Focus and Shoot: Efficient Identification over RFID Tags in the Specified Area

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Abstract. In RFID systems, the reader usually identifies all the RFID tags in the interrogation region with the maximum power. However, some applications may only need to identify the tags in a specified area, which is usually smaller than the reader's default interrogation region. In this paper, we respectively present two solutions to identify the tags in the specified area. The principle of the solutions can be compared to the picture-taking process of a camera. It first focuses on the specified area and then shoots the tags. The design of the two solutions is based on the extensive empirical study on RFID tags. Realistic experiment results show that our solutions can reduce the execution time by 46% compared to the baseline solution.
Key words: RFID, tag identification, experimental study, algorithm design

1 Introduction

RFID systems have been widely used in various applications, such as inventory control, sampling inspection, and supply chain management. Conventionally, an RFID system consists of one or multiple readers, and a larger number of tags. Each tag is attached to a physical item and has a unique ID describing the item. The reader recognizes the object by identifying its attached tag.

In recent years, many existing research works have concentrated on RFID tag identification, aiming to identify a large number of tags efficiently [1][2][3][4]. Instead of identifying all the tags, detecting the missing tags [5][6] and searching a particular subset of tags [7] only concern the part of tags. Rather than tag identification, cardinality estimation protocols count the number of tags [8][9][10]. However, all the literature do not research the problem of tag identification in a specified area, which is rather important in many applications. Taking the inventory for example, we may only need to identify the tags in some specified boxes while ignoring the others. Sometimes, it is difficult to move the objects out for tag identification, especially for the objects obstructed by obstacles. A traditional solution is to identify the tags with the maximum power. It may identify the tags out of the area, which is rather time-consuming. Due to the large number of tags, the time-efficiency is very important. Therefore, it is essential to identify the tags in the specified area efficiently without moving the tags.

Fortunately, we note that tag identification in the specified area can be compared to the picture-taking process in a camera. The camera needs to focus on the object before shooting, aiming to lock the target object while ignoring the others. In this paper, we propose the photography based identification method, which works in a similar way. It first focuses on the specified area by adjusting the antenna's angle and the reader's power, and then identifies the tags in the area. However, efficiently identifying the tags in the realistic environments is difficult. The reading performance in the realistic experiments is still unknown, especially for a large number of tags. There are a few research works concentrating on this problem and they mainly work in a situation close to free space [11][12][13]. Hence, we conduct a series of measurements over RFID tags in realistic settings. Based on the extensive experimental study, we respectively propose two solutions, aiming to identify the tags in the specified area efficiently. The solutions work in the realistic environments and conform to the EPC-C1G2 standards.

We make the following contributions in this paper. (1) We conducted extensive experiments on the commodity RFID system in the realistic environments and investigated the factors affecting the reading performance. (2) To the best of our knowledge, this is the first work investigating the efficient tag identification in the specified area, which is essential for many applications. We propose the photography based identification method, which works in a similar way as in a camera. Besides, we respectively propose two solutions to solve the problem, which can reduce the execution time by 46% compared to the baseline solution. (3) Our solutions work in the realistic environments with the commercial RFID system, which conforms to the EPC-C1G2 standards.

2 Problem Formulation

2.1 System Model

Each object is attached with an RFID tag, which has a unique ID. In this paper, we use the terms 'object', 'tag' interchangeably. The number of tags and the distribution of tag IDs are unknown. The reader is statically deployed and configured with an antenna. The antenna is associated with an interrogation region, within which the reader can identify the tags. The antenna is deployed in a fixed position. It cannot change its distance to the objects, but it is rotatable. The reader can control the interrogation region by adjusting the power.

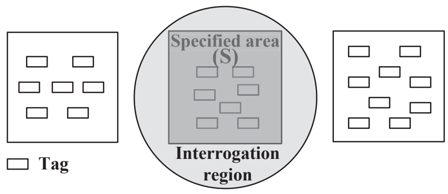


Fig. 1. Identify the tags in the specified area

The objects are packaged in boxes. The boxes out of the specified area S has reasonable distances between the boxes in S, which means that the area S has a clear boundary. As shown in Fig. 1, the tags in S are called as *target tags*, while the tags outside S are called as *interference tags*. The objective of this paper is to identify as many *target tags* as possible while minimizing the execution time.

2.2 Performance Metrics

We consider the three performance metrics for evaluating the solution's efficiency.

1) *Coverage ratio ρ constraint*: Let S be the set of tags in S (target tags), $s = |S|$. Let M be the set of the tags that are identified in S, $m = |M|$. Obviously, $M \subseteq S$ and $m \leq s$. Then, $\rho = \frac{m}{s}$, $0 \leq \rho \leq 1$. The larger the value of ρ, the better the coverage ratio. Given a constant α, ρ should satisfy $\rho \geq \alpha$. α is related to the specific scenario, when the environment and the deployment of the RFID system are fixed, the value of α can be determined.

2) *Execution time T*: It represents the duration of the whole process. It shows the time efficiency, which is rather important, especially for the identification of a large number of tags. The smaller the time T, the better the time efficiency.

3) *Misreading ratio λ*: Let U be the set of tags out of S (interference tags) that are identified, $u = |U|$, $U \cap S = \emptyset$. Then, $\lambda = \frac{u}{u+m}$. The smaller the value of λ, the lower the misreading ratio.

The objective of this paper is to minimize the execution time T, while the coverage ratio satisfies $\rho \geq \alpha$. When $\rho \geq \alpha$, minimizing T means avoiding identifying the *interference tags*, in order to reduce the identification time. There is no constraint on λ, which is related to T. However, for the same execution time, the lower the misreading ratio, the better the performance of a solution.

3 Observations From the Realistic Experiments

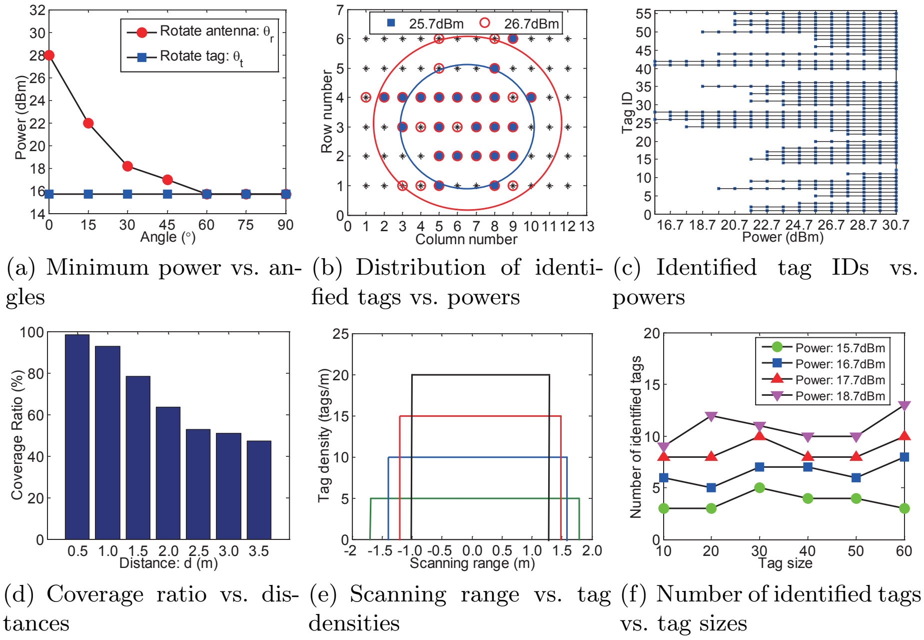
In order to know the factors affecting the reading performance in the realistic environments, we conduct the following experiments. We use the Alien-9900+ reader and Alien-9611 antenna. The reader's maximum power $maxP_w$ is 30.7dB-m and its minimum power $minP_w$ is 15.7dBm. The RFID tag is Alien 9640 tag. Each tag is attached into a distinct book. The antenna and the books are placed on the tablet chairs with a height of 0.5m. Unless otherwise specified, we make the antenna face towards the center of the objects, set the reader's power $P_w = 30.7$dBm, the distance between the tags and the antenna $d = 1$m by default. For each experiment, the reader scans the tags for 50 cycles.

3.1 Identify the tag at different angles

As the angle between the radiation direction and the surface of the antenna deceases, the reading performance deceases. However, when a tag is located in the center of the interrogation region, it can be identified efficiently. We observe the minimum power $P_{w_{min}}$ needed to activate one tag. We use θ_r to represent the angle between the antenna's radiation direction and the antenna's surface, $\theta_r \in [0°, 90°]$. In the first experiment, we rotate the antenna to change θ_r while keeping the tag unchanged. Fig. 2(a) shows that as θ_r decreases, $P_{w_{min}}$ becomes larger. In the second experiment, we rotate the tag while keeping the antenna unchanged. We use θ_t to represent the angle between the radiation direction and the tag's surface. Fig. 2(a) shows that the tag is easily identified, whatever θ_t is. Therefore, making the antenna face towards the tags ($\theta_r = 90°$) is essential for improving the reading performance.

3.2 Adjust the reader's power

The larger the reader's power, the larger the interrogation region, but the new identified tags may not be located in the interrogation region's boundary. However, if a tag can be identified with a low power, it must be identified with a larger *power.* We uniformly deploy 72 tags on the wall and the distance between two adjacent tags is 20cm, as shown in Fig. 2(b).The new identified tags may not be in the interrogation region's boundary. We cannot distinguish a tag's position only by adjusting the power. In regard to a tag, Fig. 2(c) shows that if a tag can be identified with a low power, then it definitely can be identified by a larger power. Usually, the large power can increase the number of identified tags.



(a) Minimum power vs. angles
(b) Distribution of identified tags vs. powers
(c) Identified tag IDs vs. powers
(d) Coverage ratio vs. distances
(e) Scanning range vs. tag densities
(f) Number of identified tags vs. tag sizes

Fig. 2. Observations from the realistic experiments

3.3 Vary the distance between the tags and the antenna

As the distance between the tags and the antenna increases, the reading performance decreases. Besides, when the distance is fixed, the maximum coverage ratio has an upper bound, whatever the reader's power is. We vary the distance d from 0.5m to 3.5m. Fig. 2(d) shows as d becomes larger, the number of identified tags decreases. When the distance is small (eg. $d \leq 1.5$m), the reading performance is relatively good. However, when the distance and the number of tags are fixed, the coverage ratio has an upper bound. For example, when $d = 1.5$m and $n = 55$, the maximum coverage ratio is 78%. Fortunately, some applications (eg. sampling inspection) just needs the coverage ratios meet the constraint instead of achieving 100%. However, when considering the high coverage ratio, the antenna should not be placed far away from the tags.

3.4 Effect of the tag size

The tag size can affect the effective interrogation region. However, it has little effect on the number of identified tags. We uniformly deploy the tags in a row with length 4m and vary the number of tags (20, 40, 60, 80). As shown in Fig. 2(e), given a fixed power (30.7dBm), as the tag size increases, the effective interrogation region decreases. Therefore, when the tag size in the specified area (tag density) is unknown, we can not calculate the interrogation region accurately. However, if we only want to identify a few tags (eg. for sampling), we can choose an estimated power, because the tag size has little effect on the number of identified tags, as shown in Fig. 2(f).

4 Baseline Solutions

In order to identify the *target tags* in the specified area S, while ignoring the *interference tags*, we should focus on S and identify as many *target tags* as possible. As mentioned in 3.2, the larger the reader's power, the larger the interrogation region. If we want to focus on the area S, we should use a lower power. On the contrary, if we want to identify more tags, we should use a larger power. Therefore, scanning with the minimum power and the maximum power are two baseline solutions, which are respectively called as MinPw and MaxPw.

However, if the reader's power is too small, the interrogation region cannot cover the specified area, leading to the low coverage ratio. Besides, it needs to rotate the antenna to identify more tags with multiple scans, which is rather time-consuming. If the reader's power is too large, the interrogation region may be too large, leading to the identification of the *interference tags*. It increases the time cost and the misreading ratio. Therefore, it is important to use a reasonable power to identify the tags in the specified area.

5 Photography based Identification with Distance Measurement

In this section, we propose a solution called Photography based tag Identification with Distance measurement (PID), which works with a 3D camera (eg. a Kinect). The process of PID can be compared to the picture-taking process in a camera. It focuses on the area and shoot the objects, as shown in Fig. 3. The application appoints the specified area S and the middleware collects the tag IDs in S by the RFID systems. It consists of focus module and shoot module. The focus module adjusts the reader's power and rotates the antenna to make the interrogation region focus on S. The shoot module collects tag IDs. The two corresponding process are respectively called as *Focusing Process* and *Shooting Process*.

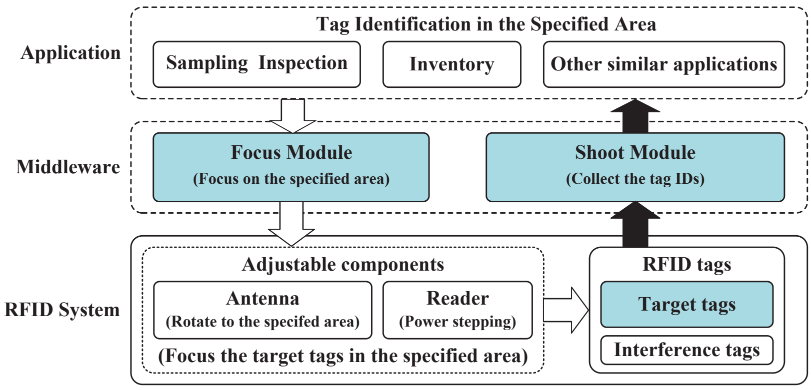


Fig. 3. The Framework of PID

5.1 Focusing Process

The focusing process aims to adjust the interrogation region to be focused on the specified area S by adjusting θ_r, P_w, while ignoring the tags outside S. It contains three phases, selecting the initial power, establishing the boundary and power stepping. The process aims to get the optimal power P_w^*, whose corresponding interrogation region is just enough to cover the area S.

Selecting the Initial Power Before the reader identifies the tags, it selects the initial power instead of the default (maximum) one to control the interrogation region. In RFID systems, the reader's interrogation region of an antenna is like an ellipsoid. The larger the angle θ_r between the radiation direction and the antenna's surface, the longer the reader's scanning range. However, in the realistic environment, the tag size, the reader's power P_w, the radiation angle θ_r, and the distance d all affect the effective interrogation region, as mentioned in section 3. Therefore, in the realistic environments, we measure the minimum power $P_{w_{min}}$ based on θ_r and d, and use them to calculate the initial power. In this paper, we measure $P_{w_{min}}(\theta_r, d)$ with the distances $d_j = 0.5\text{m} \times j, j \in [1, 7]$ and the angles $\theta_i = 90° - 15° \times i, i \in [0, 6]$. For example, we get $P_{w_{min}}(90°, 1.0) = 15.7\text{dBm}$, $P_{w_{min}}(75°, 1.5) = 18.8\text{dBm}$, $P_{w_{min}}(60°, 2.0) = 23.4\text{dBm}$. The reader first selects the reference angle θ_i closest to θ_r, $|\theta_r - \theta_i| \le |\theta_r - \theta_k|$ ($k \in [0, 6]$ and $k \neq i$). Then, it uses d to calculate the initial power $P_{w_{min}}(\theta_r, d)$

$$\begin{cases} P_{w_{min}}(\theta_i, d_j) & if \quad d = d_j \\ \frac{P_{w_{min}}(\theta_i, d_j) + P_{w_{min}}(\theta_i, d_{j+1})}{2} & if \quad d \in [d_j, d_{j+1}]. \end{cases} \tag{1}$$

However, the power is only used as the initial power. In order to identify more tags, the reader can repeatedly increase the power by ΔP_w. We set $\Delta P_w = 1\text{dBm}$, which is achievable by most of the commercial readers [14].

Establishing the boundary The 3D camera can recognize the specified area by RGB camera and measure distance by 3D depth sensors. However, the reader can hardly find the boundary of S, due to the unknown distribution of tag IDs. Therefore, PID first establishes the boundary S_b of the area S based on the *interference tags* located around S, as shown in Fig. 4. PID uses the 3D camera to calculate the minimum distance d_b between the *interference tags* in S_b and the antenna, and the distance d_s between the center of S and the antenna. Furthermore, it calculates the rotation angle $\varphi = arccos(\frac{d_s}{d_b})$, $\varphi \in (0°, 90°)$. Then, the antenna rotates φ degree to face the *interference tags* in S_b for identification. The identified tags are used as reference tags to describe S_b.

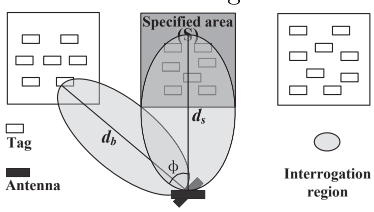


Fig. 4. Identify the tags in the specified area with a 3D camera

In PID, the antenna always faces towards the center of the objects, $\theta_r = 90°$. Then, the reader selects the initial power P_{wb} according to the distance d,

$P_{wb} = P_{w_{min}}(90°, d)$. If the power P_{wb} is not large enough, the reader increases the power by ΔP_w and identifies n_b tags, as shown in Algorithm 1. It repeats the above process until $n_b \geq n_\varepsilon$, which means that it has collected enough tag IDs $N_b = \{ID_1, ID_2, \ldots, ID_{n_b}\}$ from the boundary. However, if the reader's power has achieved to the maximum value $maxP_w$, n_b is still less than n_ε, which indicates most of the *interference tags* are far away from S. Then, the reader stops the process and gets the optimal power $P_w^* = maxP_w$. After that, the antenna rotates towards the center of S for *power stepping* and tag identification.

Algorithm 1: PID: Establishing the boundary

Input: The specified area S
Determine the boundary S_b of S by the 3D camera, and calculate d_b and d_s.
The antenna rotates to S_b with $\varphi = arccos(\frac{d_s}{d_b})$.
$P_{wb} = P_{w_{min}}(90°, d_b)$, $P_w = P_{wb}$, $n_b = 0$.
while $n_b < n_\varepsilon$ *and* $P_w < maxP_w$ **do**
  Collect tag IDs with P_w and get n_b responses.
  if $P_w = maxP_w$ *and* $n_b < n_\varepsilon$ **then** $P_w^* = maxP_w$, Return.
  $P_w = min(P_w + \Delta P_w, maxP_w)$.
Get the tag IDs $N_b = \{ID_1, ID_2, \ldots, ID_{n_b}\}$.
Output: Tag IDs in the boundary: N_b

Power stepping If P_w^* has not been determined, the reader will adjust the power through power stepping. Firstly, the reader chooses an initial power $P_{ws} = P_{w_{min}}(\theta_r, d)$ according to φ and d_b, where $\theta_r = 90° - \varphi$ and $d = d_b$. It is a critical value in theory, whose interrogation region just achieves the boundary of S. However, as shown in Fig. 2(e), the tag size can affect the effective interrogation region, P_{ws} may not be the most reasonable power. Thus we properly adjust the power by checking the tag IDs in N_b, as shown in Algorithm 2.

Algorithm 2: PID: Power Stepping

Input: Tag IDs in N_b
$P_{ws} = P_{w_{min}}(\theta_r, d) = P_{w_{min}}(90° - \varphi, d_b)$, $P_w = P_{ws}$.
Check the tag IDs in N_b and get n_c responses N_c.
if $\frac{n_c}{n_b} = \delta$ **then** $P_w^* = P_{ws}$.
if $\frac{n_c}{n_b} > \delta$ **then**
  while $P_w > minP_w$ **do**
    $P_w = max(P_w - \Delta P_w, minP_w)$.
    Check IDs in N_c, get Δn_c responses, $n_c = \Delta n_c$.
    if $\frac{n_c}{n_b} \leq \delta$ **then** $P_w^* = P_w$, Break.
if $\frac{n_c}{n_b} < \delta$ **then**
  while $P_w < maxP_w$ **do**
    $P_w = min(P_w + \Delta P_w, maxP_w)$.
    Check IDs in $N_b - N_c$, get Δn_c responses, $n_c = n_c + \Delta n_c$.
    if $\frac{n_c}{n_b} \geq \delta$ **then** $P_w^* = P_w$, Break.
Output: The optimal power P_w^*

In the commercial RFID systems, the reader (eg. Alien-9900+) selects a specified tag by setting the mask equal to the tag ID. If the tag gives response, the reader gets a nonempty slot. Otherwise, it gets an empty slot. The reader checks all the IDs in N_b and gets n_c responses N_c. Obviously, $n_c \leq n_b$. When $\frac{n_c}{n_b} = \delta$, the interrogation region just achieves the boundary of S. The corresponding power is the optimal power P_w^*. However, if $\frac{n_c}{n_b} > \delta$, the reader reduces the power by ΔP_w and checks the verified tag IDs in N_c. If a tag does not give response, the reader removes it from N_c. It repeats the above process until $\frac{n_c}{n_b} \leq \delta$ and gets the optimal power P_w^*. On the contrary, if $\frac{n_c}{n_b} < \delta$, the reader increases P_w by ΔP_w and checks the unverified tag IDs in $N_b - N_c = \{ID_i \mid ID_i \in N_b \; and \; ID_i \notin N_c\}$. If the tag gives response, the reader adds the ID into N_c. It repeats the process until $\frac{n_c}{n_b} \geq \delta$ and gets the optimal power P_w^*. In the following process, the reader uses P_w^* to identify the *target tags*.

5.2 Shooting Process

In this process, the reader collects the tag IDs in S. The reader's power is equal to P_w^* and we use frame slotted ALOHA (FSA) protocol to identify the tags. FSA is a popular anti-collision protocol. In FSA, the reader first broadcasts a number f, which specifies the following frame size. After receiving f, each tag selects $h(ID)$ mod f as its slot number, h is a hash function. If none of the tags respond in a slot, the reader closes the slot immediately. If only one tag responds in a slot, the reader successfully receives the tag ID. If multiple tags respond simultaneously, a collision occurs, and the involved tags will be acknowledged to restart in the next frame. The similar process repeats until no tags respond in the frame. The collected IDs are considered as the *target tag IDs*.

5.3 Performance Analysis

In order to definitely describe the boundary S_b, PID needs to steadily get at least n_ε interference tag IDs, n_b satisfies $n_b \geq n_\varepsilon$. We measure the value of n_ε with different tag size $|N|$. When $|N| = 20, 60, 100, 140, 180, 220$, we respectively get $n_\varepsilon = 2, 4, 7, 9, 11, 12$. The tag size $|N|$ has a little effect on n_ε, which is usually very small. In order to definitely get enough tag IDs in S_b, we set $n_\varepsilon = 15$ by default, while considering the stability and time efficiency. In regard to δ, the smaller the value of δ, the lower the *misreading ratio*, the smaller the execution time. The larger the value of δ, the larger the value of *coverage ratio* ρ. Considering the constraint of ρ and time efficiency, we set $\delta = \alpha$. When $\frac{n_c}{n_b} = \delta = \alpha$, the interrogation region just achieves the boundary, while satisfying $\rho \geq \alpha$. Besides, the antenna rotates to the target direction immediately, the time for rotating the antenna can be neglected compared to the tag identification time.

6 Photography based Identification with Angle Rotation

In PID, a 3D camera is used in the focusing process. However, in some environments, the 3D camera cannot work well (eg. in a dark space). Besides, considering the cost savings, it will not be used. Therefore, identifying the *target tags* efficiently without the auxiliary equipment is important. For this problem, we propose a solution called Photography based tag Identification with Angle rotation (PIA). It also consists of *Focusing Process* and *Shooting Process*. The only difference between PID and PIA is how to determine the boundary of S. We only describe how to find the boundary in PIA, while ignoring the others.

Without the 3D camera, PIA cannot calculate any distance, it explores the boundary by rotating the antenna, as shown in Fig. 5. Firstly, the application appoints S and the antenna rotates towards S. Then the reader sets its initial power equal to the minimum power $minP_w$ and identifies n_s tags in S. If $n_s < n_\varepsilon$, the reader repeatedly increases the power by ΔP_w and identifies the tags until $n_s \geq n_\varepsilon$, the identified *target tags* are $N_s = \{ID_1, ID_2, \dots, ID_{n_s}\}$. If $P_w = maxP_w$, PIA gets $P_w^* = maxP_w$. Otherwise, the antenna rotates away from S to get the interference tag IDs in the boundary, as shown in Algorithm 3.

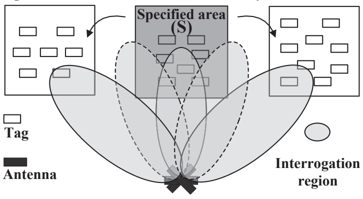


Fig. 5. Identify the tags in the specified area without any auxiliary equipment

Algorithm 3: PIA: Exploring the boundary

Input: The specified area S
$P_w = minP_w$, $n_s = 0$, $n_l = 0$, $\Delta\theta_{r_l} = 0°$.
while $n_s < n_\varepsilon$ *and* $P_w < maxP_w$ **do**
  Get n_s tag IDs, $P_w = min(P_w + \Delta P_w, maxP_w)$.
if $P_w = maxP_w$ **then** $P_w^* = maxP_w$, Return.
Get tag IDs $N_s = \{ID_1, ID_2 \dots, ID_{n_s}\}$.
while $n_l < n_\varepsilon$ *and* $\theta_r \in [0°, 90°]$ **do**
  The antenna rotates to the left by $\Delta\theta_r$, $\Delta\theta_{r_l} = \Delta\theta_{r_l} + \Delta\theta_r$.
  while $P_w < maxP_w$ **do**
    Δn_s tag IDs in N_s disappear, $n_s = n_s - \Delta n_s$.
    Get Δn_l new tag IDs, $n_l = n_l + \Delta n_l$, update the set of new tags N_l.
    if $n_l \geq n_\varepsilon$ **then** Break.
    if $\Delta n_s > 0$ **then** $P_w = min(P_w + \Delta P_w, maxP_w)$. **else** Break.
$N_b = N_l$.
The antenna rotates to the right in $[0°, \Delta\theta_{r_l}]$, gets N_r, it rotates $\Delta\theta_{r_r}$ degree.
if $\Delta\theta_{r_l} = \Delta\theta_{r_r}$ **then** $N_b = N_l \cup N_r$. **else if** $\Delta\theta_{r_l} > \Delta\theta_{r_r}$ **then** $N_b = N_r$.
Output: Tag IDs in the boundary :N_b

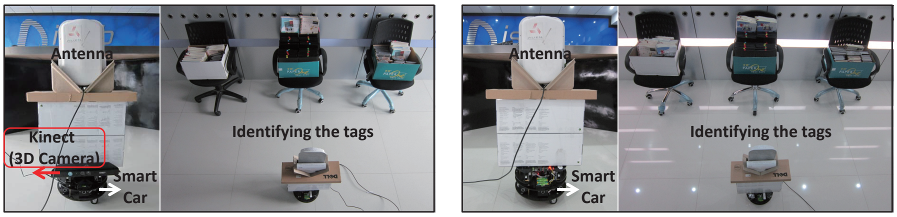
When the antenna rotates to another direction (called as *left*), n_s decreases. As shown in Algorithm 3, when the radiation angle decreases by $\Delta\theta_r$, Δn_s tags in N_s disappear. The reader gets n_l new tag IDs, which are considered as the tag IDs from the boundary. If $n_l \geq n_\varepsilon$, the reader collects enough tag IDs $N_l = \{ID_1^{'}, ID_2^{'}, \dots, ID_{n_l}^{'}\}$ from the boundary. Otherwise, it increases the power by ΔP_w and gets Δn_l new tag IDs. Everytime, it should make sure that $\Delta n_s > 0$, which indicates the new tag IDs are not from the area S. If $\Delta n_s = 0$, the antenna keeps rotating away from S. PIA repeats the above process until $n_l \geq n_\varepsilon$. Then, the antenna has rotated $\Delta\theta_{r_l}$ degree. After that, the antenna rotates to the opposite direction (*right*) and works in the same way. It rotates $\Delta\theta_{r_r}$ degree to the right side. If $\Delta\theta_{r_r} > \Delta\theta_{r_l}$, it indicates the boundary in the right side is farther than the left one, then the reader terminates the process. Otherwise, it obtains $N_r = \{ID_1^{''}, ID_2^{''}, \dots, ID_{n_r}^{''}\}$. The reader compares $\Delta\theta_{r_l}$ and $\Delta\theta_{r_r}$ to find the nearer boundary with the smaller angle, and gets the new set N_b of interference tags. If $\Delta\theta_{r_l} = \Delta\theta_{r_r}$, $N_b = N_l \cup N_r$. If $\Delta\theta_{r_l} < \Delta\theta_{r_r}$, $N_b = N_l$. If $\Delta\theta_{r_l} > \Delta\theta_{r_r}$, $N_b = N_r$. N_b is used for *power stepping*.

The values of parameters in PIA are equal to those in PID. In regard to $\Delta\theta_r$ in PIA, we set $\Delta\theta_r = 30°$. Based on Fig. 2(a), when $\theta_r \in [75°, 90°]$, the reader undoubtedly has good performance. Therefore, when $\Delta\theta_r = 30°$, each tag can be requested in the region with $\theta_r \in [75°, 90°]$.

7 Performance Evaluation

We evaluate the performance of each solution in the realistic environments. The experimental facilities are the same as those used in the observations. The *execution time*, *coverage ratio*, and *misreading ratio* are used for performance metrics.

In the experiments, each book is attached with an RFID tag, and the tag ID is 96 bits. The books are randomly deployed in three boxes and the distribution of the tag IDs are unknown. Each box is placed on a tablet chair with a height of 0.5m, as shown in Fig. 6. PID uses a 3D camera, while PIA does not. The antenna is deployed on the smart car, which is controlled by the program and can rotate with the antenna flexibly. The antenna faces towards the tags to be identified. The specified area here is the center box, which is the *target box*, while the other two boxes are *interference boxes*. The distance between the target box and the antenna is d. The minimum distance between the interference box and the target box is l. s and u respectively represent the number of target tags (in target box) and the number of interference tags (in interference boxes). We verify the values of the parameters d, l, s, u to evaluate the performance of each solution. We set $d = 1$m, $l = 1$m, $s = 80$, $u = 70$ by default.



(a) PID (b) PIA

Fig. 6. System prototypes work in the realistic environments

7.1 Upper bound of α

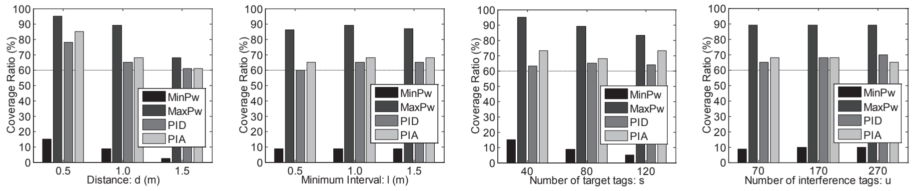
As mentioned in section 2.2, when the distance d, the number of tags n are fixed, we can determine the value of α. In table 1, we give the upper bound of α under different conditions. We set $\alpha = 60\%$ for the following experiments by default.

Table 1. Upper bound of α

n \ d (m)	0.5	1.0	1.5
40	100%	100%	90%
80	95%	85%	65%
120	89%	81%	63%

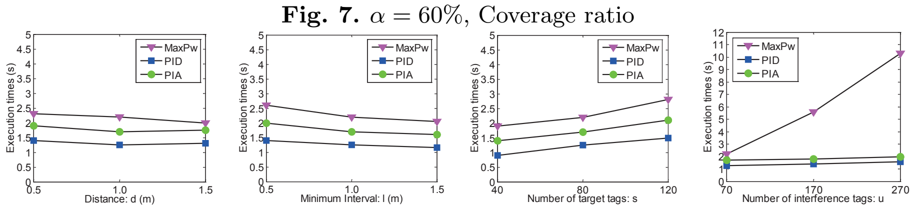
7.2 Coverage Ratio ρ Constraint

We first investigate the coverage ratio ρ of each solution, as shown in Fig. 7. We can observe that scanning with the minimum power (MinPw) can not achieve the requirement of coverage ratio ($\alpha = 60\%$). Because the power is too small to activate the majority of the tags. When we identify the tags with the maximum power (MaxPw) or our proposed solutions (PID and PIA), the coverage ratios are all larger than 60% ($\rho \geq \alpha$), which satisfy the requirement. As mentioned in section 2.2, the coverage ratio must be satisfied. Therefore, the solution MinPw is invalid and we ignore it in the following comparisons.



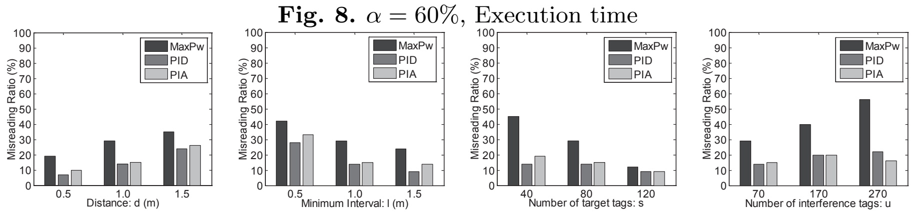
(a) ρ vs. d (b) ρ vs. l (c) ρ vs. s (d) ρ vs. u

Fig. 7. $\alpha = 60\%$, Coverage ratio



(a) T vs. d (b) T vs. l (c) T vs. s (d) T vs. u

Fig. 8. $\alpha = 60\%$, Execution time



(a) λ vs. d (b) λ vs. l (c) λ vs. s (d) λ vs. u

Fig. 9. $\alpha = 60\%$, Misreading ratio

7.3 Execution time T

Fig. 8 shows the execution time of each solution. Our solutions PID and PIA have better performances than MaxPw. Because PID and PIA only focus on the *target tags* in S. MaxPw identifies all the tags in the interrogation region, including a lot of *interference tags*. Usually, PID has a better performance than PIA, due to the use of a 3D camera. In Fig. 8(a), 8(b), the difference in execution time between PID, PIA and MaxPw is small. This is because the tag size is relatively small. When the tag size becomes large, our proposed solutions become more efficient. When $s = 120$, PID reduces the execution time by 46% compared to MaxPw, as shown in Fig. 8(c). When $u = 270$, PID even can reduce the execution time by 84.5% compared to MaxPw, as shown in Fig. 8(d).

7.4 Misreading Ratio λ

In section 2.2, we analyze that the execution time is related to the misreading ratio. Fig. 9 shows the misreading ratio of each solution. Our solutions PID and PIA have lower misreading ratios than MaxPw. This is because PID and PIA use the optimal powers instead of the maximum one (30.7dBm). PID and PIA mainly focus on the *target tags*, while avoiding identifying the *interference tags*.

When we change the value of α, our solutions can also work well. For example, when $d = 1$m, $l = 1$m, $s = 80$, $u = 70$, we set $\alpha = 80\%$. The coverage ratio of MaxPw, PID, PIA is respectively equal to 89%, 82.5%, 86%, which satisfy the constraint of ρ. The execution time of MaxPw, PID, PIA is respectively equal to $2.2s$, $1.45s$, $2.0s$. Our solutions outperform the baseline solutions.

8 Conclusion

In this paper, we investigate the problem of identifying the tags in the specified area. We conduct extensive experiments on the commodity RFID system in the realistic environments and present two efficient solutions, PID and PIA. Both PID and PIA work in a similar way of picture-taking in a camera, they first focus on the specified area and then identify the *target tags* efficiently. The realistic experiments show that our solutions outperform the baseline solutions.

Acknowledgement

This work is partially supported by the National Natural Science Foundation of China under Grant No. 61100196, 61073028, 61021062; the JiangSu Natural Science Foundation under Grant No. BK2011559; and NSF grants ECCS 1231461, ECCS 1128209, CNS 1138963, CNS 1065444, and CCF 1028167.

References

1. Vogt, H.: Efficient object identification with passive RFID tags. In: Proc. of Pervasive, pp. 98-113. Springer (2002)
2. Maguire, Y., Pappu, R.: An optimal q-algorithm for the iso 18000-6c rfid protocol. IEEE Transactions on Automation Science and Engineering. 6, 1, 16-24 (2009)
3. Zhen, B., Kobayashi, M., Shimuzu, M.: Framed aloha for multiple rfid objects identification. IEICE Transactions on Communications. E80-B, 3, 991-999 (2005)
4. Lee, S., Joo, S., Lee, C.: An enhanced dynamic framed slotted ALOHA algorithm for RFID tag identification. In: Proc. of MobiQuitous, pp. 166-172. IEEE (2005)
5. Tan, C.C., Sheng, B., Li, Q.: How to Monitor for Missing RFID Tags. In: IEEE ICDCS, pp. 295-302. IEEE (2008)
6. Li, T., Chen, S., Ling, Y.: Identifying the Missing Tags in a Large RFID System. In: ACM MobiHoc, pp. 1-10. ACM (2010)
7. Zheng, Y., Li, M.: Fast Tag Searching Protocol for Large-Scale RFID Systems. In: IEEE ICNP, pp. 363-372. IEEE (2011)
8. Kodialam, M., Nandagopal, T.: Fast and reliable estimation schemes in RFID systems. In: ACM MobiCom, pp. 322-333. ACM (2006)
9. Qian, C., Ngan, H., Liu, Y., Ni, L.M.: Cardinality Estimation for Large-scale RFID Systems. IEEE Transactions on Parallel and Distributed Systems. 22, 9, 1441-1454 (2011)
10. Zheng, Y., Li, M., Qian, C.: PET: Probabilistic Estimating Tree for Large-Scale RFID Estimation. In: IEEE ICDCS, pp. 37-46. IEEE (2011)
11. Buettner, M., Wetherall, D.: An emprical study of uhf rfid performance. In: Proc. of MobiCom, pp. 223-234. ACM (2008)
12. Arror, S.R., Deavours, D.D.: Evaluation of the state of passive uhf rfd: An experimental approach. IEEE Systems Journal. 1, 2, 168-176 (2007)
13. Jeffery, S.R., Garofalakis, M., Franklin, M.J.: Adaptive cleaning for rfid data streams. In: Proc. of VLDB, pp. 163-174. ACM (2006)
14. Xu, X., Gu, L., Wang, J., Xing, G.: Negotiate Power and Performance in the Reality of RFID Systems. In: IEEE PerCom, pp. 88-97. IEEE (2010)