Negotiate Power and Performance in the Reality of RFID Systems

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***Abstract*—Recent years have witnessed the wide adoption of the RFID technology in many important application domains including logistics, inventory, retailing, public transportation, and security. Though RFID tags (transponders) can be passive, the high power consumption of RFID readers (interrogators) has become a critical issue as handheld and mobile readers are increasingly available in pervasive computing environments. Moreover, high transmission power aggravates interference, complicating the deployment and operation of RFID systems. In this paper, we present an energy-efficient RFID inventory algorithm called *Automatic Power Stepping (APS)*. The design of APS is based on extensive empirical study on passive tags, and takes into consideration several important details such as tag response states and variable slot lengths. APS dynamically estimates the number of tags to be read, incrementally adjusts power level to use sufficient but not excessive power for communication, and consequently reduces both the energy consumption for reading a set of tags and the possibility of collisions. We design APS to be compatible with the current Class-1 Generation-2 RFID standards and hence a reader running APS can interact with existing commercial tags without modification. We have implemented APS both on the NI RFID testing platform and in a high-fidelity simulator. The evaluation shows that APS can save more than 60% energy used by RFID readers.**

***Keywords*-RFID; Automatic Power Stepping (APS); energy-efficient;**

I. Introduction

In recent years, we have seen increasing adoption of the RFID technology [1] in many application domains, such as logistics, inventory, retailing, public transportation [2], and security [3]. As a result, the RFID technology has been an active area for research and development. To improve the performance of commodity RFID systems, extensive research work has been conducted on various issues, such as collision avoidance, read rate, and response time [4][5][6].

Despite the significant efforts on RFID research, very few studies have focused on the energy efficiency of RFID readers (interrogators). It is commonly assumed that the power consumption of the reader is an insignificant issue as long as it is within the maximum power defined by regulations. Unfortunately, such an assumption is only valid for a small number of RFID readers sparsely distributed in a wired installation, but does not hold in more pervasive and portable deployment, which is a trend we have already been witnessing in recent years.

Firstly, handheld and mobile RFID readers become popular because of their flexibility and portability. A few major RFID providers have released various handheld, portable, or add-on mobile readers or reader modules to the market [7][8][9][10]. For example, DAILY RFID has manufactured DL710/720, a PDA-based RFID reader [7]. In addition, RFID enabled mobile phones have become available on the market. Both Nokia and Samsung developed RFID-enabled mobile phones and reader chips for mobile phones [11][12]. Wireless Dynamics has released SD cards, SDiD 1212, which can turn a cell phone into an RFID reader [8]. Secondly, in many applications, such as retailing business and transportation checkpoints, it is often necessary to deploy readers densely for the convenience of customers.

Such a trend of pervasive, portable, and sometimes dense deployment of readers leads to the following technical issues concerning reader transmission power.

- It is crucial to reduce the power consumption of handheld and mobile RFID readers because these systems are battery-powered. Without efficient power management, current handheld and mobile RFID readers only last for a short period of time before the depletion of battery energy. For instance, the CSL CS101 handheld reader can continuously read tags (transponders) for only 1.5 hours [9]. The situation is even worsened for PDA or mobile phone-based RFID systems due to their tighter power budget.
- If multiple readers transmit at their maximum power, the interference could severely limit the system performance [13], though frequency hopping can mitigate the problem to some extent. A common practice adopted by operators is to tune down the power level to a point that transponders need to be very close to the reader in order to be activated. This solution is certainly suboptimal and limits the functionality and usefulness of an RFID system. How to automatically optimize the power level to use "as low as possible, but not lower" power to operate an RFID system is an open problem.

Thus, it is critical to reduce the power consumption of readers for the sake of system lifetime and collision avoidance. Meanwhile, in reducing the power consumption of readers, we also need to take the following issues into

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consideration. Firstly, due to the criticality of many RFID applications, the reduction of power consumption must not sacrifice the performance of an RFID system (e.g., the read rate of tags). Secondly, a energy-efficient RFID reader should be compatible with existing standards as massive commercial tags have been deployed.

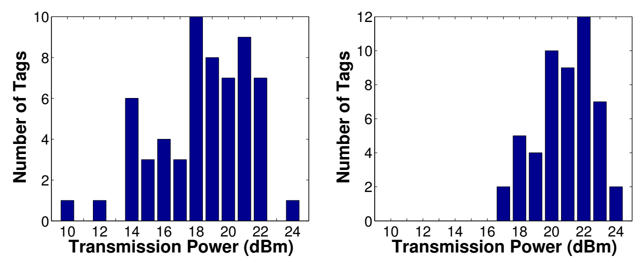
Aiming to significantly reduce energy consumption while maintaining comparable system performance, we develop a new energy-efficient RFID inventory algorithm called *Automatic Power Stepping (APS)*. Running on a reader, APS dynamically estimates the number of tags to be read, incrementally adjusts power level to use sufficient but not excessive power for communication, and consequently reduces both the energy consumption for reading a set of tags and the possibility of collisions. We have designed APS by using standardized operations, which can be easily incorporated into commercial readers. Moreover, APS is compatible with the current Class-1 Generation-2 RFID standards [14] and hence does not need any changes to be made on tags. The contributions of this work are summarized as follows.

1) We have conducted extensive experiments on several commodity RFID systems to explore the relationship between the transmission power and the response quality. We reveal that there exists a *lossy* state of passive tags where the reader cannot detect tags due to insufficient power although tags could have responded. Moreover, we verify that passive tags often exhibit significant diversity in the responsiveness. The lossy transition state and diversity of tags may cause low tag detection rate, resulting in energy waste on readers. We show that, by differentiating the lossy state from the collision state and exploiting the diversity of tags, the energy consumption of readers can be significantly reduced while maintaining high tag detection rate.
2) To improve the read rate with reduced transmission power on RFID readers, we exploit the difference in durations of MAC slots when choosing the optimal frame length. As shown by empirical results, the read rate can be substantially improved by considering actual lengths of different time slots.
3) Based on empirical study and a new optimal frame length selection mechanism, we design and implement an energy-efficient inventory algorithm, APS, for C1G2-compatible systems. We have implemented APS on the NI RFID platform and in a high-fidelity simulator, and conducted extensive experiments based on these implementations. We show that APS can save more than 60% energy with slight increase in the read time of tags.

The remainder of the paper is organized as follows. Section II analyzes the power characteristics of wireless communication in the RFID system, and illustrates the opportunities for saving energy in RFID protocols without compromising the performance. Section III presents the design of APS. Section IV reports the evaluation results. Section V discusses the related work, followed by Section VI which concludes the paper.

II. Motivation and Approach

In practical RFID systems, tags are spatially distributed rather than collocated at the same position, and the transmission power level the reader needs to use to effectively energize and identify a tag varies for different positions. To examine the correlation between spatial diversity and power diversity, we place 60 passive tags in front of the antenna of a reader, and identify them in multiple rounds as we increase the transmission power of the reader from 10dBm to 24dBm in 1dBm increments. Tags that have responded to the reader in one round will refrain from replying in later rounds. Fig. 1 shows the number of detected tags at each power level with two different distributions of passive tags. Even when all tags are distributed in a flat plane parallel to the surface of the antenna, Fig. 1(b) still clearly demonstrates the diversity of responsiveness. This diversity in power sensitivity introduces uncertainty in the performance of RFID protocols, which, however, also brings the opportunity to improve the energy efficiency.



(a) Tags are randomly placed (b) Tags are placed on a flat plane

Figure 1. The number of passive tags detected at different transmit power

Most of the current commercial readers use constant transmission power, which wastes the energy of readers, especially for those battery-powered ones. Based on empirical results from our own experiments (Fig. 3), excessive power does not necessarily enhance the quality of communication. Thus, it is possible to design an RFID protocol which uses "just enough power" to read tags, save energy, and accomplish similar reading performance. Before we introduce our design, we first briefly introduce the Class-1 Generation-2 (C1G2) RFID protocol, which is the most widely used MAC protocol in current RFID systems. We then introduce the tri-state phenomenon identified in our experiments and power saving opportunities in RFID systems.

A. The C1G2 RFID protocol

The C1G2 RFID protocol is based on Dynamic Frame Slotted ALOHA (DFSA) [15], where each frame has a variable number of slots and each tag replies only once in no more than one randomly selected slot in the frame. The number of slots in a frame, denoted as L, is determined by parameter Q (Eq. (1)) set at the reader. According to the number of tags responding in each slot, we can classify the slots in a frame into empty slots, successful slots (also known as single-occupied slots) and collision slots.

As the number of tags that have replied in each slot follows binomial distribution [4], given Q and N_{tag} (the total number of participating tags), the expected number of different types of slots can be calculated as follow:

$$TotalSlots: \quad L = \quad 2^Q \tag{1}$$
$$EmptySlot: \quad N_0 = \quad L * (1 - \frac{1}{L})^{N_{tag}} \tag{2}$$
$$SuccessfulSlot: \quad N_1 = \quad N_{tag} * (1 - \frac{1}{L})^{N_{tag}-1} \tag{3}$$
$$CollisionSlot: \quad N_x = \quad L - N_0 - N_1 \tag{4}$$

Among the parameters in the C1G2 protocol, Q has a strong impact on the throughput of the RFID system, and it shall be carefully chosen according to the number of participating tags. If Q is too small, tags have higher probability to choose the same slot and cause more collisions, resulting in fewer successful slots and degradation of throughput. On the other hand, an excessively large Q causes a large number of empty slots resulting in a waste of time and channel capacity in a frame.

B. The tri-state power-performance relationship

Existing RFID models often assume that passive RFID tags have two power states – *on* and *off*. In the *on* state, the tag is powered, and can backscatter to the reader with a reasonably high probability (often close to 100%). In the *off* state, the tag is not powered and cannot be read. The transition stage from *off* to *on* is so short that it is often considered negligible. Traditionally, the response rate, referred to as the *MAC-layer response rate* in this paper, is measured by using a reader to interrogate a tag continuously.

However, the response rate measured at the MAC layer does not necessarily represent the actual activities of the tags and the signals on the radio channel. To obtain more accurate information on the RFID operations, it is desirable to measure the actual response rate at the physical layer, which is referred to as the *PHY-layer response rate* in this paper. This PHY-layer response rate is, by definition, different from the MAC-layer response rate because a tag responding with backscatter signal to a reader does not guarantee that the signal can be demodulated by the reader.

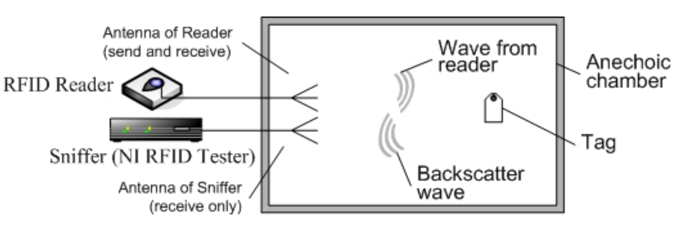


Figure 2. Setup of the experiment

According to the experiments, we observe that, in reality, the difference between such two response rates can be significant. Our experiments are conducted as follows. As shown in Fig. 2, we set up a reader and a passive tag (Alien ALN-9540), with a distance of 1m, and use a sniffer to capture the backscatter signals at the spot of the reader's antenna, in order to calculate the PHY-layer response rate and record the signal waveform in the air. Increasing the transmission power of the reader from 14dBm to 20dBm with a 0.1dBm step, we program the reader to interrogate the tag for 500 times at each power level, and log the response rate from both the PHY-layer (by the sniffer) and the MAC-layer (by the reader). We have performed this experiment in an anechoic chamber a few times to ensure the repeatability of results. Fig. 3 shows that the PHY-layer response rate increases from 0 to 100% around 15.5dBm, but the reader could not detect the tag at the MAC layer until the power reaches 18dBm. Since the reader consumes almost twice as much power at 18dBm as it does at 15.5dBm, such a 2.5dBm difference is significant for energy-constrained systems.

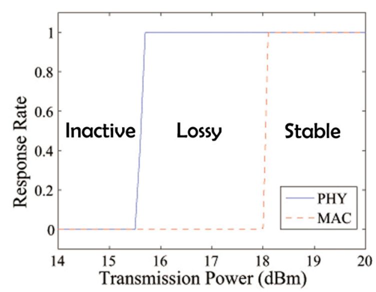
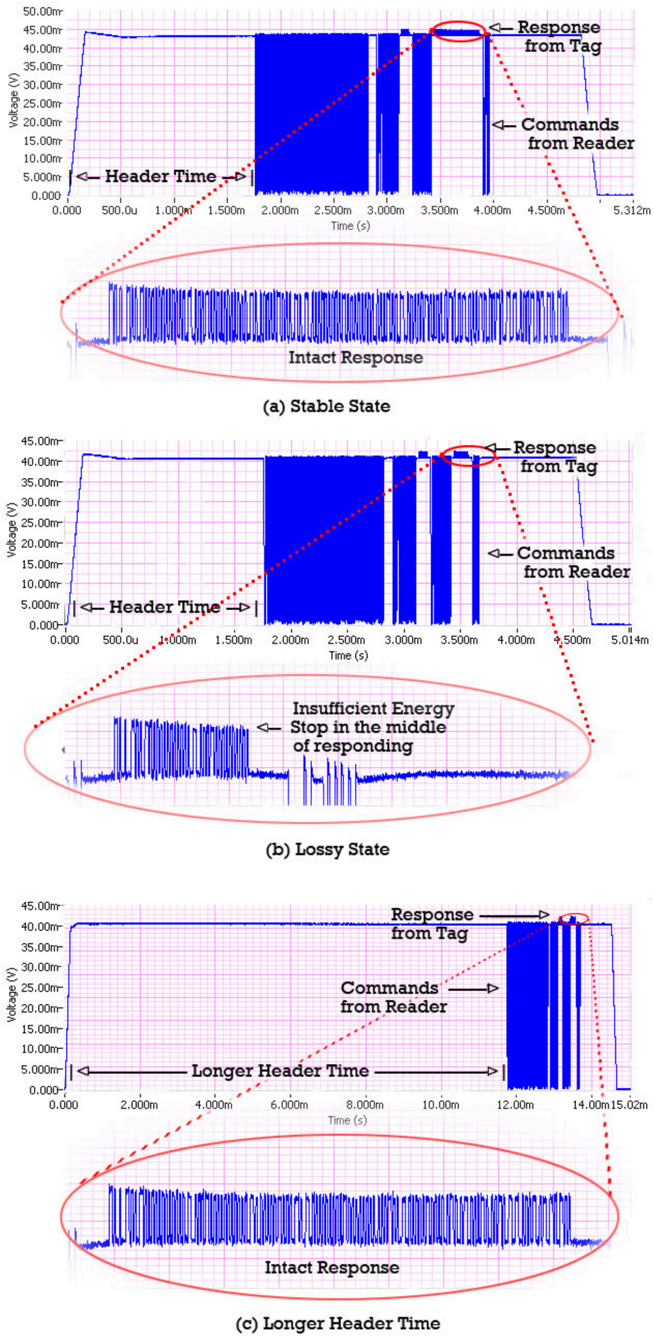


Figure 3. Response rate of a tag detected at different layers

We further examine the signal waveform at the physical layer, as shown in Fig. 4, to illustrate the reason for such a disparity. Fig. 4(a) shows a typical frame where a tag is successfully detected; Fig. 4(b) demonstrates an abnormal frame which is recognized as "no response" at the MAC layer of the reader, while the tag has indeed responded with unstable backscatter signals. Comparing with the enlarged waveform of Fig. 4(a), we note that the tag abruptly stops responding in Fig. 4(b) when transferring its EPC (Electronic Product Code). Moreover, the backscatter signal strength from the tag in Fig. 4(b) is almost as strong as that in Fig. 4(a), which is sufficient for demodulation. Experimenting with several commercial passive tags from different vendors, we rule out the possibility of tag flaws, and believe that it is insufficient energy store in the passive tag that makes the tag abruptly stop responding and results in "no response" at the MAC layer.

We verify this observation with an additional experiment – we use the same power level as in Fig. 4(b) but a much longer header time to read the same tag at its original spot. Header time is a period of time at the beginning of an RFID inventory process, which is used by the reader to send a non-stop carrier wave to charge a tag, turn it on, and



(a) Stable State

(b) Lossy State

(c) Longer Header Time

Figure 4. Signal waveform captured by a sniffer

give it sufficient energy for continuous participation in the following communication. Therefore, we give the tag longer time for charging by extending the header time. As shown in Fig. 4(c), the same tag now manages to finish the entire response process, and is successfully detected by the reader at the MAC layer. According to such repeatedly observed results, it is clear that insufficient energy store is the reason of the premature termination of EPC transmission. Note that it is the premature stop, not the low SNR (Signal to Noise Ratio) as commonly expected, that causes the intermediate "lossy" state between the *off* state and the *on* state. This phenomenon also correlates with the forward-link-limited nature [16] of passive RFID systems.

The lossy state is, however, largely ignored in system modeling in the literature [5][17], and a swift and negligible transition from *off* to *on* is assumed instead. We believe that disregarding such realities would be an over-simplification, and would likely result in the designs with suboptimal performance. Though power-oblivious systems can circumvent this problem by using a high power level, such practice leads to undesirable energy waste.

We characterize passive RFID tags to have three states as summarized below.

1) *Inactive state*: the tag is powered off and unable to respond to the reader due to insufficient reader power.
2) *Lossy state*: the tag is charged with an amount of energy from the reader that is sufficient for it to respond but insufficient to maintain uninterrupted communication till the end of the whole process.
3) *Stable state*: the tag is charged with sufficient energy so that it can respond with almost 100% success rate.

Accordingly, the power has three ranges – $P_{inactive}$, P_{lossy}, and P_{stable}. For a tag characterized by Fig. 3, the transmission power ranges of $P_{inactive}$, P_{lossy} and P_{stable} are $[0dBm, 15.5dBm]$, $[15.5dBm, 18dBm]$, and above $18dBm$ respectively.

The range P_{lossy} of a specific tag mainly depends on the characteristics of the tag and the RF setting (e.g. header time, data rate, etc.). Some tags show a very narrow P_{lossy} range, but some show wider ranges (Fig. 5). Any power level in range P_{stable} results in nearly 100% successful detection rate without collisions. Hence, using higher power level does not help in this power range.

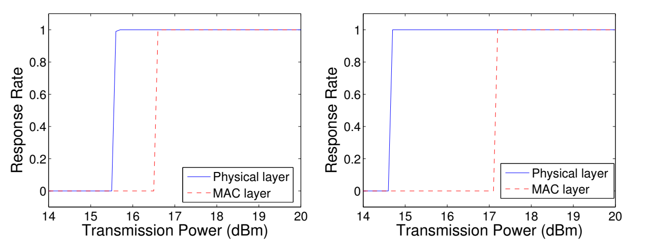


Figure 5. Diversity of tri-state

C. Power-saving opportunities in RFID protocols

The tri-state property of passive RFID tags, as well as the variation of $P_{inactive}, P_{lossy}$, and P_{stable} for different tag units, adds further complexity into the design space of RFID systems. Though tags in the lossy state are undetectable at the MAC layer, they cause extra collisions due to the backscatter signals at the physical layer. Moreover, lossy tags disrupt the tag number estimation algorithm, which is crucial to the efficiency of the inventory operations.

Meanwhile, there exist opportunities that we can exploit the tri-state property to improve the system performance. Based on the tri-state power model for tags, once the power level reaches P_{stable}, the performance, as measured by the response rate, is as high as that at the maximum power level. Hence, if we adjust the transmission power of the reader to P_{stable} when reading a tag, a significant portion of energy can be saved without performance degradation!

More often than not, tags are spatially distributed at different distances from the reader. We can further enhance the RFID system performance by exploiting the tag diversity resulted from variation in distances and other tag-specific properties. If we start the inventory process from a low power level and gradually escalate the transmission power, all tags are naturally "partitioned" into smaller groups where tags enter stable state at different power levels. Thus, the possibility of collision is reduced, and the overall performance of RFID system is improved.

III. Design

In this section, we present the energy-efficient RFID inventory algorithm, named Automatic Power Stepping (or APS for short), and analyze the impact of the key parameters on the performance of the proposed RFID inventory algorithm.

A. The energy-efficient inventory algorithm

APS runs on the RFID reader. It adjusts power levels in the inventory process, and enables the reader to use "just enough power" to interact with commodity C1G2 tags without changing the tag hardware. Not introducing new state or operations for tags to handle, APS uses information provided by the C1G2 protocol to estimate the current system state, determines the tasks to be performed at a certain power level, and employs standard C1G2-specified operations to interact with tags and accomplish energy saving.

Requiring no *a priori* knowledge on system configuration, such as the network size, tag positioning, or the power-sensitivity distribution, APS steps through a series of power levels, and executes one or more read frames at each power level with different numbers of slots. As the transmission power varies in the inventory process, APS naturally divides the whole tag set into several groups, and deals with one group at a time. The grouping is a result of the diversity of tags in terms of their distance to the reader and sensitivity to transmission power. A key advantage of the grouping is the significantly reduced collision because the number of tags in each group is much smaller. In APS, this is achieved without introducing additional communication overhead for grouping.

Table I shows the notation we use in this paper. Algorithm 1 describes the operations in pseudo code.

We now explain the key steps of the algorithm. The $N_{tag} \rightarrow Q_{opt}$ mapping list (in Step 1 of Algorithm 1) can be pre-calculated off-line and stored in the memory of the reader, as discussed in Section III-B in order to further reduce the complexity of the algorithm. The inner **while** loop from Step 9 to 23 in Algorithm 1 is the inventory process at each power level p. Two variables, N_x and C_i, control the termination of the inner loop.

As long as there is no collision slot (condition in Step 11 is true), we can conclude that there's no unread tag in stable state at current power level p, since all identified tags will refrain from responding in the following steps. Thus we jump to Step 23 and directly step up to the next power level $p+k$.

If both collision slots and successful slots are detected in a frame (condition in Step 15 is true), there are still unread tags in the system. Thus, the algorithm continues the inventory operation at current power level p.

Two possible cases may cause an abnormal situation where there exists collision but no tag is read (condition in Step 17 is true): the existence of colliding stable tags or lossy tags. In order to practically differentiate such two

Table I
Notations

$P_{min/max}$	The minimal/maximal power level available at the reader
N_{tag}	The total number of responding tags in the current power
$N_{0/1/x}$	The number of slots with 0/1/collision tag response(s)
L	The number of slots in a frame. $L = N_0 + N_1 + N_x$
Q_{opt}	Optimal Q that can achieve the maximum throughput
Q_{int}	Initial Q used in the first frame of each power level
k	Power increment
$C_{i/bound}$	Iteration counter/bound.
$T_{0/1/x}$	Time length of a(n) empty/successful/collision slot
T_{frame}	The time length of a whole frame.

Algorithm 1 The Automatic Power Stepping Algorithm

1: Calculate $N_{tag} \rightarrow Q_{opt}$ mapping list according to the RFID system settings configured by the users, using Eq. (1)-(5)
2: Set current transmission power $p \leftarrow P_{min} - k$
3: **repeat**
4: $\quad Q \leftarrow Q_{init}$, $C_i \leftarrow 0$
5: $\quad p \leftarrow p + k$, increase the transmission power by k.
6: $\quad$ **if** $p > P_{max}$ **then**
7: $\quad\quad p \leftarrow P_{max}$
8: $\quad$ **end if**
9: $\quad$ **while** $C_i < C_{bound}$ **do**
10: $\quad\quad$ Launch a new inventory frame with $L \leftarrow 2^Q$ slots, update N_0, N_1, N_x.
11: $\quad\quad$ **if** $N_x == 0$ (no tag left unread) **then**
12: $\quad\quad\quad C_i \leftarrow 0$ //reset C_i
13: $\quad\quad\quad$ break //directly step into next power level
14: $\quad\quad$ **else if** $N_x > 0$ (collision slot detected) **then**
15: $\quad\quad\quad$ **if** $N_1 > 0$ (normal situation) **then**
16: $\quad\quad\quad\quad C_i \leftarrow 0$ //reset C_i
17: $\quad\quad\quad$ **else** //$N_1 == 0$ and $N_x > 0$, abnormal: //No tag is read, but collision exists.
18: $\quad\quad\quad\quad C_i \leftarrow C_i + 1$ //increase C_i
19: $\quad\quad\quad$ **end if**
20: $\quad\quad$ **end if**
21: $\quad\quad$ Estimate the number of tags to be read, N'_{tag}, in the current power level using N_0, N_1, N_x [18].
22: $\quad\quad$ Select the optimal Q for N'_{tag} using the corresponding $N_{tag} \rightarrow Q_{opt}$ mapping list.
23: $\quad$ **end while**
24: **until** $p \geq P_{max}$

cases, we use the second variable C_i, which is bounded by C_{bound}, to control the outer loop. In Section III-C, we will further discuss how C_{bound} affects the performance of the algorithm and how we select a suitable C_{bound} value.

B. Optimal Q Selection

Optimal Q selection is to find the suitable Q in each frame so as to achieve the highest throughput of the RFID system where throughput of each frame is defined as follows:

$$Throughtput = \frac{N_1}{T_{frame}}$$

Here, N_1 is the number of successfully detected tags (successful slots), and T_{frame} is the time length of a whole frame.

Many existing works assume that all the time slots are equal [5][6][19]. A widely accepted conclusion following this assumption is that the highest throughput can be achieved when $L = N_{tag}$.

However, in real RFID systems, the lengths of all three types of time slots are different. As shown in Fig. 6, a successful slot is much longer than the other two types of slots, due to the transmission of the 96-bit EPC of a tag.

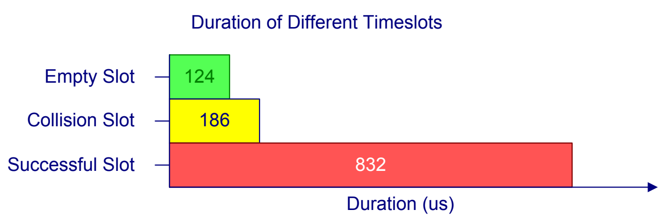


Figure 6. Duration of different time slots in our typical setting (Table III)

Therefore, if we consider the different length of time slots, throughput should be calculated as follow, which is also known as read rate.

$$Throughtput = \frac{N_1}{N_0 \times T_0 + N_1 \times T_1 + N_x \times T_x} \quad (5)$$

To choose an optimal Q, first we should know the number of tags to be read, N_{tag}. Although the exact number of tags in usually unknown in practice, we can use the information (N_0, N_1, N_x) obtained in the previous frame to estimate the approximate N_{tag}. Many estimation algorithms with satisfactory accuracy [4] [18] [20] have been proposed.

Given the estimated number of tags to be read, N_{tag}, we can compute the appropriate Q to maximize the throughput. For each possible Q ($[0, 15]$), we calculate the expected values of N_0, N_1 and N_x using Eq. (1)-(4). According to the RF parameters (i.e., data rate between the reader and the tags), we can obtain the length of different types of time slots (T_0, T_1, T_x) from C1G2 protocol [14]. Then we calculate the throughput for each Q and N_{tag} using Eq. (5). For every N_{tag}, we choose Q_{opt} so that the throughput is maximized. Table II shows two example mapping lists for two RF settings.

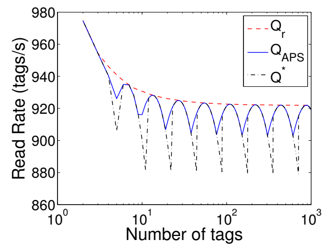
Table II
$N_{tag} \rightarrow Q_{opt}$ MAPPING LISTS

(a) Tag to reader data rate: 320kbps

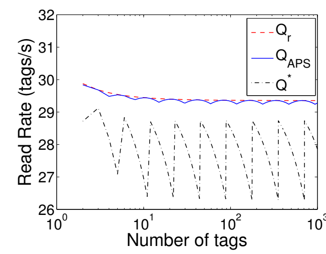
N_{tag}	0-2	3-4	5-9	10-18	19-37	38-76	77-152	...
Q	1	2	3	4	5	6	7	...

(b) Tag to reader data rate: 5kbps

N_{tag}	0-1	2	3-4	5-7	8-14	15-29	30-58	...
Q	1	2	3	4	5	6	7	...



(a) Tag to reader data rate (BLF): 320kbps



(b) Tag to reader data rate (BLF): 5kbps

Figure 7. Expected read rate when the optimal Q value is selected for a set of tags to maximize the read rate. Q_r: the Q value can be a real number; Q_{APS}: the Q value is an integer and slot length diversity is considered; Q*: the Q value is an integer and the lengths of slots are assumed to be equal.

As we can see from Fig. 7, the throughput achieved when Q is selected according to our proposed approach outperforms the throughput achieved when optimal Q is determined based on the assumption that all time slots have the same length. Such a throughput improvement becomes more significant when the BLF (Backscatter Link Frequency) is low as shown in Fig. 7(b), due to the larger differences of different kinds of slots. We use Q_{APS} to select Q_{opt} in our Algorithm 1.

The study on realistic throughput also leads to two important observations. First, the adaptive Q setting makes APS resilient to imperfect Q_{init} values. In reality, it is difficult to determine Q_{init} without *a priori* knowledge on the network size. Second, the throughput benefits from smaller incremental changes of power levels and the resultant smaller groups. Hence, we choose, as the default settings in APS, $Q_{init} = 4$ and $k = 1dBm$, which is the smallest step available in many RFID readers.

C. Handling Lossy Tags with C_{bound}

The iteration counter C_i increases as the abnormal situation occurs, and is reset to 0 otherwise. An abnormal situation may occurs when all tags in stable state collide, coincidentally, in some slots. After adjusting Q and interrogating another few frames, these stable tags will gradually be read ($N_1 > 0$ and $C_i \leftarrow 0$). On the other hand, if the abnormal situation continuously occurs in multiple consecutive frames, it is possible that the responding tags are in lossy state. Without the guard of C_{bound}, the inventory process would waste time and energy in attempting to resolve non-existent "collisions", and may render the system into an infinite inventory loop at a certain transmission power level.

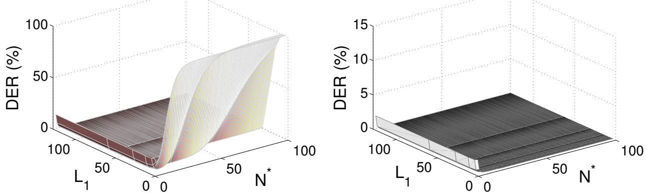
The selection of C_{bound} affects system performance. If C_{bound} is too large, the reader may waste many extra frames on unreadable lossy tags. If it is too small, it increases the probability of forcing the stable tags to be read with higher power level, which might decrease the energy efficiency and increase collisions in the following frames. Hence, the suitable value of C_{bound} for an RFID system should be the minimum C_{bound} that can achieve desirable Differentiation Error Rate (DER for short), which is defined as the probability of mistakenly determining the stable tags as lossy ones. Let N^* be the number of unread stable tags at the current power level, L_i be the number of slots in the current frame i, and $P_{ab}(L_i, N^*)$ be the probability that all tags collide and no successful slot is present for the i-th consecutive abnormal frame at this power level. We have

$$\begin{aligned} P_{ab}(L_i, N^*) &= (1-p_1)^{L_i} \\ &= [1 - \frac{N^*}{L_i} \times (1 - \frac{1}{L_i})^{N^*-1}]^{L_i} \end{aligned} \tag{6}$$

where p_1 is the probability that a slot is a successful slot. Then DER is

$$DER(C_{bound}, L_1, N^*) = \prod_{i=1}^{C_{bound}} P_{ab}(L_i, N^*) \tag{7}$$

Fig. 8 shows that, though $DER(1, L_1, N^*)$ is quite high when $N^* \gg L_1$, we can reduce DER to below 2% when $C_{bound} = 2$. Hence, we use $C_{bound} = 2$ in our APS algorithm.



(a) $C_{bound} = 1$ (b) $C_{bound} = 2$

Figure 8. Differentiation error rate caused by lossy tags

IV. Evaluation

We have implemented the APS algorithm both on a commercial RFID platform and in a calibrated simulator. Based on these implementations, we conduct a series of experiments, as outlined below, to evaluate the performance of the RFID system and verify the effectiveness of our design.

To assure that the empirical results are generally applicable, we use multiple types of unaltered commercial passive tags in our experiments. This also verifies the compatibility of our energy efficient techniques to existing tag technology, which already has a large production base.

A. Implementation and Experimental Setting

Unless specifically defined, most test settings involve 60 passive tags placed at different distances ranging from 30 cm to 70 cm away from the reader's antenna. These tags are approximately perpendicular to the radio propagation path from the reader to the tags. Using these 60 passive tags, we evaluate and compare the RFID performance on three platforms. The performance data not only evaluates the performance of our design, but also verifies the accuracy of the simulator against the ground truth. Then the verified simulator is used for collecting performance data for larger numbers of tags. For each test, we run repeatedly for 200 to 500 times, and calculate the average in each step as the final result. The details of the three platforms are as follows:

1) The Implementation on the NI Platform: We use LabVIEW to develop our APS algorithm, and implement it on the programmable NI-VISN-100 RFID Tester platform [21]. Table III shows the RF parameters, which is also the default parameters used in our evaluation. The maximum transmission power is 24dBm on the NI platform.

2) Commercial Reader: We run the same tests using a commercial reader, CSL CS461 [22], which supports the C1G2 RFID protocol, so as to compare the performance with APS. For a fair comparison, the transmission power of the reader is set to be 24 dBm, and all remaining RF settings are the same as the NI platform.

Table III
RF PARAMETERS IN OUR EVALUATIONS

Parameters	Value
Tari	6.25us
BLF	320kbps
Backward Encoding	FM0
Tx Power Range	10-24 dBm
T_2	18.75us
T_3	28.13us
T_4	93.75us
Session	2
DR	8

3) The RFID Simulator: We have developed an RFID simulator that can accurately characterize the RFID protocol activities. It is verified by comparing with the experimental results on the two platforms mentioned above.

The evaluation focuses on two performance metrics: read rate and energy consumptions. Duplicate tag reports are ignored in the calculation of read rate, in order to reflect the true performance of the system. Suppose an interrogation process comprises F frames. We examine the total amount of transmission energy used by the RF transceiver module of an RFID reader in all the frames, which can be calculated as

$$\sum_i P_i \times T_i = \sum_i P_i \times (N_{0_i} \times T_{0_i} + N_{1_i} \times T_{1_i} + N_{x_i} \times T_{x_i})$$

where $i = 1, 2, 3, ..., F$ and P_i and T_i are the transmission power and the duration of the i^{th} frame, respectively.

The proposed APS algorithm starts from 10dBm, and steps up 1dBm each time, until it reaches the highest transmission power level (24dBm on our NI platform).

B. Evaluation Results

Table IV evaluates the performance of APS implemented on the NI platform and compares to the commercial C1G2 implementation. The "Tags Read" column shows the average number of tags detected in the inventory process. The data indicate that APS does not reduce the tag detection rate. The energy consumption data show that the APS algorithm saves more than 60% of energy as compared to the C1G2 protocol implemented in the commercial reader. APS has a slightly degraded overall read rate (9.19% less than that the commercial reader). The main reason of the small degradation in the read rate (throughput) is that the commercial reader only has 1 frame with a suboptimal Q value at the beginning of the entire inventory process because it uses a constant power, and it can terminate the frame prematurely. In contrast, APS may have 15 frames with suboptimal Q values in total (once at each time the reader escalates the power level). The difference in the read rate represents a tradeoff between the throughput and the energy efficiency. This slightly degradation in read rate, compared to the significant amount of energy saving, is unlikely to be a concern to users of RFID systems. We are confident that the benefit by far outweighs the drawback in this tradeoff.

Table IV
PERFORMANCE COMPARISON

	Tags Read	Read Rate	Average Energy Consumption (uJ/tag)
C1G2	57.8	822.72	305.31
APS	57.7	747.14	116.64
APS/C1G2	99.83%	90.81%	38.20%

C. Comparison of Simulation and Experiment Results

In parallel with the tests on the NI platform, we also run simulations to collect performance data for the same experiments. Fig. 9 includes the simulation results in comparison with the results collected from the NI-based hardware implementation. The simulation results match the experimental results very well. This enables us to use the simulator in several test scenarios to collect data that are difficult to obtain in real-world experiments (e.g., large tag populations and different power-responsiveness distributions).

D. Performance Evaluation with Larger-Scale Configurations

As the number of tags becomes larger, the collision escalates, which may cause performance degradation in terms of the throughput and power consumption. To examine the scalability of our algorithm, we use the verified simulator to

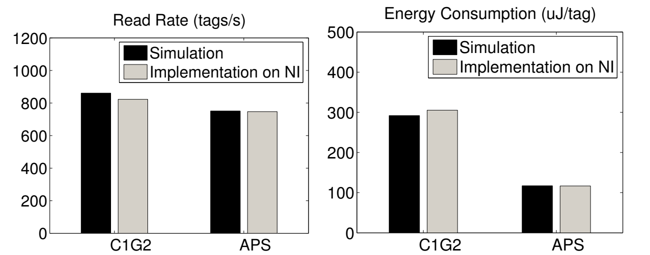
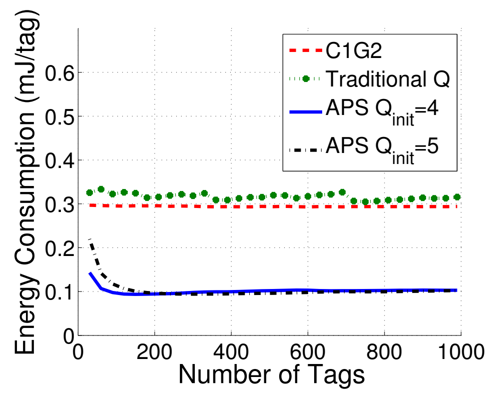
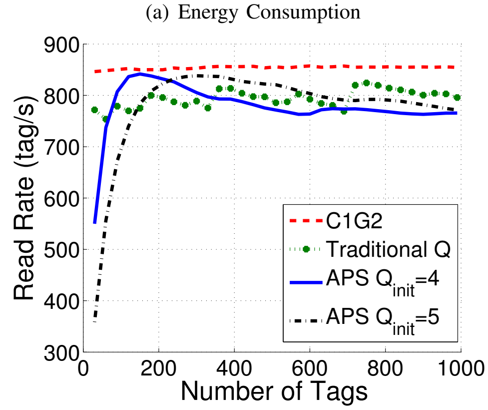


Figure 9. Comparison of the energy-efficient RFID algorithm and the inventory algorithm suggested in C1G2 protocol

evaluate and compare the performance of three algorithms, namely, the inventory algorithm suggested in the C1G2 protocol (labeled as "C1G2"), the constant-power inventory algorithm with Q selection algorithm regarding all slot lengths are equal (labeled as "traditional Q"), and our APS algorithm (using two different initial Q), with up to 1000 tags.



(a) Energy Consumption



(b) Read Rate

Figure 10. Performance comparison of different RFID algorithms

Fig. 10(a) shows the average energy consumption per tag with these algorithms. With most tag populations, the APS algorithm saves more than 2/3 energy compared to the other two algorithms. This means that potentially the system lifetime of handheld RFID devices can be extended by threefold and the interference among RFID readers in proximity can be significantly reduced.

Regarding read rate, Fig. 10(b) shows that the APS provides a comparable read rate (not lower than 90% of the best one) in most tag populations. The C1G2 algorithm excels in read rate for its ability to truncate a frame immediately when the current Q value is considered seriously suboptimal. In fact, the APS algorithm can also integrate this optimization. We leave this optimization as a future work because the NI development platform has limited support for such fine-granularity control on the communication process. The reason that the Traditional Q algorithm is always worse than the C1G2 algorithm is the simplification of the frame and slot model makes it almost always chooses a suboptimal Q.

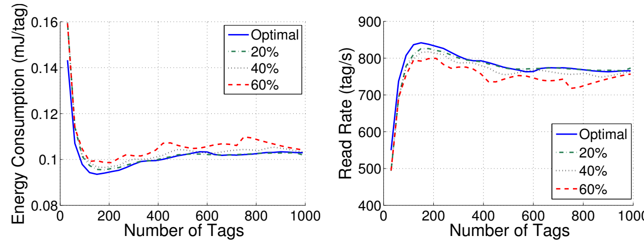
Additionally, two phenomena about the APS are worth noting in Fig. 10(b). The first one is that its read rate increases significantly at around 100–300 tags with $Q_{init} = 4$ (200–600 tags with $Q_{init} = 5$), where the number of tags responding at each power level is suitable for Q_{init} in the first frame. Hence, the performance of the APS can be further improved if the approximate number of tags is given.

The second phenomenon is that the read rate of APS is low when the number of tags is small. This is caused by the frame overhead at the beginning of an inventory frame, which becomes a large proportion of operation time and results in a significant decrease in performance when the duration of a frame is short. When the number of tags increases, the overhead is amortized among tags and the read rate increases quickly. Therefore, APS is more effective in dense-tag scenario, which is usually the case in applications like logistics and inventory.

E. Robustness

In a realistic application setting, the distribution of the power responsiveness of RFID tags is often non-uniform, and our estimation of Q is certainly subject to errors. APS is designed to be resilient to these realistic issues.

The performance of our algorithm is based on the optimal Q value we use in each frame, and the selection of Q is based on the prediction from the tag estimation algorithm we use. We run simulations to investigate the impact of the accuracy of the estimation algorithm on the performance of APS. Fig. 11 demonstrates that, even if the estimation error rate reaches as high as 60%, the final performance of our energy-efficient algorithm remains at 90% of the optimal performance. This simulation result indicates that our energy efficient algorithm is resilient to imperfect tag population estimation, which is often the case in reality.



(a) Energy Consumption (b) Read Rate

Figure 11. Tolerance on estimation error

V. Related work

The RFID communication protocols have been widely studied and some are standardized. However, no existing protocols are optimized for significantly reduce the energy consumption of the tag inventory process. A number of existing protocols aim at avoiding collisions in RFID communication. There are two categories avoidance techniques of collision protocols for RFID systems. The first one is the tree-based protocols [16][23][24]. They use the binary tree structure, by announcing a prefix of tag ID (which is shorter than EPC and should be programmed by manufacturers or users without uniqueness guarantee) at the beginning of each time slot, in order to split the collision tags into smaller subtrees until there is only one tag in a branch. However, the performance of these protocols degrade quickly as the quantity of tags grows due to the heavy overhead each round. The second category includes the ALOHA-based protocols [15], such as the widely used EPC Class 1 Generation 2 protocol [14]. Each tag replies once at a randomly selected time slot in an inventory frame, the length of which is assigned by the reader according to the population of tags. The performance of the ALOHA-based scheme is highly dependent on the frame length that the reader chooses each time. Collision avoidance benefits energy efficiency indirectly, but could not significantly reduce the power consumption.

Variable length slots are widely used in realistic RFID environments. When choosing the length of each frame in an ALOHA-based protocol, many existing works [6][18][19] failed to take the actual length of a time slot into consideration, and use the successful rate to evaluate the throughput of a scheme. However, this evaluation strategy is inaccurate in practice, as we discussed in Section III-B. Considering the empirical situation, Wang et al. [25] use the TIS (tag identification speed) to model the throughput and propose a new optimal Q algorithm to improve the C1G2 protocol.

There exists a body of literature on energy efficiency of wireless ad hoc and sensor networks. Most of the existing solutions focus on controlling the radio transmission power, turning off radios whenever they are not in use, or a combination of both. We refer to [26] for a comprehensive survey. However, these approaches are not directly applicable to RFID systems. There exist very few studies that focus on the energy efficiency of RFID readers. The Progressing Scanning (PS) algorithm is proposed in [6] to use various power levels to read RFID tags. Specifically, the reader starts inventory from the lowest power up to the highest level available. This process is repeated by the reader until there is no tags left. Compared with our APS algorithm, the PS algorithm needs an extra flash memory or extra read/write process in a tag to log its current inventory state, and therefore could not be directly used in the current C1G2

RFID systems. Moreover, the PS algorithm fails to consider the situation where some tags are in lossy state and cannot be identified at one power level no matter how many attempts are made.

VI. Conclusion

In this paper, we develop an energy efficient RFID inventory algorithm called *Automatic Power Stepping (APS)*. APS is designed based on several key observations revealed by our experimental results. First, we have shown that RFID tags exhibit significant diversity in the responsiveness. Second, we identified the existence of a lossy state of passive RFID tags in which the reader can not detect tags although tags could have responded. APS reduces the transmission power of RFID readers by exploiting the diversity and handling the lossy state of tags. In addition, APS accounts for the duration difference of MAC slots in choosing the optimal frame length. APS is fully compatible with the commonly used C1G2 protocol. Therefore, no changes need to be made on RFID tags. Our experiments on NI RFID testing platform and a high-fidelity simulator show that APS can save more than 60% energy in RFID systems.

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