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Effective Object Identification and Association by Varying Coverage Through RFID Power Control

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Abstract This paper presents an effective power scheduling strategy for energy efficient multiple objects identification and association. The proposed method can be utilized in many heterogeneous surveillance systems with visual sensors and RFID (radio-frequency identification) readers where energy efficiency as well as association rate are critical. Multiple objects positions and trajectory estimates are used to decide the power level of RFID readers. Several key parameters including the time windows and the distance separations are defined in the method in order to minimize the effects of RFID coverage uncertainty. The power cost model is defined and incorporated into the method to minimize energy consumption and to maximize association performance. The proposed method computes the power cost using the range of the outermost position for possible single association and group associations at every sampling time. An RFID reader is activated with the proper coverage range when the power cost for the current time is lower than the power cost for the next time sample. The simplicity of the power cost model relieves the problematic combinatorial comparisons in multiple object cases. The performance comparison simulation with the minimum and maximum energy consumption shows that the proposed method achieves fast single associations with less energy consumption. Finally, the realistic comparison simulation with the fixed range RFID readers demonstrates that the proposed method outperforms the fixed ranges in terms of single association rate and energy consumption.

Keywords object association, RFID power control, power scheduling, visual sensor collaboration

1 Introduction

Recently, sensor network systems have been extensively studied and used in various civilian and military applications. One of the widely deployed sensor network types is the intelligent surveillance system for tracking multiple objects using many different types of sensors including visual sensors as well as identification sensors. The objects are visually tracked for localization with visual sensors and the objects are identified with identification sensors. In these systems, RFID (radio-frequency identification) readers are often used for identification[1-4]. In these systems, as the number of deployed sensors and the system complexity increase, energy efficiency becomes extremely critical. An RFID reader often dissipates a lot of power unnecessarily. Many studies have been done concerning the trade-off between energy efficiency and surveillance performance[5-10]. A few approaches have been proposed to reduce energy consumption for the object tracking[11-14]. While object positions are tracked by visual sensors, object identifications are registered by RFID readers. However, when there are multiple objects, associating the registered identifications with the tracked positions is not a trivial task. Without accurate object association, it is almost impossible to individually track the objects.

Most of previous studies employing RFID readers in the surveillance systems have been focused on fast and accurate object identification. Engels and Karthaus *et al.* explained interference problem of multiple RFID readers[15-16]. Cha *et al.* addressed and implemented the power control that minimizes the interference problem in RFID reader networks[17-18]. Also, some researchers have proposed anti-collision protocols for energy efficient identification[19-20]. Although they pro-

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vide solutions for interference and anti-collision problems, they do not deal with association problem which is needed in the intelligent surveillance systems for multiple object tracking.

In this paper, we present an RFID reader power scheduling strategy for an energy efficient object identification and association by varying coverage through power control. The proposed method can be applied in many heterogeneous surveillance systems with visual sensors and RFID readers. Several key parameters including the time windows and distance separations are defined to minimize the effects of RFID coverage uncertainty. The power cost model is incorporated into the method to minimize energy consumption and to maximize association performance. A power cost is estimated by using estimated object positions and possible associations within the coverage. In order to avoid the problematic power cost estimation for combinatorial comparisons according to the separation between object positions, the power cost is simply estimated with the range of the outermost position for possible single association and group associations. At every sampling time, the system estimates a power cost to determine the activation time and range of the RFID readers. The RFID reader activates with the proper range if the power cost at the current time is lower than the power cost for the next time sample. We address the minimum and maximum energy consumption of an RFID reader with known and unknown object trajectories, respectively. The performance of the proposed method is compared with the minimum and maximum energy consumption in terms of association performance and energy consumption. Also, the proposed method is compared with the fixed range of an RFID reader in terms of the average energy consumption and average time for each association.

The remainder of this paper has four sections. In Section 2, we present the overview of the application model and the problem description. Section 3 addresses the relationship between the energy and association rate with known and unknown object trajectories. Also, the scheduling strategy of the RFID reader is presented with the proposed power cost model. In Section 4, the performance of the RFID reader power scheduling method is evaluated in detail in terms of association rate and energy consumption. Finally, our contribution is summarized in Section 5.

2 Application Model and Problem Description

2.1 Application Model and Background

Fig.1 shows a typical application scenario where multiple RFID readers are placed and the objects with RFID tags are free to move around. The positions of these objects are visually tracked for their localizations. Multiple objects may enter the RFID coverage. All RFID readers usually remain awake to periodically maintain the sets of registered identification with the maximum coverage of $R_{\max}$. The possible applications can be not only public areas (e.g., schools, hospitals, and shopping malls) but also highly secured areas (e.g., airports, military facilities, and government organizations). For example, visual sensors can keep tracking passengers in an airplane check-in or military personnel in a special area.

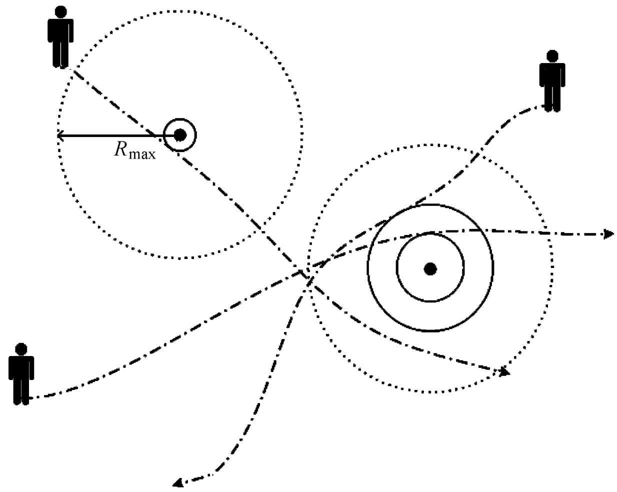

Fig.1. Illustration of association problems for multiple objects with multiple RFID readers.

In our application model, the association between multiple objects positions and identifications is a key issue. For *association problem*, most of approaches probabilistically determine the association under the assumption that two different types of sensors obtain their data at the same time[1–3]. However, they do not provide a recovery method against losing the correct identification and the number of hypotheses grows extremely fast whenever several people are close to each other. Cho *et al.* proposed an effective association method by maintaining the sets of estimated positions and identifications for each coverage of an RFID reader[4]. The estimated positions are identified with their identifications if the number of added or subtracted elements in the sets is equal to each other. When the number of the elements is one, the estimated position is uniquely identified as single association. Otherwise, they are associated as a group. Because this method simply determines the association without many hypotheses and recovers association failure for newly estimated positions in the coverage of an RFID reader, our paper is based on this association method. The proposed method can be utilized in many heterogeneous surveillance systems with visual sensors and RFID readers where energy efficiency as well as association rate are critical.

2.2 Problem Description and Approach

The RFID reader typically has a small coverage range and is used only in narrow corridors or at the door. A wide open space can be covered by simply extending the coverage of the RFID reader. However, the energy consumption will be increased significantly when the objects are not present within the range. Moreover, the wide coverage range of the RFID reader may increase chances that multiple objects may enter the coverage simultaneously. Hence, the multiple objects may create many group associations when the coverage range becomes large. In the surveillance systems, the group associations are not useful for individual object tracking. Hence, single association is highly desirable.

The key principle behind the proposed power control method is to determine when to activate and by how much of power. For energy efficiency, it is desirable for the system to activate RFID readers only when the object association is possible with the shortest range. In the case of multiple objects within the coverage, the proposed system avoids group association for single association. This may delay the activation time of the RFID, causing the increase of time to establish the association. In addition, the activation time and range of the RFID reader are determined by considering the distance between an object position and the center of the RFID reader. In order to find the activation time for the shortest range, the system is required to estimate object trajectories. However, the estimation accuracy usually degrades for the long period of estimation time and makes it difficult to find the instant of the shortest range. Also, when multiple RFID readers are deployed, it is not easy to select one of them because of the inaccurate estimation.

In the proposed approach, several key parameters including the time windows and distance separations are defined to minimize the effects of the RFID coverage uncertainty. The power cost model is incorporated into the method to minimize energy consumption and to maximize association performance. A power cost is estimated by using estimated object positions and possible associations within the coverage. Object positions for the next power cost are estimated by the simple linear trajectory model. In order to avoid the problematic power cost estimation for combinatorial comparisons according to the separation between object positions, the power cost is simply estimated with the range of the outermost position for possible single association and group associations. At every sampling time, the system estimates a power cost to determine the activation time and range of the RFID readers. An RFID reader is activated with the proper range when the power cost for the current time is lower than the power cost for the next time. In the proposed method, the system forces the activation of an RFID reader to maximize single associations.

3 Object Identification Through Power Control

3.1 Known Object Trajectory

3.1.1 Single Object with Single RFID Reader

Fig.2 illustrates a simple scenario with an RFID reader and an object. The object position and the distance between the object and the RFID reader are estimated by the system with visual sensors. The RFID reader is capable of covering the range up to $R_{\max}$. If the object trajectory is known to the system, the RFID reader is activated to identify the object when the distance between the object and the RFID reader is at the minimum in order to minimize the power consumption. The power consumed during the identification is represented by

$$P_i^k = f(d_i^k(t_{\min})),$$

where $d_i^k(t)$ denotes the Euclidean distance between the RFID reader R^k and the object O_i at time t within $R_{\max}$, $t_{\min}$ denotes the time instant of the object which is at the minimum distance, and $f(\cdot)$ denotes a function to convert range $d_i^k(t)$ to the power.

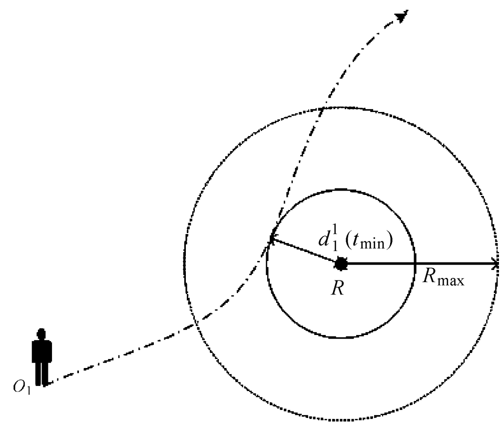

Fig.2. Illustration of a basic operation with a single RFID reader.

3.1.2 Multiple Objects with Single RFID Reader

A single RFID reader placement with multiple objects is shown in Fig.3. It is clear that if the distance between an object and the RFID reader is within the range, the objects can be identified. However, the object association may not be established depending on the situations. An association is not a problem when the multiple objects enter the RFID range at different times. However, establishing the association is not trivial when multiple objects enter the range within a very small time window and also the differences between the tangential distances of the objects from the RFID reader are small. Moreover, the uncertain coverage of the RFID readers may complicate the association since an RFID reader may register identification tags for objects not within the coverage but near the coverage. If the tangential distance between object positions is too small, the system may establish a group association. Hence, the system needs to check the tangential distance between object positions at the instant of the minimum distance if the system prefers single associations. $d^k_{i,j}(t)$ denotes the difference between the tangential distance $d^k_i(t)$ and $d^k_j(t)$ from the center of RFID reader R^k at time t. The required separation between the object positions to establish single associations is denoted by Δd. If $d^k_{i,j}(t_{\min})$ is smaller than Δd, a group association is established for objects O_i and O_j. For example, object O_1 has the minimum distance d^1_1 at $t_{\min} = t^1_1$ and object O_2 has the minimum distances d^1_2 at $t_{\min} = t^1_2$. Single associations for them are established only if $d^1_{1,2}(t^1_1)$ and $d^1_{1,2}(t^1_2)$ are greater than Δd. Also, the establishment of a group association also depends on the time difference. $t^k_{i,j}$ denotes the time difference of t^k_i and t^k_j. If $t^k_{i,j}$ is smaller than time threshold Δt in addition to $d^k_{i,j} \leqslant \Delta d$, a group association is established. In terms of association performance and energy consumption, we consider two approaches for multiple objects. The first approach is to achieve either single or group association as soon as possible and the second approach is to try to achieve only single association.

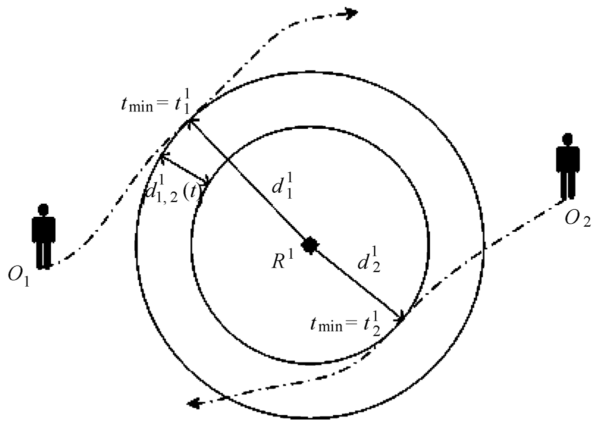

Fig.3. Illustration of a basic operation with a single RFID reader to identify multiple objects.

Fig.4 illustrates the simulation with a single RFID reader to identify multiple objects by the two approaches. An RFID reader is placed at (10 m, 10 m) and the initial positions of two objects are (1 m, 1 m) and (3 m, 18 m), respectively. The sampling period of the object trajectories is set to 0.5 s and Δd is set to 0.1 m. d^1_1 is 0.2721 m at time 14 and d^1_2 is 0.7341 m at time 13. By the first approach, a group association is established at time 13 in Fig.4(a). At time 14, each object is uniquely identified by establishing a single association. On the other hand, by the second approach, the RFID reader is not activated for multiple objects that do not satisfy Δd. As shown in Fig.4(b), the RFID reader is not activated at time 13 and the identification of the object O_2 is delayed.

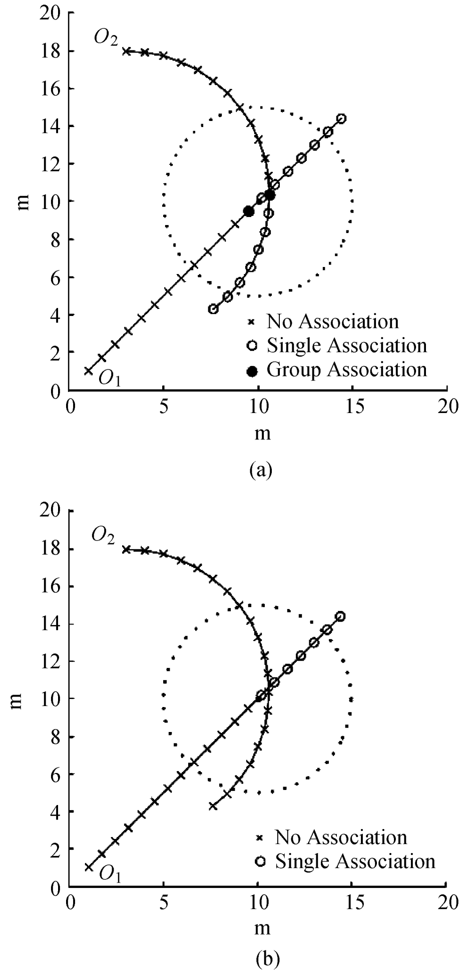

Fig.4. Illustration of the multiple object associations with a single RFID reader. (a) Single/group association. (b) Single association only.

3.1.3 *Multiple Objects with Multiple RFID Readers*

When the multiple RFID readers are placed in the environment, each RFID reader is assigned to identify each object by calculating the minimum distance. The minimum distances for all the pairs of the RFID readers and the objects are calculated, where each pair of an RFID reader and an object is determined to have the smallest distance. For the object O_i, the RFID reader R^k is selected by

$$\arg\min_k d_i^k(t_{\min}). \tag{1}$$

However, if the system prefers single associations, the object identification can be delayed because of Δd issue. For example, the system initially assigns the RFID reader R^2 to both objects O_1 and O_2 by (1) in Fig.5 but $d_{1,2}^2(t_{\min})$ can be smaller than Δd. Then, the system assigns the other RFID readers having the second smallest distance for each object. Eventually, the object O_1 is paired with the RFID reader R^1 and the object O_2 is paired with the RFID reader R^3.

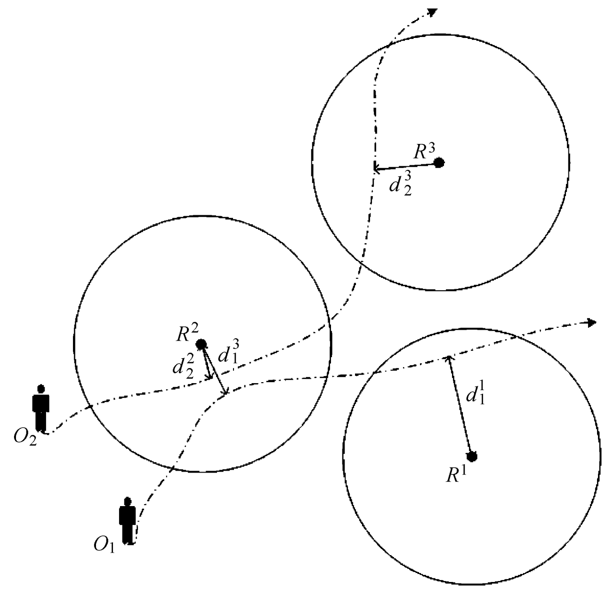

Fig.5. Illustration of the multiple object associations with multiple RFID readers.

Fig.6 shows the simulation result for the multiple objects case with multiple RFID readers. The RFID reader power scheduling for known trajectories is compared with the maximum energy consumption for unknown trajectories in terms of the association performance and the energy consumption. Because the system cannot estimate the next positions of objects for unknown object trajectories, the system tries to activate RFID readers whenever the objects enter the coverage of RFID readers. Two RFID readers, R^1 and R^2, are placed at (5 m, 10 m) and (15 m, 10 m), respectively with the maximum range 4 m. The initial positions of the other objects O_4 and O_5 are (19.5 m, 15 m) and (20 m, 10 m), respectively. In the simulation, the RFID readers are not activated for group associations. As shown in Fig.6(a) and Fig.6(b), the RFID readers are assigned to objects with the minimum range. The objects O_1, O_2 and O_3 are identified by the RFID readers R_1, R_2 and R_1, respectively according to (1). For the object O_4, no RFID reader is assigned because $d_{3,4}^2(7) = 0.08\,\text{m}$ and $d_{3,4}^2(16) = 0.48\,\text{m}$. On the other hand, in Fig.6(c) and Fig.6(d) with the maximum energy consumption, the objects are identified faster with the longer range of the RFID readers as soon as they enter the coverage. However, it increases the energy consumption of the RFID readers.

3.2 Unknown Object Trajectory

3.2.1 *Single Object Case*

In many practical situations, it is difficult to calculate the time instant of the minimum distance because object trajectories are not perfectly known to the system. Hence, the system may try to activate the RFID reader whenever an object enters the coverage. Although the immediate activation of the RFID reader for an entering object shortens the time to establish a single association, it increases the energy consumption due to the long range.

In order to reduce the energy consumption, the activation time of the RFID reader is determined by estimating the power consumption. The system estimates the power consumption with the distance between an object position and the location of the RFID reader every sampling time as shown in Fig.7. To estimate the power consumption for the next sampling time, the next position of the object is also estimated by the linear trajectory model as

$$\hat{x}_i(t+1) = x_i(t) + v_i(t) \times T_s,$$

where $\hat{x}_i(t+1)$ denotes the estimated position of the object O_i for time $t+1$ with the object position $x_i(t)$. T_s denotes the sampling period of visual sensors and is usually greater than the activation time of an RFID reader with $R_{\max}$. $v_i(t)$ denotes the velocity of the object O_i at time t and is obtained by

$$v_i(t) = x_i(t) - x_i(t-1).$$

With the estimated next position of an object, the system calculates the distance between the estimated position and the RFID reader. $\hat{d}_i(t+1)$ denotes the distance to the estimated position for time $t+1$. By comparing $d_i(t)$ with $\hat{d}_i(t+1)$, the system determines the activation time and range of the RFID reader. The smaller range means less power consumption. If $\hat{d}_i(t+1)$ is smaller than $d_i(t)$, the system waits for $t+1$ to activate with range $\hat{d}_i(t+1)$. Otherwise, the system activates the RFID reader with range $d_i(t)$ at the current sampling time because the smaller range is not guaranteed later. Besides, the system needs to consider the unknown

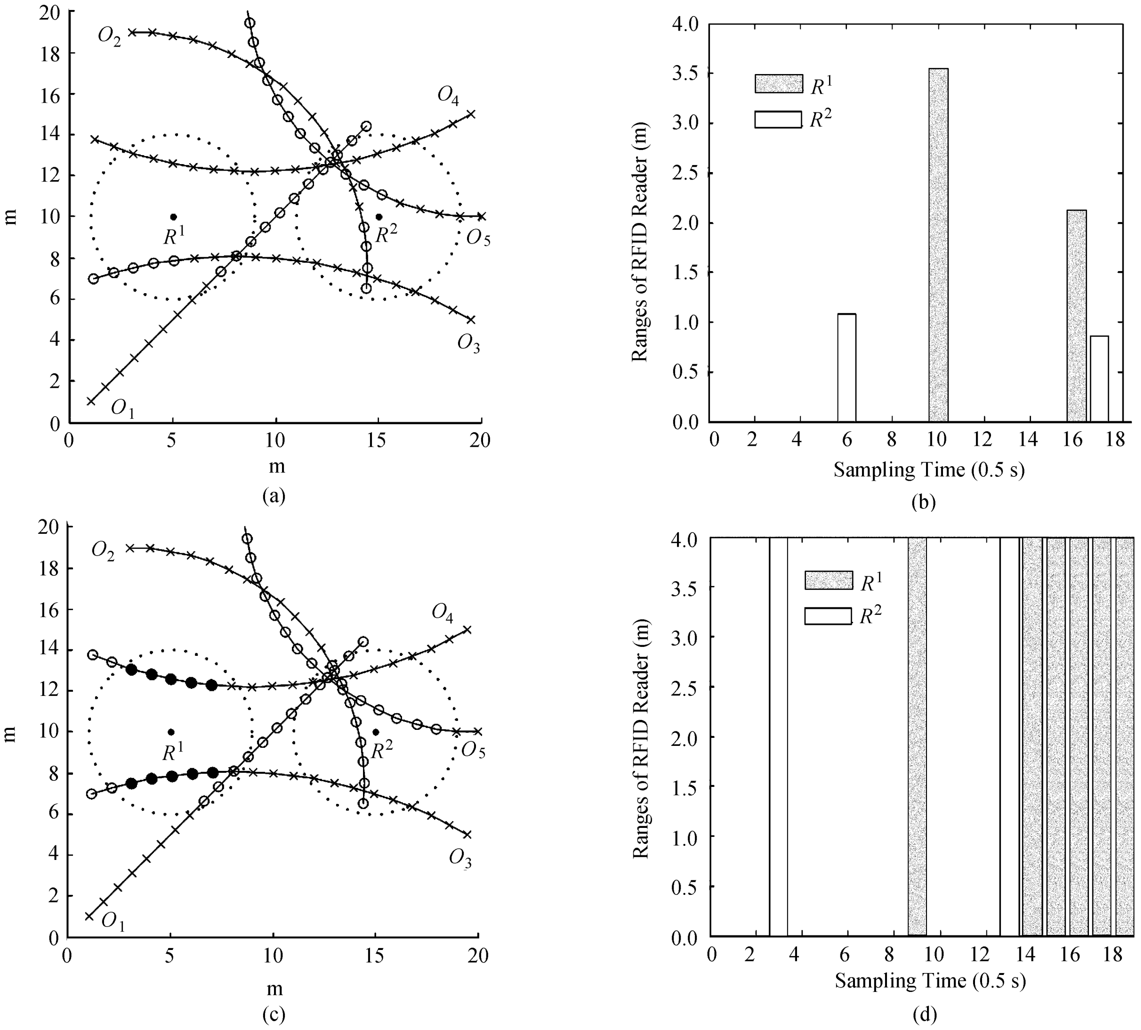

Fig.6. Energy and association comparison for five objects with two RFID readers. (a) Association status for the minimum energy. (b) Ranges of RFID reader for the minimum energy. (c) Association status for the maximum energy. (d) Ranges of RFID reader for the maximum energy.

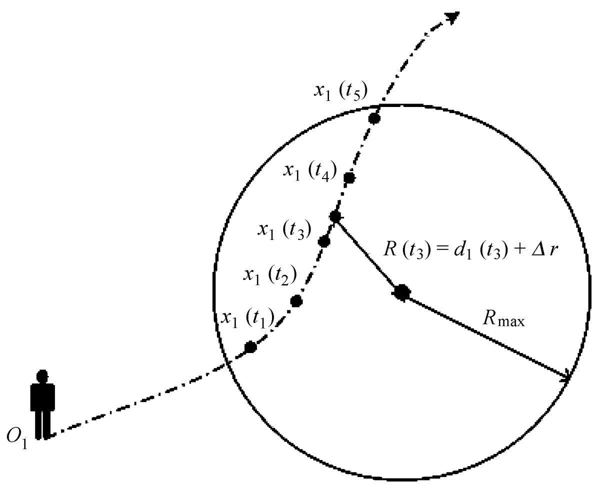

Fig.7. Identification of a single object when an object trajectory is not perfectly known to the system.

movement of an object during the activation of the RFID reader. For example, at t_3, an RFID reader is activated with the range of $R(t_3) = d_1(t_3) + \Delta r$. Δr denotes the extra range to compensate the unknown movement of an object. Δr is omitted in the rest of the paper for the simplicity.

3.2.2 Two Objects Case

When two objects enter the coverage of the RFID reader, the system also considers the association performance affected by Δd. As shown in Fig.8, the system checks $d_{i,j}(t)$ to anticipate the possibility of group associations. If $d_{i,j}(t)$ is smaller than Δd, a group association is expected.

In addition to the power cost estimation, the estimated association performances for the current and next sampling time are also compared to determine

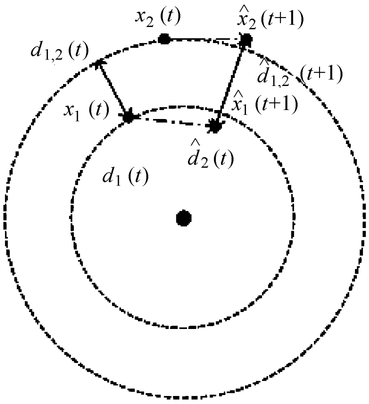

Fig.8. Identification of two objects when an object trajectory is not perfectly known to the system.

whether the RFID reader should be activated or not at the current sampling time. If both $d_{i,j}(t)$ and $\hat{d}_{i,j}(t+1)$ are greater than Δd, two single associations are expected at both the current and next sampling time. For the association performance estimation, the system has three cases to consider as shown in Table 1. The first case is that the system changes the range of the RFID reader from $\min(d_i(t), d_j(t))$ to $\max(d_i(t), d_j(t))$ at t and the power consumption is estimated with $\max(d_i(t), d_j(t))$. The second case is that the system changes the range of the RFID reader from $\min(\hat{d}_i(t+1), \hat{d}_j(t+1))$ to $\max(\hat{d}_i(t+1), \hat{d}_j(t+1))$ at $t+1$ and the power consumption is estimated with $\max(\hat{d}_i(t+1), \hat{d}_j(t+1))$. The third case is that the system activates the RFID reader with the range of $\min(d_i(t), d_j(t))$ at t and with the range of the distance to the remaining position at $t+1$. The power cost for the third case is estimated by summing the estimated power costs with the two ranges. The system selects the case having the minimum power cost among the three cases.

Table 1. All Possible Cases with the Lookahead to the Next Sampling Time for Fig.8 When $d_{1,2}$ Greater Than Δd

Case	t	$t+1$
C_1	$\{\}$	$\{\hat{d}_1, \hat{d}_2\}$
C_2	$\{d_1\}$	$\{\hat{d}_2\}$
C_3	$\{d_1, d_2\}$	$\{\}$

If $d_{i,j}(t)$ is smaller than Δd and $\hat{d}_{i,j}(t+1)$ is greater than Δd, the system has two cases to estimate the association performance. One case is that the system establishes the group association with the range of $\min(d_i(t), d_j(t))$ at t and two single associations with the range of $\min(\hat{d}_i(t+1), \hat{d}_j(t+1))$ at $t+1$. Another case is that the system waits for the next sampling time and establishes two single associations with the ranges according to the increasing order of $\hat{d}_i(t+1)$ and $\hat{d}_j(t+1)$. By comparing the power costs for the two cases, the system selects the case having the minimum power cost. If $d_{i,j}(t)$ is greater than Δd and $\hat{d}_{i,j}(t+1)$ is smaller than Δd, an RFID reader is activated at t to establish single associations. If both $d_{i,j}(t)$ and $\hat{d}_{i,j}(t+1)$ are smaller than Δd, group association is established for t and $t+1$. Because the estimated association performances for t and $t+1$ are the same, the activation time is determined by using the power cost. Power costs for t and $t+1$ are estimated with $\min(d_i(t), d_j(t))$ and $\min(\hat{d}_i(t+1), \hat{d}_j(t+1))$, respectively. If the estimated power cost for t is less than the estimated power cost for $t+1$, the system activates the RFID reader with the smaller range. Otherwise, the system waits for the next sampling time.

3.2.3 *Difficulty of Combinatorial Cases for Multiple Objects*

When multiple objects enter the coverage of the RFID reader, the activation time and the coverage range of the RFID reader are determined by estimating the association performance as well as the power cost similarly to the two-object case. If all the possible cases have the same association performance, the system selects the case with the minimum power cost. However, the system needs to check many cases as the number of objects increases. If all $d_{i,j}(t)$ and $\hat{d}_{i,j}(t+1)$ are greater than Δd, they are expected to establish single associations for both t and $t+1$. In this case, the system is required to check not only the power cost for t and $t+1$ but also Δd separation and the power cost for $t+2$ because each object can be identified at each sampling time in turn. Then, the system needs to look ahead to t to $t+2$. Table 2 shows all possible cases with the lookahead to $t+2$ for Fig.9 when all $d_{i,j}$s are greater than Δd. In addition, as described in the two-object case, there exist combinatorial cases according to Δd and the system needs to estimate their power costs. Although testing all combinatorial cases can find

Table 2. Possible Cases with the Lookahead to the Next Two Sampling Times for Fig.9 When All $d_{i,j}$s Greater Than Δd

Case	t	$t+1$	$t+2$
C_1	$\{\}$	$\{\}$	$\{\hat{d}_1, \hat{d}_2, \hat{d}_3\}$
C_2	$\{\}$	$\{\hat{d}_1\}$	$\{\hat{d}_2, \hat{d}_3\}$
C_3	$\{\}$	$\{\hat{d}_1, \hat{d}_2\}$	$\{\hat{d}_3\}$
C_4	$\{\}$	$\{\hat{d}_1, \hat{d}_2, \hat{d}_3\}$	$\{\}$
C_5	$\{d_1\}$	$\{\}$	$\{\hat{d}_2, \hat{d}_3\}$
C_6	$\{d_1\}$	$\{\hat{d}_2\}$	$\{\hat{d}_3\}$
C_7	$\{d_1\}$	$\{\hat{d}_2, \hat{d}_3\}$	$\{\}$
C_8	$\{d_1, d_2\}$	$\{\}$	$\{\hat{d}_3\}$
C_9	$\{d_1, d_2\}$	$\{\hat{d}_3\}$	$\{\}$
C_{10}	$\{d_1, d_2, d_3\}$	$\{\}$	$\{\}$

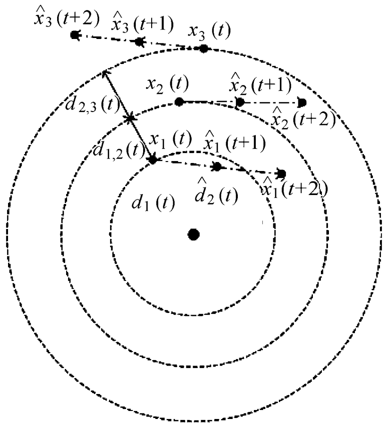

Fig.9. Identification of three objects when an object trajectory is not perfectly known to the system.

the case with the minimum power cost, the number of cases increases exponentially with the number of entering objects and it is almost impossible to estimate the power cost for all the cases in reality. Also, if other objects enter the coverage of the RFID reader at the next sampling time, the estimated association performance can be inaccurate. Thus, searching all the cases is an inefficient way to reduce the energy consumption.

3.3 Final Algorithm

The power cost model estimates the power consumption for multiple objects using the distance of the outermost object from the RFID reader by

$$\hat{P}(t) = f(\max_i d_i(t)), \qquad (2)$$

where $\hat{P}(t)$ denotes the estimated power cost at time t. When the system determines the distance of the outermost position, the system considers a possibility of single association disjointed from group association. If the object at the outermost position has a chance to establish single association by the identification of other positions, the corresponding outermost position is excluded in (2). The system activates the RFID reader at the current sampling time if $\hat{P}(t)$ is less than $\hat{P}(t+1)$. However, there is a case that the objects may leave the coverage without establishing any associations at the next sampling time. In this case, the system activates the RFID reader at the current sampling time to identify objects as many as possible even though $\hat{P}(t)$ is greater than $\hat{P}(t+1)$. Once it is determined to activate the RFID reader with its outermost position, the system also determines the order of the range according to the increasing order of $d_i(t)$ to the outermost position. If multiple distances are neighboring within Δd, the farthest distance among them is selected to ensure the group association with all positions.

However, the power cost estimation with only the distance of the outermost position may delay establishing single associations. For example, when two objects are within the coverage of the RFID reader as shown in Fig.10, $\max_i d_i(t)$ is greater than $\max_i \hat{d}_i(t+1)$ but $d_{1,2}(t)$ is greater than Δd and $\hat{d}_{1,2}(t+1)$ is smaller than Δd. According to (2), the system does not activate the RFID reader at the current sampling time. At the next sampling time, the system activates an RFID reader with the range of $\max_i d_i(t+1)$ but establishes the group association.

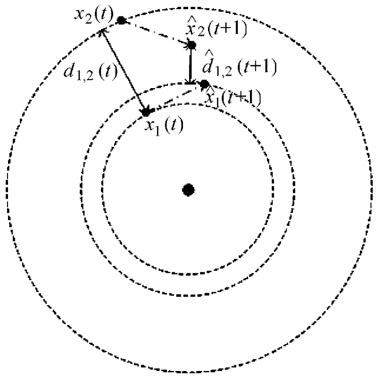

Fig.10. Delay establishing single associations by the maximum power estimation with only the distance of the outermost position.

In order to avoid delaying the establishment of single associations, the power cost also considers the effect of group associations by

$$\hat{P}(t) = \alpha_n \times f(\max_i d_i(t)), \qquad (3)$$

where α_n denotes the weight factor for establishing association with n positions with the outermost position. $n = 1$ indicates single association and $n > 1$ indicates group association for n objects. α_n ($n > 1$) is set to be larger than α_1 because group association is required to activate the RFID reader later to establish single association. By considering the weight factor for the association, $\hat{P}(t)$ becomes larger than $\hat{P}(t+1)$ according to the value of α_n in Fig.10. If α_2 is much larger than α_1, the system prefers establishing single associations. According to the weight factor, the system controls the degree of priority to establish single associations.

The two power cost models (2) and (3) make a decision with the distance of the outermost position. However, when more than two objects exist within the coverage of the RFID reader as shown in Fig.11, there is an additional case that some positions can be identified with the distance of inner positions. While $d_{1,2}(t)$ is greater than Δd but $d_{2,3}(t)$ is smaller than Δd, $\hat{d}_{1,2}(t+1)$ is smaller than Δd but $\hat{d}_{2,3}(t+1)$ is greater than Δd. By (2), the system delays the activation of the RFID reader because $\max_i \hat{d}_i(t+1)$ is smaller than $\max_i d_i(t)$. By (3), the system also delays the activation of the RFID reader because the outermost position can establish group association. Both the two power cost models lose the chance of a single association for object O_1 at time t. The power cost model (2) continuously delays the activation of the RFID reader for $t+1$ and $t+2$ again because the distance of the outermost position becomes smaller. On the other hand, the power cost model (3) activates the RFID reader to establish single association for object O_3 at $t+1$, and to establish group association for objects O_1 and O_2 at $t+2$. Because the system needs to activate the RFID reader for the group association later, the energy consumption of the RFID readers may increase.

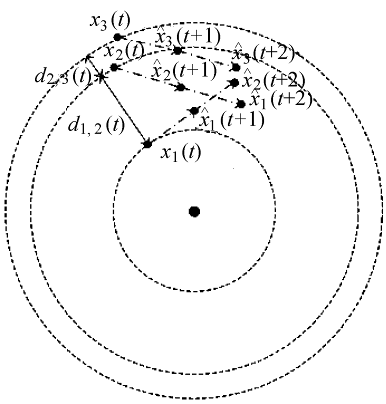

Fig.11. Necessity of activation of an RFID reader with the distance of inner positions to the center of an RFID reader for effective association.

In order to maximize the number of single associations as much as possible, the system also considers the activation of the RFID reader with the range obtained with inner positions for the additional case. The additional case is when $d_i(t)$ satisfies Δd but $\hat{d}_i(t+1)$ does not satisfy Δd. If the system has a chance to identify objects with inner positions for the additional case, the RFID reader is activated with the range of inner positions. For example, in Fig.11, $x_1(t)$ satisfies Δd but $\hat{x}_1(t+1)$ does not satisfy Δd . The system activates the RFID reader with the range of $d_1(t)$ to establish single association for object O_1. Then, objects O_2 and O_3 are also uniquely identified at time $t+1$ because $d_{2,3}(t)$ is greater than Δd.

4 Simulation and Analysis

4.1 Performance Evaluation and Analysis

4.1.1 Performance Comparison

The performance of three methods are compared in terms of energy consumption. The first method is the minimum energy consumption method to schedule an RFID reader under the assumption that object trajectories are completely known to the system. It has the lowest energy consumption regardless of association performance. The second method is the maximum energy consumption method to activate an RFID reader whenever objects enter the coverage under the assumption that object trajectories are unknown. The third method is the proposed power control by estimating the energy consumption with the weighted power cost model. It also considers the activation of an RFID reader with the inner positions of objects. For the evaluation, the sampling period of object trajectories is set to 0.5 s and the required separation Δd is set to 0.2 m. α_n is simply set to the number of positions established as group associations and set to one for single association. When one RFID reader is used, RFID reader R^1 is placed at (10 m, 10 m) with the maximum range of 5 m. For two RFID readers placement, R^1 and R^2 are placed at (5 m, 10 m) and (15 m, 10 m), respectively with the maximum range of 4 m. For four RFID readers, R^1, R^2, R^3 and R^4 are placed at (5 m, 5 m), (15 m, 5 m), (5 m, 15 m) and (15 m, 15 m), respectively with the maximum range of 4 m. The initial positions of objects O_1, O_2, O_3, O_4, O_5, O_6 and O_7 are (1 m, 1 m), (3 m, 19 m), (19.5 m, 5 m), (19.5 m, 15 m), (20 m, 10 m), (18 m, 2 m) and (20 m, 8.5 m), respectively with different velocities.

Fig.12 shows the simulation result to identify and associate 7 objects with 4 RFID readers. By the first method, objects are identified with the minimum range of RFID readers but it takes longer time to identify objects as shown in Fig.12(a) and Fig.12(d). Object O_2 is identified by RFID reader R^2 at time 20 even though the object enters the coverage of two other RFID readers R^3 and R^4 earlier. Object O_7 is not identified during the simulation because RFID reader R^2 is assigned to identify objects O_2 and O_6 and RFID reader R^1 is assigned to identify objects O_1 and O_3. On the other hand, in Fig.12(b) and Fig.12(e) with the second method, all the objects are identified faster with the longer range of RFID readers. However, the longer range increases the energy consumption of RFID readers. Fig.12(c) and Fig.12(f) demonstrate that objects are identified faster than the first method with the smaller range than the second method.

Fig.13 shows the simulation results to compare the performance of the three methods as varying the number of RFID readers and objects. The average association rate includes single associations as well as group associations. In both the first and the second method, as the number of objects increases, it takes longer time to identify objects because it is difficult to satisfy Δd. The association rate with the first method is more affected by the number of objects because it needs to

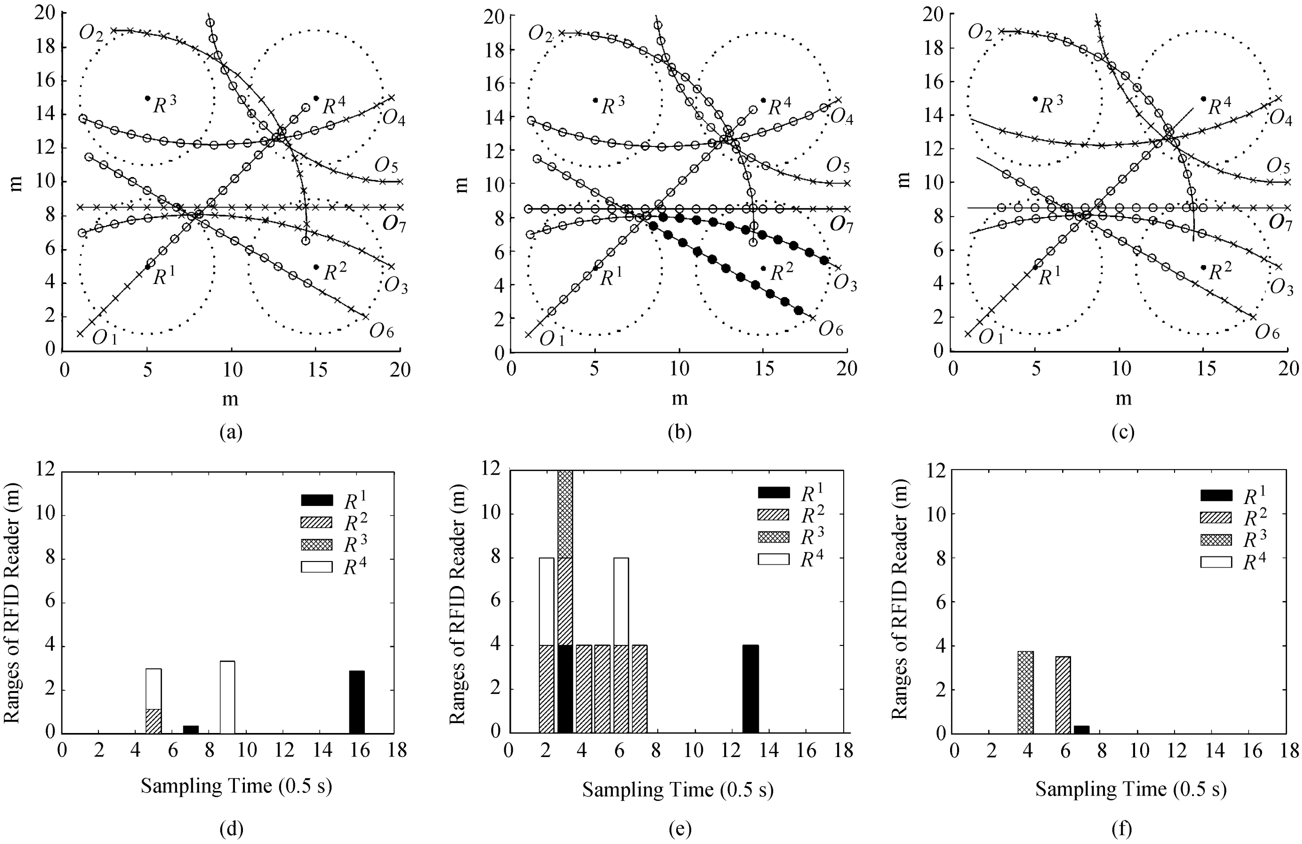

Fig.12. Comparison simulations as varying the number of objects and RFID readers in terms of activated ranges of RFID readers. (a) Association status for minimum energy consumption. (b) Association status for maximum energy consumption.(c) Association status for proposed power control.(d) Ranges of RFID reader for minimum energy consumption. (e) Ranges of RFID reader for maximum energy consumption. (f) Ranges of RFID reader for proposed power control.

satisfy both Δd and the minimum distance condition. On the other hand, with the second method, objects are identified much faster but the energy consumption is much higher than the first method. The proposed power control shows better association performance than the first method and less energy consumption than the second method.

4.1.2 Power Cost Model Analysis

Fig.14 shows the comparison simulation with three power cost models as varying the number of objects. The first power cost model only considers the distance of the outermost position and the second power cost model has the weight factor to reflect the effect of group association. The last power cost model considers only the activation of the RFID readers with the range of inner positions. Only one RFID reader is placed at (10 m, 10 m) with the maximum range 5 m to verify the performance of each power cost model. The required separation Δd is set to 0.2 m and T_s is set to 0.5 s. α_n is simply set to the number of positions established as group association and set to one for single association. The average association rate includes group association as well as single association. When the number of entering objects is small, the effect of Δd becomes insignificant. An RFID reader is activated at the same sampling time with the distance of the outermost position for all the three power cost models as shown in Fig.14(a) and Fig.14(d). On the other hand, as the number of objects increases, the two power cost models except the first cost model give a priority for establishing single associations. The second power cost model delays the activation of an RFID reader by the weight factor according to group association. The last power cost model additionally considers the establishment of single association with the inner positions. Therefore, the power cost models considering the single associations activate an RFID reader faster than the first power cost model as shown in Figs. 14(b), 14(c), 14(e) and 14(f).

Fig.15 shows the distances between positions in terms of the sampling time by the three different power cost models when the system identifies five objects. As shown in Fig.15(a), when the distance of the outermost

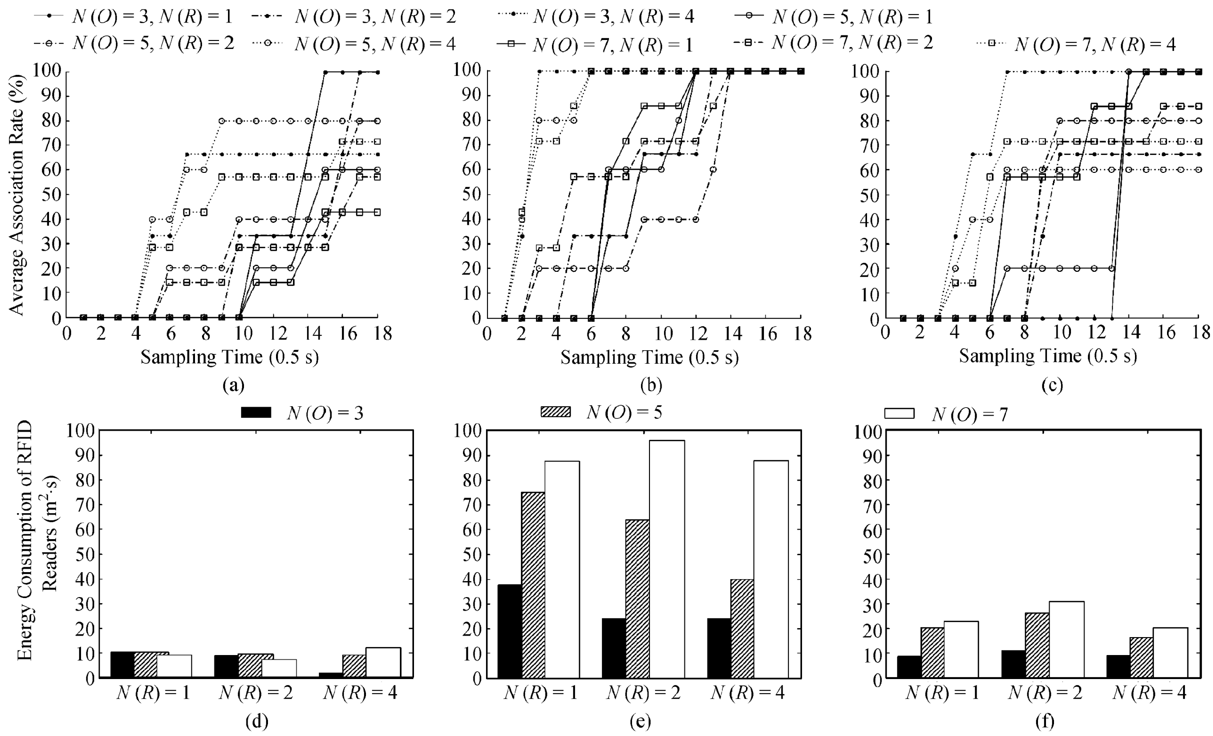

Fig.13. Comparison simulations as varying the number of RFID readers and objects ($\mathcal{N}(O)$ denotes the number of objects and $\mathcal{N}(R)$ denotes the number of RFID readers). (a) Average association rate for minimum energy consumption.(b) Average association rate for maximum energy consumption. (c) Average association rate for proposed power control. (d) Overall energy consumption for minimum energy consumption. (e) Overall energy consumption for maximum energy consumption. (f) Overall energy consumption for proposed power control.

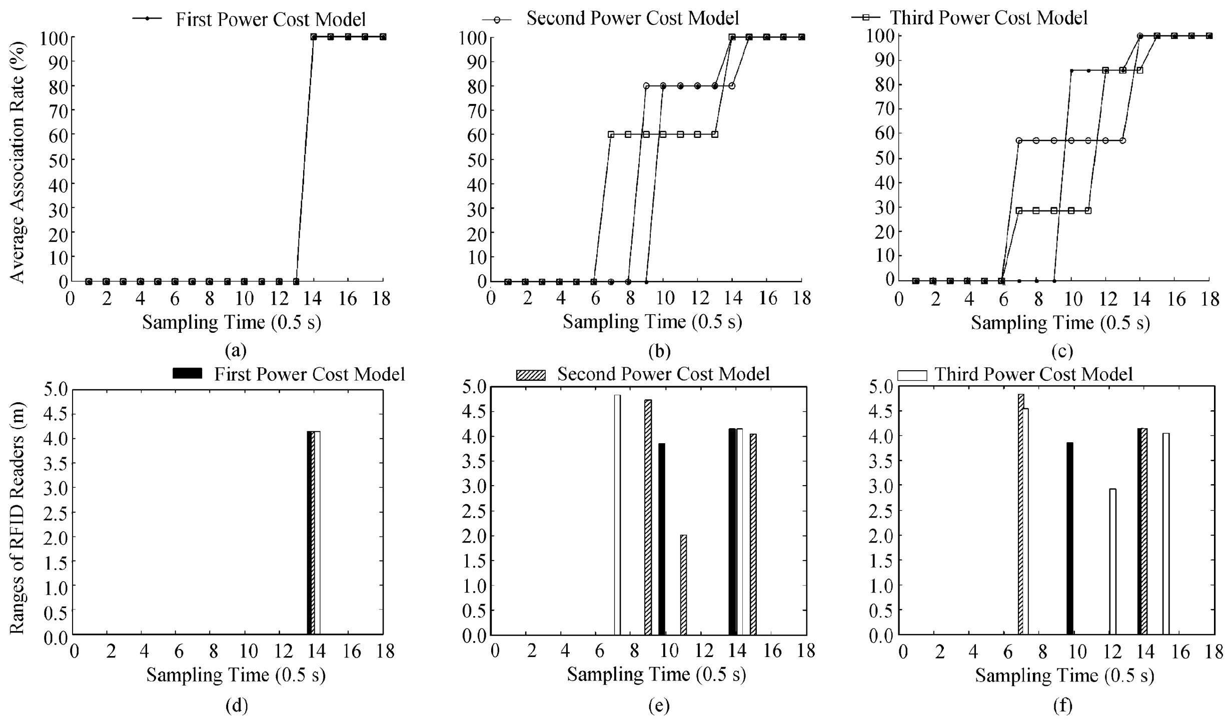

Fig.14. Comparison simulations with three algorithms for the average association rate and the activated ranges as varying the number of objects. (a) Average association rate for 3 objects. (b) Average association rate for 5 objects. (c) Average association rate for 7 objects. (d) Activated ranges for 3 objects. (e) Activated ranges for 5 objects. (f) Activated ranges for 7 objects.

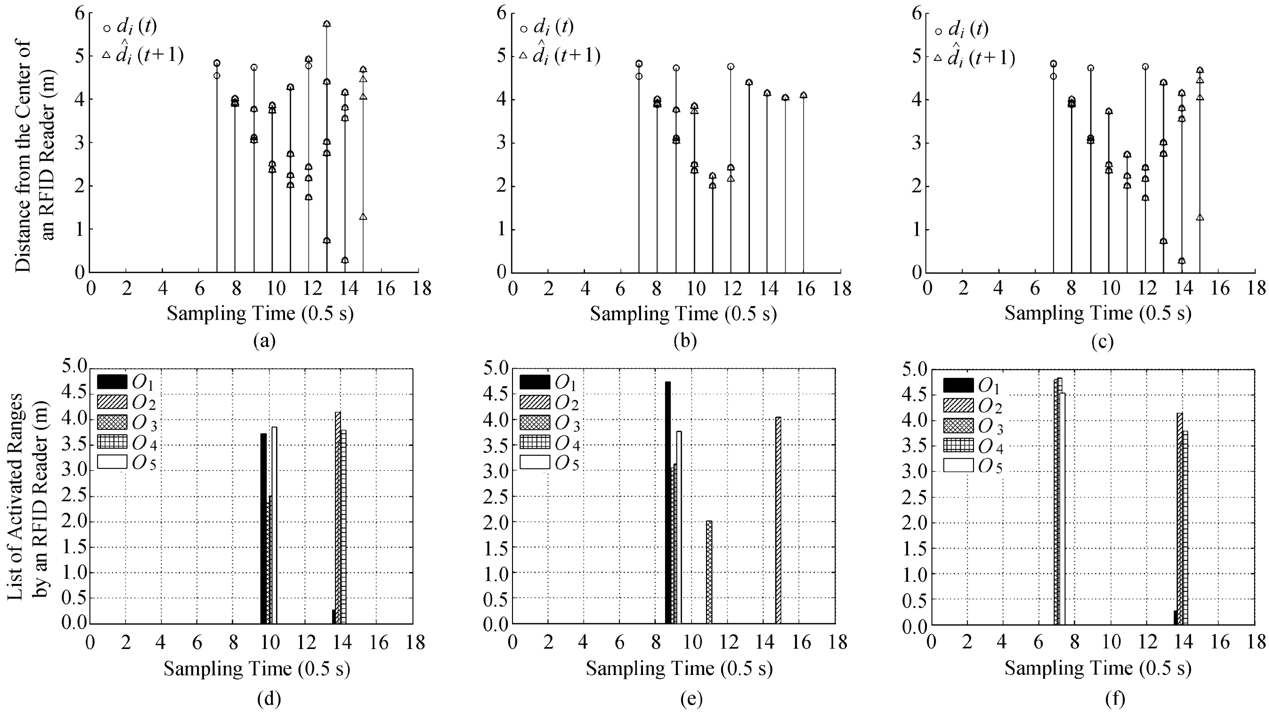

Fig.15. Comparisons of distances between object positions and activated ranges to identify 5 objects. (a) Distances between object positions by Algorithm 1. (b) Distances between object positions by Algorithm 2. (c) Distances between object positions by Algorithm 3. (d) Activated ranges by Algorithm 1. (e) Activated ranges by Algorithm 2. (f) Activated ranges by Algorithm 3.

position at the current sampling time is smaller than the estimated distance of the its estimated position at the next sampling time, an RFID reader is activated by the first power cost model. Because the first power cost model activates an RFID reader without considering association performance, an RFID reader is repeatedly activated for the same objects (i.e., O_1, O_3, O_4) at sampling times 10 and 14 as shown in Fig.15(d). On the other hand, the second power cost model activates an RFID reader as avoiding the establishment of group association of the outermost object. Hence, an RFID reader is not repeatedly activated for the outermost object but it can be repeatedly activated for the inner object (i.e., O_3) at the sampling times 9 and 11 as shown in Fig.15(b) and Fig.15(e). The last power cost model minimizes the repeated activation of an RFID reader for the same object because it considers the establishment of single associations for inner positions of the objects. Fig.15(c) and Fig.15(f) show that an RFID reader is activated for each object once.

4.2 System Evaluation with Fixed Range

Fig.16 shows the object trajectories and the corresponding association status to compare the performance of the proposed power control with the fixed range RFID readers. One RFID reader R^1 is placed at (10 m, 10 m) and the range is set to either 5 m or 2.5 m. The maximum range of the proposed power control is set to 5 m. The initial positions of the objects O_1, O_2, O_3, O_4, O_5, O_6 and O_7 are (1 m, 1 m), (3 m, 17 m), (19.5 m, 5 m), (19.5 m, 14.5 m), (20 m, 6 m), (18 m, 2 m) and (20 m, 8.5 m), respectively with different velocities. The sampling period of the object trajectories is set to 0.5 s and the required separation Δd is set to 0.2 m. As shown in Fig.16(a) and Fig.16(b), the fixed range RFID reader establishes many group associations. Because the wider range increases chances that objects enter the coverage simultaneously, the 5 m-fixed range reader establishes more group associations than the 2.5 m-fixed range reader. On the other hand, the proposed power control only activates the RFID reader for more single associations with less energy consumption as shown in Fig.16(c) and Fig.16(d).

Fig.17 shows the comparison in terms of average association rate as varying the number of objects. The average association rate includes single associations as well as group associations. The 5 m-fixed range reader reaches 100% at the sampling time of 9, the 2 m-fixed range reader reaches 100% at the sampling time of 12 $\sim$ 13, and the proposed power control method reaches 100% at the sampling time 9 $\sim$ 10. Although the 5 m-fixed range reader reaches 100% faster than the proposed power control method, most of the associations are the group associations as shown in Fig.16(a).

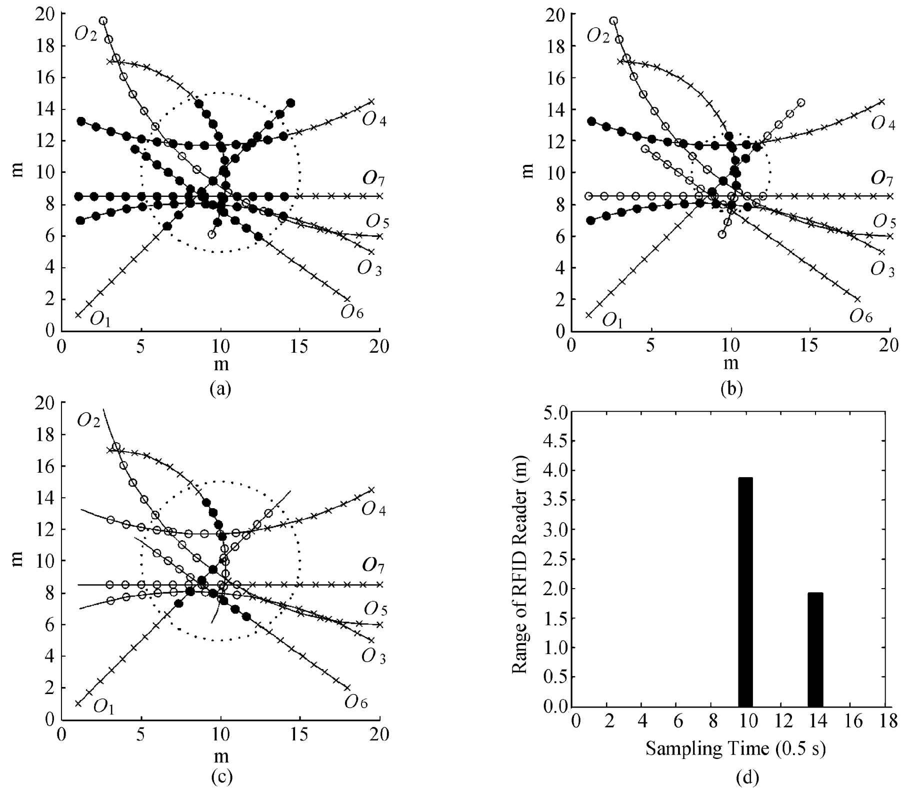

Fig.16. Object trajectories and association status of comparison simulations with the fixed range of 5 m and 2.5 m when the number of objects is 7. (a) Association status for fixed range of 5 m. (b) Association status for fixed range of 2.5 m. (c) Association status for proposed power control. (d) Ranges of RFID reader for proposed power control.

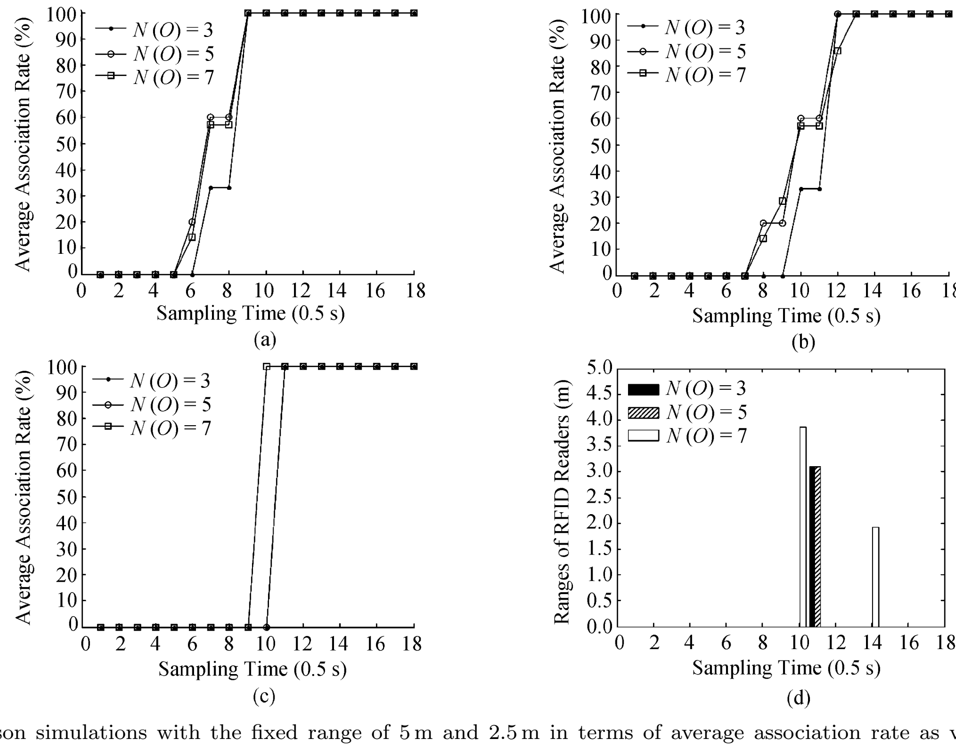

Fig.17. Comparison simulations with the fixed range of 5 m and 2.5 m in terms of average association rate as varying the number of objects. (a) Average association rate for fixed range of 5 m. (b) Average association rate for fixed range of 2.5 m. (c) Average association rate for proposed power control. (d) Ranges of an RFID reader for proposed power control.

On the other hand, the proposed control activates an RFID reader only once at the sampling time of 11 for $\mathcal{N}(O) = 3$ and $\mathcal{N}(O) = 5$, and two times for $\mathcal{N}(O) = 7$. The energy consumption is much less than those of the fixed range readers. As the number of objects increases, the number of the activations also increases to establish more single associations as shown in Fig.17(d).

Fig.18 shows the performance comparisons with the average time to establish the association and the average energy required for each association. The average time for each association does not show the big difference as shown in Fig.18(a). It is mainly because the average time includes group associations as well as single associations. Because the fixed range readers are always activated, they tend to establish many group associations for simultaneously entering objects. Fig.18(d) and Fig.18(e) show that the proposed power control achieves 100% of single association rate for all the three cases while the fixed range readers have many group associations. Also, the proposed power control is much more efficient than the fixed ranges in terms of the average energy for each association as shown in Fig.18(b). Fig.18(c) shows the energy-delay-product with the average time and the average sum of energies for each association and it proves that the proposed power control achieves an effective identification with much less activations.

Fig.19 shows the average performance comparisons with the fixed range readers from a realistic system perspective. We simulate three different RFID reader placements (i.e., $\mathcal{N}(R) = 1$, $\mathcal{N}(R) = 2$, $\mathcal{N}(R) = 4$) for 3 and 7 objects. The object trajectories are randomly generated 50 times for each case within the environment of $(x_{\min} = 3, x_{\max} = 17, y_{\min} = 3, y_{\max} = 17)$ and 50 performance results are averaged. The model of each trajectory is randomly selected with constant velocity or constant turn models[21] and the velocity is also randomly determined within the maximum magnitude of 4 m/s. The number of RFID readers is varied from 1 to 4 with the fixed ranges of 2.5 m or 5 m. The maximum range for the proposed power control method is set to 5 m. The sampling period of object trajectories is set to 0.5 s and the required separation Δd is set to 0.2 m. Fig.19(a) shows how object trajectories are generated. Obviously, the objects cross the range more often with the 5 m-fixed range readers than the 2.5 m-fixed range readers. As shown in Fig.19(b) and Fig.19(c), more RFID readers with wider ranges increase single association rate but decrease group association rate. The reason why the 2.5 m-fixed range reader has the smaller

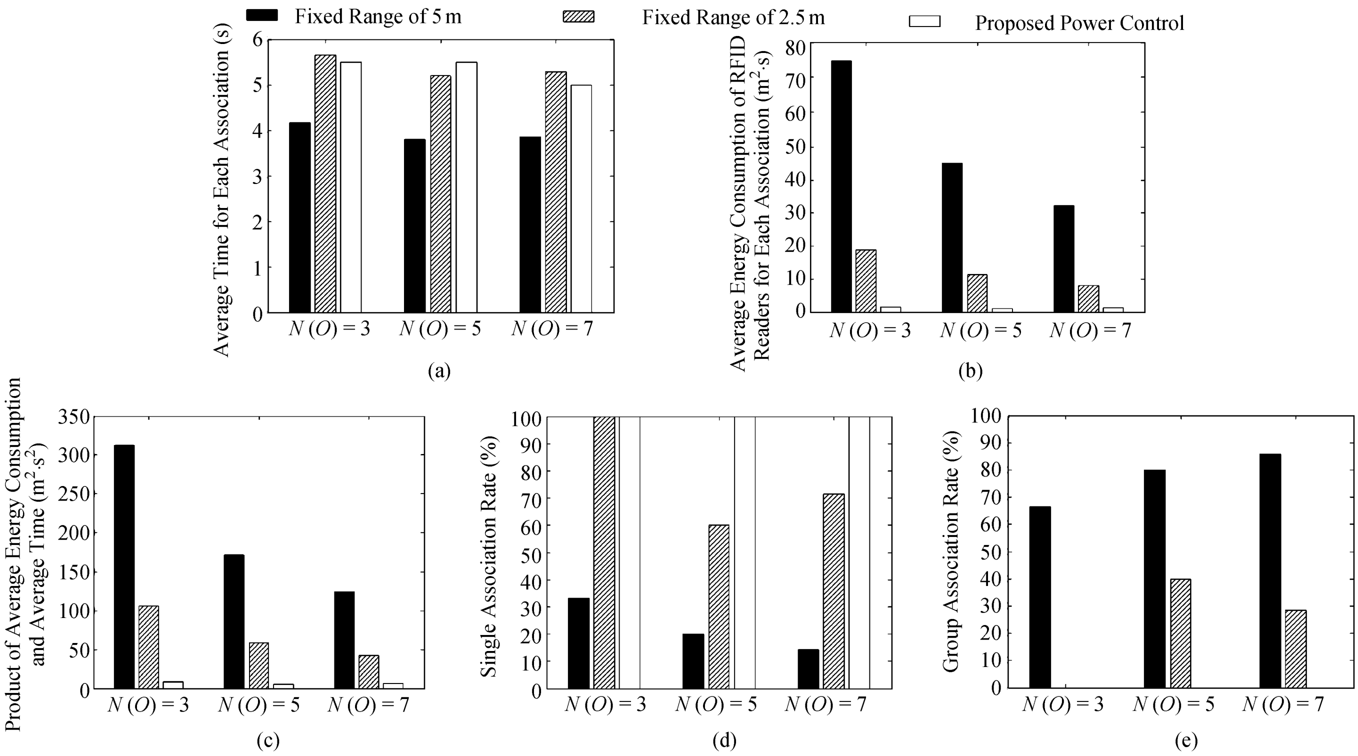

Fig.18. Performance comparisons with the fixed range of 5 m and 2.5 m as varying the number of objects in terms of average time and average energy consumption for each association. (a) Average time for each association. (b) Average energy consumption of RFID readers for each association. (c) Product of average energy consumption and average association time. (d) Single association rate. (e) Group association rate.

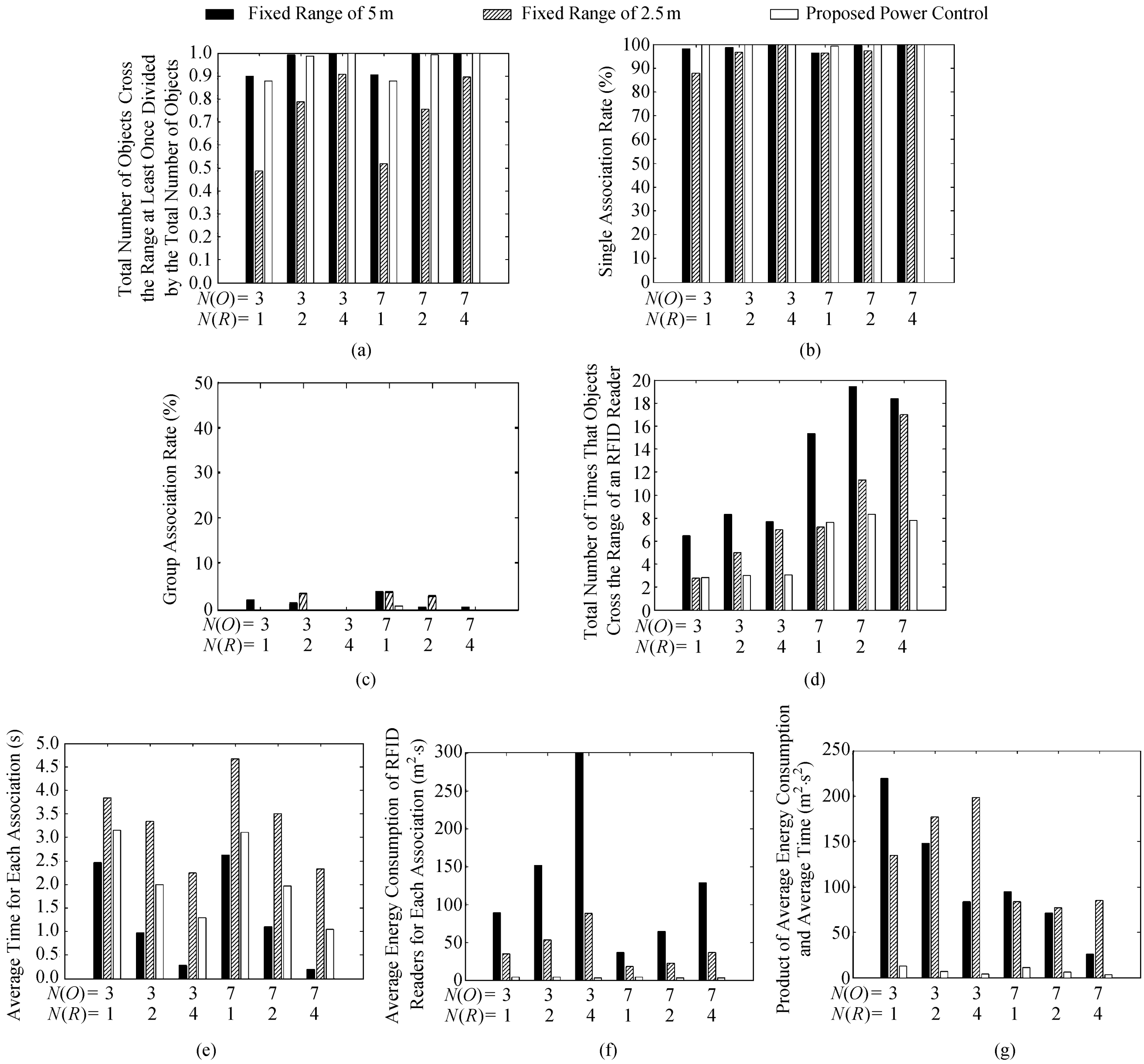

Fig.19. Average performance comparisons with the fixed range of 5 m and 2.5 m as varying object trajectories and RFID reader placements from a realistic system perspective. (a) Total number of objects cross at least once divided by the total number of objects. (b) Single association rate. (c) Group association rate. (d) Total number of times that objects cross the RFID range. (e) Average time for each association. (f) Average energy consumption of RFID readers for each association. (g) Product of average energy consumption and average association time.

single association rate is that it has less chances that multiple objects cross the range. The proposed power control has the similar total number of occurrences that objects cross the range for different RFID reader placements as shown in Fig.19(d). It is because objects cross the range only when RFID readers are activated. It shows that the proposed power control achieves object identification effectively with the minimum number of activations. On the other hand, with the fixed range readers, objects cross the range when they enter and leave the range. The fixed range readers waste the energy consumption. Fig.19(e) shows the average time for the object to establish the association. Because the 5 m-fixed range reader has the wider range than the 2.5 m-fixed range reader, the average time to get the association is shorter. On the other hand, because the proposed power control waits for the smaller power cost with the single association, it has slightly longer average time delay than the 5 m-fixed range reader. In terms of energy consumption for each association as shown in Fig.19(f), the 5 m-fixed range reader has the largest value among the three methods because it activates the range with high power level all the time. Although the 2.5 m-fixed range reader has smaller value of the average energy than the 5 m-fixed range reader, it has the largest value for the range delay product as shown in Fig.19(g) because of the long average time. The proposed power control outperforms the fixed ranges in terms of energy delay product. As the number of RFID readers increases, the average time for each association decreases but the average energy consumption for each association increases because more RFID readers increase the chances that objects cross the range.

5 Conclusions

This paper proposed an effective RFID reader power scheduling method for energy efficient multiple objects identification and association by varying coverage through power control. The proposed method can be effectively incorporated in many heterogeneous sensor networks where both visual sensors and RFID readers are deployed. The proposed method minimizes the system energy consumption by activating the RFID reader and establishing the association only when the object association can be maximized. The multiple objects positions and the trajectory estimates are used to decide the power level of RFID readers. The power cost model is incorporated into the method to minimize energy consumption and to maximize association performance. The performance comparison simulation shows that the proposed method achieves faster single associations than the method for the minimum energy consumption and less energy consumption than the method for the maximum energy consumption. Also, the realistic comparison simulation with the fixed ranges shows that the proposed method achieves higher single association rates with much less energy consumption. For the future work, we will investigate the RFID power scheduling for the overlapping coverage case with interference problem.

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