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A power control technique for anti-collision schemes in RFID systems

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ABSTRACT

The emerging technology of Radio Frequency IDentification (RFID) has enabled a wide range of automated tracking and monitoring applications. However, the process of interrogating a set of RFID tags usually involves sharing a wireless communication medium by an RFID reader and many tags. Tag collisions result in a significant delay to the interrogation process, and such collisions are hard to overcome because of the limited capabilities of passive RFID tags and their inability to sense the communication medium. While existing anti-collision schemes assume reading all tags at once which results in many collisions, we propose a novel approach in which the interrogation zone of an RFID reader is divided into a number of clusters (annuli), and tags of different clusters are read separately. Therefore, the likelihood of collisions is reduced as a result of reducing the number of tags that share the same channel at the same time.

In this paper, we consider two optimization problems whose objective is minimizing the interrogation delay. The first one aims at finding the optimal clustering scheme assuming an ideal setting in which the transmission range of the RFID reader can be tuned with high precision. In the second one, we consider another scenario in which the RFID reader has a finite set of discrete transmission ranges. For each problem, we present a delay mathematical analysis and devise an algorithm to efficiently find the optimal number of clusters. The proposed approach can be integrated with any existing anti-collision scheme to improve its performance and, hence, meet the demand of large scale RFID applications. Simulation results show that our approach makes significant improvements in reducing collisions and delay.

1. Introduction

Radio Frequency IDentification (RFID) is an emerging identification technology that has a great potential for monitoring and tracking applications [13]. It has an edge over other identification systems such as bar-code systems, optical character recognition systems, smart cards, and biometrics (voice, fingerprinting, retina scanning); that is because it requires no line-of-sight for communication, sustains harsh physical environments, allows simultaneous identification, and is cost and power efficient. RFID can turn everyday objects into a network of mobile nodes which can be tracked and monitored to trigger actions or to respond to requests.

An RFID system is typically composed of an application host, a reader, and a set of tags. A tag is designed to store between 96 bits and 64 K bytes of information. Tags can be either passive or active. A passive tag has no physical power source. It harvests energy from the reader's generated radio waves, using backscattering modulation [13,10]; and consumes that energy in carrying out processing and communication tasks. Passive tags, which

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dominate the RFID market, are very limited in terms of processing and communication. A passive tag just processes a simple state machine; it is not able to sense the communication medium or communicate with other tags. This makes the task of resolving passive tags collisions challenging. On the other hand, an active tag has a power source and may possess certain sensing capabilities for temperature or pressure. An RFID reader acts as a master for tags and a slave for the application host. This master–slave concept is depicted in Fig. 1.

Tags that can be interrogated by a certain reader are said to be within that reader's interrogation zone. Specifically, an interrogation zone is the physical area within which the electromagnetic waves, generated by the reader, are able to reach and charge the tags, and the tags' signals can be received and successfully decoded by the reader – a process known as singulation. At any arbitrary instant, a reader can read at most one tag within its interrogation zone and a tag can be read by at most one reader. Tags within the interrogation zone of a reader, and readers with overlapping interrogation zones, may simultaneously attempt to access the wireless medium for data communication. The simultaneous wireless medium access results in collisions that undermine the RFID system's overall performance. To maintain high performance operation, efficient mechanisms for Medium Access Control (MAC) are needed [10]. As with other radio-based systems, the main objective of such mechanisms is regulating access to the communication medium to reduce collisions in either a proactive or a reactive manner. In proactive mechanisms, collisions are avoided by distributing sufficient information about the medium to nodes sharing the medium. Reactive mechanisms respond to collisions and attempt to speed the system's recovery from a collision. Conventional collision avoidance methods, such as Carrier Sense Multiple Access (CSMA), cannot be adopted for RFID systems especially when passive tags are used. Avoidance mechanisms also require more complicated tags with sensing and/or synchronization capabilities. Proposals for RFID systems have, therefore, favoured reactive anti-collision approaches to deal with collisions. Specific to RFID systems, collisions can be classified based on the type of entities involved in the collision as follows [13,27]:

(1) *Tags-to-reader Collisions:* which occur when more than one tag within a reader's interrogation zone attempt to reply to a reader's request at the same time. Tags-to-reader collisions are the most devastating, especially when passive tags are involved. They result in reduced reading rates, wasted resources, and longer delays.

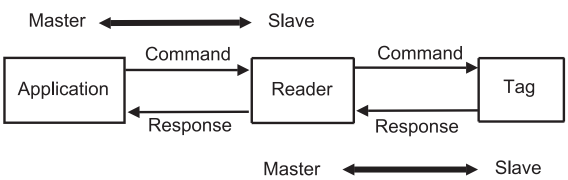

Fig. 1. A master slave architecture for RFID systems.

(2) *Readers-to-tag Collisions:* which occur when one tag is interrogated by more than one reader. In such a scenario, multiple readers try to singulate the same tag which results in corrupting the tag's internal state. As a result, the tag may not be detectable. Classical scheduling techniques are usually employed to overcome such collisions.

(3) *Reader-to-reader Collisions:* which occur as a result of the conventional frequency interference, i.e., multiple neighboring readers transmit using the same frequency at the same time. Existing mechanisms such as frequency-hopping, dynamic frequency allocation and dynamic power adjustment can be utilized to overcome these collisions.

The focus of our work in this paper is to overcome tags-to-reader collisions. While several schemes have been proposed to deal with tags' collisions in RFID systems, the interrogation delay is still a problem for some applications that involve dense and/or fast moving passive tags. This causes immense data collisions at the reader. For instance, Walmart buys hundreds of billion dollars worth of packaged good annually and is looking into RFID to provide better product visibility from distribution centers to its retails shelves. These items are brought from across the globe to its numerous supply management plants, involving hundreds of thousands of items on a daily basis, on its conveyors belts. This requires the tags to be readable with 100% success at 600 feet/min. However, the broadcast nature of the backscattered signal from the tags and the reader inability to process them in parallel affect the reading rates of current RFID systems. Moreover, the limited available bandwidth and low data rates reduce the reading rates further. For instance, existing RFID readers can support reading rates of up to 700 tags/s theoretically. Such reading rates (which are much lower in practice) are not adequate for typical item-level applications such as the one in Walmart which involves thousands of moving tags. Therefore, sophisticated anti-collision algorithms needs to be sought after to both meet existing applications requirements and attract new ones.

A promising direction to avoid a significant amount of collisions is to partition the interrogation zone spatially into smaller clusters (circles), and to have tags in each cluster being read separately (i.e., one cluster at a time). Any existing anti-collision scheme can be used to resolve collisions in a single cluster. That should reduce the number of collisions as it reduces the number of tags that may respond at the same time. To the best of our knowledge, the proposed Power-based Distance Clustering (PDC) scheme is the first to exploit such an approach. In PDC, the reader tunes the transmission power so that tags within the interrogation zone are clustered based on their distance from the reader. Tags which are being interrogated within the current cluster will not respond to the reader's queries for the subsequent clusters; as once read, these tags are forced into a sleep mode. A major advantage of the PDC approach is that it is not an alternative to existing approaches; it rather has the ability to be integrated smoothly with any existing anti-collision scheme to boost its performance and enable higher reading rates that meet the demand of large scale RFID applications.

We studied the viability and efficiency of the PDC scheme in [1]. However, it was not clear how to find the best partitioning scheme. Indeed, having too many clusters may result in many empty clusters, which is an extra overhead, and few clusters may result in having crowded clusters; both situations affect the performance of that approach significantly. In this paper, we use mathematical optimization to find the optimal number of clusters for the PDC scheme.

The contributions of this paper are as follows. We formulate two optimization problems for finding the clustering scheme that minimizes the number of collisions and, hence, reduces the interrogation delay. The first problem targets an ideal setting in which the transmission power and, hence, the transmission range of the RFID reader can be tuned with high precision. In the second problem, we relax this assumption and consider an RFID reader with finite, discrete transmission ranges. For each optimization problem, we present a mathematical delay analysis and devise an efficient method to find the optimal clustering scheme. Our proposed methods have been designed to adapt to different system environments such as the number of tags and their distribution. We also show the results of several experiments, using the ns-2 simulator [31], which verify the effectiveness and performance improvements of the PDC scheme in terms of number of collisions, reading rates, and delay.

The rest of the paper is organized as follows. Section 2 surveys existing literature related to RFID anti-collision protocols. Section 3 introduces our PDC scheme. In Section 4, we present a mathematical analysis and an optimal algorithm for clustering the interrogation zone of an RFID reader whose transmission range can be tuned with high precision. In Section 5, we present a mathematical analysis and an optimal algorithm for clustering the interrogation zone of an RFID reader with a finite number of transmission ranges. Section 6 presents the results of our experiments. Finally, Section 7 concludes our work.

2. Literature survey

Several anti-collision schemes exist in the literature. These schemes are generally divided into two categories: probabilistic and deterministic. Probabilistic schemes are usually variations of the slotted ALOHA scheme in which the reader initiates slots, and each tag randomly picks a slot and uses it for its transmission. In deterministic schemes, which are typically based on binary tree traversal and polling algorithms, the reader specifies a set of tags that are allowed to transmit in each slot. The main idea in these tree-based schemes is that upon detecting a collision, the reader gives the colliding tags turns to access the wireless channel. These turns are arbitrated based on the binary IDs of tags.

2.1. Deterministic anti-collision schemes

The Binary Search Tree (BST) is a prefix-based scheme that relies on the ability of the RFID reader to determine the position of the colliding bits [13]. An RFID reader starts with broadcasting an inquiring request in which all bits are set to 1. In case of a collision, another inquiring request is created and the most significant colliding bit is set to 0 in that request. Thereby, only those tags with an ID value less than or equal to that of the request will respond. This process continues until a single tag is identified. Once a tag is being read successfully, it is put into a sleep mode. During the sleep mode, the tag will not respond to any further requests until it is reset by the reader. This process continues until all the tags are identified. In the BST scheme, inquiring requests and tags' responses involve complete IDs. To overcome this, the dynamic binary search algorithm, which is proposed in [13], gets the tags to send only the less significant bits starting from the last colliding bit. This reduces the number of bits transferred between the tags and the reader; however, the number of identification cycles is the same as that of the BST scheme. An Enhanced BST (EBST) with backtracking is proposed in [26]. In the EBST scheme, the reader sends the location of the most significant colliding bit rather than sending a complete ID to compare with. When a tag receives such a location, it responds only if it has that bit, corresponding to that location, set to 0. When a tag is identified successfully by the reader, the reader backtracks to previous unsuccessful requests. The EBST scheme reduces the amount of data sent by the reader and lowers the tag reading delay because the singulation process does not start from the root of the tree as is the case with the conventional BST algorithm.

The bit-by-bit binary tree (BBT) scheme uses a bit-wise arbitration [16]. In the BBT scheme, a tag maintains a pointer to the last sent bit. Initially this pointer points to the Most Significant Bit (MSB) of a tag ID. The reader broadcasts an inquiring bit, either 0 or 1. A tag whose pointed bit matches the broadcasted bit sends the next less significant bit and updates the pointer. A non-matching tag will go into a sleep mode. On the reader's side, if the reader receives a bit without a collision, it uses this bit as the next inquiring bit. In case of a collision, the reader uses 0 as the next inquiring bit. A tag is identified once the pointer reaches the Least Significant Bit (LSB). The reader resets sleeping tags only after a single tag is successfully identified.

The Modified Bit-By-Bit Binary Tree (MBBT) scheme, which is proposed in [9], requests the bits one by one, starting from the LSB. In case of a collision at the kth bit, the reader deactivates all tags whose kth bit is 1. In the MBBT scheme, if tags' IDs are sequential, the identification time is reduced, otherwise, it shows the same performance as that of the BBT. The Enhanced Bit-By-Bit Binary Tree (EBBT) algorithm is proposed to overcome this [9]. In the EBBT scheme, the reader initially requests tags to send their IDs. The reader keeps track of the position of the collision bits while saving the non-collided bits. The reader sequentially requests the bits at the collision positions only and one by one. The EBBT scheme is energy efficient as it reduces the data transmission between the tags and the reader.

The adaptive memoryless protocol was proposed in [22] to effectively handle mobility (i.e., tags join and leave the interrogation zone) without requiring extra memory. To reduce tags' collisions, the scheme utilizes the information obtained from the previous identification process. The ID patterns resulting into idle cycles (i.e., no tag responses) and readable cycles are saved for the next identification process. Tags' collisions are reduced only when the tags' IDs do not change significantly.

The Query Tree (QT) is a memoryless scheme that does not require the tag to maintain any inquiring history (e.g., a bit pointer) [19]. During each interrogation cycle the reader broadcasts a query (which is a sequence of bits defining a prefix), and only those tags whose IDs matches the broadcasted prefix send the remaining of their ID bits back to the reader. If the reader detects a collision, it generates two queries: one with 0 and one with 1 appended to the prefix of the last query, and pushes them into a stack to be pulled one by one. The reader continues to pull queries from the stack and broadcast them until all tags have been identified. Several variations of the QT algorithm exist [3–8,12,25,30]. In the scanning-based pre-processing scheme, the tags' IDs are initially scanned to find the position of the collision bits [20]. A bit position map, consisting of the positions of all colliding bits, is sent to all tags. This mechanism condenses a tag ID length and its value to the length and value of the bit position map. The BBT or the QT protocol is used for arbitrating collisions of the condensed IDs. This scheme lowers data transmission and increases throughput at the cost of extra memory requirement of the tags.

An analytical approach for evaluating the performance of binary-tree-based anti-collision protocols is presented in [34].

2.2. Probabilistic anti-collision schemes

Probabilistic schemes are variations of the framed ALOHA scheme in which the reader broadcasts the frame length, and each tag picks a time slot and uses it to transmit its ID.One of these schemes is the framed slotted ALOHA in which the frame is divided into a number of slots and each tag randomly picks a slot and uses it to respond to the reader. The probability of a collision is then proportional to the number of tags using the same frame. The enhanced dynamic framed slotted ALOHA algorithm, which was proposed in [21], adjusts the frame size dynamically according to the number of tags.

Probabilistic schemes can be classified into two subcategories: static and dynamic. In static schemes, the frame has a fixed number of slots, which is suitable only for low tag densities. While static schemes are easy to implement, they do not adapt to different system variables such as the total number of tags, and this affects their performance. Dynamic schemes, on the other hand, tune the frame size to be in line with values of different system variables (e.g., number of tags). For example, the Dynamic Framed Slotted ALOHA (DFSA) scheme [13] sets the size of the current frame based on statistics from previous frames such as the number of successful slots and that of the collision ones. The EPC Class-1 Gen-2 Q-Algorithm [11] is another example of a probabilistic, dynamic scheme. The Q-Algorithm maintains a variable Q whose value is between 1 and 15. The frame size is 2^Q. At the beginning of a frame, a value for Q is broadcasted to all tags within the interrogation zone of a reader, and each tag randomly chooses a slot number from 0 to $2^Q - 1$ to use it for its transmission. Based on numbers of collision slots, idle slots, and successful slots; a new value for Q is selected for the next frame. Several dynamic schemes adjust the frame size based on estimates to the number of tags (tag count) [2,23,24,28]. The Advanced Framed Slotted ALOHA (AFSA) algorithm [28] estimates the number of tags, prior to initiating the interrogation process, and adjusts the frame size based on that. AFSA, however, may increase the frame size indefinitely, which is not practical with large tags populations. The Enhanced Dynamic Framed Slotted ALOHA (EDFSA) [21] overcomes this limitation by partitioning tags into groups and reading tags one group at a time (i.e., group by group). At the beginning of each reading round, the number of groups is determined based on the number of unread tags, and each tag joins one group based on its ID. While this scheme puts a bound on the number of tags sharing the same frame, it puts extra processing burden on tags.

Statistical algorithms [14,15,17] exploit statistical information to speed up the interrogation process. The Adaptive Slotted ALOHA Protocol (ASAP) [17] utilizes information relative to the tag population, from previous interrogation cycles and reading processes, to estimate the number of tags presently within the interrogation zone of the reader. The ML-based estimation algorithm is used for this purpose. The frame size is adjusted optimally to reflect the tag estimation. The mobility is supported by accounting for tag arrival and departure rate, while initiating the estimation and frame adjustment at the beginning of every interrogation cycle. The statistical algorithm resembles the deterministic anti-collision category and shares the same pros and cons.

3. The Power-based Distance Clustering (PDC) anti-collision scheme

The PDC is a divide-and-conquer anti-collision scheme in which tags are divided into clusters based on their distance to the reader. Tags in different clusters are then read separately (one cluster at a time). This has the potential to reduce the number of tags which can be concurrently active, lower the collision probability, and, hence, expedite the interrogation process. Partitioning the interrogation zone can be achieved by controlling the reader's antenna power level. The reflected power density and the reader range can be computed using the following formulas [13,29]:

$$S = \frac{\lambda^2 \cdot P_{reader} \cdot G_{Reader} \cdot G_{Tag}}{(4\pi)^2 R^4} \tag{1}$$

and

$$R = \frac{\lambda}{4\pi} \cdot \sqrt[4]{\frac{k \cdot P_{reader} \cdot G_{Reader}^2 \cdot G_{Tag}^2}{P_{back}}} \tag{2}$$

where S is the reflected power density, λ is the wavelength of the emitted electromagnetic wave, P_{reader} is the power supplied to the reader's antenna, R is the distance between the reader and the tag, G_{Reader} and G_{Tag} are respectively the antenna gain for the reader and the tag, and P_{back} is the power received by the reader from the tag. It follows from (1) that the power density reflected back by the antenna is proportional to the fourth root of the power transmitted by the reader. Also it follows from (2) that the reading distance between the tag and the reader can be changed by changing the power supplied to the reader's antenna while maintaining P_{back}. Hence, the interrogation range of the reader can be reduced by lowering P_{reader}.

An example of such a partitioning is shown in Fig. 2, where the interrogation zone is divided into three clusters: D_1, D_2, and D_3. When the reader sends a request to a particular cluster, only those tags in that particular cluster may respond. For example, assume that the reader just sent a request (query) to cluster D_2 after it had finished reading tags from cluster D_1. Then only tags from cluster D_2 (i.e., tags marked as t_2) will respond to that request. After all tags marked as t_2 have been read successfully, they are put into a sleep mode. Then, the reader transmission range is increased to cover cluster D_3 and a new request is sent. Now only tags from cluster D_3 (i.e., tags marked as t_3) will respond to the reader requests. This identification process continues until the reader reaches its maximum interrogation range. Any anti-collision scheme can be used to resolve collisions within a single cluster.

It is also important to notice that our PDC scheme can accommodate mobility of tags. To clarify this, let's consider two scenarios on the example of Fig. 2. In the first scenario, a tag t in D_1 moves to D_2 after being successfully read in D_1. In this case, the PDC protocol puts t into a sleep mode and, therefore, t will not respond to the reader's subsequent queries until it is reset by the reader. In the second scenario, the reader completes reading all tags in D_1 and then a tag t in D_2 moves to D_1. In this case the tag t will be read successfully because it will receive and respond to the reader's queries sent to D_2. This is actually because those queries will be sent over a distance covering D_1 and D_2, and all those tags that are not read yet (and, therefore, not in a sleep mode) will respond and get identified.

The scheme is sensitive to the size and the number of clusters. A large number of clusters in a sparse tag environments yields longer delays as a result of many empty clusters and idle cycles. On the other hand, a small number of clusters may result in having too many tags in one cluster which renders the scheme ineffective, especially in dense tag environments.

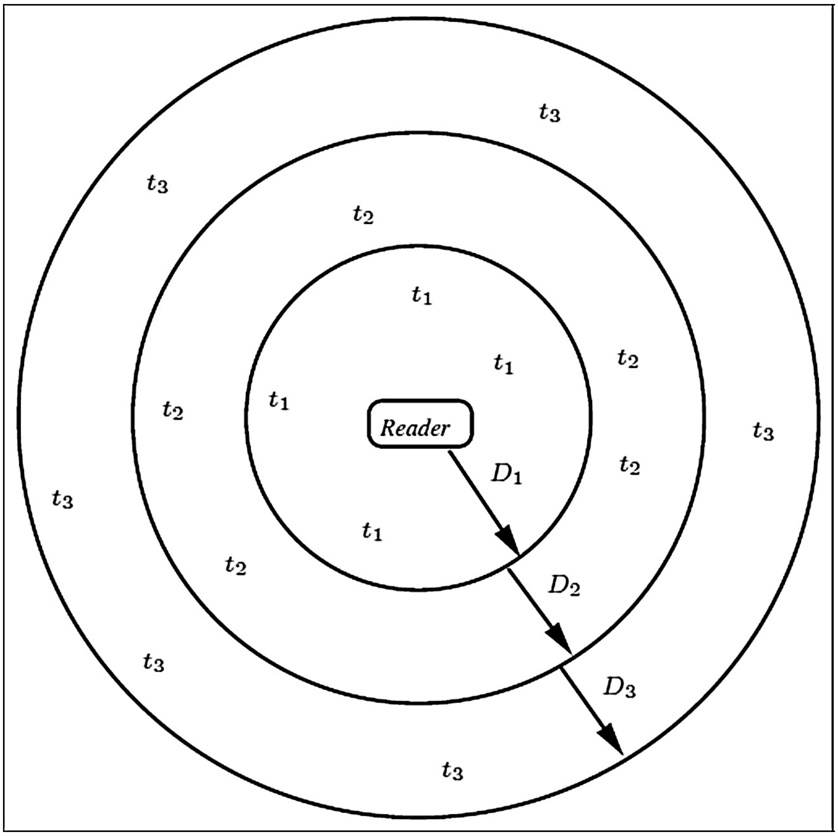

Fig. 2. An example of an interrogation zone of three clusters.

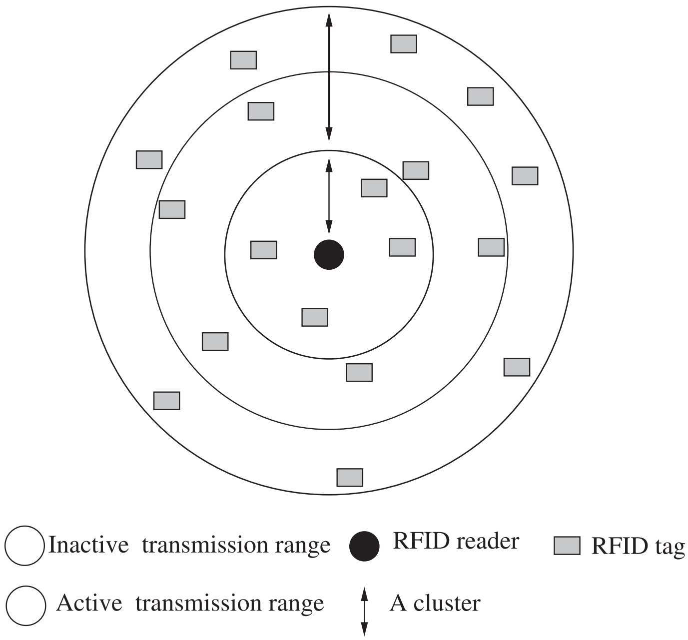

Fig. 3. An example of three transmission ranges and two clusters.

The Static PDC, which we proposed in [1], divides the interrogation zone into clusters based on a fixed stepping value *d*. This means that the transmission range of a cluster is more than that of the previous cluster by a fixed value *d*. While very simple, this scheme does not divide the interrogation zone into equal-size clusters and does not adapt to different tags densities. However, it has the ability to be integrated with any anti-collision scheme and it has shown acceptable improvements as shown in Section 6.

Another way to partition the interrogation range of a reader is to use Space Division Multiple Access (SDMA), which divides the interrogation range into cake-slice sectors [33]. However, this requires the use of special multi-antenna readers, and has the drawback of not utilizing half of the sectors when the reader is attached to a wall for example. Nevertheless, our optimization schemes can be equally applied to SDMA-based clustering.

4. Optimal Power-based Distance Clustering (O-PDC)

In this section we present our theoretical analysis and methodology for finding the optimal power-based distance clustering scheme. This scheme targets RFID readers whose transmission power can be tuned with a high precision so that the transmission range can be controlled with high accuracy.

4.1. System model and problem definition

We consider an RFID system consisting of an RFID reader and *n* passive tags. The interrogation zone is modeled as a circle centered at the RFID reader with a radius of *R* units; the RFID reader can communicate with, and read, all tags located within its interrogation zone.

The interrogation zone is divided into *k* equal size clusters, and tags in each cluster will be read separately (existing protocols use $k = 1$). In general, any anti-collision protocol can be used to resolve collisions in a particular cluster. The RFID reader and tags will go through several cycles during the reading process; in each cycle the RFID reader sends a request and zero, one, or more tags respond to the request by sending their IDs. An idle cycle is one in which no tag responds, a successful cycle is one in which exactly one tag responds, and a collision cycle is one in which two or more tags respond. Upon detecting a collision, the RFID reader will send a more restricted request which excludes some of the colliding tags. Eventually, a tag will be read successfully. This process will be repeated until all tags are read successfully. Now, the problem can be defined as follows:

> Find the optimal number of clusters that minimizes the total number of cycles required to read all tags.

4.2. Assumptions

To resolve collisions within a single cluster, we use the Query Tree (QT) protocol [19]. Nevertheless, any existing tree-based protocol can be equally used for that purpose. We also assume that tags are uniformly distributed over the interrogation zone. However, a very similar analysis can be performed to deal with other distributions. We also assume that the total number of tags is known to the reader; several schemes in the literature (e.g., [18]) are able to find a precise estimation to the number of tags in a negligible time.

4.3. Delay analysis

Let $f(n)$ denote the number of cycles required to read a set of n tags, and let $E[f(n)]$ denote the expected value for $f(n)$. For the QT protocol, it has been shown in [19] that for $n \geqslant 4$,

$$2.881n - 1 \leqslant E[f(n)] \leqslant 2.887n - 1 \tag{3}$$

To generalize our analysis to other tree-based anti-collision schemes (e.g., the recent work in [26][1]), we will have:

$$E[f(n)] = c\ n - 1, \tag{4}$$

where c is a constant.

Now, assume that the interrogation zone is divided into k equal size clusters, and tags are uniformly distributed over the interrogation zone. Let $g(n,k)$ denote the number of cycles required to read a set of n tags uniformly distributed over k clusters and using distance-based clustering. Thereby, we deduce the following lemma.

Lemma 1. *If we have n tags, and the interrogation zone is divided into k equal size clusters, then*

$$E[g(n,k)] = c\ n - k + 2s, \tag{5}$$

where s is the number of empty clusters (i.e., clusters which do not contain any tag).

Proof. We have s empty clusters and t non-empty clusters. Let n_i denote the number of tags in the ith non-empty cluster. For each empty cluster, we will have a single idle cycle; this results in a total of s cycles. The expected number of cycles required to read tags in the ith non-empty cluster is $c\ n_i - 1$. Therefore, the expected number of cycles required to read tags in all non-empty clusters is $c\ n - t$. Therefore, the expected total number of cycles is $c\,n - t + s$, but $t = k - s$, so we get $c\ n - k + 2s$. □

Now, we deduce the following lemma for the expectation of the number of empty clusters.

Lemma 2. *If tags are uniformly distributed over the interrogation zone, then*

$$E[s] = k\left(\frac{k-1}{k}\right)^n \tag{6}$$

Proof. Let P_i denote the probability that the ith cluster is empty (i.e., no tag is located in that cluster). Then,

$$E[s] = \sum_{i=1}^{k} P_i \tag{7}$$

$$= \sum_{i=1}^{k}\left(\frac{k-1}{k}\right)^n \tag{8}$$

$$= k\left(\frac{k-1}{k}\right)^n \quad \square \tag{9}$$

[1] The scheme proposed in [26] has $f(n) = 2n - 1$.

The following theorem is a direct result from Lemmas 1 and 2.

Theorem 1. *If we have n tags uniformly distributed over k equal size clusters, then*

$$E[g(n,k)] = c\ n - k + 2k\left(\frac{k-1}{k}\right)^n \tag{10}$$

4.4. Optimizing the delay

The objective of this sub-section is to find the optimal number of clusters (i.e., the value of k that minimizes $E[g(n,k)]$). We start with the following lemma.

Lemma 3. *$E[g(n,k)]$ is a convex function over the interval $[1,\infty)$.*

Proof. $E[g(n,k)]$ is twice differentiable with respect to k over the interval $(0,\infty)$, and

$$\frac{d^2}{dk^2}\ E[g(n,k)] = \frac{2n}{k^3}(n-1)\left(\frac{k-1}{k}\right)^{n-2} \tag{11}$$

Since $n \geqslant 1$ and $k \geqslant 1$, $\frac{d^2}{dk^2}\ E[g(n,k)]$ is non-negative. Therefore, $E[g(n,k)]$ is convex over the interval $[1,\infty)$. □

From Lemma 3, we know that the optimal value for k is the one at which $\frac{d}{dk}E[g(n,k)] = 0$. Therefore, we need to solve the following equation.

$$-1 + 2\left(\frac{k-1}{k}\right)^n + \frac{2n}{k}\left(\frac{k-1}{k}\right)^{n-1} = 0 \tag{12}$$

Let x_{opt} denote the solution to Eq. 12. In general, there is no closed-form solution to Eq. 12. However, it can be solved by numerical methods. Moreover, since the number of clusters is integer, we just need to find an integer x_{int}, such that $x_{int} \leqslant x_{opt} \leqslant x_{int} + 1$; the optimal number of clusters is either x_{int} or $x_{int} + 1$. The following lemma shows that $1 \leqslant x_{int} \leqslant n - 1$.

Lemma 4. *When there are n tags, the optimal number of clusters is at most n.*

Proof. To prove Lemma 4, it suffices to show that the expected number of cycles with n clusters is less than that with $n + i$ clusters, where $i \geqslant 1$, (i.e., we need to show that $E[g(n,n)] < E[g(n,n + i)]$). With $n + i$ clusters, we are certain (with probability 1) that at least i clusters are empty, which results in i idle cycles. Thus,

$$\begin{aligned} E[g(n,n+i)] &= E[g(n,n+i)|\text{at least } i \text{ clusters are empty}] \\ &= i + E[g(n,n)] > E[g(n,n)] \quad \square \end{aligned} \tag{13}$$

Since $E[g(n,k)]$ is convex and the optimal number of clusters is at most n, $\frac{d}{dk}E[g(n,k)]$ is a non-decreasing function. Therefore, one can find the optimal solution through binary search over the set $\{1,2,\ldots,n\}$. Algorithm 1 finds the optimal number of clusters in $O(\log n)$.

Algorithm 1. Optimal Clustering

Function Derivative(n, i)
Input: n: the number of tags.
i: an integer between 1 and n.
Output: $\frac{d}{dk}E[g(n,k)]$ at $k = i$.
begin
  return $-1 + 2\left(\frac{i-1}{i}\right)^n + \frac{2n}{i}\left(\frac{i-1}{i}\right)^{n-1}$;
end
Function FindOptimal(n)
Input: n: the number of tags.
Output: the optimal number of clusters.
begin
  left = 1;
  right = *n*;
  while right-left > 1 **do**
    if Derivative $\left(n, \left\lfloor\frac{left+right}{2}\right\rfloor\right) < 0$ **then**
      $left = \left\lfloor\frac{left+right}{2}\right\rfloor$;
    else
      $right = \left\lfloor\frac{left+right}{2}\right\rfloor$;
    end
  end
  if |Derivative $(n, left)$| < |Derivative $(n, right)$| **then**
    optimal = *left*;
  else
    optimal = *right*;
  end
  return *optimal*;
end

5. Optimal Discrete Power-based Distance Clustering (OD-PDC)

In the previous section we presented an exact, optimal scheme that is suitable for an ideal setting in which RFID tags are uniformly distributed and the RFID reader has a precisely tuneable transmission range. In this section we present a near-optimal scheme that suits RFID readers with discrete transmission ranges (i.e., a finite number of transmission ranges). To the best of our knowledge, this applies to all today's commercial RFID readers (e.g., SkyeTek/M10 RFID reader [32]). Furthermore, the scheme we present here is not limited to any particular distribution for the tags nor to any particular anti-collision protocol to resolve collisions in single clusters. We present a dynamic-programming algorithm that finds a near-optimal set of clusters for this setting.

5.1. System model and problem definition

We consider an RFID system consisting of an RFID reader and n passive tags. The interrogation zone is modeled as a circle centered at the RFID reader with a radius of R units; the RFID reader can communicate with, and read, all tags located within its interrogation zone.

The RFID reader has k discrete transmission ranges Tr_1, $Tr_2, \ldots, Tr_k$; where $Tr_1 < Tr_2 < \cdots < Tr_k = R$. We also use $Tr_0 = 0$ to denote a virtual transmission range. Each transmission range may and may not be used in interrogating RFID tags; this makes it possible to divide the interrogation zone into up to k clusters. A cluster is the area between two consecutive active (i.e., used) transmission ranges as shown in Fig. 3. For example, when $k = 3$, we can have three clusters if all transmission ranges are active. We may also have two clusters if only Tr_1 and Tr_3 are active, and we may have only one cluster if only Tr_3 is active. Note that Tr_k must be active in order to cover the whole interrogation zone. A *clustering scheme* is defined by a subset of transmission ranges to be active. A clustering scheme defines the set of clusters used in reading all tags in the interrogation zone. Now, the problem can be defined as follows:

> Find a clustering scheme that covers the whole interrogation zone, such that the total number of cycles required to read all tags is minimized.

5.2. Assumptions

To resolve collisions within a single cluster, any anti-collision scheme can be used. We assume that the distribution of tags is known; yet we do not assume a particular distribution. In fact all what is required by this scheme is the probability that a particular cluster is empty of tags; a detailed distribution does not have to be available. We also assume that the total number of tags is known to the reader.

5.3. Delay analysis

This subsection explains how each cluster decreases or increases the total number of cycles. A cluster is defined by a pair of transmission ranges that bound it (e.g, the cluster (i,j) is the area between Tr_i and Tr_j). It is obvious that more clusters results in less collisions; we can for example add more clusters until each cluster has at most one tag and, hence, there will be no collisions. However, increasing the number of clusters arbitrarily results in having many empty clusters and, hence, additional idle cycles. Based on this observation, we should maximize the number of non-empty clusters and minimize the number of empty clusters. While the negative effect of an empty cluster is straight forward (which is one additional idle cycle), quantifying the positive effect of a non-empty cluster depends heavily on the anti-collision scheme used within single clusters. To make a general optimization scheme, we assume that an empty cluster adds one extra idle and a non-empty cluster saves d cycles. Therefore, the objective is:

$$\text{MAX } \alpha d - \beta, \tag{14}$$

where α is the number of non-empty clusters and β is the number of empty clusters.

For some anti-collision schemes, finding the exact value of d is trivial. For example, the binary anti-collision algorithm with backtracking has $d = 1$ [26]. On the other hand, it is not easy to find the exact value of d for some

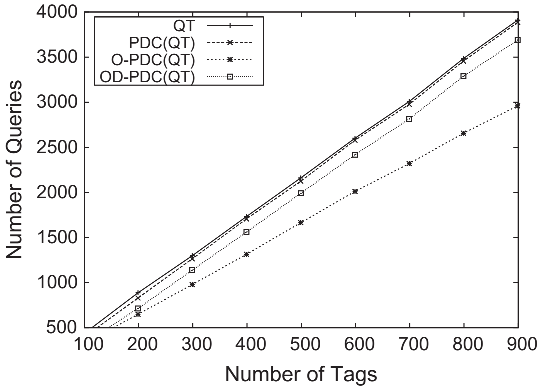

Fig. 4. Total number of queries with the QT scheme.

probabilistic anti-collision schemes. Nevertheless, we can use $d = 1$ to reflect the objective of maximizing the number of non-empty clusters and minimizing the number of empty clusters regardless of the anti-collision scheme being used to resolve collisions within single clusters.

Each cluster will contribute to the objective function in (14). Let us give each cluster a rank based on its expected contribution to the objective function, and let $h(i,j)$ denote the rank of a cluster (i,j). $h(i,j)$ can be computed as follows.

$$h(i,j) = P(n_{(i,j)} > 0) * d - P(n_{(i,j)} = 0), \tag{15}$$

where $n_{(i,j)}$ is the number of tags located in the cluster (i,j) and $P(e)$ is the probability of an event e, which can be computed based on the distribution of tags. This is based on the fact that a non-empty cluster saves d cycles and an empty one adds an extra idle cycle. When the rank of a cluster is negative, it means that the cluster is expected to add an extra cycle rather than to save cycles. The rank of a clustering scheme cl, which is denoted by $H(cl)$, is the sum of the ranks of clusters composing cl. The optimal clustering scheme is one with the maximum rank.

5.4. Optimal clustering algorithm

In this sub-section we present an algorithm that finds the optimal clustering scheme (a clustering scheme is defined by a subset of transmission ranges to be active). In general when there are k transmission ranges, there will be 2^{k-1} possible clustering schemes that cover the whole interrogation zone; it is actually equivalent to the number of all subsets of a set of $k - 1$ elements. We present a dynamic programming algorithm to solve this problem. This algorithm finds the clustering scheme whose rank is maximum.

We start with some definitions. Let $CL[i]$ denote the set of all clustering schemes in which Tr_i is active and Tr_j is inactive for all $j > i$. Let $M[i]$ denote the maximum rank of a clustering scheme in $CL[i]$ (i.e., $M[i] = \text{MAX}_{cl \in CL[i]} H(cl)$). It is obvious that when we have k transmission ranges, $CL[k]$ will belong to the optimal clustering scheme. The algorithm is described in Algorithm 2.

Algorithm 2. Optimal Discrete Clustering

```
Function Find Optimal (n,k)
Input n: the number of tags.
      k: the number of transmission ranges.
Output: The optimal clustering.
M[0] = 0;
for i = 1 to k do
  Next[i] = 0;
  M[i] = h(i,0);
  for j = 1 to i − 1 do
    if M[j] + h(i,j) > M[i] then
       M[i] = M[j] + h(i,j);
       Next[i] = j;
    end
  end
end
return (M[k],Next[]);
```

6. Experimental results

In this section, we present the results of a simulation based study we conducted to evaluate the performance of the PDC schemes. We investigate the performance improvements that can be made by the three PDC schemes presented in this paper: the static PDC which is presented in Section 3, the Optimal PDC (O-PDC) which is presented in Section 4, and the Optimal Discrete PDC (OD-PDC) which is presented in Section 5. We study the performance of these schemes by generating random RFID networks (topologies) and comparing the performance of a particular pure classical anti-collision scheme (i.e., without PDC) with that of the PDC scheme integrated with the same classical scheme. We may, for example, compare the performance of the pure QT scheme with that of the O-PDC integrated with the QT scheme (i.e., the O-PDC scheme withe the QT scheme being used to resolve collisions within single clusters).

6.1. Experimental methodology

We extended the ns-2 simulator [31] to implement RFID. We generate random RFID topologies in which tags are uniformly distributed in a grid of $20 \times 20\ \text{m}^2$. A single reader is located at the center of the grid. The reader has a maximum transmission range of 10 m. For the PDC scheme, we have a stepping value of 0.5 m (i.e., $d = 0.5$ m). For the OD-PDC, we have 30 transmission ranges. Tags have randomly generated IDs. In each RFID network, an anti-collision scheme is applied and its operation continues until all tags are successfully identified by the reader. We use several performance metrics to evaluate and compare different schemes. The main metric is the total number of queries (cycles) needed to identify all tags, which is a direct indicator to the performance of different schemes. We also consider the ratio of successful queries, the ratio of collision queries, and the ratio of idle queries. The results are averaged over 20 randomly generated topologies.

Our PDC schemes are compared with three existing schemes, namely the QT scheme, the EBST scheme, and the Q-Algorithm scheme. To compare the performance of our PDC schemes with these existing schemes, we show, for each performance metric, the result of the existing scheme without any clustering and the results of the PDC schemes when integrated with that particular existing scheme. This clearly shows the improvements that can be achieved using different PDC schemes. The O-PDC scheme is compared with the QT and EBST schemes only because they meet the assumptions made for the O-PDC scheme. On the other hand, the PDC scheme and the OD-PDC scheme do not have any assumptions on the classical anti-collision scheme being used to resolve collisions in single clusters and, hence, they are compared with the QT scheme, the EBST scheme, and the Q-Algorithm scheme.

6.1.1. Total number of queries

The main indicator for the efficiency of an anti-collision scheme is the total number of queries needed to identify all tags. Fig. 4 shows the improvements made by the PDC schemes when integrated with the QT scheme as compared to the pure QT scheme. The O-PDC scheme saves around 35% of the queries. The OD-PDC scheme saves around 20% of the queries. Fig. 5 shows the results of the PDC schemes when integrated with the EBST scheme. The O-PDC scheme saves around 25% of the queries. The OD-PDC scheme saves around 10% of the queries. Fig. 6 shows the results of the PDC schemes when integrated with the Q-Algorithm scheme. The OD-PDC scheme saves around 25% of the queries. The static PDC scheme saves around 10% of the queries.

6.1.2. Ratio of successful queries

To understand the behavior of different schemes, we look into the ratio of successful queries to the total number of queries in different schemes. In fact, this metric is inversely proportional to the total number of queries. This is because the total number of successful queries should be the same for all schemes; it is actually the same as the number of tags. However, this metric helps to see how the behavior of different schemes changes with different tags densities. Fig. 7 shows the ratio of successful queries achieved by the PDC schemes when integrated with the QT scheme and that of the pure QT scheme. Fig. 8 shows the ratio of successful queries achieved by the PDC schemes when integrated with the EBST scheme and that of the pure EBST scheme. It is not a surprise to see constant ratios for the pure QT scheme and for the pure EBST scheme. The reason is that for these two schemes, the total number of queries is a linear function of the number of tags. The nice observation here is the stable behavior of the PDC schemes, and specially the O-PDC scheme. Indeed, this means that the improvements made by the O-PDC scheme are the same regardless of the number of tags. Fig. 9 shows the ratio of successful queries achieved by the PDC schemes when integrated with the Q-Algorithm scheme and that of the pure Q-Algorithm scheme. The probabilistic nature of the Q-Algorithm makes the ratio of successful queries less stable than those of the QT and the EBST schemes. This directly affects the stability of the same ratio for the PDC schemes when integrated with the Q-Algorithm. However, as shown in Fig. 9, the improvements made by the PDC schemes stay significant regardless of the tags densities.

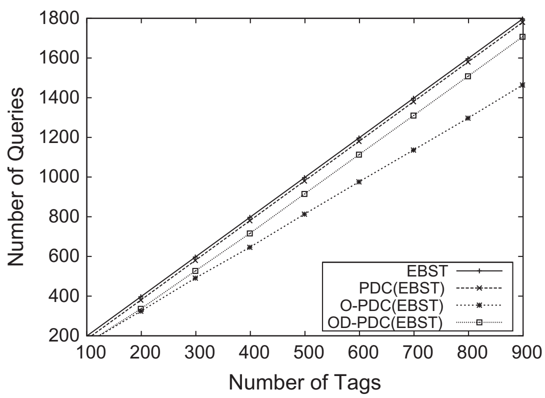

Fig. 5. Total number of queries with the EBST scheme.

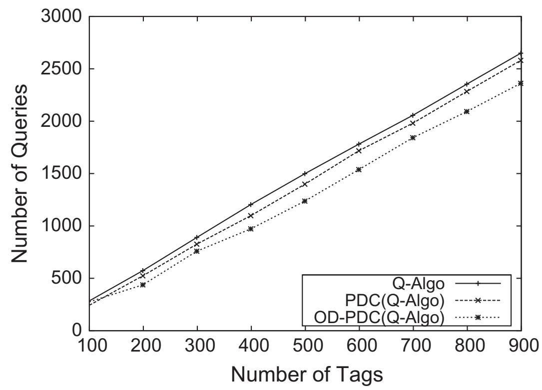

Fig. 6. Total number of queries with the Q-Algorithm scheme.

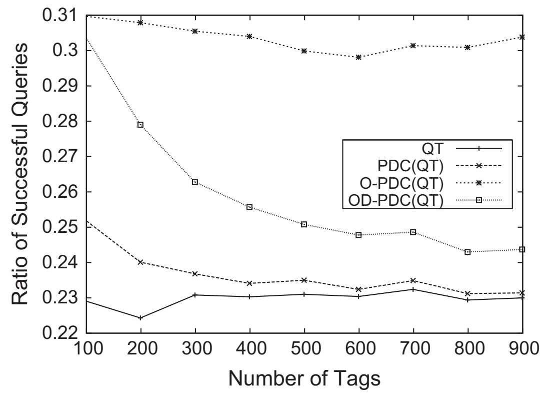

Fig. 7. Ratio of successful queries with the QT scheme.

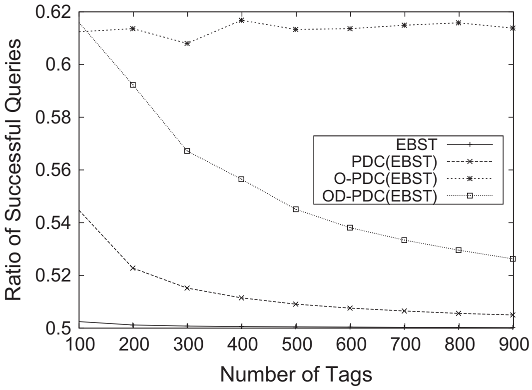

Fig. 8. Ratio of successful queries with the EBST scheme.

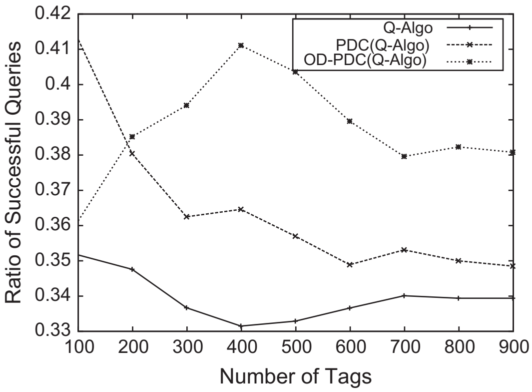

Fig. 9. Ratio of successful queries with the Q-Algorithm scheme.

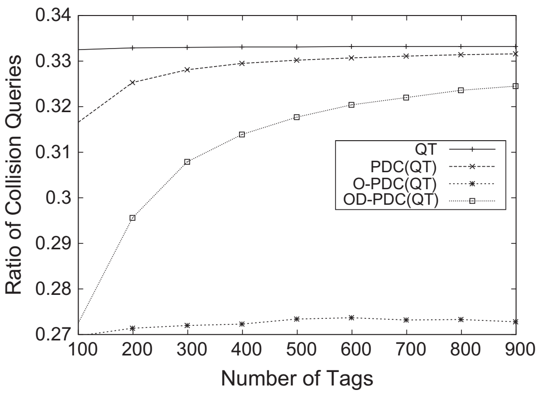

Fig. 10. Ratio of collision queries with the QT scheme.

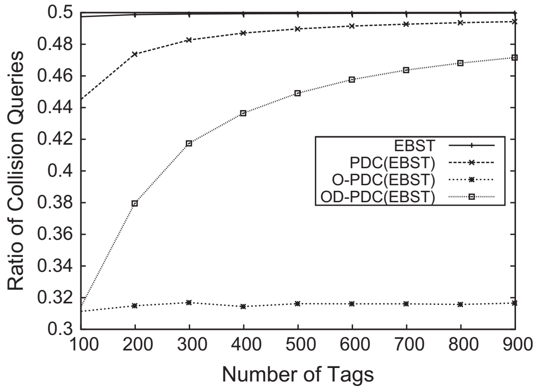

Fig. 11. Ratio of collision queries with the EBST scheme.

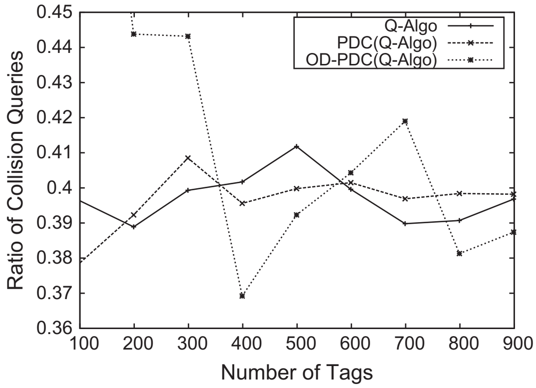

Fig. 12. Ratio of collision queries with the Q-Algorithm scheme.

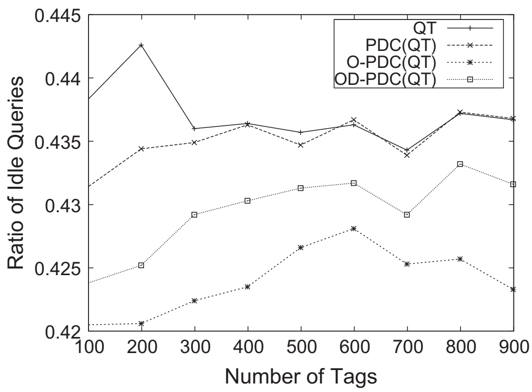

Fig. 13. Ratio of idle queries with the QT scheme.

6.1.3. Ratio of collision queries

Fig. 10 shows the ratio of collision queries observed using the PDC schemes when integrated with the QT scheme and that of the pure QT scheme. Fig. 11 shows the ratio of collision queries achieved by the PDC schemes when integrated with the EBST scheme and that of the pure EBST scheme. These ratios for the pure QT and EBST schemes are almost constant for the same reason mentioned earlier for the constant ratio of successful queries. The PDC schemes also show stable ratios over varying tags densities. Fig. 12 shows the ratio of collision queries achieved by the PDC schemes when integrated with the Q-Algorithm scheme and that of the pure Q-Algorithm scheme. Values for this metric has nothing to do with the performance because they are relative to the total number of queries achieved by different schemes.

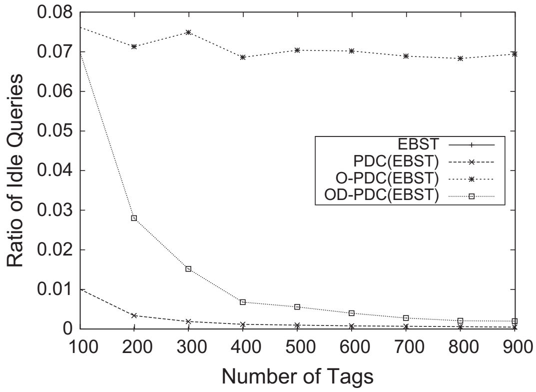

Fig. 14. Ratio of idle queries with the EBST scheme.

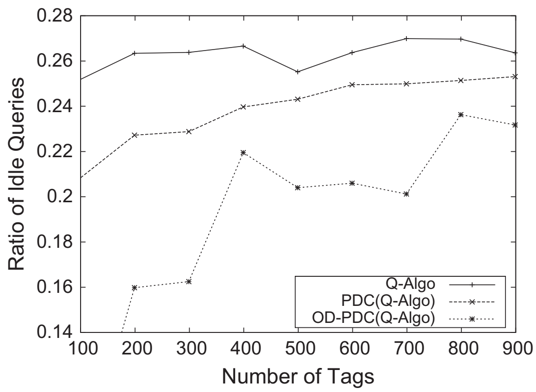

Fig. 15. Ratio of idle queries with the Q-Algorithm scheme.

6.1.4. Ratio of idle queries

Fig. 13 shows the ratio of idle queries achieved by the PDC schemes when integrated with the QT scheme and that of the pure QT scheme. Fig. 14 shows the ratio of idle queries achieved by the PDC schemes when integrated with the EBST scheme and that of the pure EBST scheme. As explained in Section 2, the EBST scheme does not have any idle queries. This makes these ratios for the PDC schemes, when integrated with the EBST scheme, very low; idle collisions come only from empty clusters. Ratio of idle queries with the Q-Algorithm scheme is shown in Fig. 15. When the PDC schemes are compared with the QT and the Q-Algorithm schemes, no significant changes are observed between the PDC schemes and the pure classical ones. As is the case of the ratio of collision queries, values for this metric has nothing to do with the performance because they are relative to the total number of queries achieved by different schemes.

7. Conclusion

In this paper we introduce the power-based distance clustering scheme for tag collision resolution in RFID systems. The main idea in our approach is to divide tags into clusters based on their distance to the reader, and tags in each cluster are read separately. Since the number of tags in a single cluster is less than that in the whole interrogation zone, the likelihood of a collision is reduced. However, the number of clusters has to be selected carefully as having too many clusters results in having many empty clusters, which causes a significant number of idle cycles. Our approach finds a balance between reducing the likelihood of collisions and reducing the number of empty clusters by finding an optimal number of clusters. Theoretical analysis and simulations have been presented to verify performance improvements of our approach. Moreover, our approach can be integrated with any existing anti-collision scheme and improve its performance.

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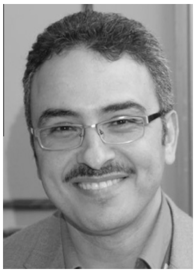

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