Digital Baseband Modulation Termination in RFID Tags for a Streamlined Collision Resolution

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Abstract— **Radio Frequency Identification (RFID) technology has attracted much attention due to its variety of applications, e.g., inventory control and object tracking. Tag identification protocols are essential in such applications. However, in such protocols, significant time and power are consumed on inevitable simultaneous tag replies (collisions) because tags can't sense the media to organize their replies to the reader. In this paper, novel reader-tag interaction method is proposed in which low-complexity Digital Baseband Modulation Termination (DBMT) circuit is added to RFID tags to enhance collision resolution efficiency in conjunction with Streamlined Collision Resolution (SCR) scheme. The reader, in the proposed SCR, cuts off or reduces the power of its continuous wave signal for specific periods if corrupted data is detected. On the other hand, DBMT circuit at the tag measures the time of the reader signal cutoff, which in turn, allows the tag to interpret different cutoff periods into commands. SCR scheme is applied to ALOHA- and Tree-based protocols with varying numbers of tags to evaluate the performance under low and high collision probabilities. SCR provides a significant enhancement to both types of protocols with robust synchronization within collision slots. This novel reader-tag interaction method provides a new venue for revisiting tag identification and counting protocols.**

Keywords— *RFID, Anti-collision, Continuous Wave (CW), Passive tags, Envelope detection, Collision slots*

I. Introduction

Passive Radio frequency identification (RFID) technology comprises secure, low cost, and non-line-of-sight object identification features. Moreover, the battery-less and small size features of RFID tags promote RFID systems in several object tracking and inventory applications [1-3]. In these applications, an RFID system facilitates rapid and reliable object ID collection [4,5].

In RFID systems, a reader transmits an RF signal to identify one or more tags. The tags harvest the reader's signal to power up their ICs. Data communication with the reader is achieved through continuous wave (CW) backscattering instead of power-hungry transceivers and power amplifiers. In backscattering, the tag alters the impedance of its antenna to reflect, absorb, or modify the phase of the CW signal from the reader. Concurrently, the receiver module of the reader filters the reflections and decodes the data based on the tag's impedance alterations.

Backscattering simplifies the passive tag design at the expense of complicated reader frontend and half-duplex (HDX) channels limitation, which motivates this work. In backscattering channels, the tags cannot decode any signal from the reader while modulating their data [6], which prevents the reader from controlling data transmission from the tag. A prominent disadvantage of the HDX backscattering channel is the irreducible tag collision time (when two or more tags are modulating their data simultaneously) [6,7]. During collisions, if the reader sends a command to indicate the reception of corrupted data, the tags cannot decode such command.

Previously, the Modulation Silencing Mechanism (MSM) has been proposed to stop backscattering at the tag during collision slots [9]. MSM mitigates the HDX channel challenge by allowing the reader to control the amount of information to be received from the tag. In MSM, once the reader stops CW transmission, the continuous wave absence detection (CWAD) circuit [10] detects CW cutoff and interrupts the ongoing backscattering. MSM comprised a preliminary design of CWAD circuit at the *RF interface* of the tag. In this paper, we propose a novel Digital Baseband Modulation Termination (DBMT) circuit at *the baseband* of the tag. Besides, DBMT is capable of detecting CW cutoff precisely at all tags regardless of their distance from the reader, while preliminary design of CWAD detects CW cutoff during time intervals that are dependent on the received power of the reader [6,7,8, 10]. DBMT's prompt and uniform detection of CW cutoff at all tags allow for precise measurement of the duration of such cutoff. This capability is utilized in a new Streamlined Collision Resolution (SCR) scheme. In SCR, the reader cuts off CW for predefined time intervals and the tag(s) interpret the interval length as a command from the reader. We utilized DBMT with SCR to identify at least one tag within a collision slot.

The rest of this paper is organized as follows. In Section II, the modulation silencing mechanism is discussed with emphasis on CWAD design limitations. In Section III, we introduce the proposed DBMT circuit design at the tag's baseband. In Section IV, we propose a Streamlined Collision Resolution scheme utilizing DBMT. Performance of ALOHA- and Tree-based protocols with SCR are evaluated in Section V; then we conclude the paper in Section VI with highlights on potential applications of DBMT and SCR.

II. MSM OVERVIEW AND MOTIVATION

In passive RFID tag identification protocols, time division multiple access (TDMA) is the standardized technique in tags identification [11]. The main protocols under TDMA are ALOHA- and Tree-based protocols [11]. In such protocols, the tags transmit their data (e.g., their ID) within time intervals (slots), which are synchronized by the reader. The reader sends a command and starts CW transmission, and the addressed tag(s)[1] reply back through backscattering the reader's CW. In every slot, one, two or more, or even no tag may reply. Ideally, all slots should have one reply since two or more replies (collision slots) or no reply (empty slots) are waste of the identification time and reader's energy. Empty slots can be early ended by the reader by sending a new command [12]. However, the early ending of collision slots is problematic.

During collision slots, the reader is unable to control the amount of the tag's data transmission because sending any command to the tags will not be decoded by the tags. To save power, the reader during a collision can stop CW transmission. Nonetheless, this is also not possible as passive tags depend on CW to maintain their IC power. Furthermore, initiating a new slot by the reader will cause another collision because the tags in the previous collision slot are still backscattering their data. In short, if the reader is receiving corrupted data from two or more tags, it has no option but to continue CW transmission until the tags conclude their replies in that slot. Therefore, MSM [9] was previously proposed to overcome the time and power depletion in RFID systems in collision slots.

The tags start their reply with a preamble bit sequence in the standardized RFID protocols [13]; hence, if two or more tags reply, the received bit sequence at the readers will not be as the expected preamble sequence by the standard. Once this condition is detected, the reader in MSM stops CW transmission for a predetermined time. The tags, on the other hand, are equipped with Continuous Wave Absence Detection (CWAD), a circuit to sense the reader's CW availability at the tag's antenna. However, even though the previously proposed CWAD circuit [10] is capable of detecting CW cutoff from the reader, it has three main limitations:

1) CWAD was placed after the tag's energy harvesting module, as shown in Fig. 1. By this placement, the detection of CW cutoff required the main capacitor voltage to drop below a predefined voltage to trigger backscattering termination (BT). This is risky as the tag's voltage drop can cause a reset in that specific tag and in other tags that did not even participate in backscattering.

2) Since BT is triggered by the drop of the main voltage, CW cutoff detection depends on the initial voltage level before the drop. And since the voltage level at the main capacitor is a function of the received power from the reader [6,7]. A unified cutoff period of the CW cannot be determined. An example of such a case is depicted in Fig. 2. in which two tags with different harvested voltage levels (due to being at different distances from the reader). CW cutoff is detected if the rectifier voltage V_H drops below a reference voltage V_{ref} by a given threshold V_{diff}. Note that the two tags detect such cutoff after two different times (i.e., T_1 for tag 1 and T_2 for tag 2).

3) The previously designed CWAD circuit was based on analog current-driven components as shown in Fig. 3, which increase power consumption at the power starving passive tags.

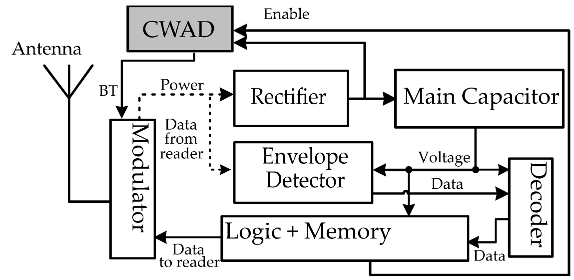

Fig. 1. CWAD location within typical passive RFID tag components [10].

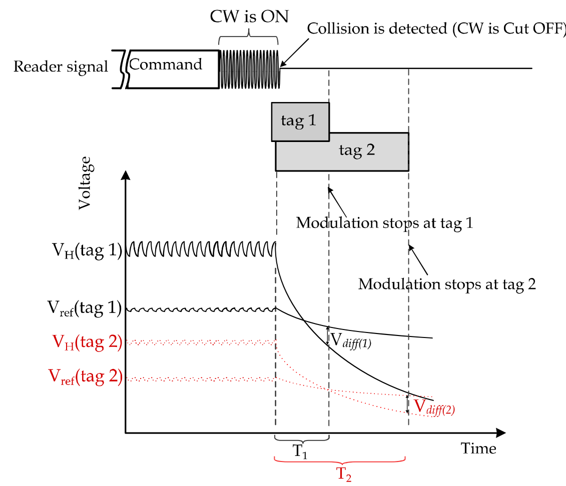

Fig. 2. CW cutoff detection in two tags (Tag 1 and Tag 2) at two different times (T_1 and T_2) depending on the initial rectifier voltage at each tag.

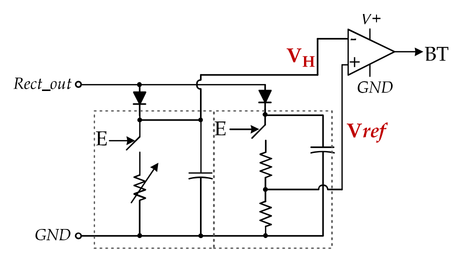

Fig. 3. CWAD circuit consisting mostly of analog components [10]

[1] Reader commands may address more than one tag. (e.g., query command for any tag with ID starts with a given sequence)

In this paper, we propose a digital baseband modulation termination (DBMT) circuit to replace CWAD. The proposed design will have the following advantages over previously proposed CWAD:

- It does not modify the RF interface of the tag; instead, it is added to the digital baseband section.
- DBMT allows immediate interpretation of the CW reduction
- DBMT enables the tag to interpret not only the CW cutoff but also the period of this cutoff independently of the received power from the reader.

In addition, these advantages are utilized in a collision resolution scheme named Streamlined Collision Resolution, which takes advantage of the new DBMT capability of determining the period of CW cutoff to be interpreted differently to yield, at least, one correct tag identification during a collision slot.

III. Digital Baseband Modulation Termination

In our design the Digital Baseband Modulation Termination circuit is placed at the output of the envelope detector (ED) as shown in Fig. 4. By this configuration, DBMT and the decoder (The output of the ED is connected to the decoder) are in parallel. The rationale behind this placement is taking advantage of the ED of faster reaction to the reader's signal change when compared to the rectifier [6, 8]. The output of the ED is connected to the input of the DBMT circuit, as shown in Fig. 5. Since the output of the ED is binary (output of the operational amplifier), DBMT can be realized through digital logic components.

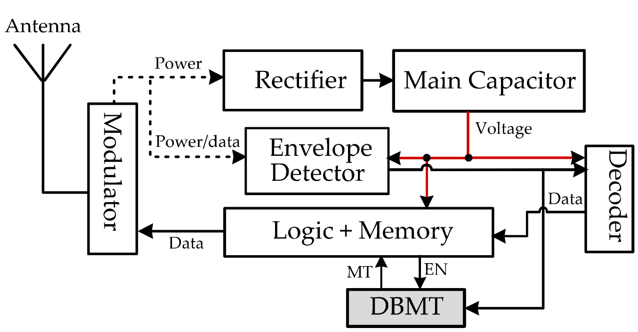

Fig. 4. DBMT circuit location within typical passive RFID components

A. DBMT Design Components

The ED and the main components of DBMT circuit are illustrated in Fig. 5. DBMT is connected to an enable control signal (EN) from the logic and memory module. In addition, two D-Flip Flops (DFF) are controlled by a common clock signal (clk) to latch the output of the ED. The output of DBMT is noted as modulation termination (MT) signal which is asserted if all DFFs outputs 1 at their Q_1, Q_2, and Q_3. MT is connected to the logic and memory module to halt any further data modulation.

B. DBMT Operation

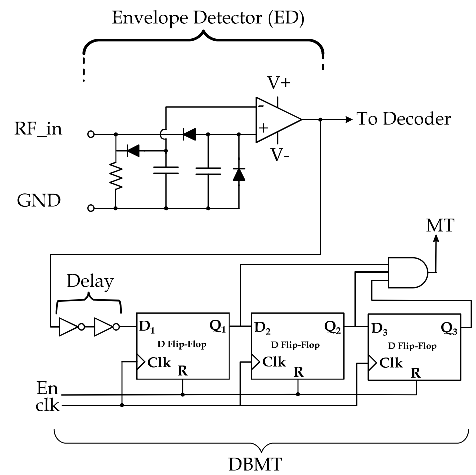

Fig. 5. DBMT circuit diagram consisting of 3 DFFs and an AND gate.

When a tag is addressed by a reader command, it starts modulating its antenna impedance to backscatters its data to the reader. DBMT is enabled by the EN pulse signal to reset the three DFFs (i.e., Q_1, Q_2, and Q_3 are 0s). MT signal is asserted if the CW is absent for three consecutive clock cycles. The main reason for the serial DFF placement is that the tag backscatters its data through Pulse-Interval Encoding (PIE) with On-Off Keying Modulation [7, 13]. In PIE, *low* and *high* intervals exist during the backscattering of 0s and 1s to the reader. The *low* intervals are decoded by the reader as the tag "absorbs" the CW signal by changing the antenna impedance to a matching value. The *high* intervals, on the other hand, are decoded by the reader as the tag "reflects" back the CW signal by modifying the antenna impedance to a maximum mismatch [6]. During *low* intervals, the CW power is directed to the rectifier and the ED. No CW power is rectified during *high* intervals, as all the CW is reflected to the reader. The latter case may indicate CW cutoff to the DBMT, even if the CW still available. Hence, the three serial DFFs in DBMT will not trigger the MT signal unless the power at the antenna is absent for more than maximum high period in PIE[2].

[2] Tags that uses Phase Modulation (PM) for backscattering absorbs power during low and high periods of the encoded data. Therefore, one DFF can be utilized in the DBMT of such tags.

To illustrate DBMT operation, an operation timing example is provided in Fig. 6. Once the tag starts backscattering its encoded preamble sequence to the reader, it initiates DBMT by pulsing the EN signal. By modulating its antenna load to reflect/absorb the CW, the first DFF will output 1 whenever the tag is reflecting the CW (*high* period to the reader), and output 0 if the tag is absorbing the CW (*low* period to the reader). Since there are no three consecutive reflection periods in the encoded data, the three DFFs during CW transmission will never have 1 on Q_1, Q_2, and Q_3, simultaneously. If at some point, the reader detects a collision, it cuts off CW transmission (within the 6th clock cycle in Fig. 6) for a period that is long enough to have 1 at the outputs Q_1, Q_2, and Q_3, which will trigger the MT signal through the three-input AND gates (at the 9th clock cycle in Fig. 6).

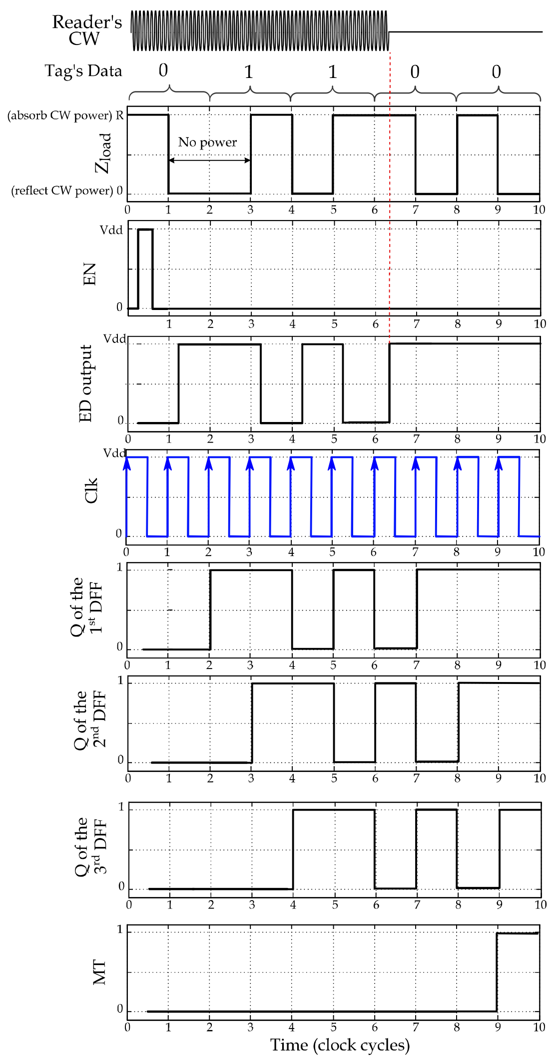

Fig. 6. Timing diagram of a tag sending data with CW is ON. When CW is cutoff, cutoff is detected aftre 3 clock cycles by DBMT.

IV. Streamlined Collision Resolution

Since the ED of the tag is utilized during backscattering to provide prompt CW cutoff detection. The tag is now capable of determining not only CW cutoff but also the duration between CW cutoff and its resumption. This feature is exploited during collision slots in a novel collision resolution scheme named Streamlined Collision Resolution (SCR).

In SCR, during a collision slot with N replying tags, the reader cuts off its CW for four predefined durations, P_1, P_2, P_3 and P_4 to be interpreted differently by the tags, where $P_1<P_2<P_3<P_4$. Each tag among the N tags interprets the different intervals as follows:

If the reader cuts off the CW for P_1, during P_1 each tag generates an *m*-bits random number (RN). Tags with an RN with all bits are 1s will consider replying again; hence, the probability of replying is $\frac{1}{2m}$. Therefore, three possibilities will occur based on the RN check for all 1s:

1- If no tag of the N tags considered replying, the reader cuts off the CW for P_2, during P_2 the N tags generate (*m-1)*-bits RNs; hence, the tag's probability of replying is increased to $\frac{1}{2m-1}$. This process is repeated until one or more tags have an RN with all 1s.
2- If M tags decided to reply ($M > 1, M \in N$), their transmissions will produce another collision (i.e., corrupted preamble sequence). The reader cuts off CW for P_1, during P_1 each tag in M generates m-bits RN and check for all 1s. The remaining $N - M$ tags will stay silent and $N = M$.
3- If one tag n decided to reply, the reader receives the tag's data and checks the CRC, if the CRC is correct, the reader cuts off its CW for P_4 and sends a regular acknowledgment (ACK) command so that all tags can recognize the end of the collision slot. If CRC is erroneous, the reader cuts off the CW for P_3 to indicate negative-ACK (NACK). The tag n retransmit its data until its followed by P_4.

In Fig. 7, SCR scheme interpretation circuit at the tag is shown for P_1, P_2, P_3 and P_4 are 2, 3, 5, and 7 data symbols durations, respectively. The circuit is simply a counter that is connected to logic combinational components. To count the number of symbols during CW cutoff, the frequency of the clock signal is first divided by the highlighted leftmost DFF in Fig. 7, since the duration of the tags' symbol equals to the duration of two clock cycles [13]. Note that the clock is divided only if the MT signal from DBMT circuit is asserted. If the counter is two (i.e., $Q_a = 0, Q_b = 1$), and MT is no longer asserted, the tags follow the procedure after P_1. P_2 is asserted if $Q_a = Q_b = 1$, and $MT = 0$. If $Q_a = Q_c = 1\ and\ Q_b = MT = 0$, then P_3 is asserted and the tag assumes NACK and transmits again. If the counter reaches 7 (i.e., $Q_a = Q_b = Q_c = 1, MT = 0$), P_4 is asserted and the tag assumes ACK (an ACK command will follow by the reader). After each cutoff duration the counter is reset by the control signal EN_2.

Fig. 8 shows an example of the three possible conditions after detecting a collision by the reader. In the first waveform, a collision is detected and the reader cuts off CW for P_1. Then one tag happened to have an RN with all 1s and replies back. However, its replay was received with a wrong CRC at the reader, hence, a CW cutoff for P_3 to indicate NACK. In the second waveform, a correct CRC is calculated, and CW is cut off for P_4 to indicate correct reception of the tag reply at the reader. In the third waveform, the reader detects a collision and cutoff CW for P_1 and no tags decided to reply, so it cuts off CW for P_2 until one or more tag decides to reply.

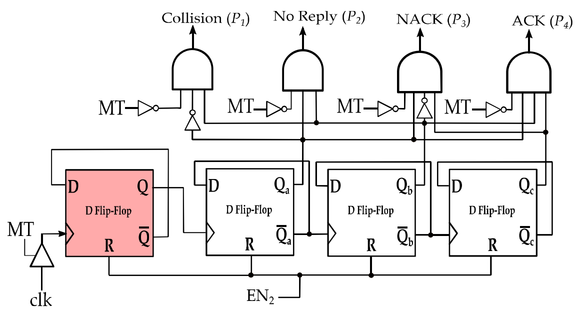

Fig. 8. SCR circuit diagram with frequency divieder (leftmost DFF) and a 3-bit counter. SCR circuit is controlled by MT and EN_2 signals

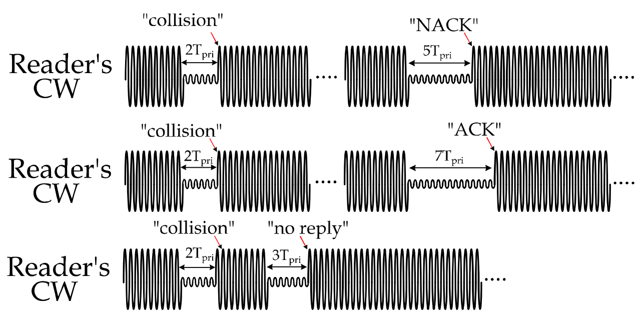

Fig. 7. CW waveform with different cutoff duration to be translated differently by the tag through SCR circuit.

SCR provide a resolution of proper identification for one tag among the N tags that initially participated in the collision slots. Consequently, the remaining $N - 1$ tags remain unidentified after the collision slot. This is a key difference when compared to collision slots outcome in traditional anti-collision protocols, in which none of the participated tags in a collision slot will be identified. It's worth mentioning that the RN of m- or m-1-bits is generated and checked for all 1s once the CW is cut off by the reader, not at the end of the periods P_1 or P_2.

V. Performance Evaluation

In this section, we evaluate the efficiency of DBMT with and without SCR method in ALOHA- and Tree-based protocols. When DBMT is applied without SCR (noted as "DBMT-only"), the detection of CW cutoff is followed immediately by a NACK command. In DBMT with SCR (noted as "DBMT-SCR"), SCR scheme is applied during collision slots to achieve a successful reply from a group of tags in that collision slot. The efficiency of "DBMT-only" and "DBMT-SCR" are evaluated for 40 different tags counts in the set $C = [100, 200, \ldots, 4000]$. In our evaluation, the time slot structure and timing are based on EPC standardized specifications [13].

Note that the ratio of the collision slots to overall slots will accentuate the effect of "DBMT-only" and "DBMT-SCR" on anti-collision protocols. In ALOHA-based protocols this ratio is probabilistic and depends on the total slots in the frame. If a frame size (i.e., total slots in a given identification round) is larger than the tag count, most slots will be single-reply slots or empty slots. Otherwise, the slots will mostly be single-reply and collision slots. However, in the standardized anti-collision protocols, the Q-Algorithm, the single, empty, and collision slots are equally likely as the Q-algorithm maintains such likelihood by modifying the frame size [13] as shown in Fig. 9. For instance, identifying 60 tags will require 60 single-reply slots, 60 collision slots, and 60 empty slots. In Tree-based protocols, the identification is a deterministic process in which collision slots is proportional to the tag count [11, 14]. Collision-to-total-slots ratio differs in Tree-based protocols according to the pre-knowledge of the tag count or the tag count is unknown to the reader.

Fig. 9. Numbre of collisoin slots during the identification of the tag counts in C (100 tags to 4000 tags)

In Tree-based protocols, knowing the tag count beforehand allows for optimizing the queries to minimize the ratio of both collision and empty slots to overall slots. The total number of collision slots for a tag population c, where $c \in C$ for ALOHA- and Tree-based protocols (with a known and an unknown number of tags to be identified) are plotted in Fig. 9.

The mean identification times for the tags count in C are evaluated through 1) tag identification without DBMT (noted as "none-DBMT"), 2) tag identification with "DBMT-only", and 3) tag identification with "DBMT-SCR". Fig. 10 and Fig. 11 provide the simulation results under EPC standardized slot duration (with reader symbol duration of $25\mu s$, FM0 encoding, and divide ratio of 8).

In Fig. 10, the mean identification time of tag count c is reported using Q-algorithm for "none-DBMT", "DBMT-only", and "DBMT-SCR". The results show a speedup of 28.7% and 35.9% by applying "DBMT-only" and "DBMT-SCR", respectively. "DBMT-SCR" outperforms "DBMT-only" in the Q-algorithm as average number of the tags participating in collision slots, N, is 2.38 tags [11, 13]. And since one tag will be correctly identified by SCR, instead of 2.48 none identified tags as in "none-DBMT" or "DBMT-only", only 1.38 tags will remain unidentified. It's worth mentioning that the Q-algorithm can be further modified to accommodate SCR scheme; this will be left as future work.

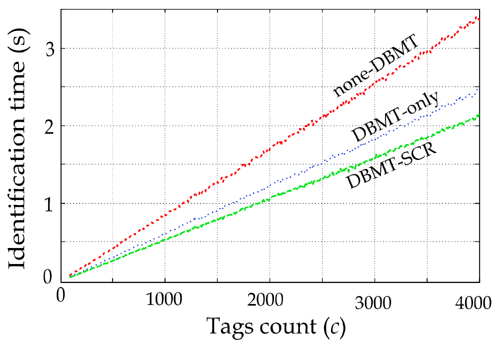

Fig. 10. Total identification time for 100 tags to 4000 tags using Q-Algorithm

In Fig. 11, the mean identification time of tag count c is shown using a Tree-based algorithm with *unknown* tag count for "none-DBMT", "DBMT-only", and "DBMT-SCR". The results show a speedup of the none-DBMT by 37.1% and 50.1% by applying "DBMT-only" and "DBMT-SCR", respectively. The same trend is observed in Tree-protocols for *known* tag count, and the time saving by "DBMT-only" is 23.6%, while "DBMT-SCR" saves 41.4% of the identification time.

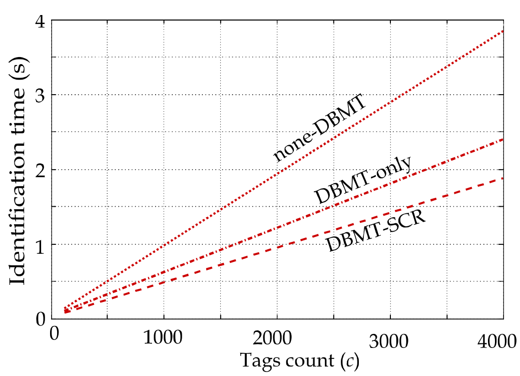

Fig. 11. Total identification time for 100 tags to 4000 tags using Tree-based protocols (tag count is *unknown* to the reader)

VI. Conclusion

In this paper, a new collision time reduction circuit, Digital Baseband Modulation Termination, is proposed. DBMT is designed using digital components at the baseband part of the tag to promptly sense CW cutoff from the reader. Besides, DBMT is capable of measuring the duration of the CW cutoff when supported by the SCR scheme counter circuit. SCR scheme allows the tag to interpret different CW cutoff periods into commands. DBMT with and without SCR provides a significant reduction in the total identification time for a given number of tags. DBMT, by its own, reduces the identification time of ALOHA- and Tree-based protocols up to 28.7% and 37.1%, respectively. When DBMT is combined with the SCR scheme, one tag can be identified within a collision slot; hence, further enhancement is achieved in the identification time of ALOHA- and Tree-based protocols that can reach up to 50% time-saving. Faster tag identification will result in less power consumption at the reader.

Since identification protocols are designed to count for collision, single, and empty slots, identifying a tag within a collision slot is a new feature in which the slot is not entirely a collision nor a single slot. Therefore, further investigation is needed to design identification protocols in which the expected number of tags per collision slot can be optimized to increase identification efficiency. Also, considering the ability of the tag to measure CW cutoff duration may lay the ground for command-less protocol in which CW cutoff durations are the commands not only in collision slots but also in empty and single slots.

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