RSAA: Reliable Splitting Aware ALOHA to Capture Passing Tags

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***Abstract*—The Radio Frequency Identification (RFID) technology has been widely applied to labeling moving objects. In some RFID application scenarios, e.g., product checking on conveyor belt, the tags labeled on the products need to be identified and accessed before moving out of the reader's probing range. Due to the uncertainty of ALOHA protocol and unreliability of wireless links, passing tags will suffer from collisions and link failures, and then move away without successful response. One important requirement for RFID systems is to reliably identify and access all the tags. There is naturally a tradeoff between system throughput and reliability, e.g., tag may have no chance to successfully respond in high moving speed and system throughput drops in low tag moving speed. In this paper, we introduce an integrated software system Reliable Splitting Aware ALOHA (RSAA), which is used to improve system throughput while maintaining a threshold of tag loss probability. Given a tag loss probability, RSAA is able to approach to the optimal system throughput. We implement RSAA on our NI EPC Class 1 Generation 2 UHF RFID Reader Emulator to read and access commercial tags. Experiments in indoor and outdoor scenarios are conducted to demonstrate the efficiency of RSAA. Compared with moving unaware schemes, RSAA can reliably enhance the throughput by 50%∼100%. We further use trace-driven simulation to show that RSAA is able to support diverse tag density and large-scale UHF RFID systems.**

***Index Terms*—RFID; ALOHA; RSAA**

I. Introduction

Radio Frequency Identification (RFID) is an emerging wireless technology used in everyday scenarios, such as supply chain control, object tracking and asset management[2, 16, 17]. The key driver behind this widespread adoption is the simplicity of RFID tag. There are three kinds of tags: passive tags, semi-active tags, and active tags. The passive tags are usually powered up by the consecutive probing signal from the reader, and then transmits the data stored in its memory [15]. Semi-active tags are powered by the reader in the same way, but they can drive other on-board circuitry by their own power source. Smart active tags have their own CPU, memory and power source, e.g., a wireless sensor node. Today's large-scale UHF RFID systems generally involve passive tags.

To read or write some information in or to a tag's memory is usually conducted during the procedure of tag identification. ALOHA-based algorithm, used by EPC Global Class 1 Generation 2 (C1G2) UHF RFID protocol [15], is widely placed in the off-the-shelf RFID products. The ALOHA algorithm works as follows: the reader probes tags with a Q value, each tag in the probing range randomly picks one time slot in the interval $[0, 2^Q - 1]$. Each tag responds the reader in one randomly selected time slot. A collision occurs when two or more tags respond the reader in the same time slot. Only when one single tag picks one slot, this tag can be identified. If one tag has been identified, the reader will choose to read or write the current identified tag or move to next time slot. Another tag identification method is called query tree (QT) [9, 26], which was defined by Class 1 Generation 1 UHF RFID protocol [14].

Most RFID application scenarios [16, 17] consist of tags that are arriving and leaving frequently. That may be caused by the moving tags/readers and the limited probing range of reader, such as products checking on conveyor belt and warehouse stock taking by a mobile reader. The properties of such applications are access time constraint and identification entireness, e.g., tags have limited life time in the probing range but tag loss is undesired. An important question is whether the existing protocols or algorithms can work efficiently with passing tags.

We start with a common application (rewrite the EPC number of the tag) built in the commercial reader CSL CS-461 [29]. First, we continuously write 10 randomly selected tags to see the performance difference between different tags. As illustrated in Fig. 1, the worst tag can only achieve 20% of average throughput and 10% of the best one. According to the "Bucket Effects", the overall tag access performance will be restricted by the worst one. In dynamic environment, the poor performance tags will waste the channel resource and drop the overall performance. To see how the overall performance is affected by poor tags and tag arriving speed, we let the reader write multiple tags passing the reader's power range. The result is shown in Fig. 2 and we can see the big gap between our expectation and experimental results. That is because the tags, especially the tags with poor performance, suffer from collisions and link failures, and then leave without successfully responding the reader. To avoid tag loss, we must lower the arriving speed of tags, which will dramatically drop the throughput of the system. In our work, we want to enhance the tag reading/writing speed in dynamic environment and bridge the gap between the static and dynamic curves.

In this paper, we design a software system called Reliable Splitting Aware ALOHA (RSAA) to enhance the throughput and reliability in mobile RFID systems. The RSAA mainly

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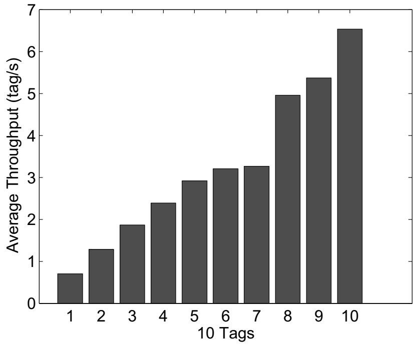

Fig. 1. Different Tags' Writing Speeds.

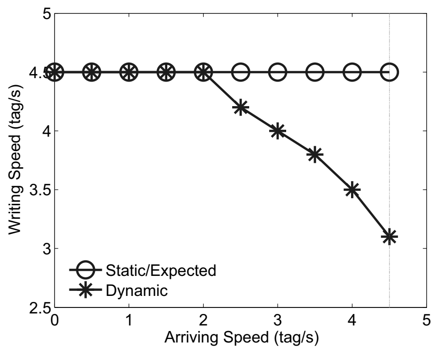

Fig. 2. The Gap Between Expected and Experimental Results.

consists of four components. First, with practical optimal frame length, the RFID reader can reach optimal throughput in single query round. Second, it provides a First Come First Serve (FCFS) work mode under the random access nature of ALOHA-based algorithms, which can avoid tag loss (especially the tags with poor performance) in under load situation and approach to the optimal throughput in the dynamic environment. Third, it estimates the tag arriving speed and calculate the optimal frame length based on it in dynamic environment. Fourth, it maintains the identified tags' states when cutting down the probing signal and discontinuously probe the tags to save the energy usage of the reader. **The RSAA is fully compatible with the most widely used EPC Class 1 Generation 2 UHF RFID protocol**. We implement RSAA in a UHF RFID reader emulator. The extensive evaluations demonstrate that the emulator installed with RSAA can outperform fine grained configured commercial readers and moving unaware schemes in terms of reliability and throughput. **To our best knowledge, this is the first work to study tag loss problem and implement a software system to reliably enhance the system throughput under real experiments for the limited life time of tags**. We further simulate RSAA to demonstrate its efficiency in large-scale RFID systems.

The rest of this paper is organized as follows. The related work is discussed in Section II. In Section III, we build the system model and define the tag loss problem. The main components of RSAA are presented in Section IV. We present the detail design and implementation in Section V. In section VI we compare implemented RSAA with the other schemes and conduct simulations to further demonstrate the advantages of RSAA. We make a conclusion and discuss the future work in Section VII.

II. Related Work

RFID tag identification is a very attractive topic and many excellent arbitration mechanisms [6–12, 26, 34] have been proposed in the past decades. They are generally classified into two categories: ALOHA-based algorithm and Query Tree(QT) based algorithm. The framed ALOHA protocol can get the maximum throughput when the frame length is set to be the number of tags [2, 10]. Some estimation schemes [1, 4] are also designed to count the number of tags in a very short time interval. The query tree (QT) scheme [9] takes the advantage of tag ID to match binary string with the prefix of it. The performance of QT depends on the distribution of tags' ID. A smart trend traverse (STT) protocol [12] is proposed to tolerate different ID distributions. In [26], IQT (Intelligent Query Tree) is proposed to identify RFID tags more efficiently in the scenarios where tags IDs have some common prefix. The DFS (depth first search) liked binary tree [6, 8] iteratively split the collided tags into multiple tag subsets until only one tag make response. This process continues until no tag make response. However, these protocols are designed only for static tags and cannot efficiently identify moving tags. Also, L. Kang etc. propose a CSMA-based tag identification protocol to enhance RFID system throughput, but the protocol is not fully compatible with current EPC C1G2 UHF RFID protocol and has not been evaluated in dynamic environment.

Toward the localization and movement of tags, the LANDMARC system [5] can be an attractive alternative for indoor object localization. In the scenario of object tracking and management, several much efficient methods proposed in [3], which take the advantage of current stored tags information to facility the identification of new arriving tags. Though, they did not consider how to deal with the tag loss problem. A similar mobile scenario is discussed in [18], which is to maximize the number of identified tags by adjusting the arriving speed of conveyor belt. Their work focuses on the speed adjustment of the conveyor belt, but we think that adjusting the reader to the environment is more practical. L. Xie [30] design a probabilistic model to discussion the influence on passing tag identification by real conditions, e.g., path loss and multi-path effect, but the tag loss problem is not discussed. Our scheme can be friendly compatible with the current proposed protocol without any change of reader and tag. W. Luo etc. [34] propose to detect missing active tags in the perspective of energy, but we focus on passive tag as UHF RFID passive tags have mature standard and more broad applications.

Our work falls in the field of multiple accesses in a time limited situation [19]. But [19] only focus on the TDMA as

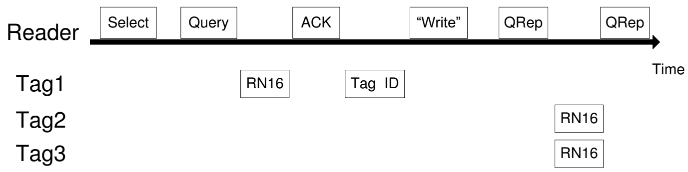

Fig. 3. The EPC C1G2 UHF RFID Protocol.

a time limited communication protocol. The scheduling of packets in time critical environments is investigated in [22], which prove a variety of results that establish the optimality of the STE (shortest time to extinction) policy, which cannot be used in RFID systems as tag can only work in listen before talk mode. Another class of related works is queuing system with impatient costumers [20, 21, 25]. In [20], the different service disciplines (FCFS, first come first served, and SIRO, serve in random order) are discussed and compared in the presence of impatient customers. Scheduling policy optimization for a class of queues with customer deadlines is analyzed in [21], which only focus on the FCFS service disciple only. The traditional queuing theory mainly focus on the FCFS discipline, which is unsuitable for the ALOHA related system, as ALOHA is naturally random and impossible to implement strict FCFS.

III. System Model

In this section, we present the overview of EPC C1G2 UHF RFID protocol and formally define the tag loss problem. Some important metrics for our analysis and evaluation are also given.

A. Reader to Tag Communication

As shown in Fig. 3, the reader starts Query Rounds by "Select" and "Query" commands to identify or access RFID tags. The "Select" command is used to set or change the state information of the passive tags (we will explain the detail in Section IV). In one Query Round, the reader broadcasts a "Query" command (or Q value) to the tags. Each tag randomly picks one time slot from 0 to $2^Q - 1$, the tag picked zero will transmit a "RN16" (16 bits Random Number) to the reader. If the reader fails to receive a RN16, collision or empty slot happens. If only one tag respond the reader, a single "RN16" will be received by the reader and we call this slot is a singulation slot. In a singulation slot, the reader transmits a "ACK" command to enable the tag respond its EPC number (tag ID). If one tag's EPC number can be successfully received by the reader, the reader can choose to write this tag or enter the next slot. After one slot is over, the reader sends a "QRep"(Query Repeat) command to move to next time slot. The slot number picked by the tag will be decreased by one for each received "QRep" command. The RFID reader can also define and modify the state flag of the tag in the field, e.g., the tag's flag will be switched from A to B after identification.

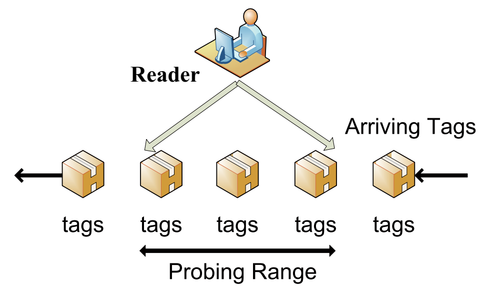

Fig. 4. An Illustration of Passing Tags.

B. Problem Description

The RFID system considered in this paper consists of one reader and many tags. The tags are coming and leaving. As shown in Fig. 4, the range covered by the reader signal is called probing range, which is L when the tags comes in a stream. This range is decided by the power of the reader and the distance D between the antennas to the tags. We treat it as a straight line for simplicity. The moving speed of the tags is v, so the life time of the tags is $t_c = L/v$. Suppose the average arriving interval between two tags is $1/\lambda$, the arriving speed of tags can be represented by λ. In some application scenarios, such as conveyor system, the average density of tags can be known as d, and the arriving speed of the tag can be represented by $\lambda = v \times d$. We will mainly discuss three system parameters: the probing range L, the distance D and the arriving speed of tags λ.

The arriving of tags can be under load or overload. The under load situation happens when the arriving speed of the tags is below the capacity of the system in a static environment. For example, the capacity of framed ALOHA in a static environment is 10 tag/s, hence, if $\lambda \leq$10 tag/s, the arriving speed is an under load speed. The overload situation means that the arriving speed of the tags is beyond the capacity of the system. Therefore, the tag loss is inevitable for single reader. We focus on under load situation and single reader setting in this paper, and leave other combinations, e.g. multiple readers in under load situation and overload situation for future work.

Let θ denotes the threshold of tag loss probability (or loss rate). Suppose the probability of a tag can be identified in one Query Round is $p(t)$, the loss probability then is $1-p(t)$, so the probability that the tag will move out of the transmission range before successfully respond the reader is $P(t) = \prod_{j=1}^{m}(1 - p(t))^j$, where m is the number of Query Rounds that the tag is involved in the time constraint, and we want to achieve $P(t) \leq \theta$.

We can find similar observations as in [19] from the above equations: Given a fixed arriving speed, the larger the imposed time constraint, the smaller the loss rate. Given a fixed loss rate, the larger the arriving speed, the larger the time constraint needed to realize this fixed loss rate. Given a fixed time constraint, the larger the arriving speed, the larger the loss rate. The problem solved in this paper can be easily described as: in a listen-before-talk system (such as RFID system, tags listen to the reader and then talk back), given a fixed loss probability (or loss rate), what is the largest throughput we can achieve.

IV. Reliable Splitting Aware ALOHA

We present the big picture and detail design of RSAA in this section. RFID tag has very simple hardware and limited functionalities. Here we mix the component design principle and protocol detail to show that the proposed algorithm is truly feasible in today's RFID systems.

A. How RASS Works

The efficiency of ALOHA-based protocol depends to the offered load, which is the number of tags over the frame length. In other words, the framed ALOHA can get the optimal capacity when the frame length is equal to the number of tags[10]. The assumption therein is that the frame length can be arbitrary integer value, which is not the case in RFID systems. The the frame length in current RFID systems can only be 2^Q, or the power of 2, e.g., 2, 4, 8 etc. In this case, we need to find the optimal Q value first.

Also, for the coming stream of tags, an ideal protocol should identify or write the tag with shortest expected life time. This is, however, not exactly achievable in today's RFID systems. It is difficult to estimate the link quality and rest life time of a particular RFID tag. Therefore, in RSAA, we split the arriving tags into groups. For the current (say 10) tags in the range, we focus on accessing the 10 tags first. During this process, new tags may come in, but we simply ignore them. After we finish these 10 tags, we switch to the new coming ones. This is, what we call, a first come first serve approach.

Besides, we need to estimate tag arriving speed (or the number of new coming tags by the time the identification starts) to enhance the capacity of the ALOHA algorithm. Because the system capacity of RFID system depends on the ratio of frame length to the number of tags. The frame length is configurable, so the number of tags is crucial to the system capacity. In some scenarios, the general tag arriving speed is far below the system capacity, we can periodically turn off the reader to save energy while maintaining the states of identified tags under the condition of no power supply.

B. Optimal Frame Length

For the simplicity of tag design, the current RFID system use Q value to control the frame length and the frame length must be the power of 2[21]. We want to find an optimal Q value when the number of tags is given. Let n denotes the number of tags and f denotes the frame length. The system performance can be calculated by $\frac{n}{f} \times (1-\frac{1}{f})^{n-1}$, which refer to the probability that only one tag respond the reader in one time slot. Toward $f = 2^Q$, the optimal Q value for a given n need to meet the following conditions.

$$\begin{aligned} \frac{1}{f}(1-\frac{1}{f})^{n-1} &\geq \frac{2}{f}(1-\frac{2}{f})^{n-1} \\ \frac{1}{f}(1-\frac{1}{f})^{n-1} &\geq \frac{1}{2f}(1-\frac{1}{2f})^{n-1} \end{aligned} \quad (1)$$

Given the number of tags n, the corresponding optimal Q value can be calculated as

$$g(n) = \left\lfloor \log_2(\frac{1}{\sqrt[n-1]{2}-1}+2) \right\rfloor \textit{ or } \left\lceil \log_2(\frac{1}{2(\sqrt[n-1]{2}-1)}+1) \right\rceil$$

or

For a given Q value, and $f = 2^Q$, the number of tags it can optimally serve is in the interval

$$[I^Q_{min}, I^Q_{max}]$$

where

$$I^Q_{min} = \frac{1}{\log_2(\frac{f-1}{f-2})} + 1 \textit{ and } I^Q_{max} = \frac{1}{\log_2(\frac{2f-1}{2f-2})} + 1$$

Further, the duration of each time slot depends on the operations on the tag, e.g., read or write. We assume that the time cost of empty slot and collision slot is t_0. The slot only one tag make response will cost t_1, which could involve in the time cost for identification or further operation. The total time cost is $t_f = f \times t_0 + n_1 \times t_1$, where $1/f$ is the contention probability of each tag, n_1 is the expected number of tags that successfully make response in one round. We can know that $n_1 = n \times (1-\frac{1}{f})^{n-1}$, where n is the number of tags in the probing range. The throughput of one Query Round is $\frac{n_1 \times t_1}{t_f}$, which is the proportion of time cost that used for tag access. The throughput of one normal Query Round is $\frac{n_1 \times t_1}{f \times t_0 + n_1 \times t_1}$.

To achieve the optimal capacity, we should estimate the number of tags in the range. To this end, after we finish one Query Cycle and start to access the new coming tags, we estimate the arriving speed of tags by the number of unidentified tags. During a Query Cycle, we can easily know the number of remaining tags by the number of identified tags in previous Query Rounds. We adopt the tag number estimation methods proposed in [1].

C. First Come First Serve

We propose a First Come First Serve (FCFS) scheme to access the tags with less life time. In the very beginning, we set the tags in the range to be the first group and all new coming tags fall into the second group. We start to access the tags in the second group only after all the tags in the first group have been accessed. So, all the tags in the range are divided into two different groups. The reader will focus on the group with less expected life time and simply ignore another group. After finish one group, the reader then move to the previously ignored group (there may be new incoming tags for this group during the identification or access process of previous group).

In current passive RFID tag, there is a SL value in each tag. The reader can assert or deassert a tag population to set its SL value as SL or $\sim SL$ by the "Select" command. The reader can also send several "Select" commands to participate the tags into different tag populations by the SL value. The reader can query the asserted (with SL) or deasserted (with $\sim SL$) or both tag populations to perform identification by the "Query" command.

The RSAA uses SL value to split the tags. The reader first asserts the currently unidentified tags as SL, so that the tags are logically separated from the new arriving tags which store $\sim SL$. In the coming Query Rounds, the reader only identifies the tag population with SL. If there is no collision from the SL value tag population (the identified tags will not respond the reader) or after a pre-assigned time limit, the reader sends another "Select" command to reverse the SL value of the tags in the probing range. The reader again starts to query the tags with SL. The interval between two consecution reverse commands is called a Query Cycle. As the staying tags and the new arriving tags are stored different SL values, the reader can split them and focus on the query of the tag population with less life time.

The capacity of each Query Round is nearly the same and independent to the number of tags (by changing the frame length adaptively). Suppose there are N_0 tags in the probing range, the remaining life time of them is $t_r = t_c - N_0/\lambda$. We see the N_0 tags as whole and the life time of them depends on the one with the least life time. We will adaptively change the frame length so that the time cost of each Query Round could be $N_0(t_0 + p \times t_1)$,$N_0(1-p)(t_0 + p \times t_1)$,...,$N_0(1-p)^{k-1}(t_0 + p \times t_1)$, where p refers to the probability that one tag can be identified in one Query Round and k is the number of Query Rounds in one Query Cycle. Meanwhile, the loss probability of each tag is $\theta = (1-p)^{k-1}$. We assume a fixed loss probability value in each Query Round here.

We can easily find three constraints in our system model. First, suppose there are k Query Rounds in one Query Cycle, the time cost of this Query Cycle should be less or equal to the remaining life time of the tags, $N_0(t_0 + p \times t_1) \times \sum_i^{k-1} = (1-p)^i \leq t_r$. Second, we want the loss probability of any tag therein to be less than or equal to θ. We should guarantee that $(1-p)^k \leq \theta$. Third, after the identification of the N_0 tags, the number of new arriving tags should be less or equal to N_0, i.e. $\lambda(t_0 + p \times t_1) \leq 1$, so that we can still finish the identification or maintain a desirable loss probability in the next Cycle.

D. Arriving Speed Estimation

The estimation of the tag arriving speed is important. Based on the estimation, we can know the number of tags in the probing range. Meanwhile, we can compare the estimated arriving speed with the capacity of the RFID system to see if the arriving speed is overload speed. Firstly the reader records a start time t_s when identifying all the tags in the range with the value of SL. After all the tags in the range are identified, the reader reverses the SL value of all the tags to estimate the number of new arriving tags $N(SL)$ and record the current time t_c. The estimated arriving speed of tags is simply $v = N(SL)/(t_c - t_s)$. We renew the estimated v by average all the currently estimated values.

E. Energy Efficiency

We preserve the energy of the reader by discontinuously probing the tags in low speed situations. To this end, we choose the session $S2$ to conduct identification and calculate a probing interval. In current RFID protocol [15], each tag has four Sessions $S0$, $S1$, $S2$, and $S3$. Each Session has a flag value to indicate if the tags have been identified in that Session. The flag is default A and will be turned to B after identification. We choose $S2$ because the inventoried flag will be maintained more than 2 second even no continuous RF wave (CW) received [15].

In the low speed situations, the first arriving tags are the first choice of identification. However, when we probe the new arriving tags, there could be no tags come in the current Query Cycle. The redundant probes will cost extra energy so that the energy efficiency drops. If we stop probing and the state information of tags will change, the old tags will be identified again in next probing period. To avoid the cost on redundant identification, we choose Session $S2$ as the flag value in this Session will keep more than $2s$ even no signal received. Sometimes, we should keep the probing speed in a low level to tolerate the varied tag density in the realistic deployment. We need a probing interval to discontinuity initialize each Query Cycle. If we wait too long (less than $2s$), the arriving tags become too many to be identified in the range, the loss probability will increase. The interval can be calculated as N_0/λ.

V. Implementation

We implement RSAA on the NI VISN RFID test software (or an EPC Gen2 Reader Emulator) [26]. This RFID test software has built in capability to make the user generate self demand RFID signal of global requirement, ISO/IEC 18000-6C (EPC Global Class 1 Gen 2) [15]. It supports the National Instruments vector RF modules, including the 2.7GHz Upconverter PXI-5610, the 2.7 GHz Downconverter PXI-5600 and FPGA-Based RF Transceiver PCI-5640R. The implementation of RSAA focuses on the protocol layer and invokes the reader to tag commands by graphical language Labview. We do not choose the commercial readers, e.g. CSL CS-461, as which encapsulate the most command parameters and only open scanty APIs to the users. We use the 3000794 Dual Dipole "Frog" tags produced by UPM Raflatac [27], which show best performance among all kind of tags we have.

A. Antenna Setting

The NI emulator has two antenna ports, one for transmitting and the other for receiving. Two antenna setting will decrease the efficiency of the system compared to the commercial reader's single antenna setting. If the orientations of the two antennas (about 60° directional) are parallel, the probing range will be quite small, and the passing tags will have very limited life time. If we enlarge the overlap of their work range, the transmitter will produce extra noise (The work mode of RFID system is receiving when probing) to obstruct the receiver's receiving and decoding. This influence can be reduced by increasing the distance of tag and antenna. To eliminate the influence of the antenna setting, we fix the orientation of the two antennas to be parallel. Other settings may show different performance on tag identification or tag access. However, the

TABLE I
EXPERIMENT SETTING

	d(tag/m)	D(m)	L(m)	Power(dBm)
Indoor	12.5	0.3	0.32∼0.56	16∼20
Chamber	12.5	0.3∼1	0.32∼1	18∼24

discussion about attenna orientation is out of the scope of this paper.

B. Driver Constraints

We implement RSAA as a two stage tag access scheme. RSAA only requires to modify the tag identification parameters in each reader command. The NI emulator opens all the parameter settings but the driver of which is encapsulates. The time gap between a “Select” command and a “Query” command is less than one microsecond [15], so it is impossible to implement these two successive commands by advanced programming language, e.g., Labview. The NI emulator has a self-contained multiple tag identification and single tag identification. The normal process of one tag access can be finished in one Query Round as long as it can be identified, but we cannot interrupt the multiple tag query process of the NI emulator.

The only thing we can do is to firstly identify the tags and then access each by its EPC number. This will cause extra one Query Round for each tag access. The modified RSAA works as follows. The RFID reader firstly collect all the EPC numbers of the RFID tags in the field. For each collected RFID tag EPC number, the RFID reader uses another Query Round to identify and access the tag with known EPC number. We implement RSAA in the way described here. The real RSAA could perform 10∼100 percent better in different access mode.

VI. PERFORMANCE EVALUATION

Our evaluation consists of two parts, emulation part and simulation part. In the emulation evaluation part, we compare implemented RSAA with CSL commercial reader and other moving unaware schemes implemented on NI emulator to demonstrate its feasibility and efficiency. In the simulation evaluation part, we test the performance of RSAA in the high speed and large scale RFID systems.

We compare RSAA with ALOHA with Frame Estimation (AFE), Real and Simulated Commercial Reader (CR and SCR) and Smart Trend-Traversal (STT) [12]. The RSAA and AEF use the same frame estimation algorithm [1]. We assume the commercial reader always know the number of tags, so it represent the best access approach in static environment. STT is a tree-based algorithm and simulated by its default settings [12]. AFE and STT represent the best approaches of ALOHA-based algorithm and tree-based schemes we can find. The tree-based protocol usually has low throughput as it requires the reader to send long “Select” command for each Query Round. To select a group of tags, the reader needs embed the ID prefix into the “Select” command, which will waste the bandwidth especially under low reader rate conditions.

A. Evaluation Results

We evaluate the RSAA by rewriting the EPC number (or ID) of the tags, which is a quite general application as we need to rewrite the EPC number of the tag before or after labeling it on the corresponding products. It should be noted that the writing will cost a little more time than just reading the EPC number and cost less time than writing extra information on the other memory bank of the tags. Therefore, our evaluation is representative enough to all the applications related to the tag reading and writing. The CSL CS-461 EPC C1G2 RFID Fixed Reader has a build-in demo that rewrite the EPC number of the tags.

There are 20 tags attached on a board (see Fig. **??**), which is carried by a conveyor belt. The conveyor belt is controlled by the “high speed carrier”, the speed of which range from 100mm/s to 5m/s. We will compare the performance RSAA implemented in NI emulator and the demo program in the commercial reader (CR) in indoor environment and chamber. The power level of the reader is range from 10∼24dBm and the probing range is usually range from 320mm∼1m. The tag density is 12.5 tag/m, i.e. the “frog” tag is size of 80mm×80 mm. The power levels in the indoor environment and chamber are different because the chamber is wide and the distance between the tags and antennas can be adjusted from 0.3m to 1m.

1) Varying the Moving Speed: We conduct the experiment in a narrow corridor (indoor environment), the distance between the antenna and the tags are constrained (by the environment) in half meter. We fix the probing range L and distance D of the CR and the RSAA implemented on NI emulator to compare the loss probability in different moving speed of tags. In the identical setting, the distance between the antenna and tag is 0.3m and probing range is 0.4m, we test the maximum tolerated single tag moving speed of the CR and emulator. The CR can tolerate the speed of 1.8m/s to rewrite the EPC number of singe tag and RSAA can tolerate that of 1.7 m/s.

We run the process of rewrite the 20 tags 10 times for each speed, and set the reliability is to be the proportion of lost tags. In general, the reliability is one when no tag loss and zero even only one tag loss. The RSAA installed in the NI emulator can outperform the commercial reader in the similar environment parameter configuration. In a conveyer belt system, the throughput depends to the arriving speed of products. The RSAA can reliably enhance the throughput by 2× compared to the commercial reader (see Fig. 5). STT performs not good as the reader need to start a new Round (send “Select” command) after each Query, the cost of Round initialization is very high (“Query” command must follow a “Select” command). We conduct the similar experiment in the chamber and get similar results.

2) Varying the Probing Range: To better understand the performance of RSAA in a clear environment, we further test it in a chamber, which is like an open field that can eliminate the influence of the physical environment. We vary the probing

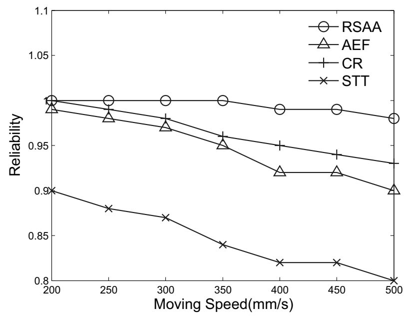

Fig. 5. Reliability vs. Moving Speed in Indoor Environment.

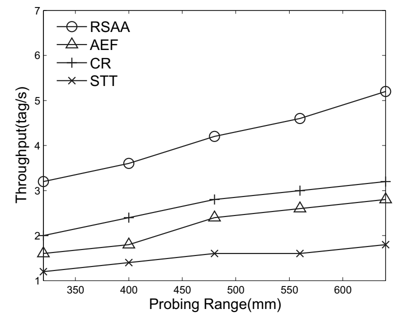

Fig. 6. Throughput vs. Probing Range in the Chamber.

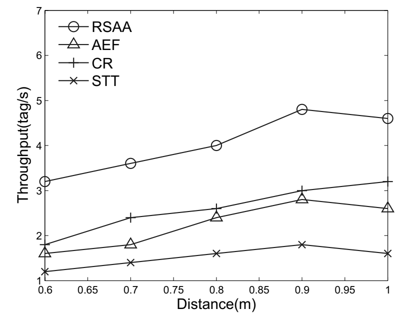

Fig. 7. Throughput vs. Distance in the Chamber.

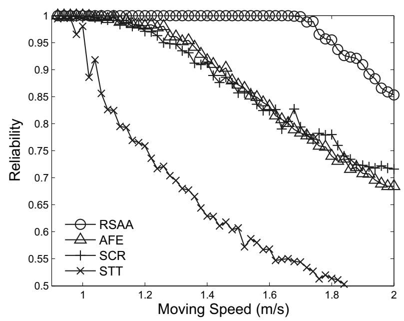

Fig. 8. Reliability Study by Simulation.

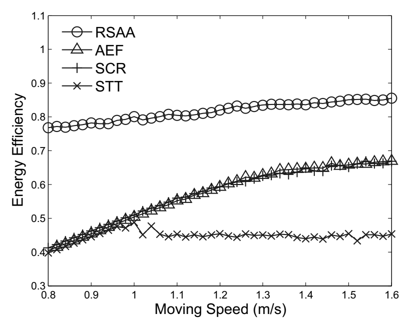

Fig. 9. Energy Efficiency vs. Moving Speed.

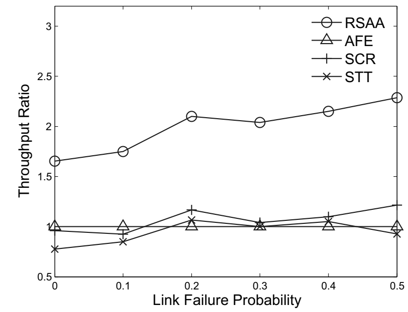

Fig. 10. Throughput When Considerng Link Failures.

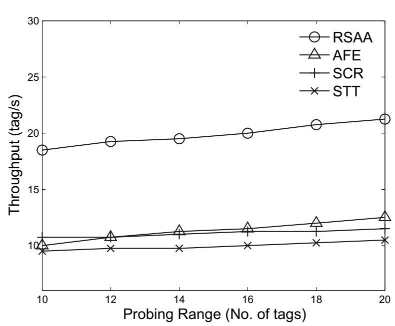

Fig. 11. Throughput Under Different Probing Ranges.

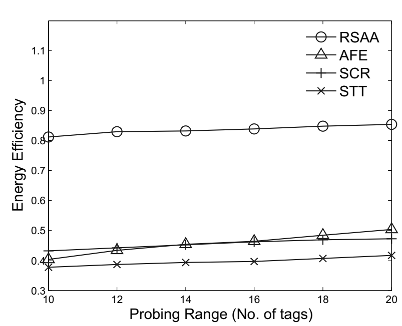

Fig. 12. Energy Efficiency Under Different Probing Ranges.

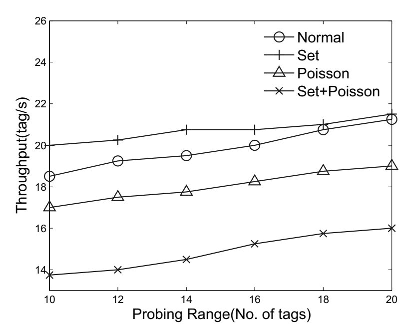

Fig. 13. Throughput of RSAA in Various Settings.

range and the distance between the antenna and the tags to compare RSAA with other moving unaware schemes. The throughput is measured as the number of written tags per second, which is measured when the reliability is equal to one. As shown in Fig. 6, the RSAA can generally increase the throughput by 1.5$\sim$2$\times$ with the same reliability. Four tags can be successfully written per second on the conveyor belt. Generally, the longer the distance, the link will be more unreliable. The RSAA can still be quite reliable because the reader writes the tags also roughly in first come first serve order.

3) Varying the Distance: Another parameter of interest is the distance between the antenna and the tags. With the increase of the distance, the probing range of the reader increase correspondingly, which may be not good for tag identification or access, thought. The results are shown in Fig. 7, the throughput of RSAA decrease slightly when the distance reach to 1m, as the link quality drops with the increase of the distance. When the distance increases, the cover range of the RFID reader on the tags increase, but the tags in the range will have less power supply, which may potentially reduce the link quality of the RFID tags. The CR does not show the same trend as the sensitive distance of single antenna is longer than our experiment setting.

B. Simulation Results

To evaluate the performance of RSAA in large scale and high speed RFID systems, we build a simulator to see how efficient RSAA can be after built in the driver. The parameter settings of our simulator are based on the EPC protocol [15]. In our system, the tags are coming and leaving in a given arriving speed. The tags may come set by set, and each set contains one or several tags. In some applications, there could be some tags arrange in a container that comes to the reader. The time interval between two coming tag sets can follow uniform distribution or Poisson distribution. Each tag will stay fixed time duration in the probing range of the reader. This setting is representative enough for the most today's applications. For simplicity, we use the probing range only to replace the combination of reader power and the distance in our simulator.

1) Performance Overview: We simulate 1000 tags coming and leaving in an even speed, the reader can probe 10 tags at most in the probing range. The reliability is measured as one minus the loss rate of the tags. We run the four methods in each moving speed of the tags only once. The results are shown in Fig. 8. RSAA can outperform AFE by the speed estimation and the FCFS work mode. Meanwhile, the frame estimation algorithm of AFE shows the similar performance compared to that of SCR. STT is worse than other methods as the cost on the reader selection process. The energy efficiency is measured as the time used on the tag access operation over the total time the reader operated. As shown in Fig. 9, RSAA can maintain much higher energy efficiency in each value of the arriving speed than other methods. The energy efficiency gain comes from the discontinuous probing of the reader when no tags make response to it in the probing range. The reader will power down and wait for the tags. The logical stay tags will maintain their states even no CW received as it chooses the Session $S2$.

We evaluate the throughput and the energy efficiency when varying the probing range in this section. The probing range is measured by the number of tags. In our system, the throughput is related to the tolerated arriving speed and bounded by the capability of ALOHA protocol. The throughput gain of RSAA is from the frame length estimation algorithm and first come first served work mode. In Fig. 11, the throughput is measured when the reliability of the system is equal to one, as we believe the throughput of the system is meaningless in a low reliability situation. As shown in Fig. 12, the energy efficiency of each method is roughly proportional to its throughput. A high throughput means that the work (e.g. write 1000 tags) can be finished in a relative short time, so as the energy efficiency. Other methods should keep probing the passing tags, so that most of energy is wasted.

2) Link Failures: The link failure means the signal transmitted from the tag (up link) is not successfully received by the reader or the tag fails to rewrite its EPC number. There are two possible reasons. First, the energized tag (power is insufficient) is shut down when writing, which will waste one slot and cause possible collision. Second, the reader successfully receives the packets but cannot decode due to a lower SNR. We vary the link failure probability in our simulator. The link failure probability is 20∼40 percent for the CSL commercial reader (varying from different power level). One common link failure is that the tag has insufficient power to rewrite the EPC number. We evaluate the several methods in different link failure settings. The throughput ratio is the ratio of the throughput of other methods to that of the AFE. The reason we select AFE as the baseline is that the frame adaptation algorithm in a normal Query Round is the same as the RSAA. As shown in Fig. 10, the performance of RSAA increases as the increase of link failure probability, which indicate that RSAA is reliable to link failures.

3) Complex Environment: In a complex application environment, the arriving interval between two tags generally follows a Poison distribution. Meanwhile, several tags may enter the probing range at the same time, as they are packed in the same container. The evaluation results in a complex application environment are shown in Fig. 13. The Normal curve represents a result in a uniform arriving interval distribution and tag comes one by one environment. The Set curve represents a result in an environment that tags comes set by set, and each set contain 4 tags. The Poisson curve represents a result that the time interval between two arriving tags follows a Poisson distribution. The Set+Poisson curve represents a result in an environment that combines those in Set and Poisson. The tags come set by set turns out to be better than that come one by one. It shows that RSAA is reliable to the application that tags come in a container. Poisson arriving tags make a little influence on RSAA, as the Poisson arriving affects the speed estimation method of RSAA. The RSAA works in a complex application environment shows better results than that other methods even work in a simple environment.

VII. Conclusion and Future Work

In this paper, we present a novel software system called reliable splitting aware ALOHA (RSAA) to capture the passing tags in UHF RFID systems. As far as we know, this is the first system work to deal with the limited life time tags. The RSAA is fully compatible with widely used EPC C1G2 UHF RFID protocol. The RSAA provides a first come first serve work mode to avoid tag loss (especially the tags with poor performance). Through extensively experiments and simulations, the RSAA can tolerate higher arriving speed of the tags in the under load situation by working in a FCFS work mode and taking the speed element into the calculation of the frame length. We believe that the techniques proposed in this paper can work effective in many application scenarios. Our ongoing research is focused on capturing arriving tag streams by multiple readers in the high arriving speed environment.

VIII. Acknowledgement

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