scattering, which are called the NLoS signals. Therefore, it could be formulated that the set of received signals X at AP is equal to in the following Eq. (1) [3].

$$X=\begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ . \\ . \\ X_M \end{bmatrix} = [a(\theta_1) \quad a(\theta_2) \quad a(\theta_3).. \quad a(\theta_D)] \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ . \\ . \\ F_M \end{bmatrix} + \begin{bmatrix} W_1 \\ W_2 \\ W_3 \\ . \\ . \\ W_D \end{bmatrix}$$

$$X = AF + W \tag{1}$$

Where, X is a vector that obtained the receive signals including LoS and NLoS. A is a matrix that obtained the amplitudes of different signals with different receiving angles θ. F is a vector that contained the frequencies corresponding to $A(\theta)$. D is a set of a number of incident signals which are reflected on the obstacle of a particular dimension/direction in the indoor environment. W is also a vector that obtained the noises corresponding to the received signals of different angles $A(\theta)$. Besides, the notations are used in this proposed method in the following Table 1.

Table 1. Symbols Used in this Method

Symbol	Description
A	A set of amplitudes of receiving signals
F	A set of frequencies of receiving signals
W	A set of corresponding noises
X	A set of received signals at AP/Rx
θ	A set of receiving angles
$\angle RL$	Receiving angle of LoS belongs to θ
$\angle TL$	Transmission angle of LoS
$\angle RNL$	Receiving angle of NLoS
$\angle RLN$	Receiving angle in-between LoS and NLoS
$\angle IRN$	Angle in-between incident signal (*IS*) and reflected signal (*RS*) of NLoS
$\angle TI$	Transmission angle in-between LoS and incident signal
$\angle RON$	Complementary angle of reflection of NLoS
$\angle ION$	Complementary angle of reflection of NLoS
π	Pi = 180^0

Before explaining the details of this proposed method, the network assumption is based on the following scenario as shown in Figure. 3. The heading of each RF device include Rx, Tx and/or the obstacle(s) are in the same direction and the transmitting or receiving angles are estimated as clock wise. The devices are on the plane of a real X-Axis, where the X-Axis is horizontally aligned on the different dimensions in the indoor environment. When a signal is emitted from a transmitter, the incident signals are propagated through the medium instantly. After that, the propagated signal could be reflected at different points on the obstacle(s) and as a result, some signals could be directed towards the AP cause of the reflection. Finally, the AP has received the LoS and NLoS signals which are propagated from the same transmitter. To accomplish this, the proposed method is formulated in different phases which are as follows:

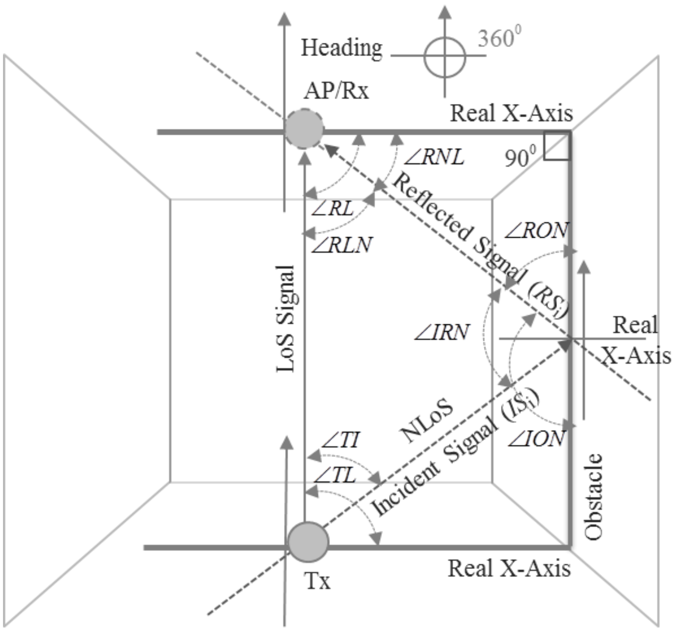

Figure 3. An Example of Signal Propagation in Wireless Indoor Scenario

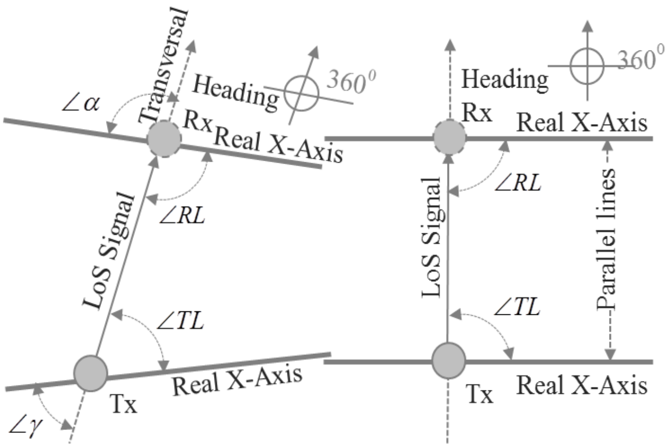

Figure 4. The Geometry of Alternate or Interior Angle Estimation

3.2.1. Transmission Angle Estimation from the Received Angle of LoS: From the information of the Angle of Arrival (AoA) of the propagated signal, the AP can estimate the ultimate transmission angle of LoS ($\angle TL$) using the simple geometry rules of transversal, where the angle pairs are on alternate sides of the transversal, and they on the interior. For instance, the vertical opposite angles are always congruent $\angle TL = \angle \gamma$ and $\angle RL = \angle \alpha$ as shown in the left side of Figure. 4. Meanwhile, if the two lines being crossed are the parallel lines, then the alternate interior angles are equal. For instance, the angle, $\angle RL = \pi - \angle TL$ is shown in the right side of Figure. 4.

3.2.2. Angle in-between LoS and NLoS Estimation from the Received Angle of LoS and NLoS: The AP has received the signals that include the multipath components and it is needed to differentiate the components as a LoS and NLoS based on the different receiving angles and amplitudes. The angle, $\angle RLN$ in between LoS and NLoS is determined from the angles information of LoS and NLoS at AP as shown in Figure. 3.

Thus, the angle, $\angle RLN = \pi - (\angle TL + \angle RNL)$, where $\angle RNL$ is the received angle of NLoS.

3.2.3. Angle in-Between Incident and Reflection Estimation from the Received Angle of NLoS: In order to determine the $\angle IRN$, firstly, it is required to estimate two complementary angles of reflected NLoS signal. In this case, the complementary angles of reflection are formed as $\angle RON$ and $\angle ION$ as shown in Figure. 3. In terms of measuring the $\angle IRN$, it is needed to estimate these two angles. Thus, the angle, $\angle RON$ is determined as $\angle RON = \pi - (\pi/2 + \angle RNL)$ and the remaining angle as $\angle ION = \pi - \angle RON$. Finally, the angle, $\angle IRN$ is estimated as $\angle IRN = \angle ION - \angle RON$.

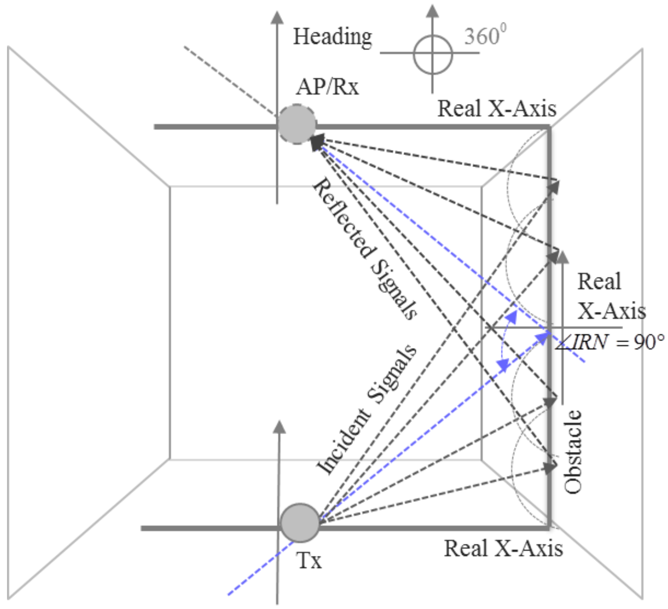

Figure 5. An Example of Possible Reflected Signals Cause of Multiple Incident Signals in Wireless Indoor Scenario

Regarding the issue of mitigating the indoor localization error of an RF device, only the angle of $0^0 < (\angle IRN) < 180^0$ is accepted, which has formed a virtual triangle. If so, this proposed method applies the virtual right angled triangulation based side obtained reference LoS length estimations. For instance, there could be a possible set of multipath components/reflected signals (D) with different angles, but only the right angle, $\angle IRN = 90^0$ is used among them in this method as shown in Figure. 5. In different cases, where the angle, $\angle IRN = 90^0$ is not existed in the angles interval $[0^0,180^0]$, this method has required to partially form the right angled triangles by dividing the virtually constructed triangle.

3.2.4. Transmission Angle in-Between Incident and Reflection Estimation: After getting the two angles; $\angle RNL$ and $\angle IRN$ of that virtual triangle, it is convenient to estimate the remaining angle, $\angle TI$ as shown in Figure. 3. So that, the angle, $\angle TI$ is determined as $\angle TI = \pi - (\angle RLN + \angle IRN)$ using the rules of a right angled triangle.

3.3. Mitigation of Localization Error

In order to estimate the distance of an RF device with high accuracy, the CSI or RSSI of X can be implemented on Eq. (1). The location estimation from the CSI or RSSI status could be more accurate, only if the noise vector W is distinguishable from the received signals at AP. For this, to measure the corresponding noise W_i of a received signal of

$A(\theta_i)$, it is required to compare the approximated distance of LoS of an RF device with the reference distance of LoS of the virtual right angled triangle.

3.3.1. Localization Error Estimation: To meet the constraint of wireless indoor localization, it can quantize the errors *W* in terms of determination of the distance of LoS. Thus, this method can utilize the virtual right angled triangle, where three sides are obtained as reflected signal (RS_i), incident signal (IS_i) and the reference LoS respectively. In order to measure the unknown factors of that right angled triangle (eg., the length of a side of a triangle), it is assumed that the distance of obstacle (*DO*) should be known to AP. The distance of RS_i between any points on the obstacle and AP is estimated from the information on receiving $\angle RNL$ of corresponding $A(\theta_i)$ and F_i.

This method is intended to estimate LoS length of an RF device in wireless indoor scenario in different cases where the LoS and NLoS are existed. Meanwhile, this method is not applicable in the case of Rayleigh fading where a LoS signal is not existed. The reference lengths of LoS estimation in different cases are as follows:

The $\angle IRN$ is equal to 90^0. In this scenario, if the length of the RS_i is fixed and the IS_i is changed (Tx device changing its positions), the angles; $\angle RLN$ and $\angle TI$ are changed respectively as shown in Figure. 6. Consequently, the length of the reference LoS corresponding to the hypotenuse of that right angled triangle is changed. For instance, in the case, the ratio of the three angles 45^0:90^0:45^0($\angle RLN$:$\angle IRN$:$\angle TI$) are corresponding to the ratio of the lengths 1:1:$\sqrt{2}$ (RS_i: IS_i: ref. LoS) of that virtual right angled triangle. Therefore, based on the information (angles ratio) of $\angle RLN$ and $\angle TI$, the reference length of LoS is estimated using the trigonometric rules in Eq. (2) and (3) or simply by applying the Pythagorean Theorem, where the factor RS_i is estimated based on the receiving $\angle RNL$.

$$\cos(\angle RON) = \frac{DO}{RS_i}$$

$$RS_i \times \cos(\angle RON) = \frac{DO}{RS_i} \times RS_i$$

$$RS_i = \left| \frac{DO}{\cos(\angle RON)} \right| \quad \text{, where } 0^0 < (\angle RNL) \le 45^0 \tag{2}$$

$$\sin(\angle TI) = \frac{RS_i}{LoSLength}$$

$$LoSLength \times \sin(\angle TI) = \frac{RS_i}{LoSLength} \times LoSLength$$

$$LoSLength = \left| \frac{RS_i}{\sin(\angle TI)} \right| \quad \text{, where } 45^0 \le (\angle TI) < 90^0 \tag{3}$$

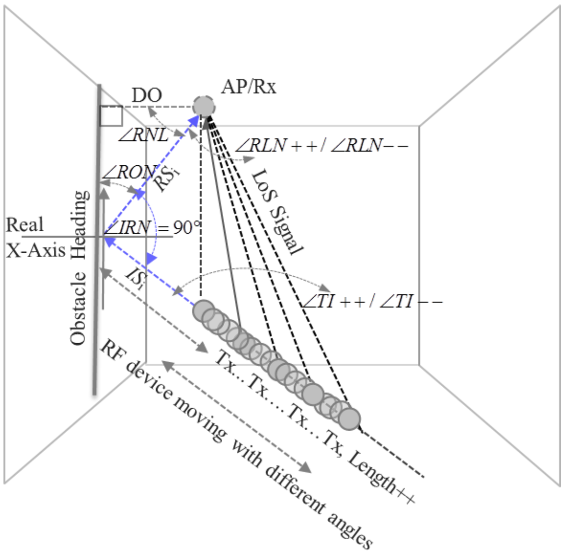

Figure 6. An Example of a Reference Length of LoS Estimation Using a Virtual Right Angled Triangle in Wireless Indoor Scenario

The $\angle IRN$ is greater than to 90^0. As an RF device can change its position, so that the corresponding $\angle RLN$ and $\angle TI$ could be changed respectively and consequently, $\angle IRN$ will be changed. In the case, when the receiving $\angle RLN$ is $45^0 \leq (\angle RLN) < 90^0$ and the estimated angle, $(\angle TI) < 45^0$, the resulting $\angle IRN$ is $90^0 < (\angle IRN) < 180^0$. Therefore, the forming virtual triangle is not being a right angled triangle as shown in Figure. 7.

To accomplish this scenario, this method has suggested bisecting the $\angle IRN$ by the factor 2, so that the virtual triangle is formed into two different right angled triangles with the same side as opposite (*OP*). After formation of the right angled triangles, the factors RS_i and *OP* are estimated using the Eq. (4) and (5). Finally, the summation of the adjacent sides of the right angled triangles is the corresponding reference length of LoS in Eq. (8) which is derived from Eq. (6) and (7).

$$RS_i = \left| \frac{OP}{\cos(\angle RLN)} \right|, \text{ where } 90^0 < (\angle IRN) < 180^0 \tag{4}$$

$$OP = \left| RS_i \times \cos(\angle RLN) \right| \tag{5}$$

$$\tan(\angle RLN) = \frac{OP}{LoSLength-1}$$

$$LoSLength-1 \times \tan(\angle RLN) = \frac{OP}{LoSLength-1} \times LoSLength-1$$

$$LoSLength-1 = \left| \frac{OP}{\tan(\angle RLN)} \right| \text{ where } 0^0 < (\angle RLN) < 45^0 \tag{6}$$

$$LoSLength-2 = \left| \frac{OP}{\tan(\angle TI)} \right|, \text{ where } 0^0 < (\angle TI) < 45^0 \tag{7}$$

$$LoSLength = (LoSLength-1) + (LosLength-2) \tag{8}$$

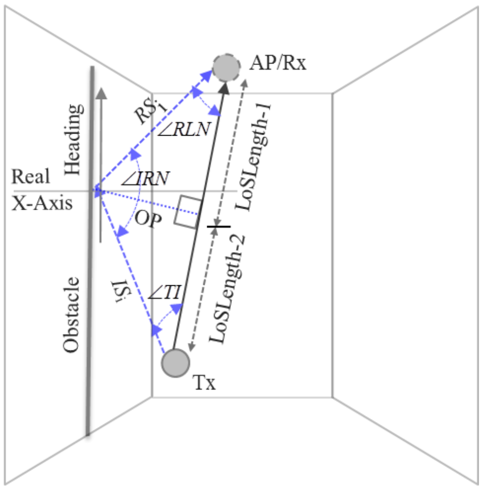

Figure 7. An Example of a Reference Length of LoS Estimation in Case of ∠*IRN* is $90^0 < (\angle IRN) < 180^0$ in Wireless Indoor Scenario

The ∠*IRN* is less than to 90^0. This method also examines the other different network scenarios, where the angle ∠*IRN* is $0^0 < (\angle IRN) < 90^0$. In the case, if the receiving ∠*RLN* is $90^0 < (\angle RLN) < 180^0$, the forming virtual triangle is not being a right angled triangle. In order to form a virtual right angled triangle, this method has approached to bisect the angle, ∠*RLN* by the factor 2. So that the triangle is formed into two different right angled triangles with the same *OP* as shown in Figure. 8.

In this case, it is sufficient to utilize one of the right angled triangles to estimate the reference length of LoS, in Eq. (9).

$$OP = \left| RS_i \times \cos(\angle IRN) \right| \tag{9}$$

$$LoSLength = \left| \frac{OP}{\tan(\angle TI)} \right|, \text{ where } 90^0 < (\angle RLN) < 180^0 \tag{10}$$

$$W = [LoSLength - LoSLength \in CSI(X)] \tag{11}$$

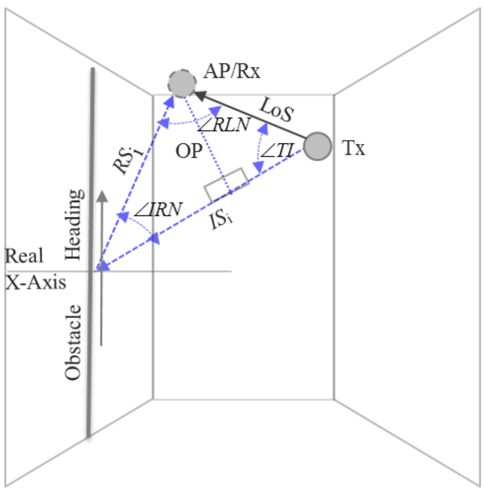

Figure 8. An Example of a Reference Length of LoS Estimation in Case of ∠*IRN* is $0^0 < (\angle IRN) < 90^0$ in Wireless Indoor Scenario

By measuring the factor W, the CSI(X) could accomplish the indoor localization of an RF device with significant accuracy. For this, the vector W is estimated using Eq. (11), which obtaining the adjustable difference of the referenced and the approximated length of LoS. For convenient, the following Algorithm 1 is the skeleton of this proposed method in which to estimate the reference length of LoS.

Algorithm 1. Reference Distance of LoS Estimation

Input: The receiving angle of LoS and NLoS:
$\angle RL \in A(\theta_i)$, and $\angle RNL \in A(\theta_j)$
Output: Reference length of LoS estimations: LosLength
for each $\angle RL$ **do**
    if $(0^0 < (\angle RL) < 180^0)$
        $\angle TL = Pi - \angle RL$
    else *under another AP*
for each $\angle RNL$ **do**
    if $(0^0 < (\angle RNL) < 90^0)$
        $\angle RLN = Pi - (\angle RL + \angle RNL)$
        $\angle RON = Pi - (\angle RL + \angle Pi/2)$
        $\angle ION = Pi - \angle RON$
        $\angle IRN = \angle ION - \angle RON$
    else *under another AP*
for each $\angle IRN$ **do**
    if $(\angle IRN == 90^0)$
        $\angle TI = Pi - (\angle RLN + \angle IRN)$
        LoSLength = according to Eq. (3)
    else if $(90^0 < (\angle IRN) < 180^0)$
        LoSLength = according to Eq. (8)
    else if $(0^0 < (\angle IRN) < 90^0)$
        LoSLength = according to Eq. (10)
    else *under another AP*
End

3.3.2 Localization Error Correction: After completion the task of that error estimation, AP has needed to adjust the localization error W with the measuring distance (approximated length) of LoS $\in$ CSI(X). The following Eq. (12) and the corresponding Algorithm 2 are to accomplish the localization error.

$$LoSDistance = [LoSLength \in CSI(\mathrm{X})] \pm W \tag{12}$$

Algorithm 2. Localization Error Correction

Input: Reference and Approximate length of LoS:
LoSLength, LoSLength $\in$ CSI(X)
Output: Distance of LoS estimations: LoSDistance
For each W **do**
    if (W != 0) // *according to Eq.* (11)
        LosDistance = according to Eq.(12)
    else *LosDistance = LoSLength* $\in$ CSI(X)
End

4. Conclusion and Future Work

This work briefly presents a method to differentiate the noise factor includes with the LoS length estimation in wireless indoor scenario. Thus, this method reveals the reference distance of LoS to compare with the approximate distance of LoS from the receiving CSI of an RF device. The difference of that comparison is adjustable in the case of locating an RF device with a fine-grained accuracy. Therefore, the utilization of the virtual triangulation for wireless indoor localization is so beneficial in terms of improving localization accuracy. As a future plan, we are intending to extend and apply this method with the practical experiment in a wireless indoor localization scenario.

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