INDOOR HEADING DIRECTION ESTIMATION USING RF SIGNALS

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ABSTRACT

Heading direction information is crucial to many ubiquitous computing applications. The main stream has been resorting to inertial sensors, such as accelerometer, gyroscope and magnetometer, which suffer from severe accumulative errors or large degradations indoors. In this paper, we utilize the radio frequency (RF) signals, received from the commercial off-the-shelf (COTS) WiFi devices, to accurately estimate the heading direction in indoor environments. Based on the time-reversal (TR) technique, we make use of the channel state information (CSI) and the geometry of the antenna array to design the proposed algorithm. A prototype is built using a single access point (AP), without knowing its location, and a two dimensional (2D) antenna array to validate the proposed method. Experiments, conducted in strong non-line-of-sight (NLOS) scenarios with rich multipaths indoors, have shown that the median error for heading direction estimation is 6.9°, which surpasses the inertial sensors. With the high accuracy and low cost, it illustrates the proposed system as a promising solution to large varieties of applications that require accurate heading direction information.

***Index Terms*—** Heading direction, time-reversal (TR), CSI

1. INTRODUCTION

Heading direction information is important to various applications, such as indoor localization, virtual reality (VR) gaming, and gesture control. The global market for the indoor localization alone is predicted to reach USD 7.8 billion by year 2021 [1], which demonstrates the growing demand and importance in accurate moving direction estimation.

Nowadays, Global Positioning System (GPS) is widely used outdoors, and the moving direction can be roughly estimated using successive location estimates. (The compass reading is only the orientation of the device, not necessarily the heading direction.) For indoors, however, GPS does not work because of the multipath effect and lack of reliable GPS signals.

To estimate the heading direction indoors, most of the state-of-the-art rely on inertial measurement unit (IMU) [2–7], which is composed of gyroscope that measures the angular velocity, accelerometer that estimates linear acceleration, and compass that indicates the magnetic north. These sensors, however, are erroneous and have drifts that are difficult to recalibrate [8]. For example, the gyroscope is notorious for its cumulative error due to integration; the accelerometer reading is too noisy to yield good speed estimate by integrating the linear acceleration; the compass has large errors because of the ferro-magnetic interference in typical indoor environments. Such limitations prevent them from providing accurate moving direction estimates for many applications.

Wireless sensing is an emerging area that has been drawing more and more attention because of the promising solutions it provides for various kinds of applications [9, 10]. Specifically for targets localization and tracking, much progress has been made using RF signals in the recent years. Even though some novel systems can achieve decimeter or centimeter level accuracy in localization [11–14], they all have some of the following drawbacks which prohibit ubiquitous accurate heading direction measurements: (1) They cannot directly measure the moving direction but rather can only get a rough estimate from successive location estimations. (2) Following triangulation, multiple precisely installed APs and their location information are needed. (3) Based on fingerprinting, they have to collect the features of the targeted area, which is cumbersome and susceptible to dynamic environment changes. (4) They degenerate or even fail in Non-Line-Of-Sight (NLOS) scenarios under rich multipath environments.

In this paper, we propose a novel indoor heading direction estimation method that utilizes both the CSI and the geometry of the 2D antenna array with only a single AP. Based on the spatial decay property of the time reversal resonating strength (TRRS), which is first utilized in indoor localization by [15], a 2D antenna array is designed according to the location of the first peak in the TRRS curve. Inspired by the virtual antenna alignment proposed in [16], which can be used to calculate the moving speed in high accuracy, our key idea for estimating the moving direction is to make use of multiple speed estimates along different aligned antenna pairs. Combining the speed estimates with the known and fixed geometric relations of the antenna array, we propose a novel moving direction estimation algorithm that has continuous resolution with high accuracy. The median error for the proposed algorithm is $6.9°$ for experiments under strong NLOS scenarios, which outperforms the IMU counterpart. The promising performance and low cost make the proposed heading direction estimation method suitable for applications that need accurate moving direction information.

The rest of the paper is organized as follows: In Section 2, we discuss the relation to prior work. Section 3 provides the background of TRRS and TR Focusing Ball for the basis of the proposed algorithm. Section 4 explains the proposed heading direction estimation algorithm in detail. The experimental evaluation is given in Section 5. Finally, we draw the conclusion in Section 6.

2. RELATION TO PRIOR WORK

The related work falls into two categories: IMU-based or RF-based. For the IMU-based methods [2–7], they either rely on periodic human walking patterns for calibration, or suffer from drifting errors of gyroscope. The proposed algorithm has no assumptions on the moving pattern of the object, thus we can estimate the moving direction of robots, automated guided vehicles (AGVs) as well as human users. Furthermore, there is no accumulative error in the heading direction estimation in the proposed method. Few RF-based methods study the heading direction estimation and yield good results. RIM [16] is the first RF-based system that can measure the heading direction in strong NLOS scenarios. However, RIM can only resolve finite discrete angles, which are determined by the directions formed by antenna pairs. Our method is able to provide continuous resolution because of the novel design of the antenna array and the exploration of the geometric properties.

3. PRELIMINARIES

In this section, we introduce the theoretical foundation of the proposed heading direction estimation system.

3.1. Time Reversal Resonating Strength

Time reversal focusing effect is a physical phenomenon that the signal's energy is maximized at a specific time and location instance when combined with its time reversed and conjugated version. Such a spatial-temporal focusing effect is verified on electromagnetic waves by experiment in [17]. Based on the focusing effect, [13] can distinguish different locations at a centimeter-level resolution.

The concept of TRRS, indicating the similarity level of two CIRs, is first introduced in [18]. The equivalent form for Channel Frequency Responses (CFRs) is as follows: Given two CSIs H_1 and H_2, the TRRS is defined as:

$$\rho(H_1, H_2) = \frac{|\langle H_1, H_2 \rangle|^2}{|H_1|^2 |H_2|^2}, \tag{1}$$

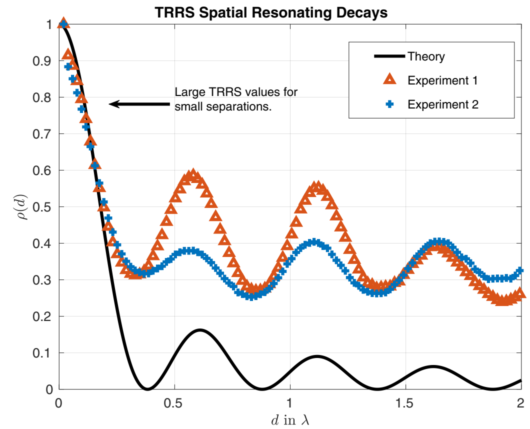


Fig. 1. TRRS spatial decay curve.

where $\langle \mathbf{x}, \mathbf{y} \rangle$ denotes the inner product of complex vectors $\mathbf{x}$ and $\mathbf{y}$, and $|\cdot|$ is the magnitude operator.

Notice that $\rho(H_1, H_2) \in [0, 1]$, and it achieves 1 if and only if $H_1 = cH_2$, where c is a non-zero complex scaling factor. Thus, TRRS can be indeed used as a similarity metric between CSIs.

3.2. Time Reversal Focusing Ball

In the indoor environment, where there exists rich multipath components (MPCs), [15] discovers a critical statistical property for TRRS in spatial domain. For two CSIs H_1 and H_2 measured at a separating distance d, their TRRS can be approximated as a determinate function:

$$\rho(H_1, H_2) \approx J_0^2(\frac{2\pi}{\lambda} d), \tag{2}$$

where $J_0(x)$ is the zeroth-order Bessel function of the first kind, and λ is the wavelength, as shown in Fig. 1.

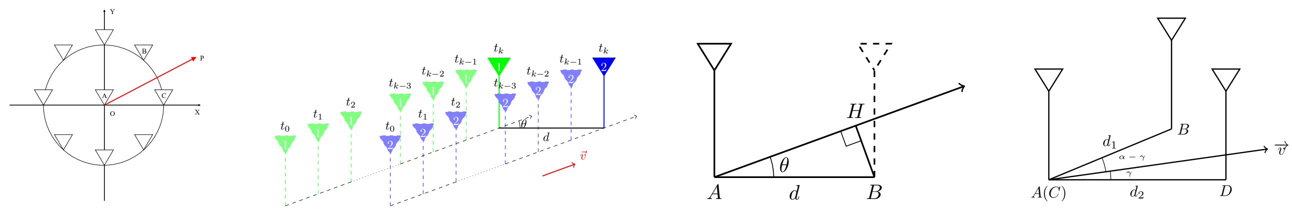
It has to be pointed out that due to the asymmetric normalized energy distribution of MPCs in certain directions, the actual TRRS is a superposition of $J_0^2(\frac{2\pi}{\lambda} d)$ and some unknown function. Nevertheless, the TRRS value for very small separating distance d is significantly larger than those with larger separations, which can be used for identifying nearest (virtual) antenna pairs [16].

4. PROPOSED ALGORITHM

Based on the TRRS spatial decay curve, a novel algorithm for estimating the moving direction is proposed in this section.

4.1. Overview

A 2D octagonal antenna array, where 1 additional antenna is at the center, and the reference coordinate system are shown in Fig. 2a. Denote the moving direction as $\overrightarrow{OP}$. There are



(a) Octagonal array. (b) Two antennas moving. (c) Closest location. (d) Direction estimation.

Fig. 2. Illustration of antenna array and aligned antenna pairs.

several pairs of antennas whose traces are close to each other, which are denoted as aligned antenna pairs, and we take 3 antennas A, B, C for illustration.

Denote the CSIs measured by those antennas at time t as $H_A(t), H_B(t)$ and $H_C(t)$. For the CSIs collected at the same time, the corresponding separations between antenna AB, and antenna AC are both the radius, which is chosen as half the wavelength. From the TRRS spatial decay curve in Fig. 1, the TRRS values $\rho(H_A(t), H_B(t))$ and $\rho(H_A(t), H_C(t))$ are small. Imagine antenna A keeps moving and collecting CSIs along the heading direction $\overrightarrow{OP}$. At time $t + \delta_{AB}$, the antenna A is closest to the location of antenna B at time t, thus $\rho(H_A(t + \delta_{AB}, H_B(t))$ yields a large value. Similarly, we expect to observe a large value for $\rho(H_A(t+\delta_{AC}, H_C(t))$. From the large TRRS values, we can infer that the moving direction is close to the directions indicated by $\overrightarrow{AB}$ and $\overrightarrow{AC}$. Hence, by identifying antenna pairs with high TRRS values, the rough heading direction is determined by the selected antenna pairs. In order to find the correct antenna pairs at time t, for any pair of antennas i and j, we calculate a TRRS vector $\mathbf{g}(t)$ through a window of length $2W + 1$:

$$\mathbf{g_{ij}}(t) = [\rho(H_i(t + k\Delta t), H_j(t)), k = -W, ..., W]^T, \quad (3)$$

where Δt is the sampling interval. For the aligned pairs, the time offset for one antenna to reach the closest location to the other is derived as:

$$\delta_{ij}(t) = (\arg\max_l g_{ij}(t, l) - W)\Delta t, \quad (4)$$

where $g_{ij}(t, l)$ represents the l^{th} element in $\mathbf{g_{ij}}(t)$.

To find the aligned pairs at every sampling time $(t_1, t_2, ..., t_T)$, a TRRS matrix G is formed by concatenating the TRRS vectors:

$$G_{ij} = [\mathbf{g_{ij}}(t_1), \mathbf{g_{ij}}(t_2), ..., \mathbf{g_{ij}}(t_T)]. \quad (5)$$

Furthermore, utilizing the time antenna A takes to reach the closest locations to antenna B and antenna C, namely δ_{AB} and δ_{AC}, we can refine the direction estimation together with the geometry of the 2D antenna array, which will be explained in the later sections.

4.2. Antenna Array Design

We use the 2D octagonal antenna array, as shown in Fig. 2a. The reasons are as follows:

1. To measure the moving direction in $[0°, 360°)$, a circular array is chosen because of the symmetry.

2. For the purpose of high resolution, an octagon array is used based on the TRRS decay curve Fig. 1. For a pair of antennas with a separation of $d = \frac{\lambda}{2}$, assume they move with a deviation angle of θ as shown in Fig. 2b. The closest distance is $\frac{\lambda}{2} sin(\theta)$. To correctly map from the largest TRRS value to the smallest separation, the TRRS for the closest distance should be higher than the first peak as in Fig. 1, which requires: $\frac{\lambda}{2} sin(\theta) < 0.26\lambda$. θ is thus constrained to be less than $31°$. The directions formed by pairs in an octagon array are multiples of $22.5°$. Thus for every moving direction, there are pairs of antennas with deviation angles less than $22.5°$, and can be used to infer the true heading direction with a high resolution of $22.5°$.

3. For the purpose of super resolution and high accuracy, one additional antenna is introduced to leverage the geometric relations of the array. By placing one antenna at the center, it is guaranteed to have at least two aligned pairs of antennas, forming different directions, for any moving direction. Thus, the continuous resolution of moving direction can be achieved by utilizing the speed estimates and geometry of the aligned pairs, which will be explained further in the next section.

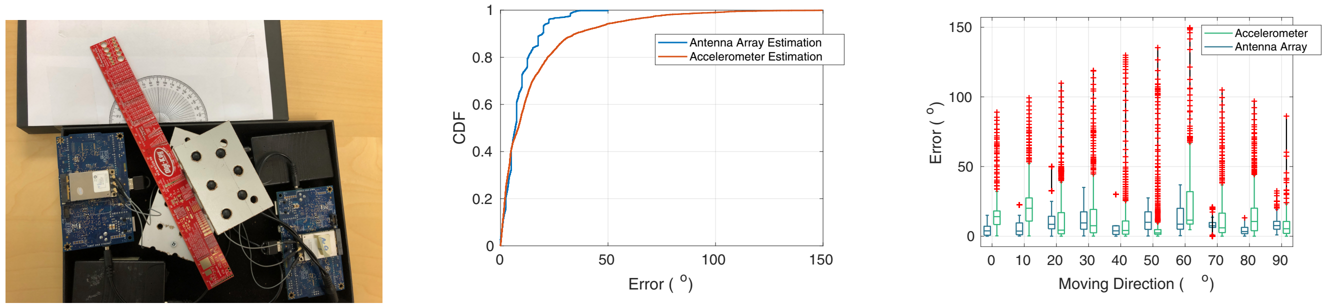
4.3. Accurate Heading Direction Estimation

The first step is to identify aligned antenna pairs, which are closest to the heading direction. Since the aligned pairs would have large TRRS values, and the time offset should change smoothly because the speed is relatively stable in a short time, we select best aligned pairs with the highest score defined as follows:

$$s(G_{ij}) = \frac{1}{T}\sum_{l=1}^{T} \max(\mathbf{g_{ij}}(t_l)) - \alpha\sqrt{\frac{\sum_{l=1}^{T}(\delta_{ij}(t_l) - \overline{\delta_{ij}})^2}{T-1}}, \quad (6)$$

where $\overline{\delta_{ij}} = \frac{\sum_{l=1}^{T}\delta_{ij}(t_l)}{T}$, and $\alpha > 0$ is a weighting scalar.

For an aligned antenna pair ij, we can derive the time offset $\delta_{ij}(t)$ as in Eqn. 4. As illustrated in Fig. 2c, the moving



(a) Half Octagonal Array

(b) Error CDF for moving direction estimation. The 90th percentile error reduces 44.1% from $34.9°$ to $19.5°$.

(c) Error bar for different moving directions. The proposed algorithm performs well over different angles with median errors less than $10°$.

Fig. 3. Experiment antenna array and results.

speed v can be calculated using the geometry and time offset as:

$$v = \frac{dcos(\theta)}{\delta_{ij}(t)} \tag{7}$$

After deriving the best aligned antenna pair, we select another pair forming a heading direction $22.5°$ away from the best pair with highest score. Assume antenna pair AB is the best aligned pair, and antenna CD is another pair selected, as shown in Fig. 2d. Then, the calculated speeds using these two pairs should be similar:

$$\frac{d_1 cos(22.5° - \gamma)}{\delta_{AB}(t)} = \frac{d_2 cos(\gamma)}{\delta_{CD}(t)}. \tag{8}$$

Finally, the heading direction is estimated as:

$$\gamma = tan^{-1}\left(\frac{\frac{d_2\delta_{AB}(t)}{d_1\delta_{CD}(t)} - cos22.5°}{sin22.5°}\right) \tag{9}$$

5. EXPERIMENTS

To verify the proposed method, we build a prototype using Qualcomm Atheros 9k chipsets. For the comparison with IMU sensors, the chipset is attached to an Intel Galileo Gen2 microcontroller board equipped with a Bosch Sensortec BNO055 sensor unit. Since the compass only reports the orientation, not necessary the moving direction, and the gyroscope is used for rotation angle estimation, we only use the accelerometer readings as comparison. For the 2D octagonal antenna array composed of 9 antennas, because of the lack of hardware, we use 6 antennas to form a half octagonal array as shown in Fig. 3a. Although the performance will degrade from 9 antennas to 6 antennas, the half octagonal antenna array can still validate the proposed algorithm.

The experiments are conducted in a busy indoor office environment. The single AP is more than 25m away from the moving area of the $2D$ antenna array, between which are multiple walls and pillars. During the experiments, the AP broadcasts packets continuously at the rate of 200 Hz, on the 5 GHz frequency band with a bandwidth of 40 MHz.

We perform the experiments covering the heading directions from $0°$ to $90°$ with an increment of $10°$. This is sufficient for validation because of the symmetry of the antenna array. We push the antenna array along a straight line for about 1m with different heading directions. The ground truth is derived from a printed protractor.

As shown in Fig. 3b, the overall median error for the proposed algorithm is $6.9°$, and the 90 percentile error is $19.5°$, which are both better than the accelerometer counterpart: $8.3°$ and $34.9°$. For different moving directions in Fig. 3c, the proposed method shows a consistent good performance: less than $10°$ median error for all the moving directions, although some directions are slightly worse because of the asymmetry of the half octagonal array.

The drifting error problem in accelerometer can be recognized in two ways: First, the maximum error can be as large as $150°$ shown in Fig. 3b, although the moving distance is only about 1m. Second, as seen in Fig. 3c, there are lots of large error outliers in every heading direction, which are due to the significant cumulative error toward the end of the movement. On the contrary, the proposed system does not suffer from the drifting error problem.

6. CONCLUSION

In this paper, we present an indoor heading direction estimation method using RF signals from COTS WiFi devices. The proposed algorithm works well in strong NLOS scenarios over a large dynamically changing environment, which is covered by a single arbitrarily placed AP with unknown location. Because of the low cost and the high accuracy, it creates the possibility for a large variety of new applications that require accurate heading direction information, such as robot tracking, VR gaming and gesture control.

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