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Accurate Indoor Navigation System Using Human-Item Spatial Relation

Qiongzheng Lin* and Yi Guo

Abstract: Indoor navigation has received much attention by both industry and academia in recent years. To locate users, a number of existing methods use various localization algorithms in combination with an indoor map, which require expensive infrastructures deployed in advance. In this study, we propose the use of existing indoor objects with attached RFID tags and a reader to navigate users to their destinations, without the need for any additional hardware. The key insight upon which our proposal is based is that a person’s movement has an impact on the frequency shift values collected from indoor objects when they near a tag. We leverage this local human-item spatial relation to infer the user’s position and then navigate the user to the desired destination step by step. We implement a prototype navigation system, called RollCaller, and conduct a comprehensive range of experiments to examine its performance.

Key words: Radio-Frequency Identification (RFID); frequency shift; human-item spatial relation; indoor navigation

1 Introduction

Have you ever searched for a specific book on a huge book shelf? Have you found at times that seeking a product in a shopping mall can be as difficult as finding a needle in a haystack? The task is manageable if all the books or products on the shelf are in order. However, books may be in disarray after being perused by others who take a look and then return the books haphazardly. The same problem also frequently occurs in supermarkets. In these cases, finding or sorting through desired items is not easy. An improved scenario could be achieved by route planning in supermarkets or libraries in which a consumer shares a list of desired items or books, and then plans an optimal shopping route. Following this optimal route, he minimizes the number of aisles followed, retrieves the desired items or books, and finally proceeds to the checkout counter. Significant amounts of time and money could be saved if there were techniques established to realize such optimal route planning services for the supermarket or library consumer to optimally navigate the borrowing/shopping processes[1].

Due to the rapid development of microelectronic technology, Radio-Frequency IDentification (RFID) techniques are now widely deployed in places as diverse as Wal-Mart and university libraries[2–8]. Before putting items on shelves, they are affixed with passive RFID tags, which can be identified at a distance by a passive RFID reader. Each tag has a globally unique ID, and the mapping relation between each tag and item is recorded in the backend database.

Assisted by the RFID technique, items can be located using RFID-based localization algorithms. Traditional RFID-based localization algorithms use the “present or absent” approach in which an item can be recognized when it comes into the reader’s interrogation range. While this approach is suitable for warehouse inventory, it is unsuitable for the above-mentioned scenarios, because coarse-grained localization may only be able to identify which shelf the item is on, or whether the item

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is in a given room. This method is of no use in finding one item among a group of densely placed items.

Most RFID-based localization algorithms utilize some inherent attribute, such as the Received Signal Strength (RSS) of the backscattered signals from RFID tags, to achieve fine-grained localization. Using these algorithms, the localization accuracy can be remarkably improved, whereby a specific item can be located to within several centimeters. The question is: how can the user be navigated to the item he wants? While he has item location information, the user still has no idea of the path to take to reach the item since his location is as yet unknown. A simple solution is to locate himself with the help of another localization algorithm. For example, we can facilitate a WiFi-based localization technique, or even utilize the existing RFID system to use an RFID-based tag-free localization technique. However, using a WiFi-based or other similar localization technique requires extra hardware deployment, which will involve extra system overhead. Due to the mobility of items on shelves, using RFID-based tag-free localization techniques is also unrealistic. In addition, asynchronization and error superposition may result in a totally wrong navigation.

Therefore, it is essential that a method be developed that can directly measure the real-time human-item spatial relation without separately measuring the locations of the person and item. In this paper, we first develop a method for measuring this local spatial relation between a person and an item, which uses the frequency shift in an RFID system. We then propose a fine-grained indoor navigation system, named RollCaller, to provide an indoor navigation service for a user to find a desired item. The function of our RollCaller system can be understood by its name: when a person wants to find an item, he then “calls” the item’s “name”. The RollCaller system then navigates him to the desired item. When the person walks up to the item, the item immediately “answers” the roll call.

To design such a system, the most essential challenge is to determine how to mine the human-item spatial relation between a person and an item without first knowing their location information. We can observe the phenomenon in which the frequency shift of signals backscattered from RFID tags to the reader antenna undergoes a significant change when the obstacle moves across the line of sight between the tag and the reader antenna. This phenomenon inspired us to depict the human-item spatial relation with the help of frequency shift.

Our major contributions may be summarized as follows:

- We propose a system that depicts the spatial relation between a person and an item using the frequency shift in an RFID system. Compared with existing localization methods, our method can work in real time and determine the spatial relation between a person and an item without separately measuring their locations, which greatly reduces system overhead.
- We propose an RFID reader antenna location method for estimating the RFID reader antenna locations, which measures the human-item spatial relation and the Inertial Measurement Unit (IMU)-based displacement. Using this method, the relative locations of reader antennas can be identified without any pre-knowledge regarding the reader antennas’ locations.
- We implement an indoor navigation system. Our comprehensive experimental results demonstrate that our navigation system works accurately.

The rest of this paper is structured as follows. We state the problem in Section 2, and describe in detail the method we developed to measure the human-item spatial relation in Section 3. In Section 4, we present the RollCaller system and describe our design of an enhanced system that supports multi-user scenarios in Section 5. We evaluate our experimental results in Section 6 and introduce related works in Section 7. In Section 8, we draw our conclusions.

2 Problem Statement

The typical library and supermarket scenarios mentioned above can be described as follows. A large number of items, which are difficult to distinguish at a glance, are densely packed on huge shelves. Among these items, there exists a specific item that someone wishes to obtain. This person will search for this item on the shelves, arrive at the nearest position to it, and take it off the shelf.

This searching process can be formalized as a localization problem of accurately locating the specific item on the shelves. When affixed with passive RFID tags, items on the shelves can be identified by RFID readers. We can apply up-to-date localization methods using an RFID technique, whose localization accuracy has been improved to a remarkable degree (within a centimeter). However, in the above scenarios,
knowing the exact location of a specific item (the exact coordinates of the item) is unnecessary and even wasteful. The person does not care about the exact coordinates of the item he wants. On the contrary, he is more concerned about how he can be navigated to the rough location of that item, by identifying the shelf it is on. While walking through the shelf aisle, he can be notified when he is right next to that item. In other words, the relative location between the person and the desired item is of more help in these scenarios.

In this paper, we do not concern ourselves with an item’s global location (e.g., the coordinates of an item in a library or supermarket), but rather facilitate the movement of the person who is looking for the specific item through the shelf aisles to “discover” the desired item. Our goal is to develop a way to locate an item relative to a person in motion. Specifically, we want to identify the nearest location of a person moving through a shelf aisle to a specific item. The only devices we utilize are a commercial smart phone and an implemented RFID reader with multiple reader antennas that inventory item RFID tags.

3 Human-Item Spatial Relation

To achieve the above goal, the first and most important task is to determine how to associate the location of the person and the desired item, namely the human-item spatial relation. This human-item spatial relation can be determined by separately measuring the location of the person and the location of the item. For example, the person’s location can be identified using WiFi-based localization approaches[9–11] and the item’s location can be identified using RFID-based localization approaches[12–19]. Then using the locations of the person and the item, their relative position can be determined. However, this approach is not satisfactory. The mean localization error for WiFi-based localization approaches can be greater than 1 m, and that for RFID-based localization approaches can be greater than 30 cm, resulting in an aggregated error greater than 1.3 m. Such a large distance drift is unacceptable when searching for one item in a stack of items. In addition, as these localization errors were measured in laboratory environments, the aggregate error would surely grow when applied to real life scenarios.

In our experiments, we take advantage of a phenomenon whereby when a person moves across the line of sight between a passive RFID tag and an RFID reader antenna, which identifies that tag, the received reader carrier signal experiences a significant frequency shift. We realized that we could utilize this phenomenon to capture the spatial relation between a person and a tagged item. The time stamp of when this frequency shift event occurs is known as the Anchor Time Stamp, which is formally defined and described in detail below. We also use the Anchor Time Stamp to describe the human-item spatial relation in the design of our system.

3.1 Frequency shift in RFID system

A frequency shift in an RFID system is known as a frequency change in the received reader carrier signal. Considering the application scenarios of most RFID systems, the causes of frequency shifts in RFID systems can be classified into three types: the Doppler effect, environmental noise, and multipath signals.

3.1.1 Doppler effect

Frequency shifts can occur due to the relative motion between the transmitter (RFID tag or the attached object) and the receiver (reader antenna)[20]. Generally, except when using a mobile RFID reader, the antenna of the reader can be reasonably treated as stationary. The major factor in a frequency shift is the motion of the tag.

Assuming that the velocity of the tag $v$ is much less than the speed of light $c$, we can calculate the frequency shift on a received reader carrier signal of wavelength $\lambda$ as $f_D = 2v \cos(\alpha)/\lambda$, where $\alpha$ denotes the angle between the velocity vector of the tag and the reader antenna. Then we apply the phase-difference method to determine the frequency shift. If we select a segment of a received reader carrier signal with a duration time of $\Delta T$, we can obtain the phase shift over the duration of this received reader carrier signal due to a frequency shift of $f_D$ by $\Delta \theta = 2\pi \times (2f_D \Delta T)$. Thus, by measuring the initial and terminal phases, we can calculate the frequency shift experienced by this received reader carrier signal segment by the following:

$$f_D = \Delta \theta / \Delta T$$

We calculate the frequency shift caused by the Doppler effect using the phase-difference method within the duration of receiving one packet from a tag. If we use more than one packet, a phase difference is likely to arise from the antenna switching during inventory or channel hopping, which strongly affects the accuracy of the measured frequency shift.
3.1.2 Noise

Environmental noise, especially thermal noise, is another factor that causes a frequency shift. For our purposes, this is the most effective factor when the environment is in a static state, for example, when no one is walking around. Figure 1a shows the frequency shift of a static tag and a static reader antenna in a room.

To distinguish between noise and a valuable frequency shift, described below, we set a noise level $f_{\text{noise}}$ to describe the boundary of the noise frequency shift value. In this example, the ±0.000 005% value is set as the noise level.

Although environmental noise has a limited effect on the frequency shift of tags, we note that this noise level is not unique. There is tag diversity with respect to frequency shift noise for different tags. Figure 1c displays the experimental results of 14 different tags. In this experiment, the frequency shift of each tag is collected without obstacles between or across the middle of the tag and reader antenna. This figure shows the tag diversity for the frequency shift, whose average noise value varies from less than 10 Hz to about 40 Hz, with the maximum value varying from 15 Hz to less than 70 Hz. Despite the variance in the average and maximum noise values, the noise values of all the tags are bounded at a reasonable level. We consider 95% of the maximum value of the frequency shift of a tag to be its noise level.

3.1.3 Multipath

The reader carrier signal received by the reader antenna from the tag is always a composition of the main path signal (line-of-sight signal) and a number of multipath signals (reflected from the surroundings). Even though the reader antenna and the tag are stationary, the reflector of the multipath signals may not be. As a result, the phase differences of these multipath signals during the measurement period are nonzero. Therefore, the composed reader carrier signal received by the reader antenna experiences a slight phase difference across the measured packet and hence causes a slight frequency shift.

This influence is slight if there is no obstacle between the reader antenna and the tag, which is the reason that the main path signal from the line of sight is much stronger than the multipath signals being reflected from their surroundings. The phase difference introduced by these relatively weak multipath signals causes only a minimal change in the composed reader carrier signal. Figure 1b shows the frequency shift result of a scenario in which people are walking in the vicinity of an active RFID system, but not crossing the line of sight directly between the tag and reader antenna. Not surprisingly, the overall frequency shift is more variant in this case but is still in a limited range (bounded by ±0.000 005% level of base frequency), which we can ignore, as compared with the large frequency shift in our next experiment. Therefore, we consider the frequency shift...
to be insensitive to the surroundings. This result is significant for applications in noisy environments, such as libraries and supermarkets.

As we can see, frequency shift values can be positive or negative. To simplify the expression, in the rest of this paper, we express all the frequency shift values as absolute values of the measured data, and the noise level values as positive.

### 3.2 Observation: Human impact on frequency shift

When people perform an action (walking, running or jumping), the effects on the tag and the reader antenna are very different. Figure 2 shows a plot of the affected frequency shift of the reader carrier signal as a person is walking normally across the line of sight between a tag and a reader antenna. We can see that the frequency shift in this scenario undergoes several phases: it initially oscillates below the noise level, as in previous experiments. Then the frequency shift starts to go beyond noise level and reaches a maximum in the center of the plot. Then, the frequency shift subsides and finally returns to the same noise level as that at the beginning.

The different periods shown in Fig. 2 correspond to the differences in the signals that occur when a person walks across the line of sight between the tag and reader antenna. These periods can be classified into the following stages:

- **Noise stage**: This stage occurs at the beginning and the end of the person’s walking behavior. In this stage, the person is not in the line of sight between the tag and reader antenna. In other words, the person is not in the range that can cause a frequency shift in the reader carrier signal.

- **Tilt stage**: This stage occurs after the person enters the range of the reader carrier signal, or before he leaves the signal range. At this stage, the person reflects the signal back from the tag to the reader antenna. The person is regarded as a signal source and his movement can cause a frequency shift as well as a phase difference, together with other multipath signals, thereby affecting the frequency of the composed reader carrier signal. The effect of this multipath signal grows stronger when the person nears the line of sight between the tag and reader antenna. This increases the frequency shift value over that of the normal noise level. Similar and symmetrical results appear when the person exits the signal range.

- **Peak stage**: This stage occurs when the person reaches the line of sight between the tag and reader antenna. The line-of-sight reader carrier signal is then obstructed and the reader carrier signal from the main path suddenly disappears. Meanwhile, if the reader antenna is receiving a packet and calculating the frequency shift via the phase difference, it will receive an initial phase caused mainly by the main path signal and a terminal phase without the main path signal. In this case, the phase difference is much larger than the value obtained previously, and reaches a local maximum. A similar maximum value can be achieved when the person leaves the line of sight of the tag and reader antenna, which results in an initial phase excluding the main path signal and a terminal phase that includes the main path signal.

It is unreasonable to assume that each time a person reaches the line of sight between the tag and reader antenna, the reader antenna will receive part of a tag packet that partially contains the main path signal and partially excludes the main path signal. In fact, the situation in which a person obstructs a complete packet’s main path signal does happen. Even though, in this situation, we cannot realize a maximum frequency shift value from the scenarios with and without the main path signal in a single tag packet receiving process, we can still distinguish the peak stages from those of the noisy surroundings. By obstructing the main path signal, multipath signals can take place of the main path signal in the composition of the receiving reader carrier signal. Therefore, unlike the insignificant multipath noise mentioned above, this time the frequency shift...
of the multipath signals caused by reflecting objects in its surroundings increases the frequency shift of the composed receiving reader carrier signal over that of the noise level. However, we find that the maximal point achieved by this condition is relatively smaller compared to that of the first scenario, which means that its effect is weaker. However, this will not prevent the recognition of an obstruction between the reader and the tag.

There is also a slight possibility that during the period that a person obstructs the line-of-sight signal, no tag packet is received by the reader. This means no frequency shift is calculated and the human anchor is missed and not extracted. However, this is a very low-possibility situation compared to the previous two situations.

### 3.3 Anchor Time Stamp

Based on the observation and analysis above, we can now define the Anchor Time Stamp as follows:

An Anchor Time Stamp, $H_{i,j}$, is the time stamp for when a person is in the line of sight between reader antenna $i$ and tag $j$.

According to this definition, we can narrow the Anchor Time Stamp to the peak stage interval mentioned above. However, we cannot simply regard the Anchor Time Stamp as the time stamp of the maximum value. Since the duration of time in which a person obstructs the line of sight is fairly short (generally less than 400 ms), the velocity during this period can be approximately assumed to be constant. Therefore, a more reasonable measure of the Anchor Time Stamp is to calculate the mean value of the peak stage time period.

Let $f_D(t)$ denote the frequency shift at time stamp $t$, and let the notation mean($\cdot$) denote the mean value calculation. We can then determine the Anchor Time Stamp by the following:

$$H_{i,j} = \text{mean}\{t \in T \mid |f_D(t)| \geq \max |f_D(t)| \cdot \beta\}$$  \hspace{1cm} (2)

where $\beta$ denotes a confidence level of the selected time stamp with a frequency shift that can be regarded as belonging to the peak stage. Additionally, the time interval $T$ in Eq. (2) meets the following condition:

$$\text{card}\{t \in T \mid |f_D(t)| > f_{\text{noise}}\} \geq C_0$$  \hspace{1cm} (3)

where $C_0$ is a constant. Equation (3) can also serve as a detection tool for identifying an Anchor Time Stamp event. When a time interval meets this condition, the system assumes that a person must have gone across the line of sight of the tag and reader antenna, and so it calculates the Anchor Time Stamp. Furthermore, to raise the accuracy of detecting an Anchor Time Stamp event, we add a constraint to limit the time interval $T$. Let $w$ denote a reasonable time interval for a person to cross the line of sight between the tag and reader antenna. Suppose a person 0.25-m wide is walking at a speed of 0.5 m/s, which is very slow, we can then set the size of $T$ to be $w = 0.25/0.5 = 0.5$ s.

## 4 RollCaller

With the Anchor Time Stamp defined in Section 3.3, we have a tool for describing the spatial relation between a moving person and items affixed with passive RFID tags. Using this tool, we propose our system, which we call RollCaller. We designed the RollCaller system to navigate a person to a specific desired item. First, the RollCaller system navigates a user to the shelf where the desired item is located. Then, as the user walks along the aisle beside that shelf, the RollCaller system determines when the user is right next to that item, and it notifies the user to stop and take the item off the shelf.

### 4.1 System overview

Figure 3 shows the architecture of the RollCaller system. To implement our RollCaller system, the following hardware is necessary: (1) Passive RFID tags. Attached by an RFID tag, items become recognizable by contact free RFID readers. (2) Passive RFID reader and multiple reader antennas for each reader. These readers transmit reader carrier signals and receive backscattered reader carrier signals from the RFID tags, which are used to identify the RFID tag and obtain the frequency shift value. The frequency shift value is then utilized to calculate an Anchor Time Stamp. These reader antennas are deployed singly on the opposite side of the aisle from the tagged items. (3) Backend server. The backend server operates the backend services to query data from the RFID reader and perform calculations for the RollCaller system. (4) Smartphone, equipped with an accelerometer and magnetometer and installed with a RollCaller client app connected with the backend server. The smartphone is carried by the user to measure his own displacement by IMU-based displacement measurement[21–23]. Also, it acts as an interface to acquire item information that the user wants, and to notify the user to stop and take the item.

The work flow of the RollCaller system can be separated into two periods: antenna allocation period.
and user navigation period. The antenna allocation period is designed to generate a relation map of the reader antennas. This map contains spatial information for each antenna, including the shelf it is on and the spatial relation with the other reader antennas on the same shelf. The map is used to detect the human-item spatial relation during the user navigation period. During this navigation period, the RollCaller system provides a navigation service to the user. According to the user’s input information about an item, the relation map of the reader antennas, and the database recording the mapping of item information to tag information, the RollCaller leads the user to the closest position to the desired item. These two periods are activated by different conditions. These antenna allocation period is triggered when the RollCaller system is activated. After it starts, the relation map of the reader antennas updates continually until the system is turned off. Unlike the antenna allocation period, the user navigation period is triggered when the user runs his system on a smart phone, inputs information about the item he wants (e.g., the item’s name), and waits for the navigation service.

4.2 Antenna allocation period

In RFID-based localization systems, the location of reader antennas is normally assumed to be pre-known. While this is feasible in labs or testbeds, in the real-life scenarios of libraries or supermarkets this assumption is far from practical: the deployment of the reader and reader antennas is always carried out by nonprofessionals who are not trained to deploy reader antennas for the system. Besides, movement of shelves is possible, which will change the earlier deployment configuration. Therefore, updating the reader antenna location message is necessary in our RollCaller system. Specifically, unlike other localization systems, in our RollCaller system there is no need to know the reader antenna location. Instead, the RollCaller system must only know the spatial relation between reader antennas. In the antenna allocation period, the goal is to generate a reader antenna relation map, which can be updated immediately to guarantee navigation accuracy.

The antenna allocation algorithm works as follows. Suppose there are $M$ tagged items on a shelf and $N$ reader antennas on the opposite side of the aisle facing the tagged items. The items are assigned with IDs from $\text{TAG}_0$ to $\text{TAG}_{M-1}$ and the reader antennas are assigned with IDs from $\text{ANT}_0$ to $\text{ANT}_{N-1}$. Antenna $\text{ANT}_0$ is deployed at one end of the aisle, serving as the reference antenna. When a user walks along the aisle, by applying the Anchor Time Stamp detection algorithm mentioned in Section 3.3, the backend server can obtain a sequence of Anchor Time Stamps $\{H_{\text{ANT}_i,\text{TAG}_j} | i = 0, 1, \ldots, \text{N} - 1; j = 0, 1, \ldots, \text{M} - 1\}$. Let $I_{t_1,t_2}$ denote the displacement of the user from time stamp $t_1$ to $t_2$ measured by the IMU-based tracking method installed on the smart phone carried by the user, and let $R_{\text{ANT}_i,\text{ANT}_j,\text{TAG}_k}$ denote the calculated directed distances from reader antennas $\text{ANT}_i$ to $\text{ANT}_j$ using Anchor Time Stamps $H_{\text{ANT}_i,\text{TAG}_k}$ and $H_{\text{ANT}_j,\text{TAG}_k}$. We can obtain the distance between antennas $\text{ANT}_i$ and $\text{ANT}_j$ using the property of similar triangles as follows:
\[ R_{\text{ANT}_i, \text{ANT}_j, \text{TAG}_k} = \frac{|H_{\text{ANT}_i, \text{TAG}_k}, H_{\text{ANT}_j, \text{TAG}_k}|}{\gamma} \]  
(4)

where \( \gamma \in (0, 1] \) relates to the ratio of similitude. However, this parameter is not exactly equal to the ratio of similitude since the user is not walking strictly parallel to the shelf. The value of this parameter is discussed in Section 6. Besides, the direction of \( R_{\text{ANT}_i, \text{ANT}_j, \text{TAG}_k} \) is a component of the direction of \( H_{\text{ANT}_i, \text{TAG}_k}, H_{\text{ANT}_j, \text{TAG}_k} \) along the aisle.

Obviously, not all \( M \) tags can be recognized by every reader antenna due to the limited transmitting power and angles. Besides, the total number of tags \( M \) on the shelf is not fixed since tagged items may be taken from or placed on the shelf at any time. Therefore, to facilitate our description, we mark the Anchor Time Stamp \( H_{\text{ANT}_i, \text{TAG}_k} \) as N/A (not applicable) if antenna \( \text{ANT}_i \) cannot recognize tag \( \text{TAG}_k \). The IMU-based displacement measurement and the reader antennas distance related to an Anchor Time Stamp marked as N/A are also N/A.

When a user walks along the aisle, a set of antenna-directed distances are obtained. Once the antenna-directed distances in this set cover all the reader antennas along the aisle, a relation map of these reader antennas is generated in this way: initially we select all the directed distances starting or ending with the antenna \( \text{ANT}_0 \). Since antenna \( \text{ANT}_0 \) is fixed at the end of the aisle, the selected antennas can be marked as such on the reader antenna relation map. Next, we select all the directed distances starting or ending with the antennas we have just marked on the relation map. Then we perform this process iteratively until all the antennas along the aisle are marked on the relation map. Finally, a relation map of all the reader antennas is generated and applied in the user navigation period described in Section 4.3.

Due to errors in stride length, direction estimation, and the like, inaccuracies exist in the IMU-based displacement measurements used to generate this map. In order to improve the accuracy of the reader antenna position map, we apply the minimal composition constraint \(^{24}\) to compensate for the above errors. The minimal composition constraint in RollCaller works as follows: initially, we assign the coordination of all the nodes to the reference reader antenna. Let \( \hat{p}_i \) be the current coordination of reader antenna \( i \), and let \( d_{i,j} = \hat{p}_i - \hat{p}_j \) be the current displacement vector between reader antenna \( i \) and a neighboring reader antenna \( j \). Suppose that the most recent \( K_{i,j} \) displacement measurement between reader antenna \( i \) and \( j \) is used to adjust the antenna position, and let \( r_{i,j,k} \) be the \( k \)-th measured displacement among these \( K_{i,j} \) measurements. Then the adjustment vector \( \epsilon_i \) of reader antenna \( i \) can be generated as follows:

\[
\epsilon_i = \frac{\sum_{i=0}^{N} \sum_{k=0}^{T} (R_{i,j,k} - d_{i,j})}{\sum_{j=0}^{N} K_{i,j,t}}
\]  
(5)

This adjustment vector describes the composite effect on the reader antenna position of multiple displacement measurements to the reader antenna position. The precision of position \( \hat{p}_i \) of reader antenna \( i \) can be improved with this adjustment vector:

\[
\hat{p}_i = \hat{p}_i + \epsilon_i
\]  
(6)

All the adjustment vectors in the aisle should update once a new displacement vector is obtained in the aisle. This is because for each change in reader antenna position, all the reader antenna positions in that aisle will change, since the calculated displacement and adjustment vector relates to all the reader antennas. In order to ensure the sensitivity of the user’s displacement measurement characteristics (such as the user’s displacement error or the unexpected movement of antennas), the \( K_{i,j} \) should be limited to a reasonable size.

We note that this reader antenna relation map is generally reused when the RollCaller system is restarted. This means that each time the RollCaller system starts, time is not wasted in building another relation map. Instead, the system automatically adjusts the current map allocation using the past relation map as a basis. Of course, if the reader antenna location undergoes significant change, such as a reconfiguration of the library shelves, the existing relation map must be removed and reconstructed.

### 4.3 User navigation period

After the reader antenna relation map has been generated, the RollCaller system can begin to provide a user navigation service. In the user navigation period, when the RollCaller system receives a navigation request, it navigates the user to the input item in two steps: rough navigation and accurate navigation. In the rough navigation step, the backend server queries the item in the database. The corresponding RFID tag ID
is then retrieved and the rough location of this tagged item (the shelf it is placed on) is determined by querying which antennas can inventory this item. According to the rough location information obtained, the RollCaller system first navigates the user to the aisle beside the shelf on which the item is placed and then immediately starts the accurate navigation step. Since the shelves are generally arranged sparsely enough to be located in a short time, the navigation process is relatively simple and is not described here.

The accurate navigation step begins immediately upon the user reaching the shelf on which the desired item can be found. To transition from rough navigation to accurate navigation, an event is required. Recalling the deployment of our reader antennas mentioned in Section 4.2, reader antenna $\text{ANT}_0$ is deployed at the end of the passage. Similarly, an extra passive RFID tag $\text{TAG}_{\text{ref}}$ is attached to the shelf at the same end of the passage facing the reader antenna $\text{ANT}_0$. Moreover, the virtual connection between tag $\text{TAG}_{\text{ref}}$ and reader antenna $\text{ANT}_0$ satisfies the requirement of being perpendicular to the passage. Utilizing this special deployment, the Anchor Time Stamp $\text{H}_{\text{ANT}_0,\text{TAG}_{\text{ref}}}$ is set to serve as the event that triggers the accurate navigation step. Also, this Anchor Time Stamp is used as a reference time stamp to assist in accurate navigation.

When the user enters this passage, the Anchor Time Stamp $\text{H}_{\text{ANT}_0,\text{TAG}_{\text{ref}}}$ is obtained and the accurate navigation service starts. Suppose the RFID tag attached on the designated item is labeled $\text{TAG}_s$, we can calculate the remainder displacement $\Delta D$ the user should move to reach the item by

$$\Delta D = \frac{(l_{\text{H}_{\text{ANT}_0,\text{TAG}_{\text{ref}}}} - 1) \cdot \gamma}{\frac{d_{\text{ANT}_1,\text{ANT}_0}}{1 - \gamma}}$$

Equation (7) can be applied when the first Anchor Time Stamp relating to tag $\text{TAG}_s$ is detected. Since the accuracy of the Anchor Time Stamp grows when the reader antenna is closer to the tag (as further addressed in Section 6), $\Delta D$ will update continuously as the user walks closer to the designated tagged item. Finally, the moment the user location is determined by our RollCaller system to be closest to the designated item, it signals the user to stop via the client program running on the smart phone. At this point, the user has been successfully navigated to the desired item, and the user navigation period is terminated.

According to our system design, the only user operation required by the RollCaller system is to input the desired item information. Given that information, the system will automatically navigate the user to the desired item with straightforward instruction. Besides, based on our experimental results, when the navigation service finishes, the user is guaranteed to reach an accurate and convenient position beside the desired item.

5 Enhanced RollCaller System for Multi-User Scenario

During the user navigation period in the RollCaller system, information is only transmitted from the system server to the users’ smart phone. Due to this one-way information path between the users and the system, the RollCaller system cannot distinguish between different users using the navigation service. Hence, the RollCaller system proposed above cannot deal with multiple users and therefore requires improvement.

Thanks to developments in microelectronic technology, mobile RFID readers have become available for commercial applications. Unlike the traditional static, passive RFID reader, the mobile RFID reader is portable, and is much smaller in size ($5 \times 5 \text{ cm}$ for Arete Pop Smart RFID Dongle Reader[25] shown in Fig. 4). It is also sufficiently inexpensive (can be less than $50) to introduce in quantity to supermarkets or libraries. In this section, we propose an enhanced RollCaller system that uses a mobile RFID reader to manage multi-user scenarios.

In the enhanced RollCaller system, when a user enters the supermarket or library, he is given a mobile RFID reader. He simply inserts the mobile RFID reader into the headset jack of his smart phone, and follows the navigation process described in Section 4.3. This mobile RFID reader is a plug-and-play device and the tag detection function is integrated into the RollCaller program app.

The enhanced RollCaller system works as follows. Let time stamp $t_{\text{detect}}$ denote the moment the RollCaller system detects that a user is next to a desired item. However, this user is not necessarily the user who is

![Fig. 4 Mobile RFID reader.](image-url)
using our RollCaller system to search for that desired item. He might be any library patron or other RollCaller user. The RollCaller system then retrieves the human-item spatial relation information on that same shelf where the desired item is located from the server during this period \([t_{\text{detect}} - \tau, t_{\text{detect}}]\). From the retrieved information, the RollCaller system selects items that have a user standing next to them and this time stamp, and then forms a collection \(C_{\text{reader}}\). Items in \(C_{\text{reader}}\) can be entered in duplicate since there may be several instances in which persons were standing next to it. The collection \(C_{\text{reader}}\) is ordered by the time stamps of each item. Let collection \(C_k\) denote the sequence of items detected by user \(k\)'s mobile RFID reader and let the collection \(C_{\text{user}}\) denote the users in the same passage of the reader mentioned above. Collection \(C_k\) is also ordered by the time stamps of each item. Then, the system can select the most likely user \(p\) next to the desired item, as expressed in Eq. (8).

\[
|LCS_p| = \max(\forall user_k \in C_{\text{user}}, |LCS_k|) \tag{8}
\]

where \(LCS_i\) denotes the Longest Common Subsequence between \(C_{\text{reader}}\) and \(C_{\text{detect}}\). If user \(p\) is the specific user who is searching for the desired item, the enhanced RollCaller system notifies the user and terminates the navigation service. Otherwise, the navigation period continues.

Considering that \(C_{\text{user}}\) may contain several redundant subsequences due to the detection of multiple tags, in order to reduce system load before calculating the longest common subsequence, the system will remove redundant subsequences.

6 Implementation and Evaluation

In this section, we describe the implementation of the RollCaller system and evaluate its performance.

6.1 Implementation

For this study, we implemented the RollCaller system in a laboratory environment. We used an Impinj Speedway Revolution RFID reader to transmit the carrier signal to the passive RFID tags, and received backscattered carrier signals from these tags. We uploaded software version Octane 4.8 to the reader and equipped it with four directional reader antennas. In addition, we used nine Alien ALN-9634 passive RFID tags to evaluate the performance of our system. We placed both the tags and reader antennas in line formation. The “tags line” and the “reader antennas line” form a passage 100 cm wide, as shown in Fig. 5. We labeled the reader antennas Antenna A, Antenna B, Antenna C, and Antenna D from left to right. Similarly, we labeled the tags from left to right as Tag 0 to Tag 8.

In addition to the RFID implementation, the other device required in the RollCaller system is a smart phone equipped an accelerometer and a magnetometer. We selected the HTC One Android smartphone for this purpose. In our experiments, to measure the displacement of the user when walking, we choose a simple frequency-based model\(^{[26]}\) for the smart phone. This model calculates the step length of the user \(L_{\text{step}}\) by \(L_{\text{step}} = a \cdot f + b\), where \(f\) is the walking frequency of the user and parameters \(a\) and \(b\) for each person were trained offline before the experiment.

Lastly, we addressed the data we measured with respect to ground truth. To make things simpler, we measured the position of an object (reader antenna, tag, or human) as the central point of that object. For example, we regarded the middle point of a human foot as the user’s central point.

6.2 Evaluation of Anchor Time Stamp

The performance of the Anchor Time Stamp measurement will fundamentally affect the whole RollCaller system. Therefore, before evaluating the performance of the other aspects of the RollCaller system, we first evaluated the accuracy and stability of the Anchor Time Stamp.

Distance drift is the most important metric we used
to evaluate the accuracy of the Anchor Time Stamp measurement. We set the distance drift of an Anchor Time Stamp as the distance between the expected and actual position of the location measured by the Anchor Time Stamp. As such, a smaller distance drift indicates greater accuracy in the measurement of the Anchor Time Stamp.

6.2.1 Accuracy of Anchor Time Stamp

First, we evaluated the accuracy of the Anchor Time Stamp measurement using general settings. In this experiment, we turned off all the reader antennas except Antenna A, and removed all the tags but Tag 1 from the identifying range of Antenna A. The orientation between Antenna A and Tag 1 was perpendicular to the aisle. At normal velocity, a person walked through the aisle 35 times. Each time the system detected an Anchor Time Stamp, the experimenter stopped and measured the distance drift, which is the distance from his position to the line of sight between the antenna and the tag.

Figure 6 shows our statistical analysis of the 35 Anchor Time Stamp measurements. From the Cumulative Distribution Function (CDF) curve, we can observe that 80% of the Anchor Time Stamps were measured within a 25-cm distance drift. This is a tolerable error for applying the Anchor Time Stamp in a real setting. In fact, the width of a person is normally greater than 20 cm, which makes the distance drift of our Anchor Time Stamp measurements more negligible. In addition, the bars of the Pair Distribution Function (PDF) shown in Fig. 6 further indicate that most of the distance drift is concentrated in the interval between 10 cm and 25 cm. This means that extreme error occurs rarely, which makes the Anchor Time Stamp measurement trustworthy.

6.2.2 Impact of human velocity

With respect to the frequency shift, the velocity of the mobile item (receiver or transmitter) is the first factor to consider. In our RollCaller system, a person walking along the aisle plays this role. In the first experiment, we evaluated the impact of human walking velocity, and the settings in this experiment are the same as in the previous experiment.

The bars in Fig. 7 show the maximum values of the frequency shift when a person walks along an aisle at a velocity of 0.8 m/s to 1.5 m/s. This velocity range corresponds to velocities from strolling to fast walking. This figure shows that the maximum frequency shift values remain stable despite velocity variation. This is not surprising due to the insignificant changes in velocity that characterize human walking. However, we consider a more direct reason to be the specific cause of the frequency shift in our RollCaller system: we calculated the maximum frequency shift values using a phase-difference method based on the obstruction of the main path signal. In this case, the moving person simply acts as an obstacle and his velocity does not significantly affect the initial and terminal phases of the measured packets with respect to their maximum value. Therefore, human walking velocity has only a negligible effect on the frequency shift.

However, this does not mean that the human walking velocity is totally irrelevant in our RollCaller system. The curve in Fig. 7 indicates that with a faster velocity, there are fewer sample points collected for Anchor Time Stamp measurement. This is due to the reduced duration in which the human obstructs the line of sight of the tag and reader. Since the Anchor Time Stamp is calculated as the mean value of these sample points, this value will affect the accuracy of the Anchor Time Stamp. Figure
8 shows statistical data for the measured distance drift with varied human velocity. The distance drift increases as the human walking velocity increases. This can be attributed to the few sample points used in the calculation. With fewer sample points, it is more likely that the Anchor Time Stamp will be set to the beginning or ending of the obstruction period, but not the line of sight point.

### 6.2.3 Impact of tag status

In this subsection, we evaluate the impact of two factors that arise due to the deployment of tag and reader antennas.

Tagged items on the shelves are always placed irregularly, which makes the direction of the tags unpredictable. Therefore, we must also evaluate the Anchor Time Stamp measurement to determine whether our method performs well for various tag directions. Figure 9 shows the impact of the tag direction. In this experiment, the tag rotates along its central axis by angles $45^\circ$, $0^\circ$, and $-45^\circ$. From this figure, we can see that tag rotation has very little effect on the Anchor Time Stamp measurement. Hence, this Anchor Time Stamp measurement approach can be applied to situations in which the tag placements are irregular.

The angle between the tag-antenna connection and the aisle (tag-antenna angle) is another factor that may influence the accuracy of the Anchor Time Stamp measurement. Figure 10 shows the relation between this angle and the distance drift of the Anchor Time Stamp measurement. Although the distance drift is still within an acceptable range, it increases as the tag-antenna angle increases. This can be imputed to the transmission range of the directional reader antenna. We can describe the transmission range of the directional reader antenna as a fusiform main lobe and several side lobes, in which tags can receive and backscatter stronger carrier signals in the main lobe. When the tags are placed close to the edge of the main lobe, or even outside the main lobe, the line of sight signal is not as strong as we would like. Therefore, this will result in a larger distance drift in the Anchor Time Stamp measurement.

### 6.2.4 Impact of human status

The most likely application setting for RFID systems is in a noisy environment, such as a library, supermarket, other retail store, or the like. In these settings, many mobile items may be in operation around the RFID system, which may cause inaccuracies when extracting the human anchor information. However, we discussed this problem in the previous section and showed that the effect of environmental noise will not affect the algorithm performance in its retrieval of human anchor information. In the remainder of this subsection, we focus on the effect of a person’s behavior on the extracted human anchor information.

Considering that the major reason for a frequency
shift is the obstruction of the main path signal of the reader carrier, we evaluated the characteristics of the
human anchor, such as behavior while walking. In our
evaluation, we examined three kinds of behaviors:

- Mode 1: A human walks though the line of sight
  between a reader antenna and tag normally;
- Mode 2: A human walks and jumps;

In our experiment, a person exhibiting each of the three behaviors walked between the tag and reader
antenna at a steady velocity, from which we generated
the result shown in Fig. 11. From this figure, we can see
that human behavior variation had little effect on the
performance of our system, which means the behaviors
of people walking through the line of sight between the
reader antenna and tag does not affect the obstruction of
the reader carrier signal received by the reader antenna.

6.3 Performance of reader antenna relation map
generation

The reader antenna relation map generated during the
antenna allocation period plays an important role in
our RollCaller system. The accuracy of this map can
strongly affect the performance of the user navigation
service. In this subsection, we evaluate the performance
of the generated relation map.

In Eq. (4), parameter $\gamma$ is still undetermined. For
this evaluation, we designed an experiment to estimate
this parameter by statistical analysis. To do so, we
turned off all the reader antennas except Antennas A
and B, and removed all the tags except Tag 1. In this
situation, our system can only receive a backscattered
signal from Tag 1 via Antennas A and B. Tag 1 was
facing the middle point between Antennas A and B,
and the distance between these two antennas was 40 cm.

During this experiment, we recorded 100 instances of
walking behavior, and we measured the displacement
of the person with a smart phone.

Figure 12 shows the results of these 100 tests, in
which the PDF bars indicate that more than 90% of
the test results were in the interval from 0.1 m to 0.4 m,
and about 40% are between 0.2 m and 0.3 m. The mean
value of these 100 tests are 0.2137. Therefore, we apply
the value of $\gamma$ as $0.2137/0.4 = 0.5343$ in our evaluation
of relation map generation and further experiments of
our RollCaller system.

From Fig. 12, we see that there exists the situation
that the measured antenna distance has a negative
value. This is reasonable because Antenna A has the
possibility of detecting the Anchor Time Stamp later
than Antenna B, due to the distance drift of the Anchor
Time Stamp measurement.

After achieving the $\gamma$ value, we could then evaluate
the accuracy of our generated reader antenna relation
map. This time, we set the reader antennas and tags
to all be working. We placed the reader antennas at
a distance of 40 cm from their neighboring antennas,
and placed the tags at a distance of 20 cm from
their neighboring tags. Figure 13 shows the generated
relation map. For ground truth, we placed Antennas
A/B/C/D in a line and separated by a distance of 40 cm.
In our relation map generation process, we set the initial relative position of these antennas with respect to their neighboring antennas as 0 cm. When a person moves from one end of the aisle to the other, the system calculates the relative positions of the antennas using the recorded Anchor Time Stamps and the measured displacement of the person, as uploaded from the smartphone. In this experiment, we calculated the relative position of these four antennas with respect to Antenna A as follows: 0 cm, 21.7 cm, 52.4 cm, and 97.3 cm, respectively. The relation map continued to update and when the number of times the person passed through the aisle reached ten, the relative positions were estimated to be 37.3 cm, 73.5 cm, and 111.9 cm, whereas the relative distance between two neighboring antennas was measured to be 37.3 cm, 36.2 cm, and 38.4 cm. This means that, after passing through the aisle ten times, the relation map realized a measurement error of less than 5 cm, which is very low.

6.4 Performance of user navigation service

With a stable Anchor Time Stamp measurement and an accurately generated reader antenna relation map, we could finally evaluate the user navigation service of the RollCaller system. In this experiment, we used seven tags and all four of the reader antennas. Of these seven tags, we assigned Tag 0 to be the reference tag, as mentioned in Section 4.3. We placed Antennas A/B/C/D in a line 40 cm apart from each other, and placed tags in a line 20 cm apart. We then generated the relation map of the reader antennas and the person walked from the end of the aisle with the reference tag to the other end.

We performed this navigation experiment 120 times. For Tags 1 to 6, we searched for each tag 20 times. When the Roll Caller system determined that the person was right next to the tag for which he was searching, it notified the user. The user then stopped and we recorded the stop point. We then plotted these 120 marked points, as shown in Fig. 14. We note that the vertical difference in Fig. 14 is used only to separate the marks for distinguishing different tags, and does not represent the walking track closer to the tags or antennas. From this figure, we can see that most of the stop points are near the searching tag. The closer to the tag, the higher is the density of the stop points. Figure 15 shows a further analysis of the performance of the user navigation service. In this figure, we can see that the average number of stop points has a nearly perfect position. Also, nearly 90% of the stop points are located less than 20 cm from the actual position of the searching tag. This means that our Roll Caller can navigate users effectively to their desired tags.

Even though the evaluation results are impressive for our Roll Caller system, we found that, with respect to searching for tags further from the reference tag, the navigation performance worsened, with a maximum navigation error of nearly 40 cm when searching for Tag 6. The reason for this result is that the IMU-based displacement measurement performs poorly over longer distances due to the accumulated error. Despite this drawback, the navigation result still has profound significance.

6.5 Real-life scenario experiment

To evaluate the practicality of our Roll Caller system in real life, we deployed our Roll Caller system in a supermarket. We randomly selected 100 distinct items distributed in three neighboring aisles. To the selected items we affixed passive RFID tags. The left figure of Fig. 16 shows one aisle in the supermarket with some
tagged items, and the right figure shows one of the tagged items.

We conducted our experiment with 25 random supermarket consumers. One or two consumers participated simultaneously in the RollCaller system and each consumer was given from one to three desired items for which to search. As temporary RollCaller system clients, the consumers each installed a RollCaller system app, inserted a mobile RFID reader into the headset jack of their smartphones, followed the system instructions, and were navigated step by step to their desired items. When the RollCaller app notified the consumers that they were standing next to their desired item, the consumers stopped and we measured the distance between the consumer and the desired item. We carried out and recorded 54 instances of RollCaller navigation.

Figure 17 shows the statistical results of these 54 experimental cases. From the PDF bars in the figure, we see that about 70% of the navigation errors are in a range from 40 cm to 60 cm. The performances of the real-life experiments were not as accurate as those in the laboratory where most of the navigation errors were less than 20 cm. This is because the environmental noises, user’s pre-existing knowledge, and tag sparsity in the real-life environment differed from those in the laboratory environment. Despite this, user feedback suggests that this level of navigation error is tolerable and that the RollCaller system indeed reduced their searching time.

From the CDF curve in Fig. 17, we also see that 96.3% of the navigation errors are less than 80 cm. In fact, only two navigation instances failed to navigate the consumer to their desired items. This occurred because not all the consumers in the supermarket were simultaneously holding our mobile RFID readers. When there were too many uninvolved consumers in the same aisle of the testing consumer, the RollCaller may have given a false termination instruction. In our experiment, we determined that more than ten irrelevant consumers in the same aisle as the testing consumers can cause this false navigation result. However, this situation was very dense and the actual consumer number is usually less than this threshold in most situations, in which the RollCaller works perfectly.

7 Related Work

Compared to outdoor localization, indoor localization faces more challenges since a GPS signal is rarely available and the accuracy level is more demanding. To satisfy the expanding demand for indoor localization services, wireless indoor localization techniques have experienced rapid development in recent years. Wireless indoor localization techniques utilize several kinds of wireless signals to locate humans, devices, or specific items at room-level or even centimeter-level accuracy. These wireless signals include WiFi\cite{9–11}, ZigBee\cite{27}, RFID\cite{12–19, 28, 29}, acoustic signal\cite{30–33}, and the like.

Wireless indoor localization methods can be classified into two kinds of classical mapping methods, geometric mapping and fingerprint\cite{34}. With respect to geometric mapping methods, physical measurements are converted into distances or directions based on reference points. In fingerprinting methods, physical measurements of an unknown location are considered to be its fingerprint, and these fingerprints are matched with those pre-measured in the database, and then returned to the location corresponding to the closest fingerprint. Currently, both method types achieve satisfactory fine-grained localization. However, considering the huge scale of the target objects to be located, such as books in libraries or commodities in supermarkets, RFID-based localization methods...
Two major types of localization approaches are applied in RFID-based localization systems: tagged approaches\cite{12-17} and tag-free approaches\cite{18,19}. In tagged approaches, the object to be identified by a localization service is affixed with an RFID tag. To locate this object, the reader retrieves valuable attributes from the transmitted signal or from backscattered signal from an RFID tag affixed to the object. These attributes include the carried tag information and other physical aspects such as Received Signal Strength (RSS) and phase. According to the utilized attribute, the localization accuracy varies from room-level to centimeter-level. Even though tagged approaches can achieve an impressive localization accuracy, it is not suitable in the scenarios described in Section 2, since they cannot provide a human-item spatial relation.

Tag-free approaches, the alternative type of RFID-based localization approaches, offer another way to achieve localization. In tag-free approaches, the tags are not attached to the object to be localized, but are distributed in the environment. In tag-free applications, the object to be localized need not be recognized before localization. This advantage enables tag-free approaches to be installed in some conditions where it would be impossible to attach the RFID tag on the object to be identified, such as in a concert hall. This kind of approach may be adaptable to the scenarios we described in Section 2, but existing tag-free approaches do not satisfy our needs because the localization accuracy of tag-free approaches in RFID-based localization is too low, especially in passive RFID systems. This is why tag-free approaches in RFID systems are more likely to be used for intrusion detection or trajectory identification. Lastly, if we use location fingerprint in our localization approaches\cite{35,36}, our results markedly worsen since the tags in these settings are always moved by people. It is hard to achieve and maintain a stable and reliable location fingerprint database in these settings.

8 Conclusion

In this paper, we proposed our design for an accurate indoor navigation system, called RollCaller, to solve the problem of searching for specific items among large numbers of items on shelves. Ours is a novel approach that uses frequency shift to measure the human-item spatial relation, which is then applied in the RollCaller system. Using this human-item spatial relation measurement approach and the generated reader antenna relation map, the RollCaller system can accurately navigate a user to the desired item. Experiment results show that our RollCaller system can accurately navigate users to the desired items at an average distance error of less than 20 cm.

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