Read More with Less: An Adaptive Approach to Energy-Efficient RFID Systems

Xunteng Xu, Lin Gu, Jianping Wang, Guoliang Xing, and Shing-Chi Cheung

***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 the transmission 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 so that a reader running APS can interact with existing commercial tags without modification. We have implemented APS both on an 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 while maintaining comparable performance on the read rate.**

***Index Terms*—RFID tags, Automatic Power Stepping (APS), energy efficiency.**

I. Introduction

The RFID technology has been used in a variety of application domains, such as logistics, inventory, retailing, public transportation [2], and security [3]. 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. Such an assumption is valid for a small number of RFID readers sparsely distributed in a wired installation, but no longer holds in today's increasingly pervasive and portable computing environment, which is a trend we will continue to witness in the next few 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 smart 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 a short period of time before the depletion of battery energy. For instance, the CSL CS101 handheld reader can continuously read tags for only 1.5 hours [9]. The lifetime of PDA or mobile phone-based RFID systems could be even shorter due to their tighter power budget.
- If multiple readers transmit at their maximum power, the resulted 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 where transponders need to be very close to the reader in order to be activated. This solution is often suboptimal and limits the functionality and usefulness of an RFID system in many application domains. 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 desirable to reduce the power consumption of readers for the sake of system lifetime and interference mitigation. Meanwhile, in reducing the power consumption of readers, we also need to take the following issues into 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, an energy-efficient RFID reader should

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be compatible with the existing RFID standards as a large number of commercial tags have been deployed.

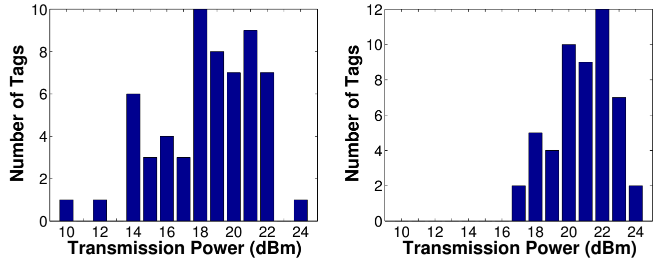
Aiming to significantly reduce energy consumption while maintaining comparable system performance, we develop a new energy-efficient RFID inventory algorithm called *Automatic Power Stepping (APS)*. Running on a reader, APS dynamically estimates the number of tags to be read, incrementally adjusts the power level to use sufficient but not excessive power for communication. Consequently, APS reduces both the energy consumption for reading a set of tags and the possibility of collisions in an RFID system. 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 require any alteration on the tag hardware. 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 tag response quality. We reveal that there exists a *lossy* state of passive tags where the target reader cannot detect their existence due to insufficient power although the 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 the actual lengths of different time slots.
3) Based on our empirical study and a new optimal frame length selection mechanism, we design and implement an energy-efficient inventory algorithm, *Automatic Power Stepping (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 almost no 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 explores 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 and outlines directions for future work.

II. MOTIVATION AND APPROACH

In practical RFID systems, tags are spatially distributed rather than collocated at the same position, and the transmission power level at which the reader can 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. Each tag responds to the reader in one round, and refrains from replying to the reader's queries in later rounds. Figure 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, Figure 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–we may "naturally" group tags into subsets by activating them with different power levels.



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

Fig. 1. The number of passive tags detected at different transmission power

Most 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 (Figure 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, let us first introduce the Class-1 Generation-2 (C1G2) RFID protocol, which is the most widely used MAC protocol in current RFID systems. We then discuss 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 the parameter Q (Eq. (8)) 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

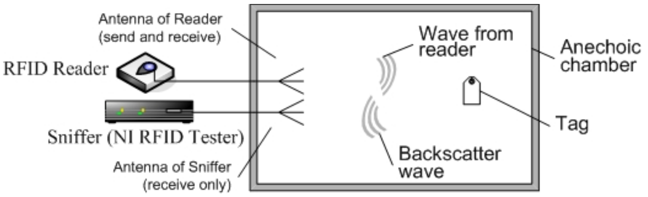


Fig. 2. Setup of the experiment

of participating tags), the expected number of different types of slots can be calculated as follow:

$$TotalSlots: \quad L = \quad 2^Q \tag{1}$$

$$EmptySlot: \quad N_0 = \quad L \times (1 - \frac{1}{L})^{N_{tag}} \tag{2}$$

$$SuccessfulSlot: \quad N_1 = \quad N_{tag} \times (1 - \frac{1}{L})^{N_{tag}-1} \tag{3}$$

$$CollisionSlot: \quad N_x = \quad L - N_0 - N_1 \tag{4}$$

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 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.

We observed from experiments that, in reality, the difference between such two response rates could be significant. We conduct a number of experiments of a configuration shown in Figure 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).

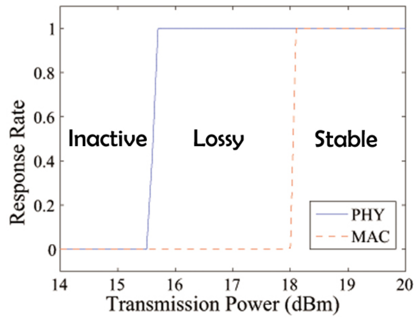


Fig. 3. Response rate of a tag detected at different layers

We have performed this experiment in an anechoic chamber several times to ensure the repeatability of results. Figure 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.

We further examine the signal waveform at the physical layer, as shown in Figure 4, to illustrate the reason for such a disparity. Figure 4(a) shows a typical frame where a tag is successfully detected; Figure 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 Figure 4(a), we note that the tag abruptly stops responding in Figure 4(b) when transferring its EPC (Electronic Product Code). Moreover, the backscatter signal strength from the tag in Figure 4(b) is almost as strong as that in Figure 4(a), which is sufficient for demodulation. Experimenting with several commercial passive tags from different vendors, we ruled out the possibility of tag flaws, and noted that it was the insufficient energy store in the passive tag that made the tag abruptly stop responding and resulted in "no response" at the MAC layer.

We verified this observation with an additional experiment — we used the same power level as in Figure 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 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 Figure 4(c), the same tag now manages to complete 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.

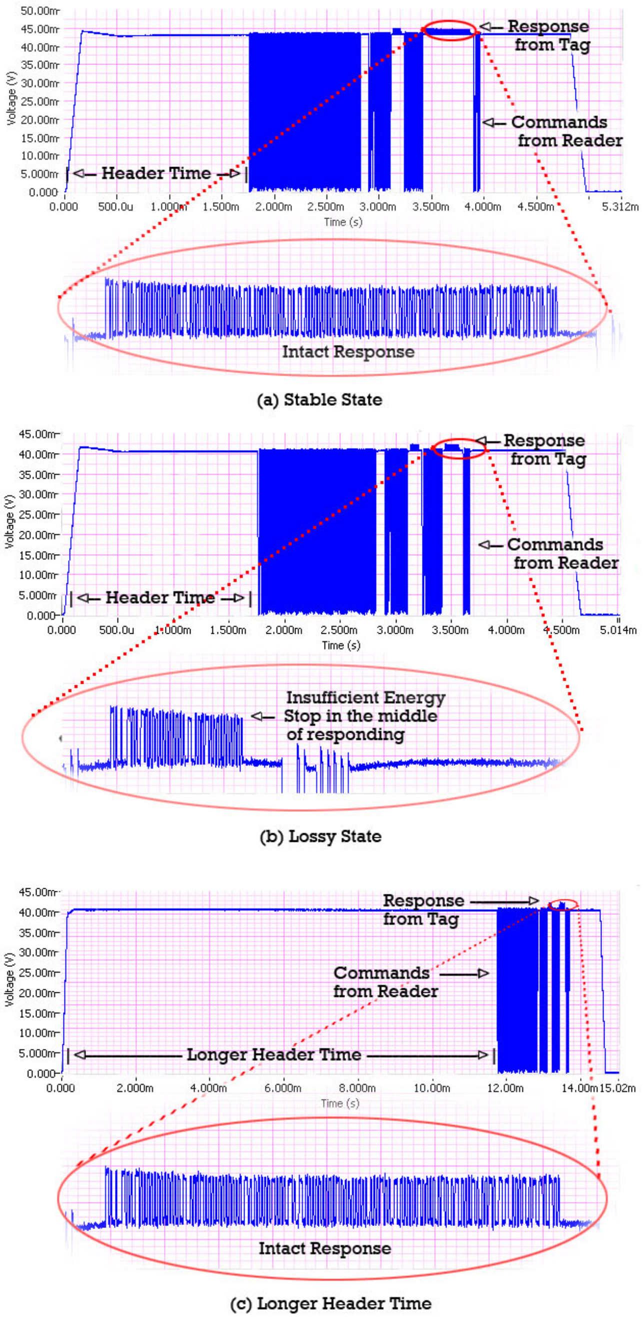


Fig. 4. Signal waveform captured by a sniffer

To verify the generality of this characterization, we conduct similar experiments on multiple types of tags from different manufacturers using different ICs, and discover the ubiquity of lossy-state in passive RFID tags. Table I shows some of experimental results.

The lossy state is, however, largely ignored by existing work [5][17] on the modeling of RFID systems, and a swift and negligible transition from *off* to *on* is assumed instead. Based on controlled experimental results and our observations in RFID testing, we believe that disregarding such realities would be an over-simplification, and would likely result in designs with suboptimal performance. Though power-oblivious systems can

TABLE I
RANGES OF LOSSY-STATE OF DIFFERENT TAGS

Manufacturer	Model	IC	Typical Range of Lossy-State (dBm)
Alien	ALN-9640	Higgs-3	0.3-3.0
UPM Raflatac	Frog UR1600	Impinj Monza 3	0.3-1.4
UPM Raflatac	Dog Bone UR1572	Impinj Monza 3	0.3-1.1

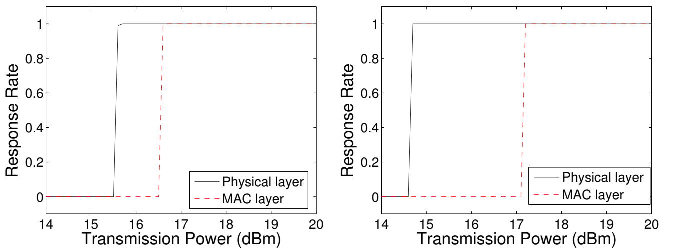


Fig. 5. Diversity of tri-state

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 throughout the query 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 Figure 3, the transmission power ranges of $P_{inactive}$, P_{lossy} and P_{stable} are $[0dBm, 15.5dBm]$, $[15.6dBm, 18dBm]$, and above $18.1dBm$ 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 (Figure 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.

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

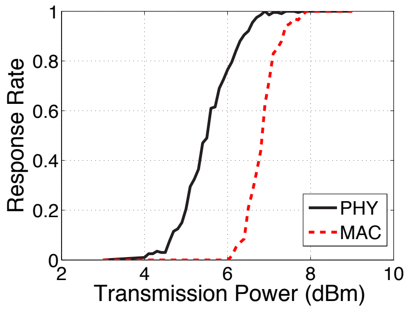


Fig. 6. Tri-state of a BAP tag

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 the RFID system is improved.

As a relevant design goal, particularly important for practicality, new RFID techniques would, ideally, maintain reasonable compatibility with the C1G2 protocol because of the vast volume of existing C1G2 RFID tags. Our algorithm design is, in fact, fully compatible – energy saving is achieved using the information and operations specified in the C1G2 protocol. Unaltered C1G2 tags can interoperate with the new energy-efficient algorithm.

D. Battery Assisted Passive (BAP) Tag

Through our extensive experiments on various types of tags from different manufacturers, we observe the ubiquity of the existence of the tri-state power responsiveness in RFID tags, even including BAP (Battery Assisted Passive) tags. Table 6 is the response of a BAP tag – PowerID A137.

The only difference in power responsiveness between the passive tag and the BAP tag is that the growth in response rate of the BAP tag is more moderate than that of the passive one, because of the embedded battery in the BAP tag. Since a tag in the transition area is not readable either, it can be handled as one in lossy state.

For ease of discussion, all the RFID tags we use in the following experiments are passive ones only, since passive tags are more widely used in reality, but the main observations and results shall also apply to BAP tags.

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.

TABLE II
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.

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 II shows the notations 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-C, 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 is 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 cases, we use the second variable C_i, which is bounded by C_{bound}, to control

Algorithm 1 The Automatic Power Stepping Algorithm

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

the outer loop. In Section III-D, we will further discuss how C_{bound} affects the performance of the algorithm and how we select a suitable C_{bound} value.

B. Finding the Minimum Power Level

For better performance, the starting transmission power P_{start} should be the lowest power level that can activate at least one tag. Instead of progressively increasing the transmission power step by step, we use a more efficient approach by running a binary search through the power levels.

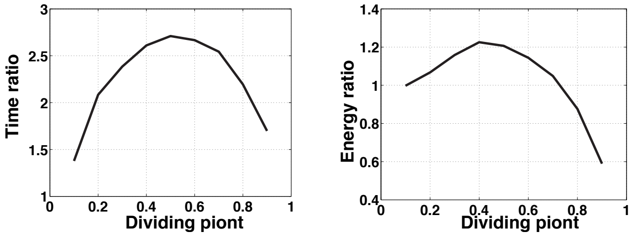
In order to find out the best dividing point for the binary search, we run a simulation comparing the performances using linear and binary search. We assume that the lowest detectable tag has the same probability to appear at each power level, and the reader starts searching P_{start} from 0 dBm to 30 dBm. Figure 7 shows the simulation results. The Y-axis in Figure 7(a) is the time ratio of linear search to binary search, and Figure 7(b) shows the energy ratio.

From Figure 7(a), we can find out that 0.5 is the best dividing point in terms of the shortest searching time, and it saves 67% time compared to the linear search. According to Figure 7(b), 0.4 is the proper value if we want to achieve the lowest energy consumption, and it saves 17% energy.

C. 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:

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



(a) Time (b) Energy

Fig. 7. Linear search vs. binary search

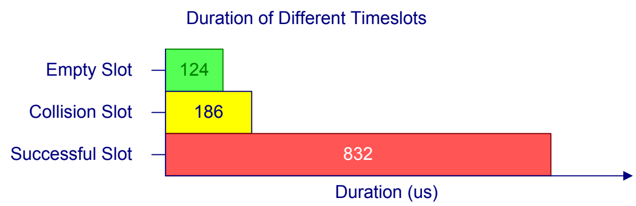


Fig. 8. Duration of different time slots in our typical setting (Table V)

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 Figure 8, 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.

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

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

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. (8)-(11). 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 III shows two example mapping lists for two RF settings.

As we can see from Figure 9, 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.

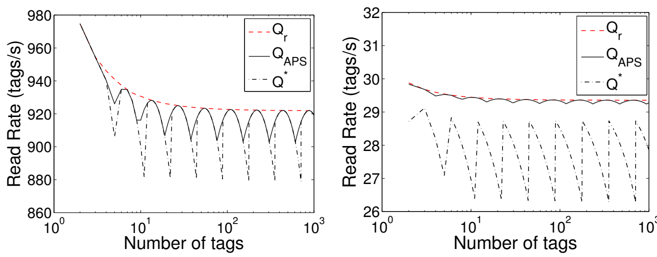
TABLE III
$N_{tag} \rightarrow Q_{opt}$ MAPPING LISTS

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

(a) Tag to reader data rate: 320kbps

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

(b) Tag to reader data rate: 5kbps



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

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

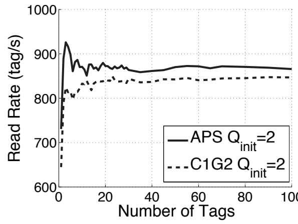
Fig. 9. Expected read rate when the optimal Q value is selected for a set of tags to maximize the read rate. Q_r: the Q value can be a real number; Q_{APS}: the Q value is an integer and slot length diversity is considered; Q^*: the Q value is an integer and the lengths of slots are assumed to be equal.

Such a throughput improvement becomes more significant when the BLF (Backscatter Link Frequency) is low as shown in Figure 9(b), due to the larger differences of different kinds of slots. We use Q_{APS} to select Q_{opt} in our Algorithm 1.

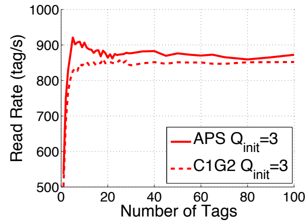
Due to the use of optimal Q selection algorithm, our APS algorithm obtains certain performance gain, and outperforms the traditional algorithm in C1G2 most of the time. According to Figure 10(a)- 10(d), we can see that the performance of Q selection algorithm in APS is greatly affected by Q_{init}, while the performance of C1G2 Q selection algorithm is relatively stable regardless the value of Q_{init}.

Moreover, when Q_{init} is assigned a small value in APS (e.g., $Q_{init} = 2$ or 3 in Figure 10(a)- 10(b)), the performance of APS is always better than that of C1G2. However, as Q_{init} is getting larger (e.g., $Q_{init} = 7$ in Figure 10(d)), ASP is less efficient than C1G2 when the number of tags is small. The reason is that C1G2 can terminate a frame prematurely, and restart a new frame with a new Q. Therefore, C1G2 is faster to converge to its optimal point. As a result, a smaller Q_{init} often gives more stable and consistent performance when we use the APS algorithm.

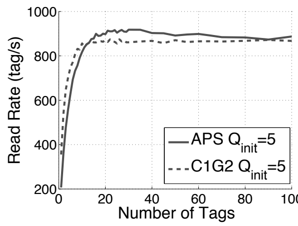
The study on realistic throughput also leads to two important observations. First, the adaptive Q setting makes APS resilient to imperfect Q_{init} values. In reality, it is difficult to determine Q_{init} without *a priori* knowledge on the network size. Second, the throughput benefits from smaller incremental changes of power levels and the resultant smaller groups. Hence, we choose, as the default settings in APS, $Q_{init} = 3$



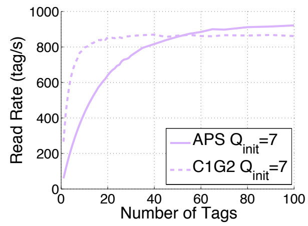
(a) $Q_{init} = 2$



(b) $Q_{init} = 3$



(c) $Q_{init} = 5$



(d) $Q_{init} = 7$

Fig. 10. Performance gain from APS Q selection algorithm

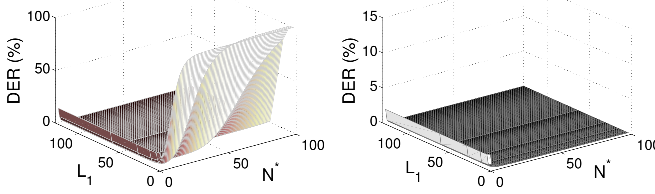
and $k = 1dBm$, which is the smallest step available in many RFID readers.

D. 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 occur 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 levels, 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

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



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

Fig. 11. Differentiation error rate caused by lossy tags

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

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

Figure 11 shows that, though $DER(1, L_1, N^*)$ is quite high when $N^* \gg L_1$, we can reduce DER to below 2% when $C_{bound} = 2$.

We also conduct an experiment to verify the mathematical result for selecting a proper C_{bound}. We place 10 Alien ALN-9540 passive tags in front of an RFID reader which is running our APS algorithm. We tune the reader to different C_{bound}, then record the number of tags it detects and the time it spends on performing an interrogation. For each C_{bound}, we repeat the experiment for 100 times, and average the results. Table IV shows the experiment results and the DER, Read Rate with different C_{bound} values.

According to both the theoretical and experimental results shown above, we can conclude that, $C_{bound} = 2$ is a proper C_{bound} value that can provide a satisfying low Differentiation Error Rate while maintaining the high read rate. When C_{bound} is larger ($C_{bound} > 2$), the reader wastes extra frames on unreadable lossy tags, and decreases the overall read rate, although it has a lower DER. When C_{bound} is too small ($C_{bound} < 2$), it has higher probability of forcing the stable tags to be read with a higher power level, which increases the DER and the probability of collision in the following frames, resulting in low read rate. Hence, we use $C_{bound} = 2$ in the APS algorithm.

E. Performance Analysis

We analyzed the performance of the APS algorithm, and compared the expected performance with the C1G2 protocol. Analytical results show that APS can save more than 60C1G2 algorithm while maintaining similar read rate. Expected performance (i.e. time and energy consumption) of APS can be calculated as follows.

$$L = 2^Q \tag{8}$$

$$N_0 = L \times (1 - \frac{1}{L})^{N_{tag}} \tag{9}$$

$$N_1 = N_{tag} \times (1 - \frac{1}{L})^{N_{tag}-1} \tag{10}$$

$$N_x = L - N_0 - N_1 \tag{11}$$

TABLE IV
C_{bound} AND DER, READ RATE

C_{bound}	1	2	3	5	10	100
Tags Detected (tags)	5.40	9.94	9.96	9.98	9.97	9.99
Time (ms)	8.99	12.92	13.27	13.72	16.03	43.81
DER (%)	46.00	0.60	0.40	0.20	0.30	0.10
Read Rate (tags/s)	600.66	764.46	749.06	728.13	621.96	227.35

Let us use $X_{r,i}$ to denote the value of a variable in the i-th inventory frame at the r-th power level. For example, $L_{r,i}$ stands for the number of slots in the i-th frame at the r-th power level.

Eq. (8)- (11) can be transformed to

$$L_{r,i} = 2^{Q_{r,i}} \tag{12}$$

$$N_{0_{r,i}} = L_{r,i} \times (1 - \frac{1}{L_{r,i}})^{N_{tag_{r,i}}} \tag{13}$$

$$N_{1_{r,i}} = N_{tag_{r,i}} \times (1 - \frac{1}{L_{r,i}})^{N_{tag_{r,i}}-1} \tag{14}$$

$$N_{x_{r,i}} = L_{r,i} - N_{0_{r,i}} - N_{1_{r,i}} \tag{15}$$

$$Q_{r,i} = \begin{cases} Q_{init} & : \quad i = 0 \\ Q_{opt}(N_{tag_{r,i}}) & : \quad i > 0 \end{cases} \tag{16}$$

The definitions of some variables are specified below.

$N_{tag_{r,i}}$: The number of tags unread before the i-th inventory frame at the r-th power level.

$Q_{opt}(N_{tag})$: The function to select an optimal Q for N_{tag}.

$T_{r,i}$: The duration of i-th inventory frame at the r-th power level.

T_{foh}: The time length of a frame overhead.

N_{frame_r}: The number of frames used at the r-th power level.

N_{step}: The total number of power steps used in the whole inventory process, from P_{min} to P_{max}.

p_r: The power used at the r-th power level.

$$N_{1_{r,0}} = 0 \tag{17}$$

$$N_{tag_{r,i}} = N_{tag_{r,0}} - \sum_{n=0}^{i-1} N_{1_{r,n}} \tag{18}$$

$$T_{r,i} = T_{foh} + N_{0_{r,i}} \times T_0 + N_{1_{r,i}} \times T_1 + N_{x_{r,i}} \times T_x \tag{19}$$

$$T_r = \sum_{n=1}^{N_{frame_r}} T_{r,n} \tag{20}$$

$$N_{step} = \frac{p_{max} - p_{min}}{k} \tag{21}$$

Finally, the expected performance of APS is:

$$T_{sum} = \sum_{n=1}^{N_{step}} T_n$$

$$E_{sum} = \sum_{n=1}^{N_{step}} T_n \times p_n$$

To compare the performance with the original C1G2 algorithm using maximum transmission power, we use concrete

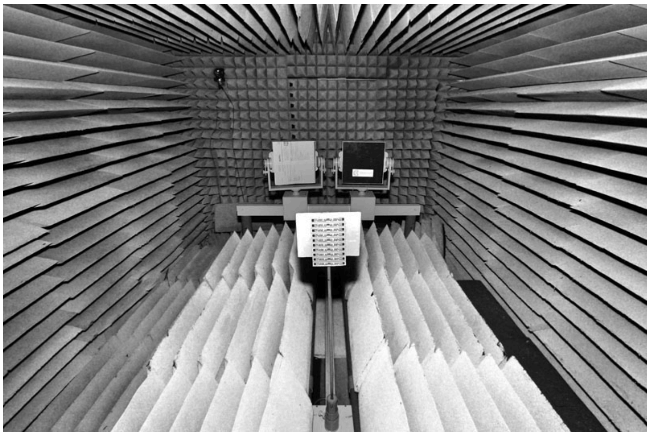


Fig. 12. The experimental environment inside the anechoic chamber

data and calculate the results. Suppose there are 110 tags evenly located in front of a reader. If we use APS algorithm, the reader will finish the inventory by increasing the transmission power from 10 dBm to 30 dBm, using T_{APS} time and E_{APS} energy. When we use C1G2 algorithm, the reader will detect all tags using its maximum transmission power 30 dBm, using T_{C1G2} time and E_{C1G2} energy. Then we have the following results:

$$T_{APS} : T_{C1G2} = 0.99$$
$$E_{APS} : E_{C1G2} = 0.31$$

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 the 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, as shown in Fig 12. Two square plates at the back are antennae. One is for the reader, and the other one is for the sniffer. The reason we do not use one single antenna is to improve the SNR (signal-to-noise ratio) of the received signal for the sniffer, and to maintain the performance of the RFID reader. 60 passive tags are attached to 4 pieces of paper supported by a wooden pole. 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.

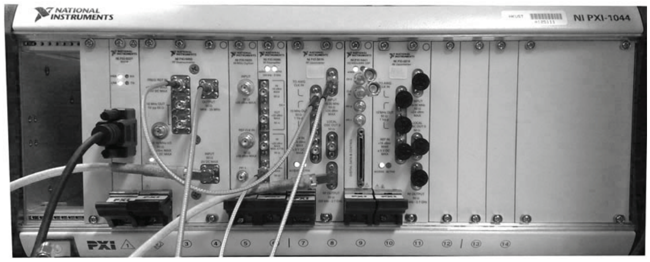


Fig. 13. The programmable NI-VISN-100 RFID tester platform

TABLE V
RF PARAMETERS IN OUR EVALUATIONS

Parameters	Description	Value
Tari	Reference time interval for a data-0 in reader-to-tag signaling	6.25μs
BLF	Backscatter-link frequency	320kbps
Backward Encoding	Encoding approach in reader-to-tag signaling	FM0
Tx Power Range	Range of transmission power	10-24 dBm
T_1	Time from reader transmission to tag response	30μs
T_2	Time from tag response to reader transmission	18.75μs
T_3	Wait time of a reader after T_1 and before it sends a new command	28.13μs
T_4	Minimum time between reader commands	93.75μs
Session	The session number 1 – 4	2
DR	Divide ratio in tag-to-reader signaling	8

Then the verified simulator is used for collecting performance data for larger numbers of tags. For each performance data point, we run the experiment repeatedly for 200 to 500 times, and report the average 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]. Figure 13 shows the prototype implementation placed in an anechoic chamber. Table V shows the RF parameters, which are 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.

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 consumption. Duplicate tag reports are ignored in the calculation of read rate, in order to reflect the true performance of the system. In practice, we avoid duplicate reports using the Inventoried Flag in Session 2 [14] of C1G2-compatible tags. Tags flip their inventoried flags after successfully sending their EPCs, and refrain from responding to further reader requests until the reader sends

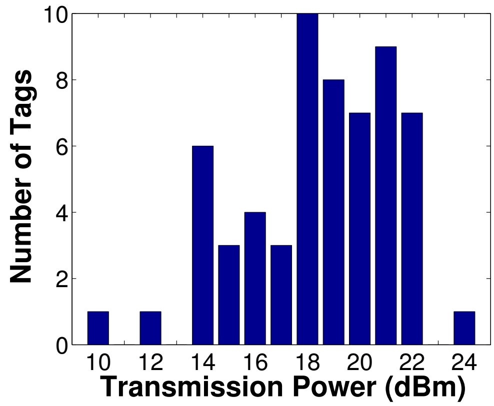


Fig. 14. The distribution of responding RFID tags at different transmission power levels

TABLE VI
PERFORMANCE COMPARISON

	Tags Read	Read Rate	Average Energy Consumption (uJ/tag)
C1G2	57.8	822.72	305.31
APS	57.7	833.17	101.07
APS/C1G2	99.83%	101.27%	33.10%

TABLE VII
EXPERIMENT SETTINGS

Index	Algorithm	Number of tags	Q_{init}
Case1	APS	10	1
Case2	APS	10	2
Case3	APS	10	3
Case4	C1G2	60	3

out a special signal or the tag has waited for a certain amount of time (usually a few seconds). 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 the NI platform).

B. Evaluation Results

To investigate the distribution of the tags' sensitivity to transmission power, we conducted a test to tally the responding tags at different power levels. Results are shown in Figure 14, which clearly demonstrates the diversity of responsiveness even in such a moderate-size tag set. This diversity results from the peculiar properties of individual tags and their positions in the setting, and is a basic observation that motivates our work.

Table VI 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. Moreover, APS maintains a similar read rate to that of a commercial reader. It is noteworthy 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).

C. Comparison of Simulation and Experiment Results

In parallel with the tests on the NI platform, we run simulations to collect performance data for the same experiment configurations as shown in Table VII. Table VIII and IX present the simulation results in comparison with the results collected from the NI-based hardware implementation. Examining multiple scenarios as shown in Table VII, we verify that 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 evaluate and compare the performance of three algorithms, namely, the inventory algorithm recommended in the C1G2 protocol (labeled as "C1G2"), the constant-power inventory algorithm with Q selection algorithm regarding all slot lengths equal (labeled as "traditional Q"), and the APS algorithm (using two different initial Q), with up to 1000 tags.

Figure 15(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 three-fold and the interference among RFID readers in proximity can be significantly reduced.

Regarding read rate, Figure 15(b) shows that the APS provides a comparable read rate (not lower than the commercial reader using C1G2 algorithm) in most tag populations. The C1G2 algorithm slightly excels in the read rate for its ability to truncate a frame immediately when the current Q value is considered seriously suboptimal.

Additionally, two phenomena about the APS are worth noting in Figure 15(b). The first one is that its read rate increases significantly at around 60–200 tags with $Q_{init} = 3$ (120–400 tags with $Q_{init} = 4$) where the number of tags responding at an operable 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,

TABLE VIII
FIDELITY OF SIMULATOR, READ RATE (TAGS/S)

	Experiment	Simulation	Error(%)
Case1	760.06	767.78	1.02
Case2	706.61	721.14	2.06
Case3	576.68	582.67	1.04
Case4	822.72	856.74	4.14

TABLE IX
FIDELITY OF SIMULATOR, ENERGY CONSUMPTION (μJ/TAG)

	Experiment	Simulation	Error (%)
Case1	104.65	108.97	4.13
Case2	111.39	114.22	2.53
Case3	137.19	140.38	2.33
Case4	305.31	293.19	3.97

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 several important classes of applications including logistics and inventory.

E. Comparison with the Progressing Scanning Algorithm

The Progressing Scanning (PS) algorithm proposed in [6] also uses variable power levels to read RFID tags. Since the PS algorithm requires an extra flash memory and an extra read/write logic in a tag to log its inventory state, we find it difficult to implement PS in our testbed. Hence, we conduct simulations to compare the performance of PS and APS algorithm.

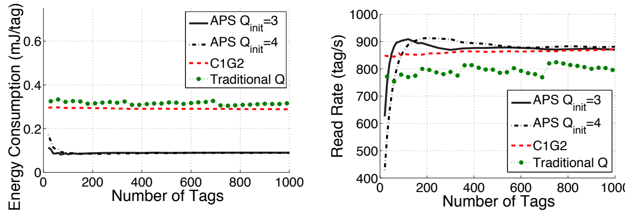
However, when we introduce the lossy state into the simulator, we find that the PS algorithm enters an infinite inventory loop, continuously attempting to identify a tag in its lossy state, and becomes too ineffective to use.

For fair comparison, we slightly enhance the original PS algorithm and add a cycle-limitation mechanism similar to our C_{bound} module, in order to constrain the number of useless inventory loops within 2. Moreover, we limit the choice of frame size to 64, 128, 256, and 512, as used in [6] when it compares with Dynamic Framed Slotted ALOHA (DFSA). Figure 16 shows the simulation results.

When no tag enters the lossy state, the PS and the APS have similar performance. As the number of tags increases, the APS algorithm gradually outperforms the PS because APS uses a more precise estimation approach to determine the frame size.

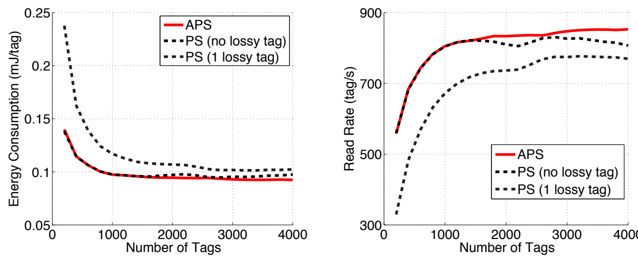
However, according to the observation in our experiments, lossy state commonly exists in passive tags. When a reader uses variable transmission power levels, it is particularly implausible to assume that no tags enter the lossy state. Therefore, we add one lossy tag in all the previous cases and examine the performance using the simulator.

Since the APS algorithm is capable of quickly detecting the lossy tag and effectively handling it (leave the lossy tag to a higher transmission power level), its performance and efficiency are almost the same as that without a lossy tag. On the other hand, the PS algorithm, albeit enhanced, shows lower performance even in such a conservative setting (only



(a) Energy Consumption (b) Read Rate

Fig. 15. Performance comparison of different RFID algorithms



(a) Energy Consumption (b) Read Rate

Fig. 16. Performance comparison of PS and APS

one tag in lossy state) due to the suboptimal usage of power levels.

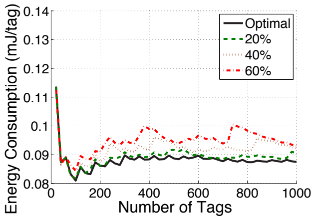
F. Robustness

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.

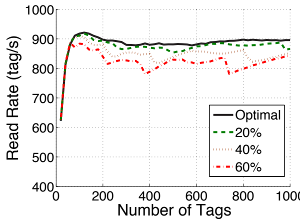
The performance of our algorithm is based on the optimal Q value we use in each frame, and the selection of Q is based on the prediction from the tag estimation algorithm we use. We run simulations to investigate the impact of the accuracy of the estimation algorithm on the performance of APS. Figure 17 demonstrates that, even if the estimation error rate reaches as high as 60%, the final performance of our energy-efficient algorithm remains at 80% 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.

V. RELATED WORK

The RFID communication protocols have been widely studied and some are standardized. However, no existing protocols are optimized for significantly reducing the energy consumption of the tag inventory process. A number of existing protocols aim at avoiding collisions in RFID communication. There are two categories of collision avoidance techniques 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



(a) Energy Consumption



(b) Read Rate

Fig. 17. Tolerance on estimation error

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] fail 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-C. 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 variable 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 are 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. We summarize the difference between the PS and APS algorithms in Table X.

TABLE X
COMPARISON OF THE PS AND APS ALGORITHMS

	PS [6]	APS
Lossy state handling	Not handled. It is possible to enter an infinite interrogation loop when one tag enters lossy state.	Handles lossy state and avoids infinite interrogation loops by controlling C_{bound}.
Compatibility	Not compatible with C1-G2. Needs hardware modification on the tag to store extra state.	Compatible with C1G2. No hardware modification is needed on the tag.
Simulation of time slots	Assumes all slots are of the same length.	Calculate the actual length of each slot according to the reader's parameters.
Q selection algorithm	Traditional Q selection algorithm. Uses a simplified model assuming fixed-length slots.	Takes the variance of slot lengths into consideration.
Starting power level	Manually configured.	Automatically adjusted by a binary search.
Estimation of the number of tags	$N = S + 2C$ (N: the number of tags; S: the number of successful slots; C: the number of collision slots) This approach only calculates the lower bound, and the estimation error may increase dramatically as the number of tags increases.	Adopts a more precise estimation by using maximum a posteriori probability rule [18].

VI. CONCLUSION AND FUTURE WORK

A. Conclusion

In this paper, we have proposed 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 cannot 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.

B. Future Work

We will consider several promising directions in our future work.

In the current research stage, we focus on a single reader mounted with a single antenna. However, system administrators might increase the number of antennas and readers, hoping to extend the overall coverage and to increase the read rate. Such practice brings in new technical issues, such as the collisions among readers due to the overlapping of their reading range. Therefore, it is an interesting research problem to explore the opportunities of reader cooperations using power stepping approach.

Furthermore, all the experiments and simulations in Section IV are based on an assumption that tags are statically located in front of the target reader. Although it holds for many application domains, there are scenarios where tags are moving at high speeds, such as in assembly lines and wireless highway toll stations. New challenges arise when we look into the case of mobile tags. We should update the distribution model when new tags are entering the reading range, and give higher detection priority for those tags that are leaving. Hence, it will also be an interesting topic to explore how to revise the current APS algorithm to handle the moving tags.

At current stage, we study the algorithm at a static carrier frequency 915 MHz. In practice, many commercial readers adopt frequency hopping to avoid interference while two or more readers are reading RFID tags in the same area. Note that the transmission power can vary significantly with frequencies due to the nonlinear frequency response of antenna. How to leverage this difference and gracefully adopt the APS in frequency hopping scenarios is also a further direction of our work.

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REFERENCES

[1] X. Xu, L. Gu, J. Wang, G. Xing, "Negotiate Power and Performance in the Reality of RFID Systems," in *the 8th Annual IEEE International Conference on Pervasive Computing and Communications (PerCom)*, 2010.

[2] R. Want, "An Introduction to RFID Technology," in *IEEE Pervasive Computing*, 2005.

[3] G. Avoine and P. Oechslin, "A Scalable and Provably Secure Hash-Based RFID Protocol," in *Proc. PerCom Workshops*, 2005.

[4] H. Vogt, "Efficient Object Identification with Passive RFID Tags," in *Pervasive 2002*. Springer-Verlag, 2002, pp. 98–113.

[5] Y. Maguire and R. Pappu, "An Optimal Q-Algorithm for the ISO 18000-6C RFID Protocol," *IEEE Trans. Auomation Sci. Eng.*, 2009.

[6] W. Su, N. Alchazidis and Tri T. Ha, "Multiple rfid tags access algorithm," *IEEE Trans. Mobile Comput.*, vol. 9, no. 2, pp. 174–187, 2010.

[7] "PDA RFID Readers/Writers DL710/DL720," *http://www.rfid-in-china.com/2009-12-04/info_4970.html*.

[8] "Wireless Dynamics SDiD 1212 SD card," *http://www.wdi.ca /products.shtml#sdid1212*.

[9] "CSL CS101 handheld RFID reader," *http://www. convergence .com.hk/products_details.php?id=9*.

[10] "IP30 handheld RFID reader," *http://www.intermec.com /products/ip30a/index.aspx*.

[11] "Nokia 3220 with NFC," *http://press.nokia.com/PR/200411/966879_5.html*.

[12] "Samsung RFID reader chip for cell phones," *http://www.samsung.com/global/business/semiconductor /newsView.do?news_id=877*.

[13] K. S. Leong , M. L. Ng and P. H. Cole, "The reader collision problem in RFID systems," in *Proc. IEEE Int. Symp. Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications*, 2005.

[14] EPC Global, *EPC TM Radio-Frequency Identity Protocols Class-1 Generation-2 UHF RFID Protocol for Communications at 860 MHz - 960 MHz Version 1.2.0*, 2008.

[15] F. C. Schoute;, "Dynamic Frame Length ALOHA," *IEEE Trans. Commun.*, 1983.

[16] D. M. Dobkin, *The RF in RFID: Passive UHF RFID in Practice*, 2008.

[17] C. Wang, K. Sohraby, and B. Li, "Performance analysis of rfid generation-2 protocol," *IEEE Trans. Automation Sci. Eng.*, vol. 8, no. 5, 2009.

[18] W.-T. Chen, "An accurate tag estimate method for improving the performance of an rfid anticollision algorithm," *IEEE Trans. Automation Sci. Eng.*, vol. 6, no. 1, Jan. 2009.

[19] J.-R. Cha and J.-H. Kim, "Novel Anti-collision Algorithms for Fast Object Identification in RFID System," in *ICPADS '05: Proceedings of the 11th International Conference on Parallel and Distributed Systems - Workshops*. Washington, DC, USA: IEEE Computer Society, 2005, pp. 63–67.

[20] M. Kodialam and T. Nandagopal, "Fast and reliable estimation schemes in RFID systems," in *MobiCom '06: Proceedings of the 12th annual international conference on Mobile computing and networking*. New York, NY, USA: ACM, 2006, pp. 322–333.

[21] "Alliance Program - VI Service Network - NI-VISN-100 RFID Tester - National Instruments," *http://sine.ni.com/apps /utf8/niaa.ind_pro_view?p_all_id=2365&p_display_all_id=14621*.

[22] "Convergence Systems Limited - CS461," *http://www.convergence.com.hk/products_details.php?id=2*.

[23] J. Myung and W. Lee, "Adaptive splitting protocols for rfid tag collision arbitration," in *MobiHoc '06: Proceedings of the 7th ACM international symposium on Mobile ad hoc networking and computing*. New York, NY, USA: ACM, 2006, pp. 202–213.

[24] L. Pan and H. Wu, "Smart Trend-Traversal: A Low Delay and Energy Tag Arbitration Protocol for Large RFID Systems," in *IEEE INFOCOM*, 2009.

[25] C. Wang, M. Daneshmand, B. Li, and K. Sohraby, "Performance Improvement of Generation-2 RFID Protocol," in *Proc. of QShine 2008*.

[26] G. Xing, M. Sha, G. Hackmann, K. Klues, O. Chipara and C. Lu, "Towards Unified Radio Power Management

for Wireless Sensor Networks," in *Wireless Communications and Mobile Computing (WCMC)*. John Wiley & Sons, Ltd., 2008, pp. 313 – 323.

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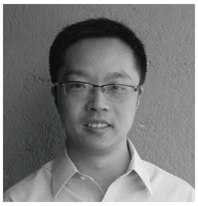

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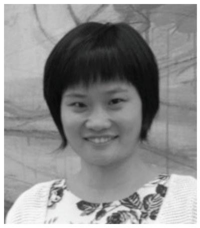

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