Less is More: Efficient RFID-based 3D Localization

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***Abstract*—Radio-Frequency Identification (RFID) technology has successfully proven its potential for locating objects in a 3-dimensional (3D) space. Current RFID-based 3D localization is built on the ethos of striving for accuracy. This paper takes the first step toward efficient localization with high time efficiency and energy efficiency, which are important for accelerating positioning operation and prolonging system lifetime. To this end, we propose leveraging known locations of deployed reference readers and reference tags to probe as a few reference tags as sufficient for localization. Counter-intuitively, localization using fewer reference tags promises rather higher efficiency yet without necessarily sacrificing accuracy. We design efficient passive scheme and efficient active scheme for both typical RFID-based 3D localization scenarios, locating a target tag using reference readers/tags and locating a target reader using reference tags. We evaluate their performance through thorough analysis and extensive simulation. The results show that the proposed schemes outperform existing schemes in time efficiency and energy efficiency by over 95% on average.**

I. Introduction

Radio-Frequency Identification (RFID) based localization prevails in more and more of our daily activities because of deployment easiness and cost efficiency. Some pioneer localization applications thrive in, for example, searching books in libraries [1], pinpointing misplaced products in supermarkets [2], [3], tracking customers in shopping malls [4], and searching tourists in forests [5]. A typical RFID-based localization scheme attaches tags to objects and locates tagged objects through communication between tags and readers fixed at known locations. Recent advances have evolved from 2-dimensional (2D) localization [6] to 3-dimensional (3D) localization [7], [8], [9], [10], [11], [12].

Most established efforts for RFID-based 3D localization strive for localization accuracy. The necessity of localization accuracy arises from the fact that early localization schemes rely on radio signal strength measurement to estimate distances, which are further used to estimate locations [7]. Radio signal strength measurement is, however, susceptible to coarse-grained accuracy due to various environmental factors (e.g., temperature and humidity) [13]. To get rid of the impact of radio signal strength measurement on localization accuracy, the proposal in [8] deploys reference readers and reference tags at fixed locations. The distance between a tag and a reference reader then approximates that between the reference reader and some reference tags, being independent of radio signal strength measurement. The proposal in [8] can also locate a reader using reference tags. Its follow-up studies further investigate reader-localization accuracy when reference tags activated by the reader do not approximate a circular communication region [9], [10]. There is also another branch of localization scheme hiring additional hardware for gaining accuracy (e.g., phase difference based scheme [11], [12]). Among these accurate localization schemes, of our great interest are those use references readers and reference tags. They are more accurate than the radio signal strength based scheme yet less expensive than the phase difference based scheme [8], [9], [10].

In this paper, we study RFID-based 3D localization from the localization efficiency perspective. To the best of our knowledge, this is the first work identifying the importance and potential of efficient localization. Intuitively, more data from reference tags yield higher localization accuracy. Existing localization schemes therefore collect data from all activated reference tags for optimizing location estimates [8], [9], [10]. We, however, observe that collecting data from more reference tags induces lower localization efficiency.

- Time efficiency measured by the execution time is absolutely a primary victim—The more reference tags to read, the more execution time to take. Time efficiency becomes increasingly important along with the explosive RFID system scale in recent years [14]. Almost all RFID system monitoring operations regard high time efficiency as a primary purpose. Time-efficient RFID solutions have already excelled in, for example, cardinality estimation [15], [16], [17], [18], [19] and information collection [20], [21]. Moreover, only when various monitoring operations achieve high time efficiency can their periodic execution be affordable to large-scale RFID systems.
- Energy efficiency is also of concern when active tags are used as reference tags. Different from passive tags that harvest power from readers' communication signals, active tags leverage self-carried batteries to initiate communication with readers. Energy efficiency is usually measured by the number of tag responses [22], [23], [24]—The more reference tags to read, the more tag responses to induce. High energy efficiency is important for prolonging the lifetime of active tags.

We summarize our proposal for efficient RFID-based 3D localization and its major contributions as follows.

- *Propose probing some instead of collecting all.* We leverage known locations of reference readers and reference tags to probe as a few reference tags as sufficient for localization. Counter-intuitively, localization using fewer reference tags promises rather higher efficiency yet without necessarily sacrificing accuracy.

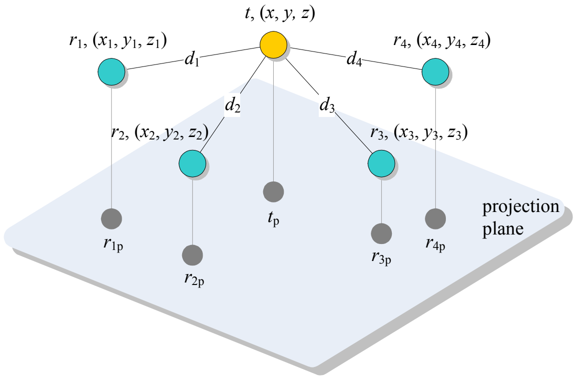

Fig. 1. Basic case of RFID-based 3D localization. The location (x, y, z) of tag t is estimated using distance estimates d_i's from reference readers r_i's, each of which with known location (x_i, y_i, z_i) $(1 \leq i \leq 4)$. (Readers and the tag are projected to a plane for ease of 3D visualization.)

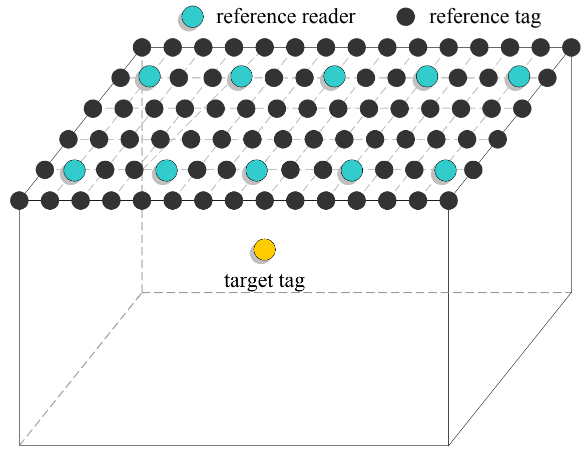

Fig. 2. Passive scheme for RFID-based 3D localization [8].

- *Design efficient passive scheme and efficient active scheme.* We implement the idea of probing some under both typical localization scenarios investigated in previous work [8], [9], [10]—passive scheme for locating a target tag using reference readers and reference tags, and active scheme for locating a target reader using reference tags. Efficient passive scheme and efficient active scheme not only promise higher efficiency than do their counterparts but also requires less computation.
- *Evaluate the proposed efficient schemes through both quantitative analysis and simulation.* The results demonstrate their significant efficiency enhancement over existing localization schemes by more than 95% on average.

The rest of the paper is organized as follows. Section II reviews existing RFID-based 3D localization schemes and demonstrates their limitation in localization efficiency. Section III proposes an efficient localization method by probing only a few activated reference tags rather than collecting all of them as existing localization schemes do. Section IV and Section V implement this method and respectively present efficient passive scheme and efficient active scheme. Section VI reports simulation results. Finally, Section VII concludes the paper and indicates future work.

II. Preliminaries

In this section, we first review RFID-based 3D localization. We then discuss the limitation of existing localization schemes and the potential for making localization more efficient.

A. RFID-based 3D Localization

The pioneer work in RFID-based 3D localization is SpotON [7], a prototype system implemented with the AIR ID product by the RFIDeas company [25]. AIR ID is capable of measuring radio signal strength with multi-bit accuracy. Radio signal strength measurements are then used to estimate distances between readers and tags [26]. Deploying reference readers at known locations, SpotON estimates a tag's location using distance estimates between the tag and multiple reference readers. Figure 1 illustrates a basic case of RFID-based 3D localization using distance estimates d_i's from at least four reference readers to locate tag t [27]. The location estimation (x, y, z) of tag t is usually calculated through least squares fitting [28] as the following:

$$(x, y, z) = \arg \min_{(\overline{x},\overline{y},\overline{z})} \sum_{i=1}^{4} |\overline{d}_i - d_i|^2, \tag{1}$$

where $\overline{d}_i = \sqrt{(\overline{x} - x_i)^2 + (\overline{y} - y_i)^2 + (\overline{z} - z_i)^2}$ represents the calculated distance between the tag with location estimate $(\overline{x}, \overline{y}, \overline{z})$ and reference reader i with known location (x_i, y_i, z_i). Since radio attenuation is susceptible to various environmental factors (e.g., temperature, humidity, and radio blockage) [13], coarse-grained localization accuracy is a long-standing limitation of localization based on radio signal strength measurements [8], [9], [10], [29].

To improve localization accuracy, recent advances in RFID-based 3D localization strive for other means of distance estimation or even get rid of distance estimation [8], [9], [10]. Among them, two representatives are *passive scheme* and *active scheme* [8]; we next briefly introduce their principles.

First, the **passive scheme** (Figure 2) locates a target tag using reference readers and reference tags deployed at known locations on the ceiling or the floor. Distances from the target tag to reference readers are not estimated based on radio signal strength measurements. Instead, the passive scheme exploits tunable transmission power levels of readers (e.g., IDENTEC SOLUTIONS' RFID readers with up to 38 levels [30]). For reference reader r_r to estimate the distance to target tag t_t, r_r reads tags until it reads t_t with transmission power level increased to l. Let T_i $(1 \leq i \leq l)$ denote the set of tags read by r_r at transmission power level i. The distance from t_t to r_r is estimated by averaging distances from r_r to reference tags in $T_l - T_{l-1}$. The passive scheme locates t_t with the location estimate that can minimize the difference between distance estimates and calculated distances (e.g., by Equation 1) [8].

Second, the **active scheme** (Figure 3) locates a target reader using reference tags deployed at known locations on both the ceiling and the floor. Distance estimates from the target reader

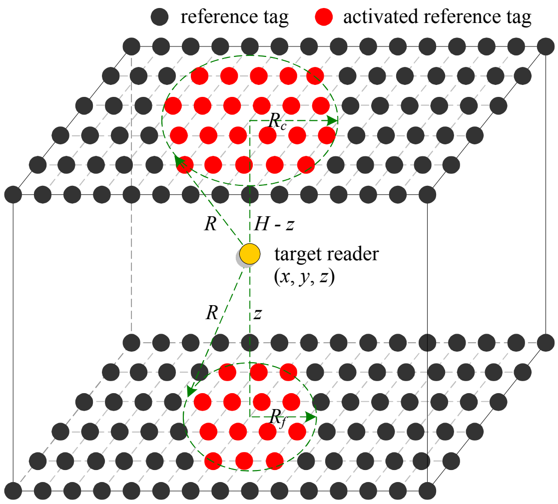

Fig. 3. Active scheme for RFID-based 3D localization [8].

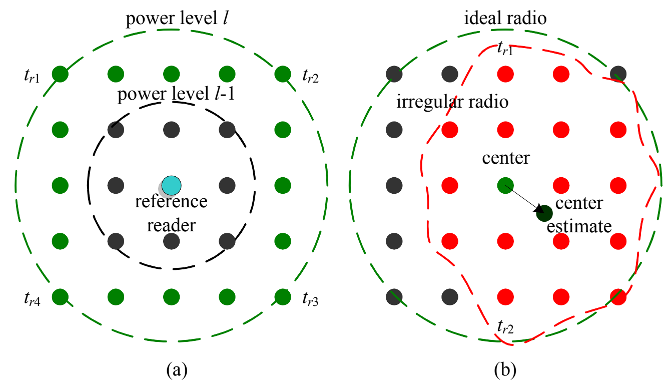

Fig. 4. Examples of more references bringing less accuracy. (a) Biased distance estimation of the passive scheme. (b) Biased center estimation of the active scheme due to radio irregularity.

to reference tags are not necessary. To obtain reference tags' locations, the target reader tunes to a high enough transmission power level for it to activate (read) some tags on the ceiling and some tags on the floor. Let R_c (or R_f) represent the radius of the target reader's communication region on the ceiling (or floor). The active scheme estimates R_c (or R_f) and coordinates x, y in such a way that they can minimize the difference between R_c (or R_f) and calculated radii (i.e., distances between (x, y) and border activated nodes). The active scheme then estimates coordinate z as follows:

$$z^2 + R_f^2 = (H - z)^2 + R_c^2 = R^2$$
$$\Rightarrow z = \frac{R_c^2 - R_f^2 + H^2}{2H},$$

where R represents the target reader's communications radius. The state of the art lies in improving localization accuracy when the target reader's communication region on the ceiling or the floor does not approximate a circular area [9], [10].

Following the dedicated efforts in [8], [9], [10], we are interested in the passive scheme and the active scheme. They are validated to be more accurate than schemes using radio signal strength measurements to estimate distances (e.g., SpotON [7]) and less expensive than schemes using additional hardware to gain accuracy (e.g., phase difference based scheme [11], [12] requiring software-defined radio receivers and additional pan-tilt units) [9].

B. Contaminated Minimum: Sometimes More is Less

Location estimates by the passive scheme and the active scheme minimize the difference between estimated distances and calculated distances. We, however, observe that the minimum is susceptible to contamination. Figure 4 exemplifies such contamination by more references bringing less localization accuracy.

In Figure 4(a), the passive scheme estimates the distance between a reference reader and a target tag using distances between the reference reader and reference tags read at transmission power level l but not $l-1$. Among all such reference tags, only t_{r1}, t_{r2}, t_{r3}, and t_{r4} can be used to nearly approximate the communication radius corresponding to transmission power level l. Incorporating other reference tags into estimation, however, shortens the distance estimate and consequently affects localization accuracy.

In Figure 4(b), the active scheme estimates a target reader's (x, y) coordinates using the center of its communication region on the ceiling (or floor). Due to radio irregularity [13], the communication region does not approximate a circular area. Among activated reference tags within the distorted circle, t_{r1} and t_{r2} nearly form a diameter of the ideal communication region. The midpoint of line segment $\overline{t_{r1}t_{r2}}$ approximates the center by basic geometry knowledge [10]. Using all activated reference tags within the distorted communication region, however, leads to a more biased center estimate.

C. Localization Efficiency: When Less is More

So why not leverage only a few of activated reference tags rather than engage all of them? Having witnessed that fewer references do not necessarily decrease localization accuracy (Figure 4), let us appreciate another treasure they bring, namely localization efficiency. In particular, we concentrate on time efficiency and energy efficiency of RFID-based 3D localization schemes.

First, **time efficiency** rises when a localization scheme requires data from fewer reference tags. Time efficiency is measured by the execution time of a localization scheme—The less execution time a localization scheme takes, the more time efficient it is. Reading data from fewer reference tags yields less execution time and therefore higher time efficiency. The increasing importance of time efficiency is attributed to the explosive RFID system scale in recent years [14]. Almost all protocols for monitoring large-scale RFID systems regard high time efficiency as a primary purpose. Time-efficient RFID protocols have already excelled in, for example, tag identification [31], [32], cardinality estimation [15], [16], [17], [18], [19], information collection [20], [21], missing-tag identification [33], [34], misplaced-tag pinpointing [2],

[3], and cloned-tag identification [35]. Moreover, only when various monitoring protocols achieve high time efficiency can their periodic execution be affordable to large RFID systems.

Second, **energy efficiency** also increases when fewer reference tags are required and active tags are in use. Different from passive tags that harvest power from readers' communication signals, active tags leverage self-equipped batteries to initiate communication with a radius up to hundreds of feet. Since it is well known that transmitting packets costs wireless nodes more energy than listening to (or receiving) queries [13], energy efficiency of protocols adopting active tags is usually measured by the number of tag responses [22], [23], [24]. For our interested localization scheme, the fewer tag responses it requires, the more energy efficient it is. Reading data from fewer active tags brings fewer tag responses and thus higher energy efficiency. High energy efficiency is desired to prolong the lifetime of RFID systems using active tags, especially when battery recharge or replacement is difficult [23].

Motivated by these efficiency potentials, we aim to design efficient RFID-based 3D localization schemes that require data from fewer reference tags than do traditional passive scheme and active scheme. Following pioneer efficient designs in the aforementioned RFID research areas (e.g., cardinality estimation [15], [16], [17], [18], [19] and information collection [20], [21]), we concentrate primarily on time efficiency and energy efficiency. Note that computation efficiency might be another favorable side product since data from fewer reference tags require less computation for estimating locations. We will investigate more on computation efficiency in our future work.

III. Methodology Overview: Probing Some Instead of Collecting All

The idea for efficient localization using fewer references is *probing some instead of collecting all*. More specifically, its principle is probing as a few reference tags as sufficient for the passive scheme to estimate the distance between a target tag and a reference reader, or for the active scheme to estimate the center of a target reader's on-ceiling (or on-floor) communication region. To probe reference tags of interest, we leverage the knowledge of reference readers and reference tags such as their IDs and fixed locations. We preview that reference tags to be probed are that lay on the same radius in the passive scheme and that are concyclic in the active scheme. Before delving into the design details, we first demonstrate the feasibility of probing some for localization.

Let us again consider Figure 4 as an illustrative example. In Figure 4(a), armed with locations of a subset of reference tags activated at transmission power level l but not $l-1$, the passive scheme can still estimate the reference reader's communication radius at transmission power level l. It clearly costs less time (and energy if active tags are in use) than collecting responses from all activated reference tags. When the probed reference tags are among t_{r1}, t_{r2}, t_{r3}, and t_{r4}, the passive scheme yields the closest estimate of the communication radius (Section II-B). For the passive scheme, probing some therefore promises enhanced localization efficiency yet without necessarily decreasing localization accuracy. We further investigate whether this benefit applies to the active scheme. In Figure 4(b), the active scheme collects responses from all activated reference tags to estimate the center of the communication region. However, only some of the activated reference tags, say the peripheric ones, are sufficient for estimating the center of the communication region they confine. A relatively extreme case is when the probed reference tags are t_{r1} and t_{r2} and the midpoint of line segment $\overline{t_{r1}t_{r2}}$ approximates the center (Section II-B). Since peripheric activated reference tags are no more than all activated ones, probing some promises localization efficiency to the active scheme as well.

Toward efficient RFID-based 3D localization, we propose lightweight implementations of probing some for both the passive scheme and the active scheme. We next present the design details of *efficient passive scheme* (Section IV) and *efficient active scheme* (Section V). We will demonstrate by analysis and simulation their efficiency advances over traditional localization schemes.

IV. Efficient Passive Scheme

In this section, we present the efficient passive scheme that probes only a subset of activated reference tags for locating target tags. We investigate localization efficiency of the efficient passive scheme through an analytical comparison with the traditional passive scheme.

A. Design of Efficient Passive Scheme

The primary design difference between the efficient passive scheme and the traditional passive scheme lies in how they estimate distances from target tags to reference readers. As we discussed in Section II-A, the traditional passive scheme collects data from all activated reference tags. In contrast, the efficient passive scheme probes only some of them. As we will show in Section IV-B and Section IV-C, the passive scheme can consequently reduce reading load by $1-\frac{1}{\pi r\sqrt{\rho}}$ and increase localization efficiency by $1-\frac{1}{e\pi r\sqrt{\rho}}$, where e is the natural constant, r denotes the communication radius of a reference reader, and ρ denotes the reference-tag density. Since the efficient passive scheme and the traditional passive scheme adopt the same location computation algorithm using distance estimates, we next detail only the design of distance estimate by the efficient passive scheme.

In the efficient passive scheme, a reference reader achieves distance estimation by leveraging known locations of its neighboring reference tags. Without loss of generality, reference readers and reference tags are d-meter spacing in a $p_r \times p_c$ grid topology, including n_r reference readers and $n_t = p_r p_c - n_r$ reference tags. It takes reference reader r_r two stages to estimate the distance to target tag t_t. In the first stage, r_r determines the minimum power level l to read t_t. In the second stage, r_r estimates the communication radius at power level l and regards the radius as the distance estimate.

Stage I: Power level determination. To achieve this, r_r queries t_t by its tag ID with gradually increased power level.

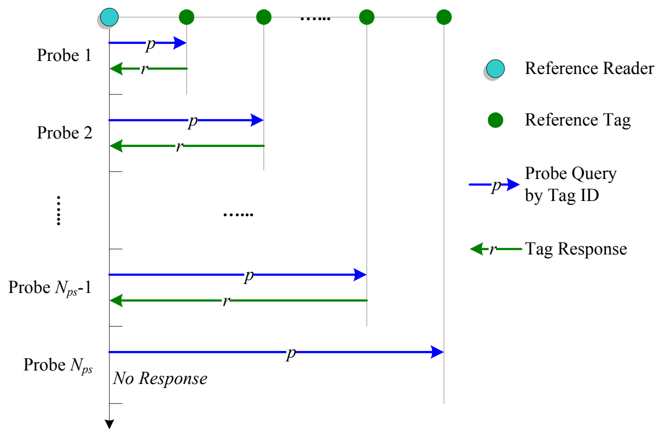

Fig. 5. Efficient passive scheme for RFID-based 3D localization.

When the power level is not high enough, neither t_t can hear the query nor r_r can receive any response. Power level l is therefore determined by the first power level for r_r to receive t_t's response. Stage I costs l time slots and only one tag response from t_t. Recall that the traditional passive scheme collects responses from all activated reference tags at each power level up to l.

Stage II: Distance estimation. The distance from r_r to t_t is estimated as the communication radius at power level l. Figure 5 illustrates how the efficient passive scheme estimates the communication radius. r_r first chooses some co-row (or co-column) neighboring reference tags using the knowledge of their known locations[1]. r_r then probes its neighboring reference tags by tag IDs at power level l, starting from the nearest one (e.g., Probe 1 in Figure 5). If r_r can receive a tag response, its communication radius at power level l is longer than the distance between it and the probed reference tag. r_r continues to probe further neighboring reference tags at power level l until it cannot receive a response from the probed reference tag (e.g., Probe N_{ps} in Figure 5). The communication radius is longer than the distance from r_r to the $(N_{ps}-1)$th probed reference tag while shorter than the distance from r_r to the N_{ps}th probed reference tag. The efficient passive scheme accordingly approximates the distance between reference reader r_r and target tag t_t as the following:

$$d_{eps} = \frac{(N_{ps}-1)d + N_{ps}d}{2} = (N_{ps} - \frac{1}{2})d. \qquad (2)$$

The distance estimation error by Equation 2 is upper bounded by $\frac{d}{2}$ because $(N_{ps}-1)d \leq d_{eps} \leq N_{ps}d$.

B. Analysis of Reading Load

We investigate the number of reference tags for the reference reader to read in Stage II. As aforementioned, Stage I of the efficient passive scheme requires only one tag response while Stage I of the traditional passive scheme collects responses from all activated reference tags at each power level below l. The number of reference tags for the traditional passive scheme to read in Stage I therefore depends on the specific value of l. To better quantify reading load, we focus on only Stage II in the following analysis and take Stage I into account by simulation in Section VI.

The traditional passive scheme requires the reference reader to read all activated reference tags within its communication region. Let r represent the communication radius (in meters) at power level l. Let ρ represent the reference-tag density (measured by the number of reference tags per square meters). We estimate ρ as the ratio of the number n_t of reference tags to the area of the grid topology:

$$\rho = \frac{n_t}{(p_r-1)(p_c-1)d^2} = \frac{p_r p_c - n_r}{(p_r-1)(p_c-1)d^2}. \qquad (3)$$

We then estimate the number N_{ca} of reference tags (for collecting all) within the r-radius communication region as the following:

$$N_{ca} = \pi r^2 \rho.$$

As we will show, the efficient passive scheme promises a significant reading-load reduction for Stage II. By the efficient passive scheme design, the reference reader chooses a line of d-spacing tags to probe at power level l (Figure 5). Once the reference reader finds the furthest tag that it can probe, communication radius r at power level l approximates the distance between the reader and the tag. The number N_{ps} of reference tags (for probing some) is therefore

$$N_{ps} = \frac{r}{d} \approx r\sqrt{\rho}.$$

The approximation uses Equation 3 and the knowledge that p_r, p_c are relatively large and $n_t = p_r p_c \gg n_r$ [8]:

$$\rho = \frac{p_r p_c - n_r}{(p_r-1)(p_c-1)d^2} \approx \frac{1}{d^2} \Rightarrow d \approx \frac{1}{\sqrt{\rho}}.$$

This complies also with the intuition that the higher the reference-tag density, the smaller the spacing interval. By now, we can deduce a favorable relation of N_{ca} and N_{ps}:

$$N_{ca} = \pi N_{ps}^2 \Leftrightarrow N_{ps} = \sqrt{\frac{N_{ca}}{\pi}}. \qquad (4)$$

To visualize the gap between N_{ca} and N_{ps}, Figure 6(a) plots them (respectively marked by "collect all" and "probe some") with varying radius r and density ρ. The gap widens as r and ρ increase and it becomes sharp when r and ρ are relatively large. Figure 6(b) quantifies the gap using the ratio of reading-load reduction:

$$\frac{N_{ca} - N_{ps}}{N_{ca}} = 1 - \frac{1}{\pi r \sqrt{\rho}}.$$

From the statistics in Figure 6(b) we can observe that the ratio of reading-load reduction increases sharply with r and ρ. Even when r and ρ are small enough (e.g., $r = \rho = 1$), the reduction ratio is as high as 68 percent.

[1]Reference reader r_r can fetch these locations from the server when necessary or store them by itself if sufficient memory is available.

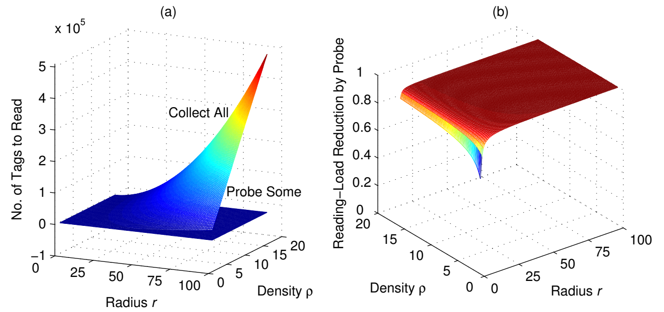

Fig. 6. Reading-load comparison of the traditional passive scheme (collecting all) and the efficient passive scheme (probing some) with varying communication radius r and reference-tag density ρ. (a) Number of tags to read. (b) Reading-load reduction by probing some.

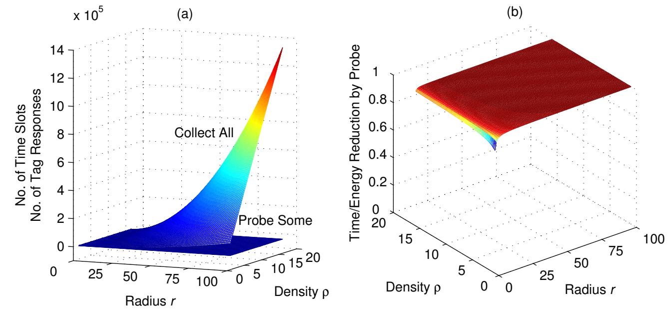

Fig. 7. Localization efficiency comparison of the traditional passive scheme (collecting all) and the efficient passive scheme (probing some) with varying communications radius r and reference-tag density ρ. (a) Number of time slots and of tag responses. (b) Time/energy reduction by probing some.

C. Analysis of Localization Efficiency

We now investigate efficiency improvement by the reading-load reduction in Stage II. Both time efficiency and energy efficiency are of interest, measured by the execution time and the number of tag responses, respectively (Section II-C). Using a typical communication protocol called *Slotted Aloha* [36], a reader informs tags to randomly respond in a frame of time slots. In a time slot, only when only one tag responds can the reader successfully receive the tag response; otherwise multiple responses cause a collision. When the number of time slots in a frame is set to the number of tags to read, slotted Aloha achieves the highest efficiency of $\frac{1}{e}$ [36]. We accordingly derive the number N_{ca}^{ts} of time slots and the number N_{ca}^{tr} of tag responses for collecting data from all N_{ca} tags as follows:

$$\begin{aligned} N_{ca}^{ts} = N_{ca}^{tr} &= N_{ca} + (1-\frac{1}{e})N_{ca} + (1-\frac{1}{e})^2 N_{ca} + \cdots \\ &\approx eN_{ca} = e\pi r^2 \rho. \end{aligned}$$

As to the number N_{ps}^{ts} of time slots and the number N_{ps}^{tr} of tag responses for probing N_{ps} tags, it is straightforward that

$$N_{ps}^{ts} = N_{ps}^{tr} = N_{ps} = r\sqrt{\rho}.$$

Similar to Equation 4, we can deduce the following relation to capture the gap between localization efficiency of collecting all and of probing some:

$$\begin{aligned} N_{ca}^{ts} = N_{ca}^{tr} = e\pi (N_{ps}^{ts})^2 = e\pi (N_{ps}^{tr})^2 \\ \Leftrightarrow N_{ps}^{ts} = N_{ps}^{tr} = \sqrt{\frac{N_{ca}^{ts}}{e\pi}} = \sqrt{\frac{N_{ca}^{tr}}{e\pi}}. \end{aligned}$$

For ease of comprehension, Figure 7 illustrates the efficiency comparison with varying communication radius r and reference-tag density ρ. Specifically, Figure 7(a) plots the efficiency; Figure 7(b) quantifies time/energy reduction using

$$\frac{N_{ca}^{ts} - N_{ps}^{ts}}{N_{ca}^{ts}} = \frac{N_{ca}^{tr} - N_{ps}^{tr}}{N_{ca}^{tr}} = 1 - \frac{1}{e\pi r\sqrt{\rho}}.$$

We observe that the reduction ratio sharply increases with r and ρ, leaping from 88 percent at $r = \rho = 1$.

V. Efficient Active Scheme

In this section, we present the efficient active scheme that probes only a subset of activated reference tags for locating target readers. We demonstrate its superior localization efficiency compared with the traditional active scheme by analysis.

A. Design Challenge

The design challenge for active scheme arises when on-ceiling (or on-floor) communication regions of target readers do not fully reside in the tagged area [8], [9], [10]. More specifically, when a target reader locates near a wall or a corner, activated reference tags are likely to confine only a part of the communication region. The communication region's center is thus harder to be accurately estimated than it is when activated reference tags confine near complete communication regions (Figure 3). Reference [10] analyzes the impact of incomplete communication regions on center estimation accuracy. Against the impact, reference [9] proposes expanding an incomplete communication region by reflecting activated reference tags to virtual tags. It then iteratively refines center estimate based on expanded communication region.

Of our interest is that no matter whether existing active schemes incorporate countermeasures against the above challenge, they need to collect data from all activated reference tags. The efficient active scheme to be proposed can, however, address the challenge yet with probing only some of activated reference tags.

B. Design of Efficient Active Scheme

We build the efficient active scheme upon a basic geometry knowledge that three nodes confine the center of their circumscribed circle [37]. By this knowledge, the efficient active schemes requires locations of only three activated reference tags close to the communication region's circumference for center estimation. It therefore no longer depends on complete communication region for accurate localization. To find three concyclic reference tags, the efficient active scheme first finds a *starting tag*. The target reader initiates a slotted Aloha frame and immediately terminates the frame upon receiving the first intact ID of a reference tag, which is regarded as the starting

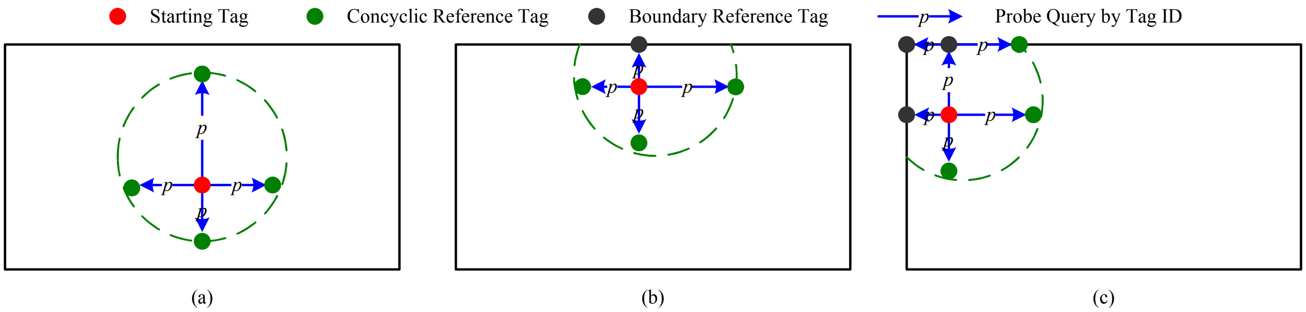

Fig. 8. Efficient active scheme for RFID-based 3D localization. (a) Complete communication region. (b) Incomplete communication region by wall. (c) Incomplete communication by corner.

tag. The target reader then continues to find three concyclic reference tags by probing.

As shown in Figure 8, the probe follows both horizontal and perpendicular directions in three cases: complete communication region (Figure 8(a)), incomplete communication region by wall (Figure 8(b)) or by corner (Figure 8(c))[2]. The specific probe process is similar to that illustrated in Figure 5. In the cases shown in Figure 8(a) and Figure 8(b), horizontal and perpendicular probes from the starting tag can find at least three concyclic reference tags. The same probe procedure, however, brings only two concyclic reference tags to the case in Figure 8(c). We address this issue by choosing a boundary reference tag as the new starting tag. Subsequent probes from the new starting tag help find the third reference tag close to the circumference of communication region.

Let (x_i, y_i) for $i = 1,\ 2,\ 3$ represent (x, y) coordinates of the three concyclic reference tags. We can compute the (x, y) coordinate of the center as follows [38]:

$$x_c = \frac{\alpha_1(y_2 - y_3) + \alpha_2(y_3 - y_1) + \alpha_3(y_1 - y_2)}{\beta},$$
$$y_c = \frac{\alpha_1(x_3 - x_2) + \alpha_2(x_1 - x_3) + \alpha_3(x_2 - x_1)}{\beta},$$

where

$$\alpha_1 = x_1^2 + y_1^2,\ \alpha_2 = x_2^2 + y_2^2,\ \alpha_3 = x_3^2 + y_3^2,$$
$$\beta = 2(x_1(y_2 - y_3) + x_2(y_3 - y_1) + x_3(y_1 - y_2)).$$

Based on (x_c, y_c), the efficient active scheme derives the target reader's x- and y-axis coordinates and then computes its z-axis coordinate the same as the traditional active scheme does.

C. Analysis of Localization Efficiency

Reading load. We first investigate the number N_{ca} of reference tags (for collecting all) in the communication region. Without loss of generality, reference tags are d-meter spacing in a $p_r \times p_c$ grid topology. The reference-tag density ρ is

$$\rho = \frac{p_r p_c}{(p_r - 1)(p_c - 1)d^2} \approx \frac{1}{d^2} \Leftrightarrow d = \frac{1}{\sqrt{\rho}}.$$

Let r represent the radius of the communication region. Let φ represent the ratio of the communication region on tagged area. We have $\frac{1}{4} < \varphi \leq 1$ by Figure 8—$\varphi = 1$ in the case of complete communication region (Figure 8(a)) and φ is about $\frac{1}{4}$ when the target reader is close to a corner (Figure 8(c)). The number of reference tags in the communication region is

$$N_{ca} = \varphi \pi r^2 \rho.$$

We now investigate the number N_{ps} of reference tags for probing some by the efficient active scheme. We observe from Figure 8 that N_{ps} is less than the number of reference tags on three diameters. We thus derive N_{ps} as the following:

$$N_{ps} < 3 \times \frac{2r}{d} = \frac{6r}{d} = 6r\sqrt{\rho}.$$

The active scheme yields lower reading load than does the traditional active scheme when $\frac{N_{ca}}{N_{ps}} > \frac{\varphi \pi r \sqrt{\rho}}{6} \geq 1$.

Localization efficiency. We derive localization efficiency using N_{ca} and N_{ps}. For the traditional active scheme, the number N_{ca}^{ts} of time slots and the number N_{ca}^{tr} of tag responses for collecting data from all N_{ca} tags are as the following:

$$N_{ca}^{ts} = N_{ca}^{tr} = eN_{ca} = \varphi e \pi r^2 \rho.$$

For the efficient active scheme, the number N_{ps}^{ts} of time slots and the number N_{ps}^{tr} of tag responses for probing N_{ps} tags are as the following:

$$N_{ps}^{ts} = N_{ps}^{tr} = N_{ps} < 6r\sqrt{\rho}.$$

The active scheme yields higher localization efficiency than does the traditional active scheme when $\frac{N_{ca}^{ts}}{N_{ps}^{ts}} = \frac{N_{ca}^{tr}}{N_{ps}^{tr}} > \frac{\varphi e \pi r \sqrt{\rho}}{6} \geq 1$.

Since localization efficiency of active schemes depends on specific scenarios in Figure 8, we compare the efficient active scheme and the traditional active scheme by simulation in Section VI. The results demonstrate that the conditions for the efficient active scheme to be more efficient than the traditional active scheme can be easily satisfied.

VI. Performance Evaluation

In this section, we evaluate the performance of the proposed efficient RFID-based 3D localization schemes by simulation. To demonstrate their contributions to enhancing localization efficiency, we compare the efficient passive scheme against the traditional passive scheme [8], [9] and the efficient active scheme against the traditional active scheme [8], [9], [10].

[2]For ease of understanding, we consider average case that the starting tag is not close to the circumference of communication region. We can easily adapt the design to other special cases by simply re-finding the starting tag.

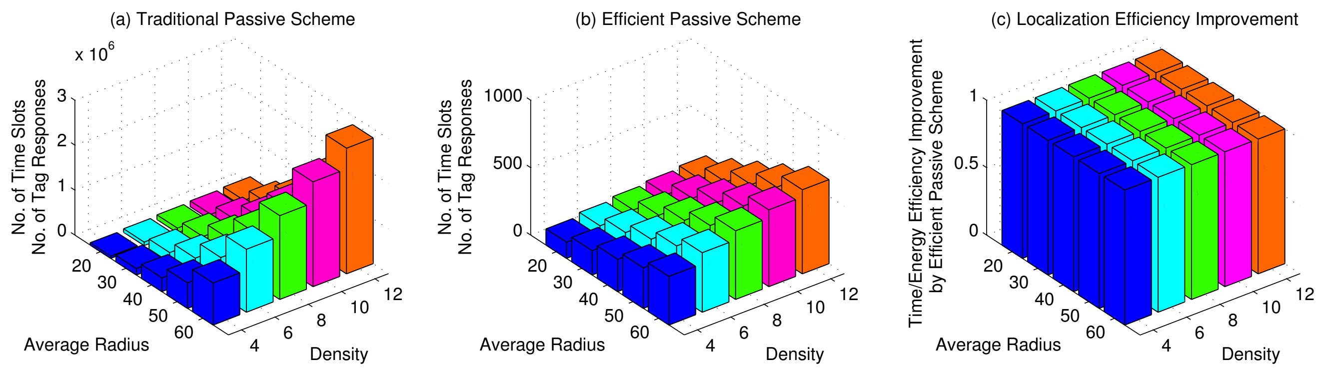

Fig. 9. Localization efficiency comparison of the traditional passive scheme and the efficient passive scheme.

We evaluate primarily localization efficiency of the proposed efficient localization schemes and of their counterparts[3]. As we discussed in Section II-C, localization efficiency of interest consists of time efficiency and energy efficiency. Performance metrics for measuring time efficiency and energy efficiency are the execution time of a localization scheme and the number of tag responses it requires, respectively. Following existing work [8], [9], [10], we adopt slotted Aloha [36] for simulating the RFID communication. In most time slots, the traditional passive/active scheme collects tag IDs from reference tags and the efficient passive/active scheme broadcasts a tag ID to probe a reference tag. We thus simply equate the average duration of a time slot in both types of localization schemes and boil the execution time down to the number of time slots. By the analysis in Section IV-B, Section IV-C, and Section V-C, we can further approximate the average number of time slots to the average number of tag responses. For simplicity, we therefore report statistics on both numbers together as how we report in Figure 7.

A. Evaluation of Efficient Passive Scheme

We first evaluate localization efficiency of the efficient passive scheme in comparison with the traditional passive scheme. When implementing passive localization schemes, we leverage an implicit constraint that reference tags cannot locate lower than the floor or higher than the ceiling [2], [3]. Distances to three reference readers are thus sufficient for 3D localization of a target tag. For ease of comparison with existing work [8], [9], we follow a single–target-tag scenario investigated therein. We randomly distribute the target tag throughout the system and run both traditional and efficient passive scheme for localization. We set 10-meter communication radius variation per power level adjustment.

Figure 9 reports localization efficiency of the traditional passive scheme and the efficient passive scheme with varying average communication radius and reference-tag density. The average communication radius refers to the average of radii of three reference readers for locating the target tag. We make three observations on the reported statistics. Figures 9(a) and (b) indicate that—First, given a certain average communication radius, time/energy cost of both the traditional passive scheme and the efficient passive scheme linearly grows with the reference-tag density; second, given a certain density, time/energy cost of the traditional passive scheme grows faster than that of the efficient passive scheme as the radius increases. Third, time/energy cost of the efficient passive scheme is rather less than that of the traditional passive scheme—As Figure 9(c) illustrates, the efficient passive scheme enhances localization efficiency over 95% on average.

[3]Due to the limit of the space, we omit reporting statistics of localization accuracy to avoid distracting interested readers from immersion in localization efficiency. We would like to refer interested readers to Section II-B and Section III for why the proposed efficient localization schemes do not necessarily trade accuracy for efficiency.

B. Evaluation of Efficient Active Scheme

We now evaluate localization efficiency of the efficient active scheme in comparison with the traditional active scheme. The configuration for evaluating active localization schemes is similar with that for evaluating passive localization schemes. Figure 10 reports localization efficiency of the traditional active scheme and the efficient active scheme with varying average communication radius and reference-tag density. The average communication radius refers to the average of radii of the target reader's on-ceiling and on-floor communication regions. The variation trend of their time/energy cost with the radius and density is similar with that of passive schemes' time/energy cost. From Figures 10(a) and (b) we easily observe that the efficient active scheme yields rather less time/energy cost than does the traditional active scheme. As shown in Figure 10(c), localization efficiency improvement by the efficient active scheme is over 95% on average.

VII. Conclusion and Future Work

We have studied efficient RFID-based 3D localization. Different from existing schemes that concentrate primarily on localization accuracy, we take the first step toward designing localization schemes from the efficiency perspective. We propose leveraging known locations of deployed reference readers and reference tags to directly probe a few reference tags for localization. Counter-intuitively, localization using fewer reference tags promises rather higher efficiency yet without necessarily sacrificing accuracy. We design both efficient passive scheme and efficient passive scheme respectively for two typical 3D localization scenarios, locating a target tag using reference readers/tags and locating a target reader using reference tags.

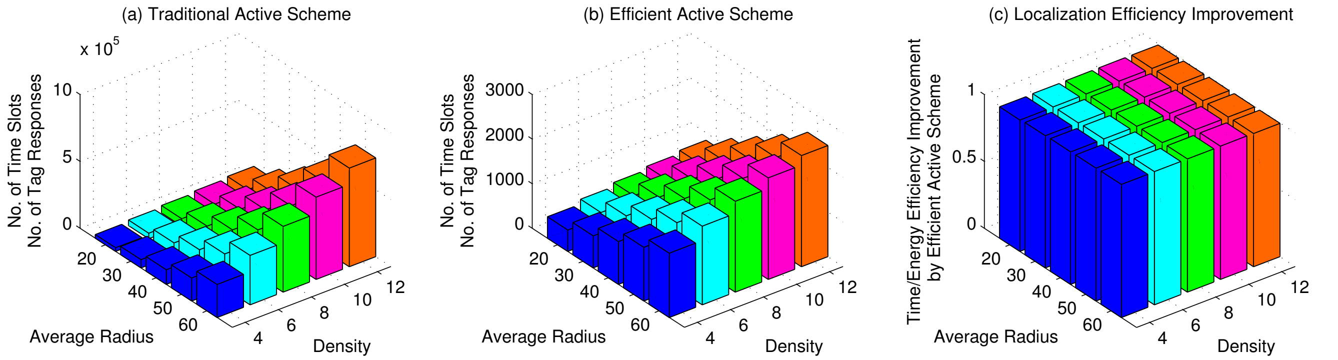

Fig. 10. Localization efficiency comparison of the traditional active scheme and the efficient active scheme.

We demonstrate their significant efficiency enhancement over existing schemes through both quantitative analysis and extensive simulation. Their favorable time efficiency and energy efficiency can benefit RFID systems with fast localization operation and prolonged system lifetime. Future work lies in empirical evaluation of the efficient localization schemes [39] and applying them to misplacement pinpointing [2], [3] and activity sensing [40], [41].

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