13-8-2007

On the Suitability of Framed Slotted Aloha based RFID Anti-collision Protocols for Use in RFID-Enhanced WSNs

Dheeraj Klair

University of Wollongong, dkk282@uow.edu.au

K. Chin

University of Wollongong, kwanwu@uow.edu.au

R. Raad

University of Wollongong, raad@uow.edu.au

Follow this and additional works at: <https://ro.uow.edu.au/infopapers>

Part of the [Physical Sciences and Mathematics Commons](#)

Recommended Citation

Klair, Dheeraj; Chin, K.; and Raad, R.: On the Suitability of Framed Slotted Aloha based RFID Anti-collision Protocols for Use in RFID-Enhanced WSNs 2007.
<https://ro.uow.edu.au/infopapers/634>

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

On the Suitability of Framed Slotted Aloha based RFID Anti-collision Protocols for Use in RFID-Enhanced WSNs

Abstract

This paper studies the energy consumption of frame slotted Aloha (FSA) based anti-collision protocols. Specifically, we investigate twelve FSA variants using a detailed qualitative and quantitative methodology to evaluate efficiency with varying tag population. Our results show that the variant that adjusts its frame size in accordance with tag population and incorporates the muting and early-end feature has the lowest energy consumption, hence most suited for RFID-enhanced WSNs.

Disciplines

Physical Sciences and Mathematics

Publication Details

This conference paper was originally published as Klair, DK, Chin, K, Raad, R, On the Suitability of Framed Slotted Aloha based RFID Anti-collision Protocols for Use in RFID-Enhanced WSNs, 16th International Conference on Computer Communications and Networks ICCCN 2007, 13-16 Aug, 583-590.

On the Suitability of Framed Slotted Aloha based RFID Anti-collision Protocols for Use in RFID-Enhanced WSNs

Dheeraj K. Klair, Kwan-Wu Chin and Raad Raad
School of Electrical, Computer and Telecommunications Engineering
University of Wollongong
Northfields Avenue, NSW, Australia
{dkk282, kwanwu, raad}@uow.edu.au

Abstract—This paper studies the energy consumption of frame slotted Aloha (FSA) based anti-collision protocols. Specifically, we investigate twelve FSA variants using a detailed qualitative and quantitative methodology to evaluate their energy efficiency with varying tag population. Our results show that the variant that adjusts its frame size in accordance with tag population and incorporates the muting and early-end feature has the lowest energy consumption, hence most suited for RFID-enhanced WSNs.

I. INTRODUCTION

Radio frequency identification (RFID) is gaining popularity in object identification and supply chain management applications. Unlike conventional barcodes, RFID enables the identification of multiple objects without requiring the line of sight. With its wide acceptance and rapidly increasing applications, researchers are actively working to enhance RFID technologies. One promising area of interest is to integrate RFID with wireless sensor network (WSN) technologies to create an RFID-enhanced WSN.

An RFID-enhanced WSN promises a self-configuring, ad-hoc, wireless RFID tag reading network that is capable of processing data from both sensors and RFID tags. Such WSNs have wide ranging applications. One can imagine a bushfire detection system comprising of RFID-enhanced sensor nodes and RFID tags with temperature sensing capabilities deployed randomly in a region. If the environmental temperature exceeds a threshold, RFID tags transmit their unique identifier to the nearest RFID-enhanced sensor node to be propagated back to a command center.

To date, there are only a handful of RFID-enhanced WSN related projects. In [7], Ho et al. outline a project that aims to build an in-home elder health care system that monitors patients' medication intake using a WSN equipped with a RFID reader. In a similar work, Intel [8] has developed a system called "Caregiver's Assistant". Their system tracks an elder's activities by collecting data from RFID tags that are fastened on household objects, thereby allowing the system to record when these objects are touched by an elder. In [13], NASA/JPL is developing a web of sensors equipped with RFID readers to track objects. Finally, BP Oil [14] is using RFID for location tracking and also to sense the working condition of machines by monitoring their vibrations.

The aforementioned works have only reported on system issues pertaining to the creation of RFID-enhanced WSNs. However, none has considered the limited battery lifetime of sensor nodes. In this paper we extend our previous work [10], which studied the energy consumption of Pure and Slotted Aloha based anti-collision protocols, to consider frame slotted Aloha (FSA) based protocols and their variants. We evaluate their reading delay and determine the energy consumed in the following collision resolution phases, i) success ii) collision, and iii) idle listening. In addition, we also study their impact on a sensor node's battery life.

The rest of the paper is organized as follows. Section II provides a background on RFID technologies and discusses FSA variants. Then in sections III and IV we outline our research methodology and system model respectively. We then present our results in Section V followed by conclusions in Section VI.

II. BACKGROUND

RFID technologies use magnetic or electromagnetic response exchange to track and identify multiple objects simultaneously. A typical RFID architecture is shown in Figure 1 where a RFID reader is deployed to read a finite number of tags. RFID tags have a small storage and also tiny integrated circuits with a small antenna for communication. RFID tags can be active, passive or semi-passive. Passive tags have no power source and on-board transmitter. They rely on the power emitted from the reader to energize and to relay their identification code (ID) to the reader. On the other hand, semi-passive and active tags have an on-board power source, and are activated by a reader's electromagnetic field. Moreover, active tags use their on-board transmitter to send their ID.

Fig. 1. Reader and tags interactions.

Collisions due to simultaneous tag responses is one of the key issues in RFID systems. It results in wastage of bandwidth, power and increases identification delay [5]. Thus, numerous anti-collision protocols have been devised to resolve these problems. Amongst them, Time Division Multiple Access (TDMA) based protocols are the most popular. They can be classified into tree, and Aloha based protocols.

Aloha based protocols are known for their low complexity and computation, thus making them attractive for use in RFID-enhanced WSNs. Examples include Pure, Slotted and FSA, and their variants [18][1][12]. In Pure and Slotted Aloha, a tag responds after a random delay, and continues doing so until it is identified. In Slotted Aloha, a tag replies in synchronized slots. However, for FSA and its variants, a tag selects a slot randomly and replies once in a frame. If there is a collision, tags defer to the next frame. Note, the frame size may vary over time.

A. FSA

FSA protocols group slots into a frame, where a frame's size may be fixed or variable depending on implementation [17]. A FSA with a fixed frame size is referred to as basic framed slotted Aloha (BFSA) and one that uses variable frame sizes is called dynamic framed slotted Aloha (DFSA) [5][19]. BFSA and DFSA can be further classified according to whether they support muting and early end. Note, when the early end feature is used, a reader closes an idle or no response slot early. On the other hand, muting enables the reader to silence tags that have been read successfully.

Fig. 2. Round structure for FSA variants. S_i indicates the slot number.

Figure 2 depicts the timing scenario for both muting and non-muting RFID systems [2][9]. The reader-to-tag communication is controlled by commands from the reader. Initially, tags are assumed to be inactive or un-powered. Tags are activated when they receive a *reset* and *calibration* command from the reader. Once tags are activated, the reader transmits a *read* command, specifying the frame size in the current read round. Tags respond by selecting a slot randomly and transmit their ID along with a 16 bit CRC. Note, *Null* signals the completion of a command and the end of a slot, thereby serving as a synchronization mechanism that allows tags to determine slots boundary. After transmission, tags wait for an acknowledgement (*ACK*) from the reader.

The *ACK* command is a string of bits, the length of which correspond to the frame size. Specifically, the position of each bit corresponds to a slot position, where a one indicates a

successful reception and a zero indicates a failed reception or no response in the corresponding slot. In muting based systems, a positive acknowledgement mutes tags. However, in non-muting based algorithms, *ACK* is optional. For FSA systems which support early end, the reader closes an idle slot early when no responses are detected after a duration of 10 data bits [9].

1) *BFSA*: BFSA has four variants; each of them can be differentiated according to whether they use muting, early-end or both in the reading process. These variants are referred to as, i) BFSA-Non Muting, ii) BFSA-Muting, iii) BFSA-Non-muting-early-end, and iv) BFSA-Muting-early-end.

For BFSA-Muting, a reader mutes the identified tags after each read round. Therefore, the number of responding tags reduces whenever a tag is identified. Note, the acknowledgment from the reader acts as a mute command; i.e., a tag is silenced after identification. When a reader receives no collisions in a particular read round, it assumes all tags have been read.

As the name implies, the BFSA-Non-muting-early-end and BFSA-Muting-early-end variants incorporate the early-end feature. Specifically, the reader transmits a *close slot* command if it does not receive any response in a particular frame slot.

2) *DFSA*: Similar to BFSA, DFSA has four variants. They are, i) DFSA-Non Muting, ii) DFSA-Muting, iii) DFSA-Non-muting-early-end, and iv) DFSA-Muting-early-end.

Unlike BFSA, DFSA and its variants have the ability to adjust their frame size according to the number of tags in a reader's interrogation zone. The reader starts collision resolution with a predefined frame size. If a large number of responses are detected, the reader adjusts its frame size to accommodate the additional tag responses. This means the reader is required to continually adjust its frame size until it achieves an optimal frame size for a given tag population. In [3], an optimal frame size is defined as one which is equal to the number of tags. Unfortunately, obtaining an optimal frame size is analytically difficult since the number of tags in a reader's interrogation zone is usually unknown. Therefore, researchers have devised various tag estimation functions to obtain an "accurate" tag estimate.

A tag estimation function relies on the status of each slot; a slot can be filled with zero, one or multiple tag responses. In [6], Floerkemeier has compared four tag estimation functions experimentally using a test-bed comprising of a field programmable RFID reader and 64 HF Philips I Code RFID tags. Floerkemeier found Vogt's tag estimation functions, which are based on Chebychev's inequality, provide a reasonably accurate tag estimate. Although Floerkemeier did propose a Bayesian approach and show it to have better accuracy than Vogt's techniques, the proposed approach is computationally expensive. Therefore, we will use Vogt's tag estimation technique [16] in our investigations of DFSA variants without muting.

Vogt also proposed a set of frame sizes for a given tag range. According to Table I, if the number of tags in a reader's interrogation is in the one to nine range, the frame size should be 16 in order to achieve low reading delays.

Lastly, for muting based DFSA protocols, we will use the estimation function by Cha et al. [4], which relies on collision

ratio. This is because the function is targeted at muting based RFID systems and does not consider tags already identified during estimation.

TABLE I
OPTIMAL FRAME SIZES FOR A GIVEN TAG RANGE.

FrameSize(N)	Low(n)	High(n)
1	—	—
4	—	—
8	—	—
16	1	9
32	10	27
64	17	56
128	51	129
256	112	∞

A limitation of all DFSA variants is that the frame size is only limited to a maximum value of 256 [16]. If the number of tags exceed this value, a reader is unable to achieve an optimal frame size. Lee et al. [11] address this issue by proposing an enhanced version of DFSA called enhanced-DFSA or EDFSA. In EDFSA, if the estimated number of tags is larger than the frame size, EDFSA divides the tags into M groups. Table II shows the value of M for a given tag range [11]. In Table II, n denotes the number of tags, N is the frame size and M is the modulus operator. Lee et al. [11] also proposed frame sizes for varying tag ranges to achieve maximum system efficiency. The value of M is one when the number of tags is lower than 355. However, when the number of tags increases, the modulo operation divides the responding tags into M groups. The reader then reads tags on a group-by-group basis. To reduce identification delay, EDFSA can be incorporated with the early end and muting features.

TABLE II
 N AND M VALUES FOR EDFSA

Number of tags (n)	Frame Size (N)	M
1 – 11	8	1
12 – 19	16	1
20 – 40	32	1
41 – 81	64	1
82 – 176	128	1
177 – 354	256	1
355 – 707	256	2
708 – 1416	256	4
1417 – 2831	256	8

From the discussion above, it is clear that a number of FSA variants exist. In this paper we will study all these variants, compare their energy efficiency, and determine whether they are suited for RFID-enhanced WSNs. In the following section we outline our research methodology before presenting our results in Section V.

III. RESEARCH METHODOLOGY

In order to evaluate the energy consumption of FSA protocols, we first evaluate the delay incurred in different phases of the tag reading process. These phases are, i) success, ii) collision, and iii) idle listening. Note, idle listening corresponds to the scenario where the reader did not receive any responses from tags. Once we have the delay in each phase, we use it to derive each tag reading protocol's energy consumption. With

the average energy consumption in hand, we then analyze its effect on a sensor node's battery lifetime.

The energy consumed by a reader is determined by the duration for which it is scanning a given set of tags. If D is the total delay to read n tags then the energy consumed by a reader during scanning is,

$$E = P \times D \quad (1)$$

where E (Joules) is the energy consumed by a reader when scanning n tags, $P = VI$ (Watts) is the power consumed by the reader during scanning, V (Volts) is the supply, I (Amperes) is the current consumed during scanning and D (seconds) is the scanning duration.

We can then use Equ. 1 to calculate a sensor node's battery lifetime, which is determined by the number of tags a battery can read in its lifetime. For a given protocol, the number of tags that can be read in its lifetime is,

$$N_{given.protocol} = n \times \frac{B}{E} \quad (2)$$

where B is the energy stored in a battery.

The battery energy wasted due to idle listening and collisions, B_{waste} (Joules), during tag identification is [10],

$$B_{waste} = B \left(1 - \frac{n \times T}{D} \right) \quad (3)$$

In Equ. 3, T is the slot duration and it is defined as,

$$T = \frac{ID(bits)}{data.rate(bps)} \quad (4)$$

where $ID(bits)$ is a tag's identity, and $data.rate(bps)$ is the tags' data rate in bits per second.

The aforementioned equations, Equ. 1, 2 and 3, play a critical role in determining the performance of a tag reading protocol. Notice that the common parameter is D or delay. In the following sections, we present various methodologies to evaluate D for each FSA variant. After deriving D , we obtain the following performance metrics, i) total energy consumed in the tag reading process, ii) battery lifetime, and iii) energy wastage.

A. BFSA

The delays incurred by BFSA variants are evaluated as follows.

1) *BFSA-Non Muting*: We first evaluate the read cycles needed to read a given set of tags with a confidence level of α . The number of read cycles is then used to determine the total delay to read a given set of tags. From the read cycles, we then extract the number of slots with idle responses and collisions, which we then used to determine the idle and collision delay respectively.

The read cycles required is evaluated as follows. With a frame size of N and the number of tags n , the probability of r tags responding in a slot in the i^{th} read round is given by [18],

$$P_r(i) = \binom{n}{r} \left(\frac{1}{N} \right)^r \left(\frac{N-1}{N} \right)^{n-r} \quad (5)$$

From Equ. 5, the probability of having an idle transmission $p_0(i)$, a successful transmission $p_1(i)$, and collisions $p_k(i)$ in the i^{th} read round can be evaluated as,

$$p_0(i) = N \times \left(1 - \frac{1}{N}\right)^n \quad (6)$$

$$p_1(i) = n \times \left(1 - \frac{1}{N}\right)^{n-1} \quad (7)$$

$$p_k(i) = N - p_0(i) - p_1(i) \quad (8)$$

Using Equ. 7 the expected number of successful transmissions in the i^{th} read round is calculated as $Np_1(i)$ [18]. From [18], the probability of having an unread tag after R read rounds is,

$$p_{miss}(i) = \prod_{i=1}^R \left(1 - \frac{Np_1(i)}{n}\right) = 1 - \alpha \quad (9)$$

In Equ. 9, α determines the confidence level of the tag reading process. Since $p_1(i)$ is the same for all read rounds in BFSA, Equ. 9 becomes,

$$\left(1 - \frac{Np_1}{n}\right)^R = 1 - \alpha \quad (10)$$

Solving Equ. 10 for R , we find that the read cycles required to read a set of tags with α confidence level must be at least,

$$R \geq \left\lceil \frac{\log(1 - \alpha)}{\log\left(1 - \frac{Np_1}{n}\right)} \right\rceil \quad (11)$$

In Equ. 11, to obtain an integral value and to avoid conservative delay values, the ceil function is used.

Using R , we evaluate the theoretical delay in each phase of the tag reading as follows. For a slot of duration T , the delay to read a set of tag successfully is,

$$D_{Succ_BFSA} = NRT \quad (12)$$

In order to find the idle delay, we need to determine the expected number of idle slots during each read cycle, which can be obtained from Equ. 6 as Np_0 for a frame size of N . Thus, the delay due to idle slots with α confidence level is,

$$D_{Idle_BFSA} = Np_0RT \quad (13)$$

Lastly, the delay incurred due to collisions during the reading process is given by,

$$D_{Coll_BFSA} = NRT(1 - p_0 - p_1) \quad (14)$$

Note, the delays as computed by Equ. 12, Equ. 13, Equ. 14 assume the number of tags is known.

2) *BFSA-Muting*: Muting reduces the number of responses after each identification round. Hence, the number of tags in the $(i+1)^{th}$ read round is either equal to or fewer than those in the i^{th} read round. The number of tags in the $(i+1)^{th}$ round is evaluated as [18],

$$n(i+1) = n(i) - p_1(i) \times N(i) \quad (15)$$

In Equ. 15, $p_1(i) \times N(i)$ is the number of tags identified in a read round and is denoted as c_1 . Therefore,

$$n(i+1) = n(i) - c_1 \quad (16)$$

Based on Equ. 16, we use Algorithm 1 to evaluate the following metrics to read n tags: a) total delay, b) delay due to collisions, and c) delay due to idle listening.

```

1 BEGIN ;
2 Initialize unread tags = actual number of tags;
3 while True do
4   Perform a read cycle for unread tags;
5   Store the number identified tags ;
6   Store the number slots filled with collisions ;
7   Store the number of slots filled with idle responses ;
8   Store current frame size;
9   if (No Collisions) then
10    Break;
11  else
12    Unread Tags = actual - identified tags;
13  end
14 end
15 Total delay =  $T \times \sum$  stored frames;
16 Collision Delay =  $T \times \sum$  stored collision slots;
17 Idle Delay =  $T \times \sum$  stored idle slots;
18 END;
```

Algorithm 1: Pseudo-code to determine the delay in each phase of the collision resolution process for BFSA-Muting.

Algorithm 1 works as follows. A reader performs a read round and stores the frame size, number of identified tags, idle slots, and collided slots. If there are no collisions, the reader calculates the respective delays; see lines 15 to 17.

3) *BFSA-Non muting-early end*: Recall that the early-end feature closes an idle slot early to reduce the total time required to read a given set of tags. However, notice that the read cycles needed to read a set of tags remain the same. This is because read cycles are independent of slot duration, see Equ. 11.

Let $t < T$ be the duration after which a reader closes a slot if no responses are detected. Let's say there are N_{Idle_early} no response slots, meaning tags will not transmit for a time period of $(T - t)N_{Idle_early}$. Therefore, the average delay to read a tag in BFSA with the early end feature is calculated as,

$$D_{Success_early} = D_{Succ_BFSA} - (T - t)N_{Idle_early} \quad (17)$$

The expected number of idle transmissions in a frame of size N in a single read round is Np_0 . Thus, for R read rounds, the number of idle slot is $N_{Idle_early} = NRp_0$. Inserting D_{Succ_BFSA} and N_{Idle_early} into Equ. 17, we get,

$$D_{Success_early} = NR(T - (T - t)p_0) \quad (18)$$

The delay due to idle transmissions is,

$$D_{Idle_early} = tNRp_0 \quad (19)$$

Note, collision delay remains unchanged in BFSa-non muting-early-end since the probability of collision is independent of slot duration. Moreover, the delay due to muting and early-end can be evaluated using Algo. 1 and using Equ. 17, 18 and 19.

B. DFSA

We now present our methodology to evaluate the delay incurred by DFSA-muting and DFSA-non-muting. Once we have the total identification delay for both protocols, we use the methodology presented in Section III-A.3 to obtain the delay incurred by DFSA-muting and DFSA-non-muting with the early-end feature.

1) *DFSA-Non Muting*: In order to evaluate the delays to read a set of tags in DFSA-Non Muting, we need to determine the i) total delay incurred to estimate a set of tags, denoted as estimation delay, and ii) the delay incurred in reading the estimated tags with α confidence level, denoted as reading delay. Summing these two delays therefore give us the delay to read a set of tags with α confidence level.

```

1 BEGIN;
2 while True do
3   Perform a read round;
4   Estimate tag numbers;
5   if (current > last estimate) then
6     Adapt and store frame size;
7     Store the number collided slots;
8     Store the number of idle slots;
9   else
10    Break;
11  end
12 end
13 Store tag estimate;
14 Store frame size;
15 /* Estimation delay calculations */;
16 Total Delay =  $T \times \sum$  stored frames;
17 Collision Delay =  $T \times \sum$  stored collision slots;
18 Idle Delay =  $T \times \sum$  stored idle slots;
19 END;
```

Algorithm 2: Pseudo-code to determine the estimation delay in each phase of the collision resolution process for DFSA-Non Muting.

Algorithm 2 [16] is used to evaluate the estimation delay incurred by DFSA-Non-Muting. In the algorithm, we first estimate the number of tags in a reader's interrogation zone before evaluating the delay due to the tag estimation function. The algorithm estimates the number of tags in each read round and compare the current tag estimate to that of the previous round. If the estimate is higher, the loop exits and the algorithm stores the current tag estimate and frame size. Lastly, the estimation delays are calculated according to lines 16-18.

Once we have the estimation delay, we need to determine the reading delay, which is calculated from the number of read cycles required to read an estimated number of tags, see Equ. 11. These two values are then fed into Equ. 12, Equ. 13 and Equ. 14 to obtain the reading delay. Finally, as mentioned, the total delay incurred by DFSA-Non Muting is obtained by adding the estimation and reading delay of each phase.

2) *DFSA-Muting*: We replace lines 9 to 13 of Algorithm 1 to the lines shown in Algorithm 3 to evaluate the reading delay of DFSA-muting. The algorithm works as follows. The reader performs a read cycle and stores the values as in Algorithm

1. If there is a collision, the reader estimates the number of tags and adapts its frame size accordingly. In addition, it determines the remaining number of unread tags in its interrogation zone. If there are no collisions, the loop exits and delays are calculated as per lines 16-18 of Algorithm 1.

```

1 if (No Collisions) then
2   Break ;
3 else
4   Estimate tags;
5   Adapt frame size;
6   Unread Tags = actual - identified tags;
7 end
```

Algorithm 3: Computing identification delays for DFSA-Muting

C. EDFSA

Lastly, we present the methodology used to evaluate the delay for EDFSA; with or without muting. We omit EDFSA-non-muting with early-end and EDFSA-muting with early-end from our discussions since they follow the early-end methodology of BFSa.

1) *EDFSA-Non Muting*: In EDFSA, the grouping of tags and frame adjustments are based on Table II. The delay in EDFSA-non muting encompasses both estimation and reading delays, similar to DFSA-non muting. Table II can be implemented as a look up table from which we obtain the value of M along with estimation delays. For EDFSA, the delay in each phase will therefore be the summation of the estimation delay, and M times the reading delay of each group, where the reading delay of each group is evaluated similarly to DFSA-non-muting.

2) *EDFSA-Muting*: EDFSA-muting can be evaluated by inserting Table II in Algorithm 3 as a look-up table. As long as the value of $M = 1$ in Table II, the delay evaluation for EDFSA resembles DFSA, hence we can apply Algorithm 3. However, when the number of tags increases, tags will be partitioned into $M > 1$ groups. Once Algorithm 3 finishes, the first group of tags will have been read completely, thus there will be $M - 1$ groups remaining. Note, when $M > 1$, the frame size is fixed to 256 according to Table II, which equates to BFSa-Muting with a frame size of 256. Therefore, the delay evaluation for the remaining $M - 1$ groups can be based on Algorithm 1. Finally, adding the delays for each group yields the total delay incurred by EDFSA.

IV. SYSTEM MODEL

The system consists of an RFID reader and n tags in its interrogation zone. The reader model is based on the design features of SkyeTek's M1-Mini RFID reader developed to mate directly with the MICA2DOT sensor mote [15]. The reader operates from a Lithium rechargeable battery (B) which has 0.48 Kilo-joules of energy. The tag to reader data rate is 26 kbps (ISO 15693). The power consumed during scanning (ψ) is 180 milli-watts.

For non-muting environments, an RFID reader is assumed to transmit energy until tags are read with 99% confidence level. For muting based environments, the reader is assumed

to transmit until it receives no collisions in a particular read cycle. We assume that tags are synchronized upon receiving a new reader command. The performance degradation due to a reader's orientation is assumed to be absent from the system. The reader detects collisions when the CRC check fails and transmits an ACK only when an ID is received correctly. The delay due to *null* commands are assumed to be negligible. The frame size is N and the slot duration is T .

We assume tags are passive, hence have no power source, and they are used in read-only mode. Further, tags are static and can be read regardless of their orientation. Finally, tags have an ID that is 112 bits in size, which includes 16-bits of CRC.

For muting based protocols, ACK is used to mute tag responses. If the early-end feature is supported, the reader sends a *close slot* command after waiting for a duration of t , which is assumed to be $\frac{T}{10}$ in our analysis [10]. Further, our analysis assumes a noise free channel and considers packet losses are due to collisions only.

V. RESULTS

We now use the algorithms developed in Section III to evaluate the energy consumption of FSA variants, and study their battery lifetime and wastage.

We consider two cases, i) low tag densities ($n < 100$), and ii) high tag densities ($n \geq 100$). Note, BFSMA-Non-muting and BFSMA-non-muting with early-end are evaluated using the theoretical formulations in sections III-A.1 and III-A.3. On the other hand, DFSA-non muting, EDFSA-non muting and their early end counterparts require both the use of simulations to obtain delays incurred by the tag estimation function and theoretical formulations to evaluate reading delays; see Section III-B.1 and Section III-C.1. Other than that, the rest of the FSA variants rely on simulations where 1000 read rounds are performed on a given tag set. The mean delay value is then computed and used to determine the energy consumption in different phases of the reading process. The delay variance (in seconds) is also recorded. The initial frame size for DFSA variants is set to 16, and BFSMA variants have a fixed frame size of 32.

A. Low tag densities ($n < 100$)

First, we evaluate the energy consumption when the number of tags in a reader's interrogation is less than 100.

1) *Total energy consumed to read n tags*: Figure 3 depicts the energy consumed by each FSA variant to read n tags. The figure comprises of non-muting and muting based FSA variants. For non-muting based variants, DFSA-non-muting with early-end has the lowest energy consumption for most tag ranges. This is because of their ability to adjust their frame sizes in accordance with tag population.

For DFSA variants employing muting, DFSA-muting has the highest energy consumption whereas EDFSA-muting with early-end has the lowest energy consumption for most tag ranges. The discrepancy in energy consumption between these two variants is due to the different methodologies used for frame adjustments. EDFSA frame sizes are smaller than those

of DFSA for the same tag population. Hence, EDFSA-muting with early-end has a lower energy consumption due to its unique frame adjustment algorithm.

EDFSA-muting with early-end is found to have a delay variance in the range of 0 to 0.9×10^{-3} seconds, which is the lowest among all variants compared. The maximum variance is observed for DFSA non-muting; 0 to 0.38 seconds. This indicates that the energy consumption distribution of EDFSA-muting with early-end is very stable whereas DFSA Non-muting is unstable. This is because of the variability in tag estimates and the different frame adjustment methodologies used by EDFSA and DFSA variants.

Overall, FSA variants with muting have the lowest energy consumption compared to those without muting. Moreover, these variants can further reduce their energy consumption using early-end.

Fig. 3. Total energy consumed versus number of tags for FSA variants in low tag density environments.

2) Total energy consumed in idle listening to read n tags:

Figure 4 depicts the energy consumption incurred by each FSA variant in idle listening. DFSA non-muting consumes the most energy in idle listening. On the other hand, BFSMA-muting early-end has the lowest energy wastage in idle listening for most tag ranges. Among the FSA variants, lower energy consumption is observed for those based on BFSMA compared to DFSA due to it using a fixed frame. As the number of tags increases, using a fixed frame means slots is likely to be filled with a tag response, thereby reducing idle listening. In DFSA's case, the frame size varies with tag population, and is increased if large number of responses is observed, which may result in higher idle listening delay if the frame size used is non-optimal. Lastly, EDFSA muting with early-end has the least variability in energy consumption.

3) *Total energy wasted in collisions to read n tags*: Figure 5 depicts the total energy wasted due to collisions when reading n tags. Firstly, it can be observed that with increasing number of tags, the energy wasted due to collisions increases for each FSA variant. The lowest energy consumption is observed for BFSMA muting, and BFSMA-muting with early-end when $n < 34$. This is because their frame size is fixed to 32 and is

Fig. 4. Total energy wasted in idle listening versus number of tags for FSA variants in low tag density environments.

comparable to the number of tags for $n < 34$. However, for DFSA-muting and DFSA-muting with early-end, the initial frame size is 16, which results in a large number of collisions and frame adjustments when the number of tags exceeds the frame size used to read them. FSA variants which do not support muting incur significant energy wastage due to collisions. In addition, it can be observed that early-end has no effect on the energy consumed resulting from collisions.

Fig. 5. Total energy wasted in collisions versus number of tags for FSA variants in low tag density environments.

4) *Summary*: DFSA-Non muting has the highest energy consumption than all FSA variants when $n < 42$. This is because it incurs both reading and estimation delays. The energy consumption of BFSA-non muting is at its highest after $n > 42$ because of its fixed frame size. Thus, DFSA-Non muting has a lower energy consumption than BFSA for high tag numbers. For low tag densities and non muting environments, DFSA-Non muting with early-end has the lowest energy consumption followed by EDFSA-non muting with early-end. DFSA-muting with early-end protocol has the lowest energy consumption among all FSA variants.

B. High tag densities ($n > 100$)

In this section we evaluate the energy consumption when the number of tags in a reader's interrogation is more than 100. BFSA variants are omitted from our plots since they experience an exponential rise in delay, hence are unsuitable for use in high tag densities scenarios.

1) *Total energy consumed to read n tags*: Figure 6 plots the energy consumption of DFSA variants. DFSA-non muting has the highest energy consumption. On the other hand, EDFSA-non-muting with early-end has the lowest energy consumption. In muting based DFSA variants, EDFSA-muting has the highest energy consumption. On the other hand, DFSA-muting-early end has the lowest energy consumption.

Both DFSA-muting early-end and EDFSA-muting with early-end have a low delay variance. On the other hand, DFSA-non muting and DFSA non-muting have the highest delay variance with values as high as 1500 seconds when n is close to 1000 tags.

Fig. 6. Total energy consumed versus number of tags for DFSA variants in high tag density environments.

2) *Total energy consumed in idle listening to read n tags*: Figure 7 plots the energy wastage of DFSA variants due to idle listening. EDFSA-non-muting wastes a large amount of energy due to idle listening compared to other FSA variants when $n > 300$. For $n < 300$, DFSA-non-muting has the highest idle listening delay. For non-muting variants, EDFSA-non muting with early-end experiences minimal idle listening delay. EDFSA-muting and EDFSA-muting with early-end have a lower energy wastage due to idle listening compared to DFSA-muting and DFSA-muting with early-end because they rely on different frame adjustment techniques discussed in Section II-A.2. The frame sizes proposed for DFSA are larger than those proposed for EDFSA, thereby causing higher energy wastage due to idle listening. Overall, EDFSA-muting with early-end has the lowest energy wastage due to idle listening, and lowest energy consumption variability.

3) *Total energy wasted in collisions to read n tags*: Figure 8 plots the energy wastage of DFSA variants due to collisions. DFSA-muting with and without early-end has the lowest energy wastage due to collisions for most tag ranges,

Fig. 7. Total energy wasted in idle listening versus number of tags for DFSA variants in high tag density environments.

and also have the lowest delay variance, maximum being 0.33 seconds when $n = 982$.

Fig. 8. Total energy wasted in collisions versus number of tags for DFSA variants in low tag density environments.

4) *Summary*: From our analysis, DFSA-non-muting consumes the most energy and DFSA-muting with early-end has the lowest energy consumption. On the other hand, for non-muting DFSA variants, EDFSA non-muting with early-end has the lowest energy consumption in high tag density scenarios.

VI. CONCLUSION

We have evaluated and determined the suitability of FSA variants for RFID-enhanced WSNs. We found that for low tag densities and in non muting environments, DFSA-non-muting with early-end has the lowest energy consumption, whereas EDFSA-non-muting with early-end performs well when tag density is high. In muting based systems, DFSA-muting with early-end has the lowest energy consumption for both low and high tag density environments. Amongst the twelve FSA variants, we found the best performing protocol to be DFSA

that uses the muting with early-end. Hence, we recommend it for use in RFID-enhanced WSNs.

VII. ACKNOWLEDGMENT

We acknowledge and thank the support of the Australia Research Council, grant number DP0559769.

REFERENCES

- [1] C. Abraham, V. Ahuja, A. Ghosh, and P. Pakanati. Inventory management using passive RFID tags: A survey. Weblink. <http://www.cs.rutgers.edu/badri/553dir/papers/MCPaperFinal-coldetect.pdf>.
- [2] Auto-ID Center. 13.56 MHz ISM band class 1 radio frequency identification tag interface specification, version 1.0. Standard. <http://www.epcglobalinc.org/standards/specs/>.
- [3] J.-R. Cha and J.-H. Kim. Novel anti-collision algorithms for fast object identification in RFID system. In *The 11th Intl. Conference on Parallel and Distributed Systems*, pages 63–67, 2005.
- [4] H.-S. Choi, J.-R. Cha, and J.-H. Kim. Fast wireless anti-collision algorithm in ubiquitous ID system. In *The 60th IEEE Vehicular Technology Conference*, pages 4589–4592, 2004.
- [5] K. Finkenzeller. *RFID Handbook, Fundamentals and Apps. in Contactless Smart Cards and Identification*. John Wiley and Sons Ltd., 2003.
- [6] C. Floerkemeier. Transmission control scheme for fast RFID object identification. In *The 4th Annual Intl. Conference on Pervasive Computing and Communications Workshops*, 2006.
- [7] L. Ho, M. Moh, Z. Walker, T. Hamada, and C.-F. Su. A prototype on RFID and sensor networks for elder healthcare: Progress report. In *Proceeding of the 2005 ACM SIGCOMM workshop on Experimental approaches to wireless network design and analysis*, pages 70–75, Philadelphia, Pennsylvania, USA, 2005. ACM Press.
- [8] Intel. Intel sensor nets/RFID research areas. Webpage. http://www.intel.com/research/exploratory/wireless_sensors.htm.
- [9] G. Khandelwal, A. Yener, K. Lee, and S. Serbetli. ASAP: a MAC protocol for dense and time constrained RFID systems. In *IEEE International Conference on Communications (ICC'06)*, 2006.
- [10] D. K. Klair, K.-W. Chin, and R. Raad. An investigation into the energy efficiency of pure and slotted aloha based RFID anti-collision protocols. To Appear. In *IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (IEEE WoWMoM'07)*, June 18–21, Helsinki, Finland, 2007.
- [11] S.-R. Lee, S.-D. Joo, and C.-W. Lee. An enhanced dynamic framed slotted ALOHA algorithm for RFID tag identification. In *The 2nd Intl. Annual Conference on Mobile and Ubiquitous Systems: Networking and Services*, pages 166–172, 2005.
- [12] E. Microelectronics. Supertag category protocols. Datasheet. <http://www.gaw.ru/doc/EM-Marin/P4022.PDF>.
- [13] NASA/JPL. Sensor webs project. <http://sensorwebs.jpl.nasa.gov/>.
- [14] M. Roberti. BP leads the way on sensors. Webpage. <http://www.rfidjournal.com/article/articleview/1216/1/2/>.
- [15] Skyetek. Skyetek module M1-Mini. Datasheet. <http://www.skyetek.com/Portals/0/SkyetekModule.M1Mini.060426.pdf>.
- [16] H. Vogt. Efficient object identification with passive RFID tags. In *The International Conference on Pervasive Computing (PerCom)*, 2002.
- [17] J. Wieselthier, A. Ephremides, and L. Michaels. An exact analysis and performance evaluation of framed aloha with capture. *IEEE Transactions on Communications*, 37(2):125–137, 1989.
- [18] B. Zhen, M. Kobayashi, and M. Shimizui. Framed aloha for multiple RFID objects id. *IEICE Trans. on Comm.*, E88-B(3):991–999, 2005.
- [19] E. Zurich and L. A. Burdet. RFID multiple access methods. Technical Report. http://www.vs.inf.ethz.ch/edu/SS2004/DS/reports/06_rfid-mac_report.pdf.