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Exploring the Gap between Ideal and Reality: An Experimental Study on Continuous Scanning with Mobile Reader in RFID Systems

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Abstract—In this paper, we show the first comprehensive experimental study on mobile RFID reading performance based on a relatively large number of tags. By making a number of observations regarding the tag reading performance, we build a model to depict how various parameters affect the reading performance. Through our model, we have designed very efficient algorithms to maximize the time-efficiency and energy-efficiency by adjusting the reader's power and moving speed. Our experiments show that our algorithms can reduce the total scanning time by 50% and the total energy consumption by 83% compared to the prior solutions.

Index Terms—RFID; Model; Realistic Settings; Continuous Scanning; Algorithm Design; Optimization

1 Introduction

Mobile RFID reading performance is critical to a number of applications that rely on mobile readers. Scanning books in a library or a bookstore, tracking merchandises in a store, all require a mobile reader to be used for continuous scanning over the tags attached to the physical goods and assets. The mobile reader moves continuously to scan a large number of tags effectively compensating for its limited reading range. In those types of mobile reader systems, two performance metrics are highly pertinent: time efficiency to reduce the total scanning time, and energy efficiency to reduce the total power consumption. Unfortunately, there is no realistic model to characterize the performance for mobile RFID reading for a large scale setting. The factors that affect the mobile reading performance are very complicated. For example, the actual scanning time for a number of tags in a realistic scenario is much longer than the time computed for free space, as shown in our experiments. In addition, RFID readers have a wide range of power selections, e.g., the Alien-9900 reader has a maximum power 30.7dBm, which is 30 times larger than the minimum power 15.7dBm. There is no guideline, however, in selecting a suitable power. Therefore, we aim to design an efficient solution to continuous scanning problem for a mobile RFID reader based on experimental study.

Although there have been some experimental studies on reading performance in a stationary RFID system [1–3], the previous studies have the following limitations. First, previous experiments were usually conducted in a small scale (fewer than 20 tags), which does not capture the complication for a large number of tags. Second, previous work has been focused on reading performance in a close to free space scenario. In reality, path loss, multi-path effect and mutual interference are common and have a big impact to RFID reading process. Third, previous work mainly examined how factors such as distance, coding scheme and frequency, affect reading performance. Very important factors, i.e., the reader's power and tag density, were neglected. Therefore, the previous work does not give a model for RFID reading process in a realistic and large scale setting; in particular, it does not include the power and tag density. Indeed, before we started our work, there was no realistic model which can guide us in designing an efficient tag identification solution in our setting.

We have, thus, conducted comprehensive measurements over a large number of tags in realistic settings by varying various parameters. Surprisingly, we have a few important new findings from the experiments. For example, we have found that the probabilistic backscattering is a ubiquitous phenomenon of the RFID system in realistic settings, i.e., during every query cycle each tag randomly responds with a certain probability, which has an important effect on the reading performance. This observation is contrary to the previous belief that tags respond to a reader with either probability 1 or 0. We have also found it is not wise to blindly increase the reader's power for tag identification, which can degrade the overall performance including the effective throughput and energy consumption. These findings are essential to improving reading performance for a mobile RFID system. Most importantly, we can (1) model the

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patterns of reading a large number of tags by giving a probabilistic model to capture the major and minor detection region, and (2) model how the reading power and tag density affect the reading performance by proving an empirical mapping.

Based on the effective models, we consider to tackle the following problem in a typical scenario of RFID applications, i.e., using a mobile reader to identify a large volume of tags deployed over a wide area. We seek to execute continuous scanning over the tags along a certain direction, while respectively considering a situation where the tags are continuously placed with a uniform/nonuniform density. We focus on several critical metrics like time-efficiency, energy-efficiency and coverage ratio. We design efficient and practical algorithms for continuous scanning, by skillfully adjusting the reader's power and moving speed, which can dramatically improve the performance, as shown in our real experiments. By exploring the inherent regularities in continuous scanning, we aim to give some fundamental guidance for future RFID system design towards more complicated realistic settings. We make the following contributions in this paper (a preliminary version of this work appeared in [4]). 1) We are the first to conduct an extensive experimental study and performance evaluation over a relatively large number of tags (up to 160 tags for experimental study and up to 480 tags for performance evaluation) and a rather high tag density (up to 90 tags per square meter) in realistic settings. To the best of our knowledge, this is the first work to propose a model for investigating how the important parameters including reader's power, moving speed and tag density jointly affect the reading performance. 2) This is also the first work to give a framework of optimizing reading performance based on experimental study. We apply our model to solve the problem of continuous scanning with mobile reader. By carefully adjusting the power and moving speed, we design efficient algorithms to optimize time-efficiency and energy-efficiency. We have a number of novel techniques in making our algorithms practical. 3) Being compatible with RFID standard (with no changes to the C1G2 protocols or low-level parameters for commercial RFID readers), our solutions can deliver significant performance gain. Experiment results indicate that, while achieving the same coverage ratio, our practical solutions respectively reduce scanning time by 50% and energy consumption by 83% compared to the prior solutions.

2 Related Work

In RFID systems, a reader needs to receive data from multiple tags. These tags are unable to self-regulate their radio transmissions to avoid collisions. In light of this, a series of slotted ALOHA-based anti-collision protocols [5–8], as well as tree-based anti-collision protocols [9–12], are designed to resolve collisions in RFID systems. In order to deal with the collision problems in multi-reader RFID systems, scheduling protocols for reader activation are explored in [13], [14]. Recently, a number of polling-based protocols [15–18] are proposed, aiming to collect information from RFID tags in a time/energy efficient approach. In order to estimate the number of tags without collecting tag IDs, a number of protocols are proposed [19–27] to leverage the information gathered in slotted ALOHA protocol for fast estimation of tag size. In regard to tag identification with the mobile reader, Sheng et al. develop efficient schemes for continuous scanning operations [28], aiming to utilize the information gathered in the previous scanning operations to reduce the scanning time of the succeeding ones.

In order to verify the impact of the physical layer's unreliability, a number of researchers conduct experimental studies in realistic settings, while trying to explore the gap between the ideal situation and the realistic situation for RFID systems. Buettner et al. [1] examine the performance of the C1G2 RFID system in a realistic setting. They identify factors that degrade overall performance and reliability with a focus on the physical layer. Jeffery et al. [3] conduct experiments in realistic settings and find that within each reader's detection range, a large difference exists in reading performance. Zheng et al. investigate into the physical layer information of tag responses for missing tag identification [29]. Realizing that the reader's transmission power actually has a significant impact on the reading performance of the RFID system, Xu et al. investigate the impact of transmission power on reading performance through extensive empirical study on passive tags [30][31]. Su et al. find that, when the transmission power is set to a reasonable range, the "capture effect" can be used to resolve the collision slots into singleton slots [32]. Therefore, they propose a progressing scanning algorithm to improve the reading throughput.

3 Problem Formulation

We consider a typical scenario of continuous scanning in realistic settings, i.e., using a mobile reader to identify a large volume of tags deployed over a wide area. We respectively consider a situation where the tags are continuously placed with a uniform/nonuniform density, we seek to execute continuous scanning over the tags along a certain direction. The performance metrics in our consideration are as follows: 1) *Time-efficiency*: considering it is time-consuming to identify a large volume of tags in realistic settings, the overall scanning time should be as small as possible. 2)*Energy-efficiency*: considering the mobile reader is conventionally battery powered, e.g., a typical battery for the mobile reader has a capacity of 3200mAh with output voltage 3.7v, if we scan the tags with a maximum radiation power 36 dBm, the mobile reader can execute continuous scanning for only 3 hours, therefore, the overall energy used should be as small as possible. 3) *Coverage ratio*: due to various issues like path loss in realistic settings, it is difficult to identify all tags with a high probability for one single scanning cycle, therefore, the coverage ratio, i.e., the ratio of the number of identified tags to the total number of tags, should be guaranteed, while each tag should have a uniform probability to be identified.

In regard to the continuous scanning, we define the scanning time as T, the overall energy used as E, and the coverage ratio as C. Assuming the tag density is ρ and the length of the scanning area is l, then the total tag size is $n = l \cdot \rho$, we denote the overall tag set as S. We assume that each tag $t_j \in S$ is successfully identified with probability of p_j after the continuous scanning. The reader's antenna is deployed towards the tags with a distance of d. We can adjust the parameters including the reader's power p_w and the moving speed v to improve the reading performance. Therefore, during the continuous scanning, the problem is how to efficiently set the parameters p_w and v such that the following objectives can be achieved:

Time-efficiency:

$$\text{minimize } T \tag{1}$$

subject to

$$E \leq \alpha \quad \text{energy constraint} \tag{2}$$

$$Pr[C \geq \theta] \geq \beta \quad \text{coverage constraint} \tag{3}$$

$$\forall t_j \in S \quad p_j = p \quad \text{coverage constraint} \tag{4}$$

Energy-efficiency:

$$\text{minimize } E \tag{5}$$

subject to

$$T \leq \gamma \quad \text{time constraint} \tag{6}$$

$$Pr[C \geq \theta] \geq \beta \quad \text{coverage constraint} \tag{7}$$

$$\forall t_j \in S \quad p_j = p \quad \text{coverage constraint} \tag{8}$$

According to the above formulation, in regard to the time-efficiency, the objective is to minimize the overall scanning time T while the energy constraint and the coverage constraint should be satisfied. The energy constraint requires the energy used should be no greater than a certain threshold α. In regard to the coverage constraint, due to the random factors in the anti-collision scheme and the communication environment, the coverage ratio C cannot guarantee to be deterministically equal or greater than a threshold θ, hence we use the probabilistic approach to denote the requirement. The probability for the coverage ratio C to be equal or greater than θ should be no less than β. Moreover, there could exist multiple feasible solutions to guarantee the coverage constraint, in some of the solutions the tags are detected with nonuniform probabilities. In fairness, we require that each tag t_j in the set S should be detected with a uniform probability p, i.e., the detection probability p_j should be equal to p. Similarly, in regard to the energy-efficiency, the objective is to minimize the overall energy E, while the time constraint and the coverage constraint should be satisfied. The time constraint requires that the scanning time should be no greater than a certain threshold, γ.

4 Deriving a model from realistic experiments

In order to understand how the reader's power and tag density affect the reading performance, while dealing with issues like the path loss, energy absorption, and mutual interference, we illustrate several original findings from our realistic experiments. In our experiments, we use the Alien-9900 reader and Alien-9611 linear antenna with a directional gain of 6dB. The 3dB beamwidth is 40 degrees. The RFID tags used are Alien 9640 general-purpose tags which support the EPC C1G2 standards. We attach the RFID tags onto the books which are placed in a large bookshelf. Each tag is attached onto a distinct book with a unique ID. The bookshelf is composed of 16 grids with 4 columns and 4 rows, the height and width of each grid are respectively 60cm and 75cm. In the experiments we only consider the grids in the 3 rows of upper layers, since the grids in the bottom layer may be greatly affected by the multi-path effect. Therefore, we choose to deploy the tags in the 12 grids with 4 columns and 3 rows. The RFID reader is statically deployed by facing its antenna towards the book shelf. Note that in order to set an appropriate value for the distance between the reader and the bookshelf, it is difficult to directly derive the optimal distance from geometry according to the beamwidth, due to issues like the multi-path effect. Therefore, we vary the distance from 0.5m to 3m and measure the number of effectively identified tags while scanning 160 tags uniformly distributed on the shelf.

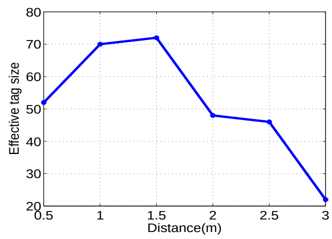

Fig. 1. The number of tags read for various distances

As shown in Fig.1, we find that the reader achieves the maximum coverage when the distance is 1.5m. Thus, we set the distance to 1.5m to guarantee the reading performance. This setting is close to a typical noisy condition, which is distinct from the free space condition, since the issues in the realistic applications like the path loss, multi-path effect and energy absorption all exist. Considering that we deploy a relatively large number of tags (up to 160 tags in experimental study and 480 tags in performance evaluation) and a rather high tag density (up to 90 tags per square meter) in realistic settings, the experimental findings from the high tag density deployment can be highly scalable and generalized to rather large scale settings. Specifically, we attach each tag to a book and put these books back-to-back in a very dense approach. We believe this tag density (up to 90 tags per m^2) should be close to extreme case in scale for conventional RFID applications. Since we use the mobile

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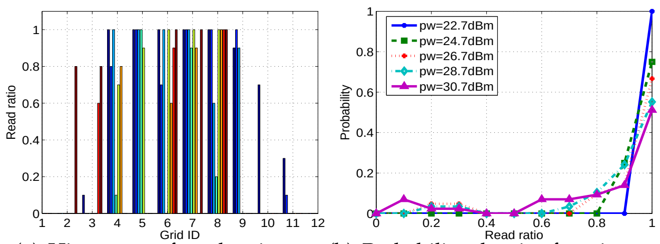
RFID reader to scan the tags within its limited scanning range, hence, after the whole process of continuous scanning, all tags can be effectively identified. Therefore, as long as we can tackle the problem in this situation, it can be guaranteed that our solution is scalable to any large scale during the continuous scanning.

On the whole, it took us over 300 hours to conduct an extensive experimental study of up to 160 tags in realistic settings. In order to sufficiently understand how the parameters separately/jointly affect the actual reading performance, we conduct up to 100 various experiments, carrying out lots of experimental comparisons and analysis on the obtained results. In the following experiments, we vary the tag density, ρ, from 10 to 40 tags/grid, while adjusting the reader's power from 20.7dBm to 30.7dBm for performance evaluation. Unless otherwise specified, by default we fix the reader towards the center of the bookshelf, set the reader's power to 30.7 dBm, and repetitively scan the tags for 50 query cycles.

4.1 Experimental findings

4.1.1 *Probabilistic backscattering*

During the query cycles, each tag responds to the reader with a certain probability between 0 and 1. We uniformly deploy 96 tags in the bookshelf with 8 tags in each grid. The grids on the left/middle/right side are respectively numbered (1,2,3)/(4,5,6,7,8,9)/(10,11,12). First, we use a static RFID reader to scan these tags for 100 times.

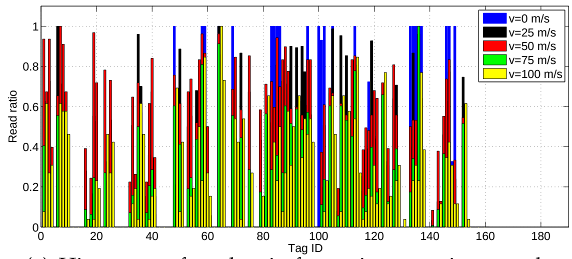


(a) Histogram of read ratio (b) Probability density functions

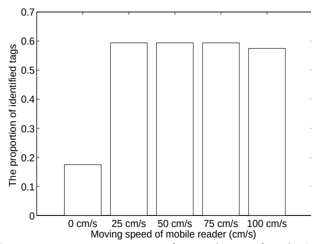
Fig. 2. Probabilistic backscattering in static situation

In Fig.2(a), we respectively compute the read ratios of each tag in the 12 grids, i.e., the ratio of successful number of responses to the expected number of responses for each tag, and illustrate them in histogram grouped by grid ID. We note that the tags respond to the reader with various probabilities between 0 and 1, although basically no parameters are changed during the repetitive scanning. This observation is contrary to the popular idea that each tag either responds thoroughly or does not respond at all. We think this is probably due to the randomness in the backscattering factors, like the power scattering, multi-path propagation. Furthermore, we vary the reader's power, p_w, from 22.7 dBm to 30.7dBm and obtain the probability density functions for the read ratio. According to Fig.2(b), we note that as the reader's power varies, the distribution of the read ratio also varies. The above observation further implies that, due to the probabilistic backscattering, multiple query cycles are essential to successfully identify a typical tag in the tag set, which may cause massive duplicated readings over other tags in the scanning area.

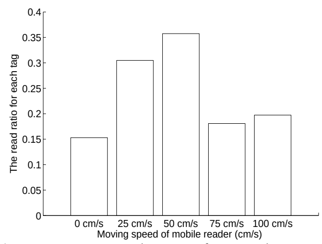
According to the experiments in static situations, we observe that, although the tags respond to the reader with various probabilities, a majority of the tags still respond with probability either close to 100% or 0. Due to the ambient multi-path effect in indoor environment, we find that even in very close positions from the reader, some tags can be easily identified and some tags cannot be identified at all. Moreover, we further conduct continuous scanning in mobile environment, by varying the moving speed of the mobile reader from 0 cm/s to 100 cm/s. We set the reader's power to 25.7 dBm and make it continuously interrogate the surrounding tags while moving. We continuously scan tags in 4 grids, and the tag density is 40 tags/grid. During the continuous scanning, as the multi-path effect is continuously changing, we find that some tags which cannot be identified in the previous round can be easily identified in current round. In regard to the change of multi-path conditions, since we use the mobile RFID reader to continuously interrogate the surrounding RFID tags while the reader is moving, the reader's antenna continuously changes its position, the incident angle and distance of the signal wave from the reader to the tag is continuously changing, which causes the multi-path conditions change a lot during the continuous scanning. Therefore, the change of multi-path conditions is essentially caused by the movement of the reader.



(a) Histogram of read ratio for various moving speeds



(b) Proportion of identified number of tags



(c) Average read ratio for each tag

Fig. 3. Probabilistic backscattering in mobile situation

Fig.3(a) shows the histogram of read ratio for various moving speeds. We observe that most of the tags which cannot be identified in static cases can be effectively identified in the mobile cases. Each tag tends to have close response probability in mobile scanning. Fig.3(b) further shows the proportion of identified tags for various moving speeds, i.e., the ratio of the number of identified tags to the overall number of tags. We find

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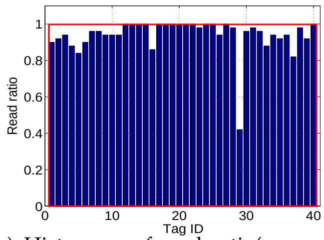
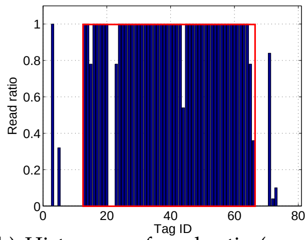
that the mobile scanning approach can greatly increase the overall ratio of identification in comparison to the static approach. Fig.3(c) further shows the read ratio for each tag for various moving speeds. We find that, while mobile scanning can effectively increase the read ratio than the static approach, the one with lower moving speed can achieve more efficiency in read ratio than the one with larger moving speed.

4.1.2 Major detection region vs minor detection region

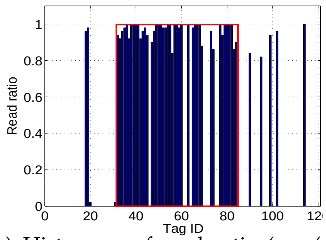
Within each reader's detection range, there are two distinct regions: the major detection region where the tags can be identified with high probability, and the minor detection region where the tags can be identified with low probability. We uniformly deploy the tags in a row with 4 grids in the bookshelf, where the tag IDs are sequentially numbered from left to right. The reader's power is set to 30.7dBm. Fig.4(a)-Fig.4(d) show the histogram of each tag's read ratio in the order of tag ID, while varying the tag density, i.e., the number of tags per grid.



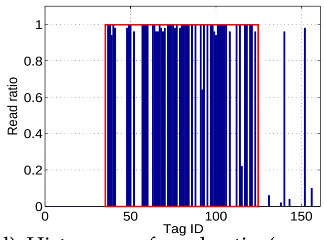
(a) Histogram of read ratio($\rho = 10$)



(b) Histogram of read ratio ($\rho = 20$)



(c) Histogram of read ratio ($\rho = 30$)



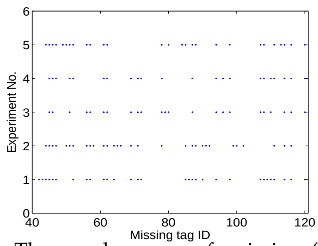
(d) Histogram of read ratio ($\rho = 40$)

Fig. 4. Major detection region vs minor detection region

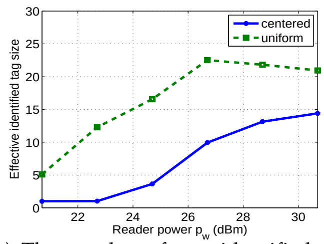
In order to see the two distinct regions, we use red window to depict the boundary of the major detection region. We observe that within each reader's detection range, the major detection region is the area directly in front of the reader, giving high detection probability, and the minor detection region extends from the end of the major detection region to the edge of the detection range, where the read ratio drops off to zero at the end of the detection range. As the tag density increases, the major detection region gradually shrinks.

4.1.3 Power density over the tags

The power density, i.e., the radiative energy diffused to per tag, has a big effect on the reading performance. According to Fig.4(a)-4(d), we find that even within the major detection region, there are a certain number of tags which still remain unidentified. While in the minor detection region, there are several tags which have high read ratios. This observation is related to the power density over the tags: according to Fig.4(a) and Fig.4(b), while the tag density is low, the power density is fairly large, nearly all tags in the major detection region have high probability to respond; according to Fig.4(c) and Fig.4(d), while the tag density increases to a large value, the diffused power is diluted among the tags, and the power density is thus reduced, causing some of the tags in the major detection region fail to respond. Besides, we observe that the missing tags in the major detection region is fairly random. According to the deployment in Fig.4(d), we randomly issue 5 query cycles and collect the missing tag IDs, by slightly adjusting the antenna's position for each query cycle. Fig.5(a) illustrates the missing tag IDs in the major detection region, where the points denote the missing tags. We note that most of the missing tag's IDs are fairly random, except a small number of tags which are always missing due to the inappropriate deployment. In order to further verify the effect of the power density, we deploy 30 tags in two distinct distributions (uniform and centered) and measure the effective identified tag size in Fig.5(b). In the uniform distribution, we uniformly deploy the tags within two adjacent grids; while in the centered distribution, we deploy all tags in the center of the antenna's radiation area. As the power increases, we note that the identified tag size in uniform distribution is always larger than the centered distribution. This is because the power density in the former case is much larger than the latter case, more tags in the former case respond to the reader. Therefore, in order to statistically depict the probabilistic backscattering property in the major detection region, the average detection probability is essential to be used.



(a) The randomness of missing tag ID



(b) The number of tags identified with various deployment

Fig. 5. Power density over the tags

4.1.4 Marginal decreasing effect

As the reader's power is increasing, the exact read efficiency including the scanning range, the detection probability, as well as the number of identified tags, is not increasing equally with the power. In Fig.6(a)-6(c), we respectively measure the width of major detection region, the average detection probability (i.e., read ratio) in major detection region, as well as the overall number of identified tags, while varying the reader's power from 20.7dBm to 30.7dBm. All three variables are increasing while the reader's power increases. However, as the power is increased by 2dB (i.e, 1.58 times in watt), they mainly increase

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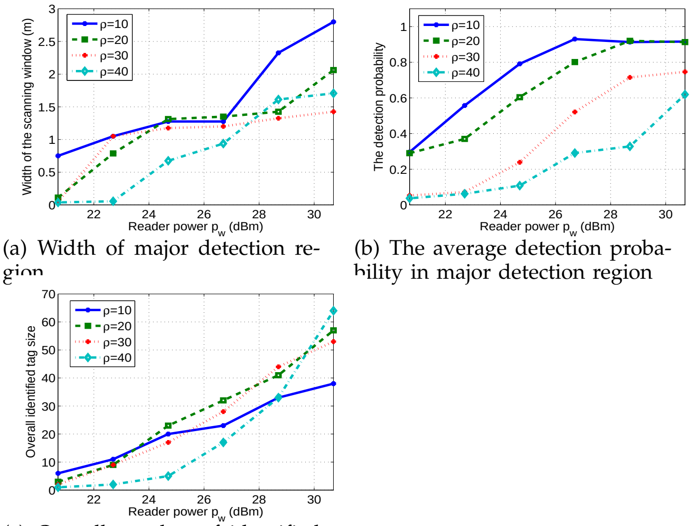
with a much smaller speed on average. This observation implies that the read efficiency cannot be sufficiently enhanced by purely increasing the reader's power.



(a) Width of major detection region

(b) The average detection probability in major detection region

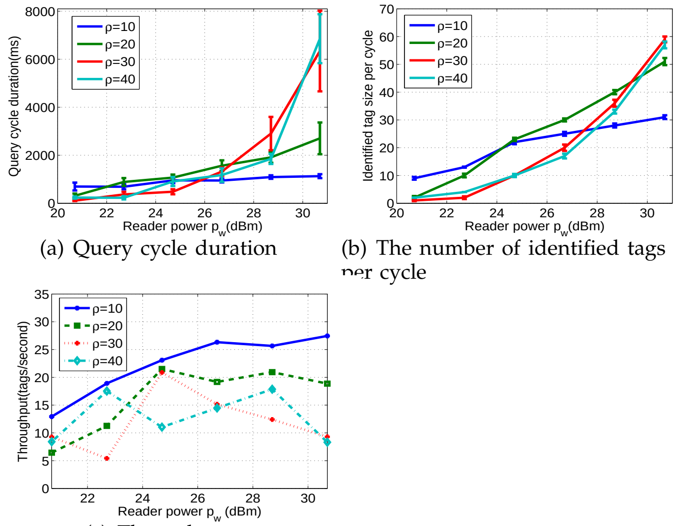
(c) Overall number of identified tags after 50 query cycles

Fig. 6. Marginal decreasing effect

4.1.5 Query cycle duration vs the number of identified tags per cycle

As the reader's power increases, the query cycle duration does not increase linearly with the number of identified tags per cycle, causing the variation of the throughput. According to the theoretical analysis in the ideal situation, if the frame size is optimally selected, the expected number of slots as well as the query cycle duration should be linearly increasing with the number of identified tags per cycle. However, in realistic settings that doesn't follow at all. Fig.7(a) and Fig.7(b) respectively show the value of cycle duration τ_c and the number of identified tags per cycle n_c while varying the reader's power. Note that the standard deviation of τ_c is much larger than n_c, which is mainly due to the randomness in the anti-collision scheme. As the reader's power increases, the values of τ_c and n_c are both increasing, however, at different rates. Therefore, the ratio of n_c to τ_c, i.e., the throughput, is also varying.

Fig.7(c) shows the throughput variation with 4 different tag densities. We find that in all cases the throughput achieves the peak value when the reader's power is set to an appropriate value between the minimum and maximum power. The reason is as follows: When the reader's power is set to a small value, the number of activated tags is small, then due to the fairly large inter-query cycle overhead, the throughput is fairly small. As the reader's power increases, more tags are involved in the query cycle, the inter-query cycle overhead is sufficiently amortized, thus the throughput is gradually increased. When the reader's power increases to a fairly large value, the number of collisions in the query cycle is greatly increased, resulting in a large value for the cycle duration, thus the throughput is further decreased. This observation implies that it is neither time-efficient nor energy-efficient to blindly increase the reader's power, an optimal value for the reader's power should be determined.



(a) Query cycle duration

(b) The number of identified tags per cycle

(c) Throughput

Fig. 7. Query cycle duration vs the number of identified tags per cycle

The above experiment results and observations are obtained from the static situation where the reader is statically deployed. In the mobile situation where the reader is continuously moving, since the moving speed cannot be too large due to the large number of tags to be identified, all the above properties should be preserved. In order to verify this statement, we conduct experiments in mobile situations while varying the moving speed from 0.3m/s to 3m/s. We find that all the obtained results, including the width of major detection region, the detection probability, and the query cycle duration are very close to the static situation. Besides, these experiment results are currently obtained from the settings constructed by the Alien reader and antennas, since the Alien reader and antennas are designed and manufactured according to industrial standard, these results can be applicable to other kinds of commercial readers conforming to the standards. Therefore, it is feasible to apply these parameters to the continuous scanning algorithm.

4.2 Model

Based on the above findings, it is essential to build a model to effectively depict the regularities in reading performance. We first propose a model for probabilistic backscattering, and then a model of the effective scanning window to evaluate the reading performance over multiple tags.

4.2.1 Probabilistic backscattering

Suppose an arbitrary tag is separated from the reader at a distance of d. In order for the tag to successfully backscatter the ID message, the reader needs to send a continuous wave to activate the tag. As the tag has

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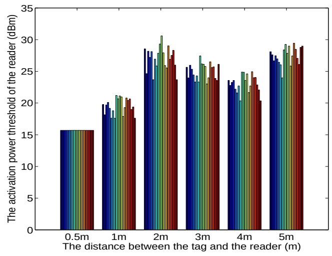
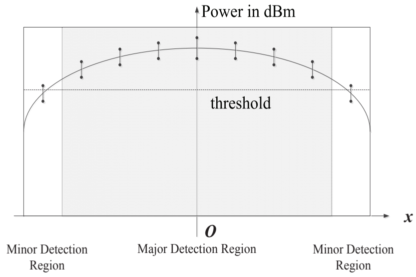
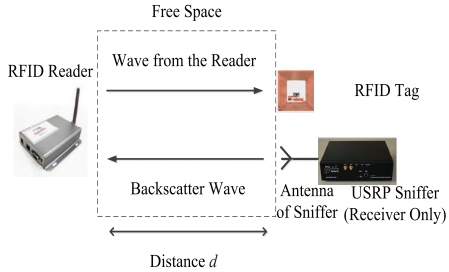


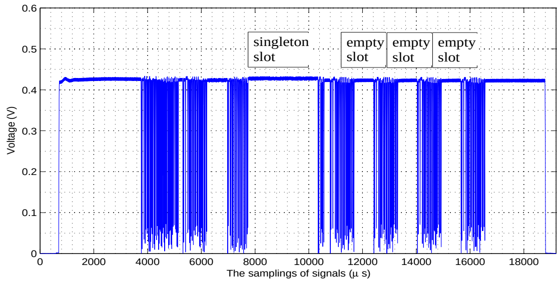
(a) The threshold of the reader's activation power with various distances



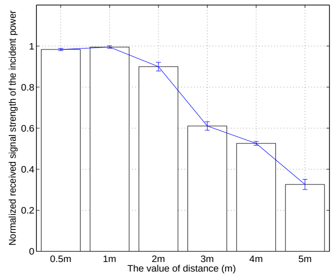
(b) The value of the incident power in the one-dimensional space



(c) Experiment settings with USRP N210



(d) The raw signal data of the interrogation between the reader and the tag



(e) The normalized average value and standard deviation of the incident power

Fig. 8. Exploring the probabilistic backscattering

a sensitivity threshold t, which is the minimum power required to activate the tag, the incident power to the tag's antenna should be larger than t. It is known that the power budget of conventional RFID systems is *forward-link limited*, which implies that well-designed passive RFID systems are always limited by the tag's sensitivity. Therefore, as long as the reader's power p_w is large enough to activate the tag, the reader is able to resolve the backscattered signal from the tag. We have conducted experiments to evaluate the threshold t. We deploy 20 tags together in front of the RFID reader and gradually vary their distance from 0.5m to 5m. Then the reader executes power stepping from the minimum value 15.7dBm to the maximum value 30.7dBm to identify the activation threshold for the reader. Fig.8(a) illustrates the experiment results. We find that, the threshold is not strictly monotonically increasing as the distance increases, which is mainly due to the multi-path effect. In regard to a certain distance, the activation power for the reader remains fairly steady among the 20 tags. This infers that the value of t basically remains unchanged among a certain type of tags.

In the reader's read zone, i.e, the region in which the incident power exceeds the threshold t, it is found that the range is the longest along the center and falls off towards the edges. In regard to a plane at a fixed distance from the reader, the incident power varies from the center towards the edges. Besides, the values of incident power has variances since the continuous wave issued from the reader has fluctuations in terms of power. Therefore, assume the reader's power is p_w, in regard to a two dimensional plane at a distance of d from the reader, we respectively use $f_{p_w,d}(x,y)$ and $g_{p_w,d}(x,y)$ to denote the average value and the variance of the incident power in the coordinate (x,y). In the settings where the tags are deployed in a row, we respectively simplify them to $f_{p_w,d}(x)$ and $g_{p_w,d}(x)$. Fig.8(b) shows a diagram of the average value and variance of the incident power $p'_w(x)$ in the one-dimensional space. Note that conventionally the incident power achieves the maximum value in the center of the read zone, and gradually decreases towards the edges. Meanwhile, in regard to multiple tags deployed in the plane, the incident power is also affected by tag density and multi-path effect.

In order to verify the above judgement, we conduct a number of experiments in the realistic settings of a configuration shown in Fig.8(c). We set up a reader and a passive tag with a distance of 3m, and use a USRP-based sniffer to capture the incident signals at the spot of the tag's antenna. We build the sniffer based on the USRP N210 system. As UHF RFID systems operate in the 902-928 MHz band, we use WBX USRP daughterboards and VERT900 omni-directional antennas to run all experiments at a carrier frequency of 915 MHz. The omni-directional VERT900 antenna is connected to a USRP N210 device to receive. The USRP samples the received signals using a rate of 25 MHz. The distance between the tag and the USRP antenna is very close (within 1∼2cm), which is much smaller than the wavelength ($< \frac{1}{4}$ wavelength), the multi-path effect thus cannot greatly affect the performance. In this way, we are able to measure the incident power to the RFID tag according to the captured signals.

Fig.8(d) shows the raw signal data of the interrogation between the reader and the tag. Note that, the sniffer at the spot of the tag not only receives the incident signals from the RFID reader but also receives the backscatter signals from the tag. Hence, in order to accurately measure the incident power to the tag, we need to effectively eliminate the backscatter signal from the mixed signals. We find that during the query cycle there exist several slots including the singleton slots and the empty slots. In regard to the empty slots, since the tag does not respond at all, the captured signal only includes the incident signal from the reader to the tag. Based on the above understanding, we can effectively extract the incident power from the empty slots. As we compare with the reference voltage U_0 when the power is 1mw, thus the measured power is $P_w = 20 \cdot \log \frac{U}{U_0}$dBm. Fig.8(e) shows the measured value of the incident power to the tag. We normalize the measured power by dividing the maximum received power, and illustrate the average value and the standard deviation in the figure by varying the distance between the reader and the tag. We note that the average value of the incident power is gradually decreasing as the distance increases from 0.5m to 5m, and there indeed exist some fluctuations for the incident power to the tag.

As shown in Fig.8(b), in regard to an arbitrary tag in the row, the tag can be successfully identified if and only if the incident power is above the tag's sensitivity threshold t. Due to the fluctuation of the incident power, the tag is successfully identified with some probability, i.e., $Pr[p'_w(x) \geq t]$. In regard to a position x in the effective scanning region, note that once the average value is relatively larger than the threshold t, as the variance is usually relatively small, the detection probability $Pr[p'_w(x) \geq t]$ will be close to 1; similarly, once the average value is relatively smaller than the threshold t, the detection probability $Pr[p'_w(x) \geq t]$ will be close to 0. This property divides the scanning region into two distinct regions, i.e., the major detection region and the minor detection region.

4.2.2 Effective scanning window over multiple tags

As we have observed, the reader's effective scanning region can be divided into a major detection region as well as a minor detection region. In the major detection region, most tags can be detected with a probability close to 100%. As the tag density increases, the diffused power cannot guarantee to activate all tags in the major detection region, each tag has a probability to be detected in a random approach. Therefore, we can use the average detection probability to depict the reading performance in this region. The minor detection region is extending from the end of the major detection region to the edge of the effective range, with the detection probability quickly drops off to 0. Based on the above analysis, we use a trapezoidal curve to denote the expected detection probability of tags in the scanning region, as illustrated in Fig.9. In fact, due to the narrow width of the minor detection region, the average probability for a tag to be detected in this region can be negligible. Therefore, in consideration of the actual reading performance, we only need to focus on the major detection region. In the rest of this paper, we use the term *effective scanning window* to denote the major detection region. We use w and p' to denote the width and the average detection probability of the effective scanning window, respectively.

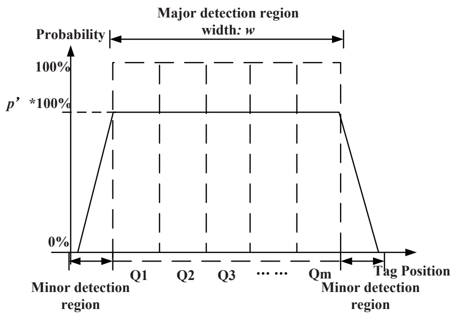


Fig. 9. The model of the effective scanning window

During continuous scanning, the effective scanning window is continuously moving forward with the mobile reader, as shown in Fig.10. Note that there exist overlapping areas between the contiguous scanning windows. During the continuous scanning, each tag gradually enters a minor detection region, then an effective scanning window, finally exits from a minor detection region. While within the effective scanning window, each tag has a probability to be detected for each query cycle. Therefore, in order to guarantee the coverage constraint, multiple query cycles should be issued over each tag while it is within the effective scanning window. Assume that the tags are uniformly deployed along the scanning area, then the tag size within the effective scanning window is always constant. This infers that the number of tags involved in a query cycle mostly remains unchanged. If the mobile reader is set to a constant power and a constant moving speed, then, after multiple query cycles, each tag has a uniform probability to be detected. This conforms to the requirement in the coverage constraint.

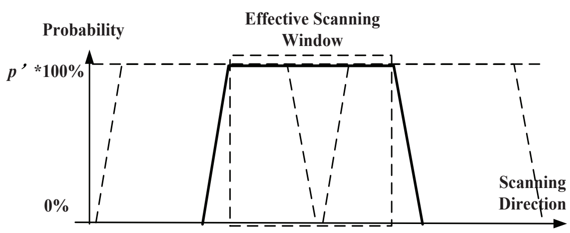


Fig. 10. Continuous scanning over the tags

Suppose an arbitrary tag is expected to be queried for m cycles while it is within the effective scanning window, we denote the detection probability in the m query cycles as $p_i(i = 1...m)$. Then, the probability for an arbitrary tag to be identified at least once is as follows:

$$p = 1 - \prod_{i=1}^{m}(1 - p_i) \tag{9}$$

As the reader's power is set to a constant value, due to the uniform tag density, the probability $p_i(i = 1...m)$ in the m query cycles should be uniform. If we use p' to denote the uniform detection probability, then Eq.(9) is

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further simplified as follows:

$$p = 1 - (1 - p')^m \tag{10}$$

In particular, the value of m is equal to $\frac{\tau_w}{\tau_c}$, here τ_w is the duration in the effective scanning window, and τ_c is the average duration of a query cycle. Moreover, τ_w is equal to the ratio of the window width w to the moving speed v, i.e., $\frac{w}{v}$, hence $m = \frac{w}{v \cdot \tau_c}$. Therefore, in order to increase the detection probability p for an arbitrary tag, it is essential to (1) increase the number of query cycles m as much as possible; (2) increase the detection probability p' as much as possible.

In Fig.6(a), Fig.6(b) and Fig.7(a), we illustrate the value of w, p' and τ_c with various power, p_w. In regard to a fixed tag density, we note that as the value of p_w increases, the value of p', w and τ_c are all monotonically increasing. Moreover, since the value of w increases much more slowly than τ_c, the value of $m = \frac{w}{v \cdot \tau_c}$ is monotonically decreasing with the value of p_w. Therefore, we reach the following conclusion: as the moving speed v decreases, the value of m is monotonically increasing, while the value of p' remains unchanged. As the reader's power p_w increases, the value of p' is monotonically increasing, while the value of m is monotonically decreasing. Thus the value of p_w should be appropriately selected to optimize the performance.

In regard to the coverage constraints in Eq.(3) and Eq.(4), we use the parameter p to denote the probability that a tag is successfully identified after the continuous scanning. We hence propose a method (readers can refer to our previous work [4] for the detailed description) to effectively obtain the solution of p, that is $p \geq \theta^*$, here $\theta^* = \theta + \sqrt{\frac{\ln(1-\beta)}{-2n}}$. This shows that, as long as the detection probability p is no less than θ^* for any tag, the coverage constraint is guaranteed.

4.3 Discussion on the model

4.3.1 Property of the model

In order to describe the inherent regularities of the probabilistic backscattering, we have proposed a *simple*, *in-depth* and *practical* model: First, the effective scanning window is very simple to formulate; second, the model is built based on in-depth understanding of the properties of the reading performance, including the major detection region, the probabilistic backscattering, the power density over tags, etc; third, the model is rather practical to use in real applications. Besides, this model is actually very flexible and applicable to various settings. The reason is as follows: in regard to various types of tags, readers, and environment, as long as we can effectively collect the detection probability $p'(p_w)$, the window width $w(p_w)$ and the average query cycle duration $\tau_c(p_w)$ through an initial phase, then we can effectively compute the optimal parameters for power and moving speed for time-efficiency and energy-efficiency according to this model.

4.3.2 Scalability of the model

Current commodity RFID systems all use the directional antenna to send continuous wave to activate and interrogate the tags. The reason of not using the omni-directional antenna is as follows: the omni-directional antenna may have very small antenna gain towards a specified direction, such that the effective scanning range is greatly reduced, it is usually within 100cm$\sim$150cm, according to our experimental observation. Our effective scanning window-based model is suitable for the RFID systems with directional antennas. It incorporates the major detection region and the minor detection region, which well depict the characteristics of the directional antennas. It uses a uniform probability to denote the success rate of tag identification in the scanning window, which right agrees with the actual observation from the mobile scanning process. Therefore, our effective scanning window-based model is rather scalable and applies to most commodity RFID systems off the shelf.

4.3.3 Tag response probability in the model

In regard to the tag response probability, i.e., p, during the continuous scanning, most of the tags (except only a few tags placed in the boundary) experience nearly the same process: the mobile reader continuously scans from the left side of the tag, then scans in front of the tag, and finally scans to the right side of the tag. If we consider the situation where the tags are uniformly deployed, and the mobile reader is moving in constant speed and power, then, according to the model, as shown in Eq. (9), each tag would have a very close detection probability (i.e., p_i) for each query cycle, while it is within the reader's effective scanning window. On the whole, according to Eq. (9), after the continuous scanning, each tag is expected to have nearly the same value for the tag response probability, which has also been verified in our experimental study (see Fig 3(a)-(c)).

5 Continuous Scanning with Mobile Reader

5.1 Baseline solution

For both the uniform and nonuniform tag distribution, in order to effectively identify all the tags with the mobile reader, conventionally the reader's power is set to maximum and the moving speed is set to a constant value which is small enough. This baseline solution is very straightforward, which however, is neither time-efficient nor energy-efficient since excessive power is used up and the moving speed is slowed down. Besides, a number of tags are interrogated multiple times during continuous scanning, which is unnecessary as each tag only needs to be identified once.

5.2 Mobile solution with uniform tag density

5.2.1 Solution

Without loss of generality, we first propose an optimized solution for the situation with uniform tag density. Considering the objective as well as the energy/time

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constraint, we need to figure out the optimized value of p_w and v such that the objective is achieved while the coverage constraints are satisfied.

In regard to the coverage constraint, since we need to guarantee $p = 1-(1-p')^m \geq \theta^*$, i.e., $1-(1-p')^{\frac{w}{v \cdot \tau_c}} \geq \theta^*$, it is equivalent to ensure $v \leq \frac{1}{|\ln(1-\theta^*)|} \cdot \frac{w \cdot |\ln(1-p')|}{\tau_c}$. As the value of w, p' and τ_c all depends on the value of p_w, let $w(p_w)$, $p'(p_w)$ and $\tau_c(p_w)$ respectively denote the mapping function from p_w to w, p' and τ_c, then

$$v^* = \frac{1}{|\ln(1-\theta^*)|} \cdot \frac{w(p_w) \cdot |\ln(1-p'(p_w))|}{\tau_c(p_w)}, \tag{11}$$

then, v^* is the maximum allowable moving speed to satisfy the coverage constraint.

Since the length of the scanning area is l, the overall scanning time $T = \frac{l}{v}$, and the overall used energy $E = T \cdot p_w = \frac{p_w \cdot l}{v}$. Therefore, considering the time-efficiency, in order to minimize T, it is equivalent to maximize v. Then, according to Eq.(11), it is essential to maximize $\frac{w \cdot |\ln(1-p')|}{\tau_c}$. It is known that as the value of p_w increases, the value of $w \cdot |\ln(1-p')|$ and τ_c are both monotonically increasing, thus an optimized value of p_w should be selected to minimize T. Considering the energy constraint $E \leq \alpha$, the optimal value p_w^* can be computed according to the following formulation:

$$\text{maximize } y_T = \frac{|\ln(1-p'(p_w))| \cdot w(p_w)}{\tau_c(p_w)} \tag{12}$$

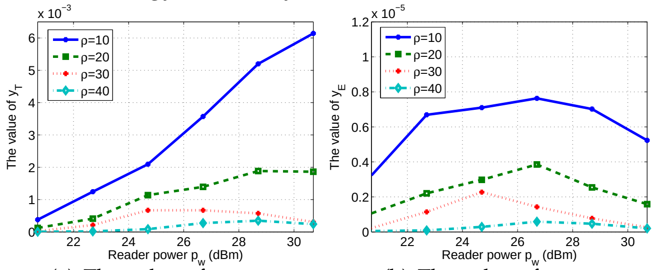
$$\text{subject to} \quad \frac{|\ln(1-p'(p_w))| \cdot w(p_w)}{p_w \cdot \tau_c(p_w)} \geq \frac{l \cdot |\ln(1-\theta^*)|}{\alpha} \tag{13}$$

Considering the energy-efficiency, in order to minimize E, it is equivalent to minimize $\frac{p_w}{v}$, then according to Eq.(11), it is essential to maximize $\frac{|\ln(1-p')| \cdot w}{p_w \cdot \tau_c}$. Therefore, considering the time constraint $T \leq \gamma$, the optimal value p_w^* can be computed according to the following formulation:

$$\text{maximize } y_E = \frac{|\ln(1-p'(p_w))| \cdot w(p_w)}{p_w \cdot \tau_c(p_w)} \tag{14}$$

$$\text{subject to} \quad \frac{|\ln(1-p'(p_w))| \cdot w(p_w)}{\tau_c(p_w)} \geq \frac{l \cdot |\ln(1-\theta^*)|}{\gamma} \tag{15}$$

In regard to a certain tag density ρ, by enumerating the candidate values of the power p_w, we can compute the value of y_T and y_E. Fig.11(a) and Fig.11(b) respectively illustrate the value of y_T and y_E while varying the reader's power p_w. We note that there exist a maximum value of y_T and y_E for each tag density. In regard to a specified tag density ρ, while satisfying the time/energy constraint, we can use the power p_w^* for the maximum value of y_T or y_E as the optimal parameter and compute the corresponding moving speed v^* according to Eq.(11). In this way, the optimal solution (p_w^*, v^*) for time/energy efficiency can be generated. Therefore, in regard to various tag densities ρ, we can collect the performance parameters like w, p' and τ_c in advance, precompute the optimal pairs of (p_w^*, v^*), and store them in a table. When dealing with an arbitrary tag density, we can directly use the optimal pair of (p_w^*, v^*) to achieve the time/energy efficiency.



(a) The value of y_T (b) The value of y_E

Fig. 11. Compute the value of y_T and y_E with various values of p_w

5.2.2 *Estimate the tag density*

According to the measured data in realistic settings, it is known that the tag density ρ has an important effect on the performance metrics. In situations where the tag density cannot be pre-fetched or the tag density varies along the forwarding direction, it is essential to accurately estimate the current tag density, such that the optimized parameters (p_w^*, v^*) can be effectively computed. Therefore, we propose a practical solution to accurately estimate the tag density. Due to the limit of space, we omit the detailed descriptions here. Readers can refer to our previous work [4] for the detailed content.

5.3 Mobile solution with nonuniform tag density

In some applications, the tags are not uniformly deployed. While the mobile reader is continuously scanning the tags, the tag density may always change along the forward direction. In this situation, a constant moving speed and power for the mobile reader are no longer suitable to improve performance. For example, in order to guarantee $p \geq \theta^*$ for each tag with respect to the coverage constraint, the value of p_w and v should be set according to the worst case, i.e., the situation with the largest tag density. In this way, the time-efficiency as well as the energy-efficiency cannot be achieved since excessive power is used up and the moving speed is reduced. Therefore, it is essential to dynamically adjust the reader's power p_w and the moving speed v to optimize the overall performance.

5.3.1 *Algorithm*

According to the observation in Section 4, while the mobile reader is moving forward, we note that if the tag density varies, the detection probability p_i is varying; moreover, the number of issued query cycles m is varying, as the tag size within the effective scanning window changes. Hence, each tag experiences a distinct process with various values of p_i and m. Therefore, it is rather difficult to make the coverage requirement $p^* \geq t$

exactly satisfied for all tags while achieving the objective. Based on the above understanding, we seek to propose an approximate solution to solve the problem.

Note that in conventional situations, the tag density changes slowly along the forward direction. In current commercial RFID systems, the reader's power p_w can only be reset for each query cycle. Therefore, in regard to each query cycle, we can assume the tag density within the effective scanning window is close to uniform, since the cycle duration is usually small. In this way, we can reduce the situation with nonuniform tag density into multiple snapshots with fairly uniform tag density. In Algorithm 1, we propose a mobile solution for nonuniform tag density. We assume the nonuniform tag density along the forwarding direction can be known in advance. While the mobile reader is moving forward, it continuously computes the average tag density in the current effective scanning window. As the reader's power varies in the effective range, the window width w is not constant, thus we set the value of w to an average value of the window width. Here, we consider an offline setting where the nonuniform tag density is supposed to be known in advance; if we consider an online setting where the nonuniform tag density is not known in advance, the current tag density has to be estimated in time during the continuous scanning. However, as multiple power levels have to be set for measuring data in a frequent approach, the time-efficiency and energy-efficiency can be affected.

Algorithm 1 Mobile solution for nonuniform tag density

1: INPUT: $\rho(x)$: the tag density along the forwarding direction, $0 \leq x \leq l$;
2: PROCEDURE
3: Precompute the optimal value of reader's power for a certain number of reference tag densities ρ, i.e., $p_w(\rho)$, according to the objective of time/energy-efficiency.
4: Set $x = 0, S = \varnothing$.
5: **while** $x \leq l$ **do**
6: Compute the average tag density ρ according to the current scanning window with width w. Find two closest reference tag density to ρ such that $\rho_l \leq \rho \leq \rho_u$.
7: Compute the optimal value p_w^* and v^* as follows:

$$p_w^* = p_w(\rho_l) + (\frac{\rho - \rho_l}{\rho_u - \rho_l}) \cdot (p_w(\rho_u) - p_w(\rho_l)),$$
$$v^* = \frac{w(p_w^*)}{|\ln(1-\theta^*)|} \cdot \frac{|\ln(1-p'(p_w^*))|}{\tau_c(p_w^*)}.$$

8: Set reader's power to p_w^*, set moving speed to v^*.
9: Issue a new query cycle. Collect the tag IDs during the query cycle, add them to the set S.
10: Record the cycle duration τ_c, update $x = x + v^* \cdot \tau_c$.
11: **end while**
12: OUTPUT: the tag set S

5.4 Extensions and Discussions

5.4.1 *Various tag distributions*

In the previous subsections, we have tackled the continuous scanning problem, respectively, for uniform tag density and nonuniform tag density, assuming that the RFID tags are located along a line. This is conventionally suitable for those typical scenarios like scanning the books in the library, making an inventory of stocks in the warehouse shelves, etc. In this situation, we can compute the optimal parameters for the distance, scanning power and moving speed. However, in some application scenarios, the situations are more complicated. The tagged items can be haphazardly distributed in a space, such that the tags are not necessarily to be located along a line. Obviously, this scenario with haphazard tag distribution is rather complicated, and it is difficult to solve well based on current techniques.

The tag distribution is a critical issue for the continuous scanning. As long as the tag distribution is obtained, we can approximately divide the overall tags into several tag sets. The tags in each tag set are mainly distributed in a nearby area, which can be roughly considered to have uniform tag density and uniform distance to the RFID reader. Then, we can further extend our continuous scanning-based solution to tackle the above complex scenarios, by reducing it into multiple snapshots with fairly uniform tag density and distance. In each query cycle, the mobile reader can be reset with the optimal parameters, like the distance d, the readers power p_w and the moving speed v, according to the nearby tag distributions in each tag set. In this way, the reading performance can be effectively improved by dynamically adjusting the above parameters.

5.4.2 *Compatibility to various identification protocols*

We aim to propose a practical solution for current commodity RFID systems towards real applications, it means that, while being compatible to the standard, no changes to the protocols should be made. As our solution only requires to adjust the parameters including the power and moving speed in application layer, it is compatible to any RFID identification protocols.

Since currently there are a number of RFID identification protocols that is either more time-efficient or more fault-tolerant than the Q-protocol, these protocols can effectively benefit from our work due to the following reasons: 1) For those protocols [5–8] which achieve better performance in time-efficiency, i.e., the identification time can be effectively reduced for each query cycle, more benefits can be obtained from our work. According to the model in Section 4.2, as shown in Eq.(10), since the average duration of query cycle τ_c is reduced, in order to satisfy $p \geq \theta^*$, the value of scanning window width w and moving speed v can be reasonably changed to keep the value of m constant. Therefore, either the moving speed can be appropriately increased, or the scanning power can be appropriately reduced, while still ensuring the performance. We can achieve better performance either in time-efficiency or in energy-efficiency. 2) For those protocols [13, 14] which achieve better performance in fault-tolerance, i.e., the rate of missed tags can be effectively reduced for each query cycle, more benefits can be obtained from our work. According to the model in Section 4.2, as shown in Eq.(10), as the rate of missed tags is reduced for each cycle, the detection probability p' is increased, then in order to satisfy $p \geq \theta^*$, the number of essential query cycles m can be reasonably reduced, hence, according to the definition $m = \frac{w}{v \cdot \tau_c}$, either the moving speed can be appropriately increased, or the scanning power can be appropriately reduced. We can achieve better performance either in time-efficiency or energy-efficiency. In summary, those RFID identification protocols which outperform the Q-protocol can get more benefits in improving performance by using our continuous scanning-based solution.

6 PERFORMANCE EVALUATION

6.1 Performance in uniform tag density

In order to evaluate the performance in uniform tag density, we deploy the tags in a row with 4 grids in the shelf, while varying the tag densities from 10 tags/grid to 40 tags/grid, the length of the scanning area is 3m.

6.1.1 Evaluate the coverage ratio

According to the analysis in Section 4, in regard to the coverage constraint $Pr[C \geq \theta] \geq \beta$, we need to guarantee $p \geq \theta^*$, here $\theta^* = \theta + \sqrt{\frac{\ln(1-\beta)}{-2n}}$. Without loss of generality, we set θ^* to 90% in our experiments. This means, on average 90% of the tags should be identified after continuous scanning. According to Fig.11, the optimal values of the power p_w^* and moving speed v^* for the mobile reader are computed in Table 1. The corresponding scanning time and energy are also illustrated.

We vary the tag densities ρ from 10 tags/grid to 40 tags/grid and verify the coverage ratio with various configurations for the parameters p_w and v. Due to the limitation of space, we only illustrate the results for $\rho = 20$ tags/grid, the other results are very similar to them. We run each experiment 20 times to obtain the average value and the standard deviation of the number of identified tags. In regard to the time-efficiency, Fig.12(a) shows the coverage of various power levels, while fixing the moving speed to the optimal value $v^* = 0.83$ m/s, the dashed line denotes the threshold for 90% coverage. We note that as the power increases, the identified tag size gradually increases to the threshold and then further decreases. The threshold is only achieved while the power is set to the optimal value 28.7dBm. Fig.12(b) shows the coverage of various moving speed, while fixing the power to optimal value $p_w^* = 28.7$ dBm. We note that as the moving speed decreases, the identified tag size gradually increases to cross the threshold for 90% coverage, the coverage is right at the threshold when the speed is set to the optimal value 0.83 m/s. The above results show that, while guaranteeing the coverage ratio, the optimal settings (p_w^*, v^*) can achieve much better time-efficiency than other settings.

Time-efficiency	$\rho = 10$	$\rho = 20$	$\rho = 30$	$\rho = 40$
p_w^*	30.7dBm	28.7dBm	26.7dBm	28.7dBm
v^*	2.65m/s	0.83m/s	0.29m/s	0.15m/s
T^*	1.13s	3.6s	10.3s	20s
E	1326.62J	2667.6J	4820.4J	14820J
Energy-efficiency	$\rho = 10$	$\rho = 20$	$\rho = 30$	$\rho = 40$
p_w^*	26.7dBm	26.7dBm	24.7dBm	26.7dBm
v^*	1.57m/s	0.625m/s	0.29m/s	0.12m/s
T	1.91s	4.8s	10.3s	25s
E^*	893.88J	2243.75J	3038.5J	11700J

TABLE 1
Optimal parameters for time/energy-efficiency

Similarly, in regard to the energy-efficiency, Fig.12(c) and Fig.12(d) respectively show 1) the coverage of various power levels while fixing the moving speed to the optimal value $v^* = 0.625$ m/s; 2)the coverage of various moving speed, while fixing the power to optimal value $p_w^* = 26.7$ dBm. It is found that, among various (p_w, v) parameter pairs, the optimal solution (p_w^*, v^*) achieves the coverage right at the required threshold. These results infer that, while guaranteeing the coverage ratio, the optimal settings (p_w^*, v^*) can achieve much better energy-efficiency than other settings.

6.1.2 Evaluate the time-efficiency and energy-efficiency

In regard to the time-efficiency, since the length of the scanning area is 3m, the scanning time $T = \frac{3\text{m}}{v}$. Therefore, while guaranteeing the coverage ratio, a high speed v is preferred. Note that as the value of v increases from 0 to 1m/s, the scanning time rapidly decreases from $+\infty$ to 3s; as the value of v further increases, the scanning time decreases rather slowly from 3s to 0, while the coverage ratio can be decreased rapidly. Considering the marginal decreasing effect, the moving speed should be appropriately selected for cost-effective consideration.

In regard to the energy consumption, according to the measurements in conventional RFID systems, the transmission power in the directional antenna dominates the total power consumption in mobile RFID systems. Besides, the RFID reader's power consumption always keeps constant regardless of the transmission power. Therefore, in the following experiments, we use the transmission power p_w to represent the overall power of RFID system. It is known that the overall energy consumption E is proportional to the power p_w and inverse to the moving speed v. Fig.12(e) illustrates the value of E while varying the value of p_w and v. Moreover, in order to guarantee the coverage ratio, the values of p_w and v are mutually restricted. Recall that Fig.11(a) actually illustrates the maximum allowable moving speed $v = \frac{y_T}{|\ln(1-\theta^*)|}$ for reader's power p_w with various tag densities. Integrating with both figures, we can effectively derive the minimum energy to satisfy the coverage constraint.

6.2 Performance in non-uniform tag density

In order to evaluate the performance in non-uniform tag density, we nonuniformly deploy 240 tags in a row with

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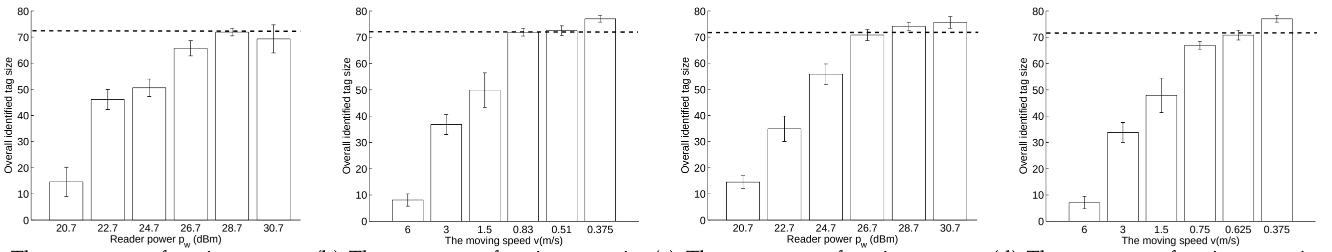
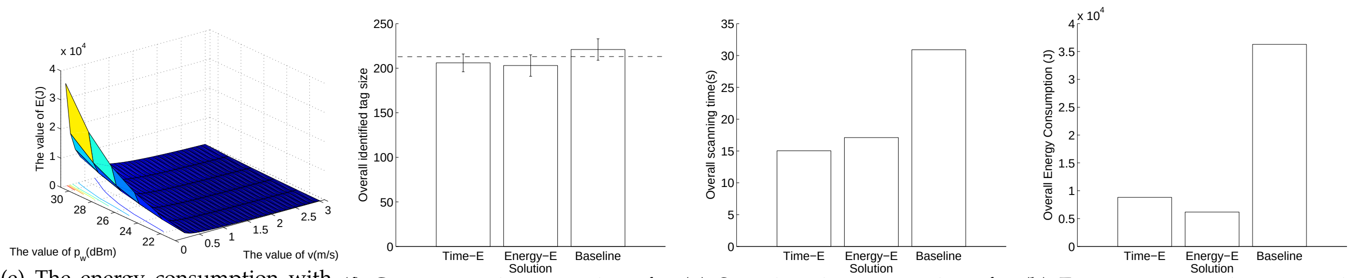


(a) The coverage of various power levels (time-efficiency) (b) The coverage of various moving speed (time-efficiency) (c) The coverage of various power levels (energy-efficiency) (d) The coverage of various moving speed (energy-efficiency)

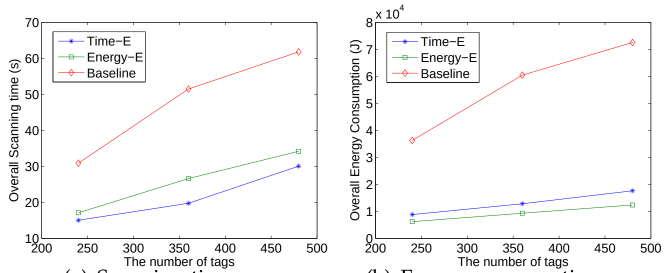


(e) The energy consumption with various power and moving speed (f) Coverage ratio comparison for various solutions (g) Scanning time comparison for various solutions (h) Energy consumption comparison for various solutions

Fig. 12. Experiment results in realistic settings

12 grids, while varying the tag density from $\rho = 10$ to $\rho = 30$ tags/grid, the length of the scanning area is 9m. We set θ^* to 90% in our experiments, which infers that, on average 90% of the tags should be identified after the continuous scanning. We compare our time-efficient solution (*Time-E*) and energy-efficient solution (*Energy-E*) with the baseline solution (*Baseline*). In regard to the baseline solution, we set the reader's power to its maximum value, i.e., 30.7dBm, which is also the standard configuration for conventional commodity readers. The moving speed is set according to the optimal value $v^* = 0.29$m/s when $\rho = 30$ to tackle the worst case. In Fig.12(f), we evaluate the coverage ratio for the three solutions. Both *Time-E* and *Energy-E* achieve the coverage which is very close to the 90% coverage ratio. *Baseline*'s coverage is slightly more than this threshold, since *Baseline* uses the maximum power and lowest speed. In Fig.12(g) and Fig.12(h), we respectively evaluate the overall scanning time and energy consumption for continuous scanning. Both *Time-E* and *Energy-E* achieves much better performance than *Baseline* in regard to the two metrics. Here, *Time-E* saves more than 50% of the s-canning time compared with *Baseline*, and *Energy-E* saves more than 83% of the energy consumption compared with *Baseline*.

In order to evaluate the actual performance for a larger scale, we further nonuniformly deploy 360 tags and 480 tags, respectively, in a row with 20 grids and 24 grids, while varying the tag density from $\rho = 10$ to $\rho = 30$ tags/grid. Fig.13(a) and Fig.13(b) respectively show the overall scanning time and energy consumption in various scales. Note that in all situations both *Time-E* and *Energy-E* achieves much better performance than *Baseline* in regard to the two metrics, while *Time-E* achieves the best performance in time-efficiency and *Energy-E* achieves the best performance in energy-efficiency. Actually our solution is scalable to any larger scale as we use the continuous scanning-based approach.



(a) Scanning time (b) Energy consumption

Fig. 13. Evaluate the performance as the scale increases

7 Conclusion

This paper considers how to efficiently identify RFID tags with a mobile reader, from the experimental point of view. We conduct measurements over a large volume of tags in realistic settings, and propose efficient algorithms for continuous scanning. Our experiments show that our algorithms can reduce the total scanning time by 50% and the total energy consumption by 83% compared to the prior solutions.

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