Modulation Silencing: Novel RFID Anti-Collision Resolution for Passive Tags

Abdallah Y. Alma'aitah
Electrical and Computer Engineering
Department
Queen's University
Kingston, Ontario, Canada
Email:8aa14@queensu.ca

Hossam S. Hassanein
School of Computing
Queen's University
Kingston, Ontario, Canada
Email:hossam@cs.queensu.ca

Mohammad Ibnkahla
Electrical and Computer Engineering
Department
Queen's University
Kingston, Ontario, Canada
Email:ibnkahla@queensu.ca

***Abstract*—RFID technology has been gaining popularity in several automated inventory management applications. In such applications, thousands of RFID tags are attached to different products and the reader(s) will be collecting tags IDs using an arbitration protocols. In the existing tag arbitration protocols, significant time and power are consumed on inevitable tag collisions. In this paper, collision time reduction mechanism, called Modulation Silencing Mechanism (MSM) is proposed. MSM accelerates ending of collision slots by allowing the collided tags to interpret the silencing feedback from the reader and stop their backscattering. The proposed mechanism achieves a considerable reduction in collision time; hence, we proposed a new generalized performance metric to consider the shorter duration of collision slots by MSM. In addition, we evaluate the main RFID arbitration protocols after applying MSM and the time efficiency of these protocols was significantly increased.**

I. Introduction

RFID technologies provide low cost and non-line of sight data collection that enable several automatic inventory applications [1]. In these applications, RFID tags are attached to thousands of objects and their unique IDs are collected by fixed or mobile readers and transferred to a database. Time efficient data collection protocols are essential in such applications to enable prompt scanning of containers moving across fixed readers and, when mobile readers are used, to lower power consumption and battery depletion.

RFID tags are simple integrated circuits with antennas to facilitate power harvesting from the readers signal, decode its commands, and backscatter its continuous Wave (CW). Due to the limited power of passive tags, tag-to-tag intercommunication capabilities are unfeasible. Therefore, tag arbitration protocols are implemented at the readers to organize tag replies through time slotted access mechanisms. Each time slot is initiated and terminated by reader commands and a single tag is expected to reply in every slot. If more than one tag replies in the same slot, the backscattered signals from the tags will collide at the reader's antenna (known as collision slot). Unfortunately, even at optimal settings of anti-collision protocols, 26% to 50% of the total slots are collision slots [2], [3].

During collision slots, replying tags will be backscattering reader's signal, hence, incapable of decoding any termination command [4]. Therefore, the tags in current anti-collision protocols and standards are informed by collisions after the completion of backscattering their ID. In this paper, we propose a novel collision resolution mechanism, called Modulation Silencing Mechanism (MSM), in which the reader can limit the *time* of collision slot. Once the MSM-enabled reader detects a collision it terminates its CW transmission. MSM-enabled tags are equipped with detection circuitry that interrupts any ongoing data transmission if CW is absent. The proposed mechanism is evaluated based on the timing and data fields of the EPC Class 1 Gen 2 standard to allow compatibility with current RFID systems. Our proposed solution is not limited to a specific protocol; in fact, it is applicable for both ALOHA-based and tree-based time slotted protocols. In this paper, we validate our mechanism and show that MSM significantly enhances the time efficiency in current RFID systems.

Our contributions in this article are summarized as follows:

- We introduce MSM as a novel reader-to-tag interaction that targets the wasted time and power in current RFID systems.
- At the reader, a Rapid Collision Detection (RCD) procedure is proposed to allow the CW termination when a collision is detected.
- At the tag, we propose the design of the Continuous Wave Absence Detection (CWAD) circuitry to allow data transmission termination when CW is turned off by the reader.
- We proposed a generalized time system efficiency metric (that considers the shorter collision slots) to verify the effectiveness of the new mechanism in both ALOHA- and tree-based protocols.
- We establish the compatibility and coexistence requirements between the current tags and MSM-enabled tags.

The remainder of this paper is organized as follows. In Section II we introduce the collision problem and the related work. We propose our mechanism in Section III and evaluate its significance on existing RFID protocols in Section IV. The deployment considerations of the proposed mechanism are given in Section V followed by the conclusion in Section VI.

978-1-4673-0328-6/12/$31.00 ©2012 IEEE

II. Motivation and related work

A. Preliminaries

Time slotted anti-collision protocols are based on either probabilistic (ALOHA-based) or deterministic (tree-based) algorithms. In ALOHA-based protocols [5]–[7], the reader defines a specific number of time slots (a frame) and the tags respond randomly in one of these slots. Alternatively, tree-based protocols [3], [8], [9] depend mainly on splitting the tags by reader commands based on their IDs (or portion of their IDs).

The reader begins the tag reading process by broadcasting a CW signal to power up the surrounding tag(s), and then it transmits a specific command to be decoded by the tags. The reader resumes the CW transmission and the addressed tags (by the last command) will start backscattering the CW by changing their antenna load to reflect and absorb a portion of the reader's CW. In single reply time slots, the reader calculates the cyclic redundancy check (CRC) of the tag's reply and sends an acknowledgment (ACK) if it was an error free transmission. Empty slots contains no transmissions and can be early ended by the reader to save power and time [10]. In collision slots, the reader continues emitting its CW until the tags conclude their reply then it sends a negative acknowledge (NACK). As a result, collision slots have a similar duration as a single reply slots. In fact, the reader cannot terminate a collision slot earlier, i.e., before its end, because it is unable to:

- Send a stop command to the tags: since the communication is on a single channel, any command from the reader during the tag's backscattering will not be decoded by the tag.
- Discontinue sending its CW transmission to save power: since the tags are harvesting that power to stay ON and synchronized with the reader's commands, stopping the CW will cause tags to reset their states (due to voltage drop).
- Ignore the collision and initiate a new slot: becasue the tags from the collision slot are still modulating their data which will overlap with the transmission of the replying tags in the initiated slot.

B. Collisions significance

1) Tree-based protocols: In tree-based protocols, the expected total time slots for identifying n tags are $2.337n$ and $2.885n$ for known and unknown tag counts, respectively [3]. Knowing the number of surrounding tags is not common in densely populated tags environments. In Table 1, the expected number of collision (R_c), empty (R_e), and total (R_{total}) slots in tree-based protocols are given for identifying n tags (number of single slots (R_s) is n).

The presented statistics in Table I shows that significant amounts of time and power are wasted on garbled data. Collisions reduce the overall performance by 28.6% in case of known tags count and 50% in the common case of unknown tag count.

TABLE I
Number of empty, collision, and total slots in tree-based protocols [3]

Scenario	Collision slots (R_c)	Empty slots (R_e)	Total slots (R_{total})
Unknown n	$1.443n$	$0.442n$	$2.885n$
Known n	$0.669n$	$0.669n$	$2.337n$

2) ALOHA-based protocols: In the most efficient ALOHA-based protocols, Dynamic Frame Slotted ALOHA (DFSA), several frames are introduced until all tags are identified. Each frame will have a variable number of slots (N) depending on the estimated number of remaining tags n. All unidentified tags will select their replying slots at random within the given N slots frame. If two or more tags select the same slot for sending their data, the reader sends a NACK and those tags will be muted for the rest of the current frame and will reply in the next frame.

Unlike tree-based protocols, collision probability in ALOHA-based protocols depends on the number of tags. Let N_k be the size of the k^{th} frame with n tags to be identified. Since the tags are randomly selecting the replying slots, the number of replying tags per slot follows a binomial distribution. Therefore, the probability of having x tags replying in a specific slot ($P(x)$) is given by:

$$P(x) = \binom{n}{x}\left(\frac{1}{N_k}\right)^x\left(1-\frac{1}{N_k}\right)^{n-x}.$$

Consequently, collision probability, $P(x >= 2)$, is $1 - P(1) - P(0)$ and the expected number of collision slots (R_c) is $N_k P(x >= 2)$. A plot of the expected number of empty, single, and collision slots, with N_k = 256 slots, is shown in Fig.1.

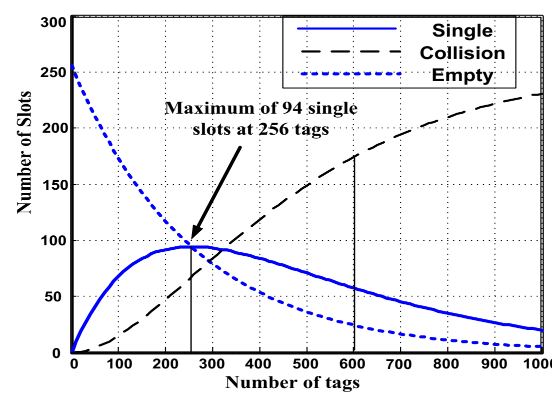

Fig. 1. Number of empty, single, and collision slots in ALOHA protocols (N=256)

Time efficiency in ALOHA-based protocols is a function of tag count. It was verified in [11] that a maximum time efficiency of 36.8% can be achieved when the tag count equals the frame size. However, even at optimal frame size, collisions are expected to occur in 26.6% of the total slots. If the tag count is much larger than the estimated frame size, collision slots will dominate the frame. For instance, in Fig. 1, if 600 tags are to be identified by a 256-slots frame, more than 67% of the total slots will be collisions.

C. Related work

The main focus of the previous anti-collision protocols was to reduce the *number* of collision slots in the identification cycle. In ALOHA-based protocols, this reduction was achieved by estimating the tag count to calculate the optimal frame length [12], [13]. In tree-based protocols, a smart-trend traversal protocol was proposed by [9] to follow the tag ID distribution and minimize collisions.

In ISO/IEC 18000-3 mode 1 extended mode standard [14], collisions are detected either by the reception of corrupted data or by CRC check. If a currupted data is detected, the reader skips the CRC check and issue a NACK. however, as discussed in Subsection II.A, the reader waits for the tags to conclude their transmissions to issue the NACK (i.e., no time saving from the early collision detection).

To reduce the time waste on collision slots, two-phase tag identification mechanism was adopted by EPC standard Class1 Gen2 [15]. In the first phase, the tag backscatters a relatively short sequence (compared to the tag's ID) to the reader. If this sequence is error free, the reader initiate the second phase by sending the same sequence back to the tag and then the tag sends its full ID. If a collision or no reply is detected in the first phase, the second phase will not be initiated. This scheme reduces time of both empty and collision slots; however, the first phase is added to every single reply. As verified by [4], the length of the first phase is comparable to the second phase and the gain of shorter collision and empty slots was hindered by the longer single time slots [4]. Recently, [16] and [17] proposed collision direct decoding schemes for the EPC standard. The schemes extract the tags information if collision occurred in the first phase. However, the modification to the tag reply limits its efficiency to low tag count applications and increases the hardware complexity at the reader.

The existing protocols are either targeting the reduction of collision count in the identification process or extracting data from collision slots. The later protocols require a complicated hardware interface at the reader and preknowledge of parts of transmitted data. We propose a mechanism that imitates a two way communication in wireless networks between the tag and reader to terminate tags replies once a collision is detected. To the best of our knowledge, no existing papers have considered collision duration reduction or tag reply termination.

III. MODULATION SILENCING MECHANISM (MSM)

In this section, we propose a mechanism that allows the reader to inform the tags of the occurrence of a collision by cutting off its CW transmission. The tags will detect this cut-off and stop modulating their data. MSM components are depicted in Fig.2. To facilitate the proposed MSM, the MSM-enabled readers employ Rapid Collision Detection (RCD) algorithm, while the MSM-enabled tags sense the reader signal availability by the Continuous Wave Absence Detection (CWAD) circuitry. The CWAD circuitry will interrupt the backscattering process by asserting the Backscattering Termination and NACK (BTN) signal.

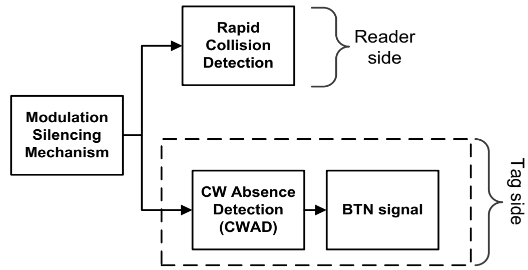

Fig. 2. Modulation Silencing Mechanism (MSM) components

A. MSM at the reader

To ensure early ending of the collision slots, collision detection should be fast and easily implemented (i.e., does not require intensive calculations or complex circuitry). RCD algorithm is an integral part of MSM to check for collisions by detecting encoding violations (not logic 0 or 1) in the received signal. Detecting collision from the received encoded violations was adopted by [14] to save the CRC check by the reader (not to reduce collision time). Tags replies are likely to be unsynchronized at the bit level due to the difference in distances from the reader, reply orientation, and IC variations factors. Unsynchronized replies will cause a violation in all overlapped symbols [4] and the reader will easily detect a violation. However, we will consider the worst case scenario of bit level synchronization between the tag replies in which a violation is detected only when the contents of replies are different [16].

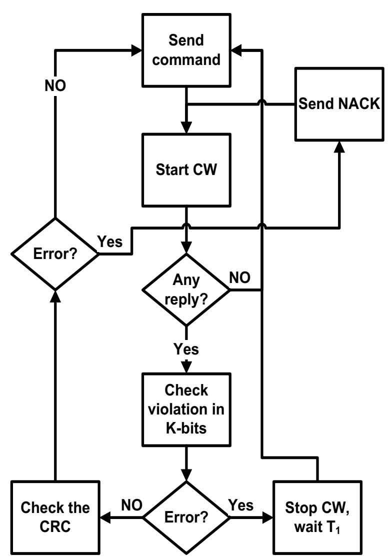

Fig. 3. Rapid Collision Detection (RCD) algorithm at the reader

RCD algorithm flow is illustrated in Fig.3. The reader sends a command to initiate the slot then starts emitting its CW to be backscattered by the addressed tag. Tag starts the reply by sending a preamble sequence (identical for all tags) followed by the tags data. Since bit level synchronization between the tags is assumed, the reader may not detect encoding violations during preamble sequence. To assure violation detection, the tag transmits a random k-bit sequence before its data.

If the reader receives the k-bit sequence with no violations, it will continue emitting its CW and receive the rest of the tag's reply then check CRC. Otherwise, the reader will stop the CW for a period of time (denoted by T_1) that is required by the tag to detect the absence of the reader's CW. After T_1, the reader sends a command to start a new time slot and to NACK the previous transmission. In case of no reply (no tag was addressed by the reader command), the reader stops its CW directly if no reply is detected after a predefined gap period in the protocol.

The length of the random sequence is crucial for collision detection accuracy. In the following, we verify that a relatively small k-bit sequence will allow efficient violation detection.

Let m be the number of replying tags in a particular collision slot. Each tag will start its reply by backscattering the preamble followed by k-bits sequence and its data. The reader will attempt to decode the combination of all m replies at its antenna. The similar symbol values at any bit will b decoded correctly [16]. Since the k-bit sequence is random, the probability of having logic 0 or 1 at the i^{th} symbol is $\frac{1}{2}$. Hence, the probability of having a similar i^{th} symbols from all tags is $(\frac{1}{2})^{m-1}$. Consequently, the reader will not detect a violation if all the tags transmit the same k-bits sequence; the probability of such case is $((\frac{1}{2})^{m-1})^k$.

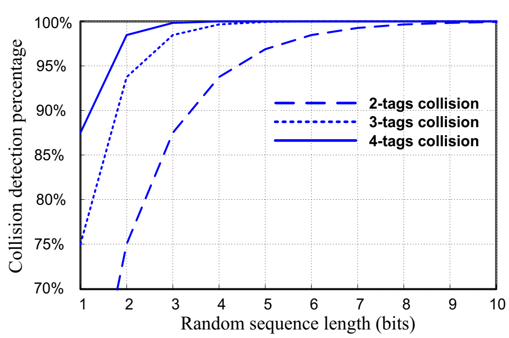

Fig. 4. The length of random sequence effect on collision detection percentage

Fig.4 plots the probability of having same k-bit sequence from (m) tags. In case of two tags replying in the same slot (m=2), the probability of having the same k-bit sequence from both tags is $(\frac{1}{2})^k$ and the expected number of violations is $k/2$ (i.e., a violation is expected in every other bit). In Fig.4, detection probability is higher than 99% for two tags replying with random sequences of k=8 bits. In Fig.5, an example of two tags reply of EPC Class1 Gen2 preamble followed by k-bit sequence is given. In EPC Class1 Gen2, the preamble purposely contains violations to distinguish it from the tag's data transmissions and those violations will not be considered collision the reader. The two k-bit sequences violate the encoding rules in the fourth bit; therefore, the reader discontinue its CW transmission for T_1.

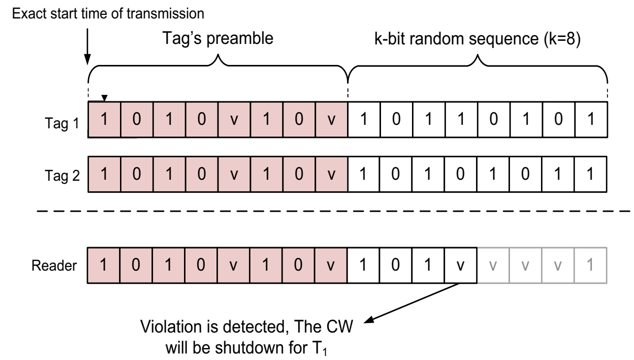

Fig. 5. Error detection for two tags sending the preamble and random sequence to the Reader

B. MSM at the tag

The purpose of the MSM at the tag side is to detect CW shutdown by the reader. Dual antenna tags [18]–[20] will employ MSM without compromising the tag's reading range. Since the reader-to-tag link is a Forward Link Limited (FLL) [21], the reading range is dictated by the power received at the tag rather than the power received at the reader. By observing the FLL property, the reader-tag link is redesigned as follows:

- In the Forward link (reader to tag(s)): The two antennas of the tag will harvest the CW power.
- In the Reverse link (tag(s) to reader): One antenna will be used to backscatter the readers CW while the other will power the modulation silencing circuitry.

A block diagram of a dual-antenna MSM-enabled tag is depicted in Fig.6. One component was added to the typical dual antenna tag design to accommodate MSM, CWAD circuit.

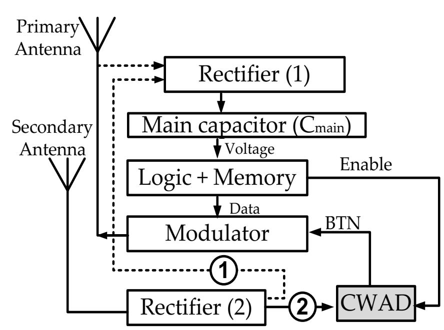

Fig. 6. Dual antenna tag with CWAD, 1- Forward link 2- Reverse link

When the tag is backscattering its data, the CWAD will be enabled and powered by the second rectifier. The main components of CWAD circuit are illustrated in Fig. 7. The capacitor C_{CWAD} is connected to the output of the second rectifier. The rectifier is a charge pump that will build up the voltage from the CW and store it in C_{CWAD}. Since the output voltage of the rectifier depends on the tag's distance from the reader, a voltage limiter (sequence of diode-connected transistors) is placed parallel to C_{CWAD} to ensure a constant voltage from the rectifier. As will be discussed shortly, the constant voltage across C_{CWAD} is crucial for a consistent CWAD operation. C_{CWAD} is also parallel to both, a pull down resistor R_{CWAD} and an active-low switch S_1 (e.g., a PMOS transistor). Once S_1 is ON, C_{CWAD} will discharge its voltage in R_{CWAD}. C_{CWAD} is also connected to an active-low switch S_2, which passes the backscattering termination signal.

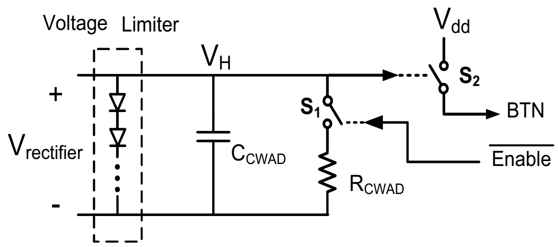

Fig. 7. CWAD circuit schematic showing the basic components

The flow of the MSM is shown at the tag is shown in Fig. 8. After receiving the reader's command, the tag(s) will activate CWAD by turning S_1 ON and starts the reply. If the random sequence is received with no errors, the reader will check the CRC and issue an ACK or NACK to the tag. In case of a collision, the CW be stopped and the second rectifier is no longer charging the capacitor C_{CWAD}. Consequently, R_{CWAD} will be discharging C_{CWAD} and its voltage will be low enough (after T_1) to turn S_2 ON to activate the BTN signal. Data modulator will be interrupted by BTN and the tag will assume that the reader has sent a NACK.

An illustration of the voltage states across C_{CWAD} is given in Fig.9. When CW is ON, C_{CWAD} is discharging in R_{CWAD} and charging from the output of the second rectifier. The upper value of rippling voltage $V_{U_{ripple}}$ across R_{CWAD} is limited by V_H. To ensure that BTN is not activated by the rippling voltage, the lower value of ripple voltage, $V_{L_{ripple}}$, is designed to be larger than V_high. When CW is OFF, the voltage at C_{CWAD} will drop from V_H to V_{low} in T_1 time duration. T_1 will have the same duration in all tags since C_{CWAD} voltage was limited to a maximum of V_H by the voltage limiter.

T_1 should be rapid not only to increase the time saving in collision slots but also to prevent the voltage at the main capacitor of the tag (much larger capacitor than C_{CWAD}) from dropping and resetting the tag. Nevertheless, T_1 should be long enough to be recognized by the tag. We select T_1 to be five times the tag's symbol duration (i.e. five bits). To determine the value of C_{CWAD} and R_{CWAD} that satisfy the above conditions, we consider V_{low} to be $V_H/10$. Therefore:

$$T_1 = ln(10)R_{CWAD}C_{CWAD}$$

Capacitor fabrication in ICs is area consuming, therefore, its value should be as small as possible to limit the overhead on

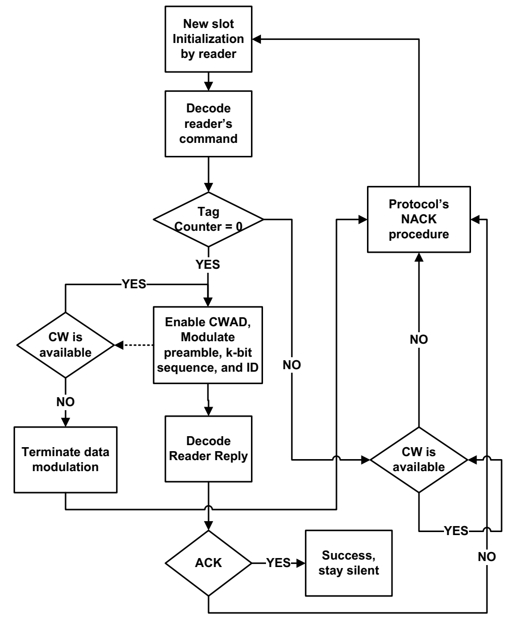

Fig. 8. Modulation silencing algorithm at the tag

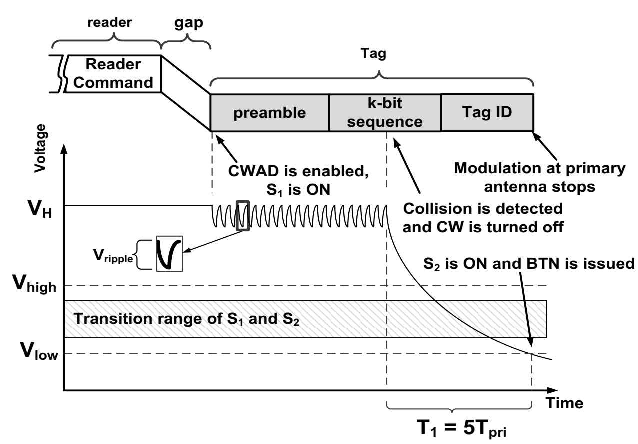

Fig. 9. Example of voltage across C_{CWAD} in a collision slot (the gap is an interval that accommodates different reply times from the tags)

die size. Resistors, on the other hand, are easier to fabricate. Therefore, a capacitor of one to two orders of magnitude less than a main capacitor (C_{main}) of the tag [22]. We design the CWAD in Virtuoso Schematic Editor for CMOS 90nm technology. At T_1 length of 23.4μs (5 T_{pri} in EPC C1G2 standard), C_{CWAD} value was selected as 5pF (compared to C_{main} of 200pF-1nF) and R_{CWAD} with 2MΩ.

C. Time efficiency metric

To evaluate the time efficiency of the MSM-enabled protocols, a performance metric that considers the difference between the different slots is required. System Efficiency (SE) is the ratio of single reply slots (R_1) to the total number of slots (R_{total}) with empty, collision, and single slots are assumed to have the same duration. Early ending to the empty

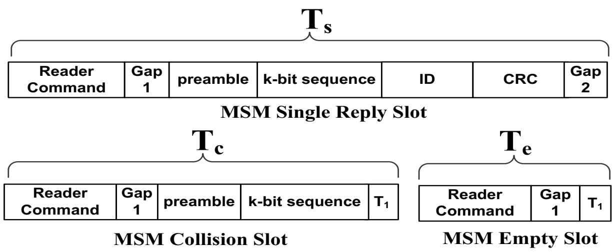

Fig. 10. Single, collision, and Empty slots data fields in MSM

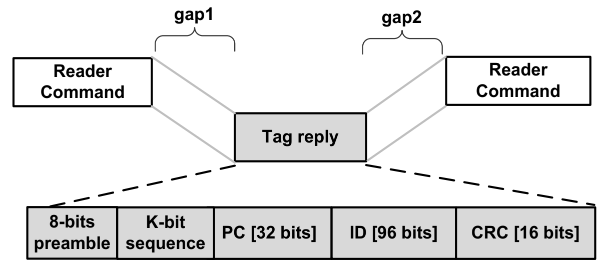

Fig. 11. Time slot data fields in Reader-tag communication

slots was proposed in [10]. Time System Efficiency (TSE) [2] considers the early ending of the empty slots by defining the time performance as:

$$TSE = \frac{R_1}{\beta R_e + R_1 + R_c}, \quad (1)$$

where β is the time ratio between empty and single slots . To evaluate the effect of the MSM on the time performance of a RFID system, the evaluation metric must consider the time saving factors in collision and empty slots. Therefore, we generalize the TSE to reflect the shorter collision slots by MSM. We denote collision to single slot time ratio by γ. Hence, the generalized TSE (TSE_g) will be:

$$TSE_g = \frac{R_1}{\beta R_e + R_1 + P_{error} R_c + (1 - P_{error})\gamma R_c}, \quad (2)$$

where P_{error} is the probability of not detecting the collision by the random sequence (as plotted in Fig.4). To overview the difference between the slots in MSM, the data fields for single, collision, and empty slots are shown in Fig.10 and denoted as T_s, T_c, and T_e, respectively.

IV. Performance Evaluation

To have a realistic evaluation of the MSM in RFID systems, MSM components must conform to the RFID standards specifications, especially the timing of the data fields. Therefore, the time slot field specifications and parameters of EPC Class1 Gen2 will be adopted to evaluate efficiency of the proposed mechanism.

A. Time slot specifications

Time slot model is based on EPC standard specifications for *data-fields* and *timing* [15]. This time slot model will also establish the compatibility requirements between current standardized systems and MSM-enabled systems.

In *data-fields* specifications (shown in Fig.11), the slot is initiated by an 8-bit command from the reader followed by a gap period. This period is defined to allow command processing at the tag and to accommodate transmission delay due to tag IC variations and distance from the reader. The tag reply begins with an 8-bit preamble followed by protocol control (PC), tag ID, and CRC sequences. Another gap period follows the tag reply to allow CRC processing at the reader. The reader then sends a single command to ACK or NACK the previous reply and start a new slot.

TABLE II
Basic Timing intervals of EPC Class 1 Gen 2 standard

Timing control unit	Used by	Description
T_{ari}	Reader	The duration of binary zero from the reader, binary 1 is 1.5-2 T_{ari}.
RT_{cal}	Reader	Reader to Tag Calibration interval to synchronize reader's transmission (2.5-3 T_{ari})
TR_{cal}	Reader	Tag-to-Reader Calibration interval to synchronize tag's transmission (1.1 - 3 RT_{cal})
Divide Ratio (DR)	Reader	Defines the number of tags symbol in one TR_{cal}. Backscatter Link Frequency ($BLF = DR/TR_{cal}$)
T_{pri}	Tag	The duration of one tag's symbol = $1/BLF$.

The *timing* and encoding of the data-fields are also based on EPC standard timing. The standard's parameters for data fields timing intervals are presented in Table II; the timing periods for each data-field presented in Fig.11 are listed in Table III.

B. Time efficiency

To evaluate γ and β with MSM, Table III presents the time (in μs) for single, collision, and empty slots based on typical timing parameters of EPC Class1 Gen2 standard. In such typical settings, collision time is 75.4% shorter than single reply slot (i.e., $\gamma = T_c/T_s$=0.246), and empty slot is shorter by 83.8% (i.e., $\beta = T_e/T_s$=0.162). In the following, those two ratios will be used to evaluate the time TSE_g for Tree- and ALOHA-based protocols.

TABLE III
Data fields timing for collision, single, and empty slots (T_{ari} = 7.5 μs, RT_{cal} = 2.5T_{ari}, TR_{cal}= 2 RT_{cal}, T_{pri} = $TR_{cal}/8$)

Field	Timing	Collision slot (μs)	Single slot (μs)	Empty slot (μs)
Reader command	8 * 1.25 T_{ari}	75	75	75
Gap 1	$10T_{pri}$	46.9	46.9	46.9
Preamble	$8T_{pri}$	37.5	37.5	N/A
Random sequence	$8T_{pri}$	37.5	37.5	N/A
PC + ID+ CRC	$144T_{pri}$	N/A	675	N/A
Gap 2	$5T_{pri}$	N/A	23.4	N/A
T_1	$5T_{pri}$	23.4	N/A	23.4
Total Time		220.3	895.3	145.3

TABLE IV
TSE FOR SYSTEMS WITH AND WITHOUT MSM (SINGLE SLOT TIME T_s)

Value of γ and β	Scenario	Collision slots time	Empty slots time	Total time
γ=1 , β =1	Unknown n	1.443T_s	0.442T_s	2.885T_s
γ =1, β =1	Known n	0.669T_s	0.669T_s	2.337T_s
γ =0.246 and β = 0.16	Unknown n	0.361T_s	0.071T_s	1.432T_s
γ =0.246 and β = 0.16	Known n	0.167T_s	0.107T_s	1.274T_s

1) TSE_g in Tree-based protocols: Table IV shows the collision and empty slots time contribution in tree-based protocols. For known tag count, TSE_g for non-MSM systems is 42.8% and with MSM early ending of collision and empty slots its raised to 78.5%. Conversely, in the case of unknown tag count, the TSE_g is doubled when MSM is employed. These significant improvements will be the key enablers of high efficiency mobile and battery powered readers.

2) TSE_g in ALOHA based protocols: In ALOHA based protocols, collisions contribution to the overall number of slots is not constant. However, when the frame size is much smaller than the number of tags, collisions dominate. Fig.12 is a plot of the TSE_g with and without early ending of collision and empty slots (γ=0.246 and β= 0.16). When the tag count equals the frame size, TSE_g achieves a maximum of 36.8% when early ending is not implemented. On the other hand, this maximum increases to 75.3% when MSM is implemented. Collision early ending factor γ flatten the efficiency curve by reducing the effect of rapid increase in collision probability at high tag population. From the Fig.12 , we note that the maximum efficiency is when N=256 slots are used to identify 207 tags (i.e., n=0.8N). Since the time efficiency is no longer maximized at frame sizes that equal tag count as in [23], the optimal frame selection in ALOHA protocols should be revised.

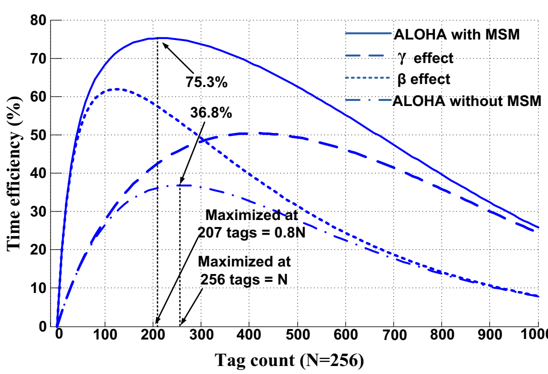

Fig. 12. ALOHA Time efficiency with MSM

C. Frame size optimization

Based on MSM, early ending of both empty and collision slots are new factors that affect the selection of the optimum frame size. In Fig.13, TSE_g is plotted for different values of γ with a normalized tag count to the frame size N. The optimal frame size trend can be found by differentiating Eq.(3) with respect to N and setting the derivative equal to zero. The optimal frame sizes for different values of γ (with β = 0.16) are given in Table V.

TABLE V
OPTIMAL FRAME SIZE WITH DIFFERENT γ (β = 0.16)

γ (β=0.16)	0.15	0.25	0.35	0.45	0.55	0.65	0.75
Optimal Frame N	n	1.2n	1.4n	1.5n	1.7n	1.8n	1.9n
Max. time efficiency (%)	79.6	75.8	73.5	70.8	68.9	67.2	65.8

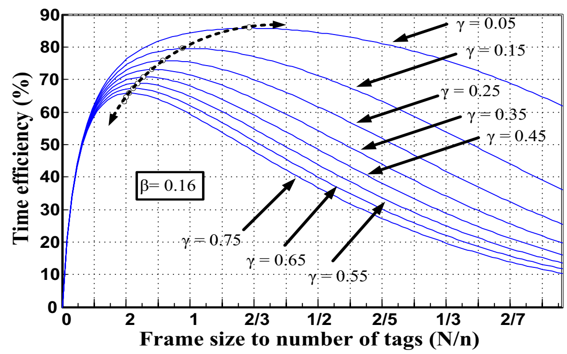

Fig. 13. Different γ values that result in shifting the optimal frame sizing

Tag count is estimated based on empty, single, and collision slots statistics from the previous frames [13], [23]. Tags number estimation is outside the scope of this paper, however, we assumed that the estimation functions are accurate enough to output the tag count in that frame n_k. Based on the expected tag count n_k, the number of remaining unidentified tags will be the tags which participated in the last frame (n_k) less the single slots in that frame (R_1). i.e., for the next frame $k+1$ is the number of tags $n_{k+1} = n_k - R_1$. After estimating n_{k+1}, with known γ and β, the next optimal frame can be easily defined as of Table V. For example, for β=0.16 and γ=0.25, the optimal frame size, N, to read n_{k+1} tags will be 1.2n_{k+1}.

MSM will not only enhance the time efficiency of the reading protocols, but also it will outperform non-MSM protocols even at high error in the selected frame N. The first frame in ALOHA protocols is non-optimal frame since slot count statistics are unavailable to estimate the number of tags. The time efficiency plot in Fig.14 shows that even if the frame is half the optimal frame for a given tag population, the MSM-based systems will have a TSE_g of more than 50% . In contrast, non-MSM protocols TSE_g will drop below 20%. In addition, the time performance degradation of MSM-based systems is slower than non-MSM when tag count is much higher than the frame size.

V. DEPLOYMENT CONSIDERATIONS

One of the main advantages of MSM is that firmware is the only change at the reader side which will allow the adoption of

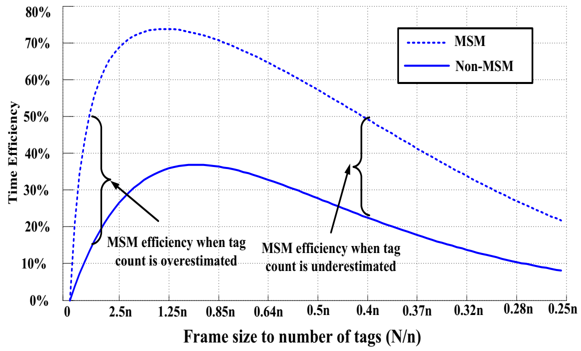

Fig. 14. Time efficiency for ALOHA-based systems with MSM, early ending of empty slots only, and no early ending of collision or empty slots (frame size = 256 slots)

TABLE VI
COOEXISTANCE SCENARIOS BETWEEN LEGACY AND MSM RFID SYSTEMS

	Legacy tags	MSM tags	Legacy and MSM tags
Legacy Reader	Standard CMD	Standard CMD	Standard CMD
MSM Reader	Standard CMD	Customized CMD	Customized CMD then Standard CMD

the proposed mechanism in rapid inventory applications (containers moving on a conveyor) and battery powered readers. At the tag side, MSM adds minimal modification to the tag's IC with no changes to the antenna interface, memory or rectifier design.

MSM effectiveness is verified based on EPC Gen2 class1 standard timing specifications. However, the reader command for MSM reply should be different than the standard command. EPC standard have several unused commands (i.e., for future use) that can be assigned for MSM-enabled tags. Therefore, if MSM-enabled tags receive a standard command, tags will not activate CWAD circuitry and will reply as the legacy tags. Therefore, during identification cycle, since the legacy tags ignore customized commands, the reader will identify MSM tags first and the legacy tags will be identified later using the standardized commands. Table VI presents the coexistence scenarios between the legacy and MSM RFID systems.

VI. Conclusion

In this paper, we addressed the time reduction of collision slots in RFID systems. We proposed a new tag-reader interaction mechanism, MSM, which allows the reader to silence the tags if a collision is detected. MSM significantly reduce the total reading time and power with a minimal modification to the tag's IC. A generalized time efficiency metrics, TSE_g, was also proposed to accommodate the shorter collision times. MSM enhances the performance of ALOHA- and tree-based protocols by doubling the time efficiency, and, hence, the reading rate. MSM is not limited to a specific protocol; in fact, MSM can be applied to any existing protocols to reduce the collision effect. MSM not only increases the efficiency of ALOHA-based protocols, but also provides a stable and considerable time performance even at non-optimal frame sizes.

References

[1] K. Finkenzeller, *RFID handbook: fundamentals and applications in contactless smart cards and identification*, 3rd ed. John Wiley & Sons Ltd, 2006.
[2] T. La Porta, G. Maselli, and C. Petrioli, "Anticollision protocols for single-reader RFID systems: Temporal analysis and optimization," *Mobile Computing, IEEE Transactions on*, vol. 10, no. 2, pp. 267 –279, Feb. 2011.
[3] D. Hush and C. Wood, "Analysis of tree algorithms for RFID arbitration," in *Information Theory, 1998. Proceedings. 1998 IEEE International Symposium on*, Aug. 1998, p. 107.
[4] D. M. Dobkin, *The RF in RFID: Passive UHF RFID in Practice*. Newton, MA, USA: Newnes, 2007.
[5] J.-B. Eom, T.-J. Lee, R. Rietman, and A. Yener, "An efficient framed-slotted ALOHA algorithm with pilot frame and binary selection for anti-collision of RFID tags," *Communications Letters, IEEE*, vol. 12, no. 11, pp. 861 –863, Nov. 2008.
[6] J. Park, M. Y. Chung, and T.-J. Lee, "Identification of RFID tags in framed-slotted ALOHA with robust estimation and binary selection," *Communications Letters, IEEE*, vol. 11, no. 5, pp. 452 –454, May 2007.
[7] K. Ali, H. Hassanein, and A.-E. Tana, "RFID anti-collision protocol for dense passive tag environments," in *Local Computer Networks, 2007. LCN 2007. 32nd IEEE Conference on*, Oct. 2007, pp. 819 –824.
[8] J. H. Choi, D. Lee, and H. Lee, "Query tree-based reservation for efficient RFID tag anti-collision," *Communications Letters, IEEE*, vol. 11, no. 1, pp. 85 –87, Jan. 2007.
[9] L. Pan and H. Wu, "Smart trend-traversal: A low delay and energy tag arbitration protocol for large RFID systems," in *INFOCOM 2009, IEEE*, Apr. 2009, pp. 2571 –2575.
[10] P. Cole, "Fundamentals in Radio Frequency Identification," Auto-ID Research laboratory- Adelaide, Tech. Rep., Mar. 2004.
[11] I. Gitman, "On the capacity of slotted ALOHA networks and some design problems," *Communications, IEEE Transactions on*, vol. 23, no. 3, pp. 305 – 317, Mar. 1975.
[12] L. Xie, B. Sheng, C. Tan, H. Han, Q. Li, and D. Chen, "Efficient tag identification in mobile RFID systems," in *INFOCOM, 2010 Proceedings IEEE*, Mar. 2010, pp. 1 –9.
[13] G. Khandelwal, A. Yener, K. Lee, and S. Serbetli, "ASAP : A MAC protocol for dense and time constrained RFID systems," in *Communications, 2006. ICC '06. IEEE International Conference on*, vol. 9, Jun. 2006, pp. 4028 –4033.
[14] "13.56 MHz ISM Band Class 1 Radio Frequency Identification Tag Interface Specification: Candidate Recommendation, Version 1.0.0," Auto-ID Center, Tech. Rep., Feb. 2003.
[15] *EPC Radio-Frequency Identification Protocols Class-1 Gen-2 UHF RFID Protocol for Communications at 860MHz-960MHz, EPCglobal,*, Std., Rev. 1.2.0, Oct. 2008.
[16] L. Kang, K. Wu, J. Zhang, and H. Tan, "Decoding the collisions in RFID systems," in *INFOCOM, 2011 Proceedings IEEE*, Apr. 2011, pp. 351 –355.
[17] R. Khasgiwale, R. Adyanthaya, and D. Engels, "Extracting information from tag collisions," in *RFID, 2009 IEEE International Conference on*, Apr. 2009, pp. 131 –138.
[18] D. Deavours, "A circularly polarized planar antenna modified for passive UHF RFID," in *RFID, 2009 IEEE International Conference on*, Apr. 2009, pp. 265 –269.
[19] H.-J. Li, S.-Y. Chen, and D.-S. Yuan, "A novel dual-antenna structure for UHF RFID tags," in *Antennas and Propagation Society International Symposium, 2009. APSURSI '09. IEEE*, Jun. 2009, pp. 1 –4.
[20] Impinj, *Monza/ID Preliminary Data Sheet, rev. 1.3*, May 2007.
[21] R. Chakraborty, S. Roy, and V. Jandhyala, "Revisiting RFID link budgets for technology scaling: Range maximization of RFID tags," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 59, no. 2, pp. 496 –503, Feb. 2011.
[22] J.-W. Lee and B. Lee, "A Long-Range UHF-Band Passive RFID Tag IC Based on High-Q Design Approach," *Industrial Electronics, IEEE Transactions on*, vol. 56, no. 7, pp. 2308 –2316, Jul. 2009.
[23] H. Vogt, "Multiple object identification with passive RFID tags," in *Systems, Man and Cybernetics, 2002 IEEE International Conference on*, vol. 3, Oct. 2002, p. 6 pp. vol.3.