Abstract—A recent development in Wireless Sensor Networks (WSNs) research is to equip sensor nodes with an RFID reader so that they can be used to track animate or in-animate RFID tagged objects. A key problem in such networks, however, is the energy efficiency of current RFID anti-collision protocols. Specifically, the energy cost incurred by a RFID reader to read and monitor \( n \) tags. This paper, therefore, aims to identify the most energy efficient variant amongst twelve Pure and Slotted Aloha based RFID anti-collision protocols. We present an analytical methodology that evaluates the energy consumed in the following phases: i) success, ii) collision, and iii) idle listening. We first calculate the delay of each phase and then use it to formulate the energy consumption, battery lifetime, and battery wastage of all variants. We found that the Pure Aloha with fast mode consumes the lowest energy and is suitable for tag identification. However, none of the protocols promises energy efficient monitoring of identified tags. In other words, the reader is required to re-read all tags every time to sense their presence; a process that consumes a significant amount of energy.

Index Terms—RFID, Anti-collision, Tag Reading, Energy Consumption, Aloha

I. INTRODUCTION

Unlike conventional barcodes, radio frequency identification (RFID) is a wireless technology that uses electromagnetic or magnetic response exchange to identify objects at a distance without direct line of sight [18]. Its increasing popularity and wide acceptance in object identification and supply chain management applications has opened doors to several new areas of research. One such area is RFID-enhanced wireless sensor networks (WSNs).

An RFID-enhanced WSNs has the ability to self-organize and form a multi-hop network capable of tracking RFID tagged objects. An example is tracking books in a library where sensor nodes with an RFID reader are placed on bookshelves. These nodes then self-organize to form a network that users can submit queries to, or used to locate the whereabouts of books.

To date, there have only been a handful of RFID-enhanced WSN related projects. In [10], Ho et al. outline an in-home elder health care system that uses such network to monitor patients’ medication intake. In a similar work, Intel [14] has developed a system that tracks an elder’s activities by recording their interactions with tagged household objects. Finally, BP Oil [28] is using RFID for location tracking and also to sense the working condition of machines by monitoring their vibration.

A limitation of the above works is that they have only addressed system issues pertaining to the creation of RFID-enhanced WSNs, and have neither addressed nor quantified the energy cost incurred by a sensor node that is operating with an RFID reader. To put this in perspective, we found that an RFID reader consumes the most energy while scanning or reading RFID tags. In fact, the energy expended to scan a single tag of 96 bits in length is higher than the energy consumed to transmit and receive 96 bits of data by a sensor node. The energy consumption becomes even higher when there are multiple tags in a reader’s interrogation zone.

To this end, this paper presents a detailed study on the energy efficiency of Pure and Slotted Aloha tag reading protocols, and evaluate their applicability in RFID-enhanced WSNs. We accurately model Aloha variants that use combinations of the early-end, slow-down, fast mode and muting feature. To the best of our knowledge, this paper is the first that analyzes their energy consumption in all phases of the anti-collision process, namely, i) success, ii) collision, and iii) idle listening. From the delay of each phase, we then quantify the battery consumption and wastage of a sensor node equipped with an RFID reader.

Our analysis shows two main causes of energy consumption: (a) collision, and (b) idle listening. Collision is reduced when Aloha variants employ the muting, slow down, and fast mode features. On the other hand, the early-end feature sharply reduces energy wastage from idle-listening, especially when the number of tags is low. The benefits of early-end, however, become negligible as the number of tags increases. From our extensive analysis, we found that equipping Pure Aloha with fast mode and muting yield the lowest energy consumption. Nevertheless, existing anti-collision protocols remain unsuitable for RFID-enhanced WSNs because none of them can be used for monitoring RFID tagged objects. This is because they need to re-read all tags even though tags are static.

The rest of the paper is organized as follows. We first provide an introduction to RFID technologies and tag reading protocols in Section II. After that, in Section II-C, we present a preliminary analysis of a reader’s energy consumption. This is followed by related works in Section III. In Section IV, we outline our system model and assumptions. Following our research methodology in Section V, we derive delay equations...
in Section VI and use them in Section VII to analyze each protocol's energy efficiency. We conclude in Section VIII.

II. BACKGROUND

RFID systems consist of a reading device called an RFID reader and a finite number of tags, which may be passive, active or semi-passive. Passive tags have the lowest complexity, no power source nor an on-tag transmitter. In contrast, semi-passive tags have an on-board power source to energize their microchip. Both passive and semi-passive tags rely on the reader's energy to transmit their ID. However, none of them have the ability to sense the channel. Lastly, active tags also have an on-board power source and a transceiver. They can sense the channel and are able to operate without a reader.

Passive tags are the cheapest [9][18], and are therefore suitable for large scale deployments. However, RFID systems using passive tags suffer from tag collisions.

Tag collisions arise when multiple tags respond simultaneously to a reader's request, as shown in Figure 1. This causes collisions at the reader, leading to bandwidth and energy wastage, and prolonged tag identification time [9]. To resolve these collisions, RFID readers use an anti-collision protocol. Those of interest to our study are presented in the following sections.

Fig. 1. Interactions between a reader and tags.

A. Pure Aloha and its Variants

In Pure Aloha based RFID systems, a tag responds at random times after being energized. It then waits for a response from the reader, which can either be, i) a positive acknowledgement (ACK), indicating the tag’s ID has been received correctly, or ii) a negative acknowledgement (NACK), meaning a collision has occurred, thus requiring the tag to retransmit after a random delay.

Pure Aloha has several variants [40][20]:

1) Pure Aloha with Muting: In order to reduce contention, a reader mutes identified tags via an ACK command.

2) Pure Aloha with Slow down: Another method to minimize contention is to reduce a tag’s response duty cycle once it is identified. This requires an identified tag to re-adjust its duty cycle after receiving an ACK from the reader.

3) Pure Aloha with Fast Mode: The reader sends a quiet command after detecting the start of a tag transmission to inhibit other tags from transmitting. However, the tag which is currently transmitting is not affected by the quiet command. Silenced tags become active again after their waiting timer expires or after receiving an ACK command from the reader, which signifies the end of communication.

The above features, i.e., fast mode, muting and slow down, can be combined to create two more variations. Namely, i) Pure Aloha with fast mode and muting, and ii) Pure Aloha with fast mode and slow down.

B. Slotted Aloha and its Variants

In Slotted Aloha based RFID systems, tags transmit their ID in synchronous time slots. Similarly, if there is a collision, tags retransmit after a random delay.

Slotted Aloha also has numerous variants [40]:

1) Slotted Aloha with Muting and Slotted Aloha with Slow down: The principle operation is similar to Pure Aloha with muting and Pure Aloha with slow down, but conducted in a slotted manner.

2) Slotted Aloha with Early End: During the identification process, there will be idle slots, where no tags reply. When the early-end feature is used, the reader closes idle slots early. This is achieved using start-of-frame (SOF) and end-of-frame (EOF) commands where a reader starts the reading cycle with a SOF command. If no responses are detected at the start of a slot, an EOF command is sent to close the slot. Closing a slot early requires the reader and tags update their timers to remain synchronized.

Two more extensions can be derived from the above protocols, namely i) Slotted Aloha with early-end and muting, and ii) Slotted Aloha with slow down and early-end.

In this paper we are interested in quantifying the energy consumption of Aloha based protocols with the following features: 1) muting, 2) slow down, 3) fast mode, 4) early-end, 5) muting and early-end, 6) slow down and early-end, 7) fast mode and muting, and 8) fast mode and slow down. Note, fast mode is only applicable to Pure Aloha protocols, whereas early-end is only used with Slotted Aloha protocols.

We like to point out that besides Aloha based protocols, there are also tree protocols, which operate in a deterministic manner and form a binary tree like structure during identification. Tree protocols however are complex, incur significant memory overheads, and require complex hardware [9][4][11]. This is in contrast to Aloha protocols, which have simpler reader designs, lower protocol complexity and bandwidth requirements, smaller number of reader to tag commands, and are able to dynamically adapt to varying number of tags. In addition, the use of muting in Aloha based protocols promises 100% read rate [16]. All these properties argue in favor of Aloha based protocols being used in RFID-enhanced WSNs.

Before presenting a detailed study of Aloha based protocols, we first compare the energy consumed by an RFID reader and a sensor node to read/transmit/receive 96-bits of tag ID.

C. Energy Consumption: A Preliminary Analysis

An RFID reader consists of an embedded micro-controller unit (MCU) and scanning circuitry. Modern MCUs can process instructions at very high speeds and consume very low energy. For example, the Texas Instruments MSP430 micro-controller only consumes 1 nJ per instruction [38][12].

Table I summarizes the current and power consumption of commercial RFID readers. Only SkyeTek's M1-Mini [33] and M1 [32] RFID readers are designed to mate with the Mica2Dot. From the table, we see that the M1-Mini [33] and M1 [32] readers consume 180 and 330 milli-watts respectively.
during scanning. In idle mode they consume 30 and 45 milli-watts, whilst in sleep mode they consume 150 and 180 micro-watts respectively. Thus, the scanning process consumes the most power. This is true for all RFID readers in Table I.

Now consider the energy consumed by an RFID reader to read one tag. The energy consumed is proportional to a reader’s scanning duration, and is dependent on the time it takes a tag to transmit its ID. In other words,

\[ T_{ID} = \frac{ID}{data\_rate} \tag{1} \]

where ID is the identification code in bits and data_rate is the tag’s data rate in bits per second. Taking the SkyeModule M1-Mini [33] as an example, which is capable of transmitting at 26 kbps and 106 kbps, the scanning duration to read one tag is 3.6 and 0.9 milli-seconds respectively.

Then using the scanning delay, we can find the total energy consumed using the following formula,

\[ E = P \times D \tag{2} \]

where \( P = VI \) (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. Note, \( D = T_{ID} \) for a single tag.

Applying Eq. 2, the energy consumed by the SkyeModule M1-Mini to receive 96 bits of ID is around 648 micro joules at 26 kbps, and 162 micro joules at 106 kbps. Similarly, for the SkyeModule M1, the energy consumed when scanning a single tag is around 1188 micro-joules at 26 kbps and 297 micro-joules at 106 kbps.

We now consider the amount of energy consumed by a sensor node to transmit/receive data. Table II details the power consumption of existing sensor nodes. In order to compare the energy consumed by a sensor node and an RFID reader, we evaluate the energy consumed by a mote when transmitting and receiving 96 bits of data in a noise free channel. We will use the Mica2Dot as an example. The power consumed by a Mica2Dot in reception and transmission is 27 and 52 milli-watts respectively. Its transceiver is capable of transmitting at 38.4 kbps. Therefore, using Eq. 1 and 2, the energy consumed to receive 96 bits of data is 67.5 micro-joules, and to transmit the same amount of data takes 130 micro-joules. On the other hand, the SkyeTek RFID readers consume energy ranging from 162 to 1188 micro-joules when scanning for a single 96-bits tag. Therefore, the energy expended by an RFID reader in scan mode is higher compared to the Mica2Dot during transmission and reception.

From the above analysis, we can see that reading just one tag consumes a significant amount of energy. In practice, we will have to consider multiple tags and the energy consumed by tag reading protocols to read them. Indeed, in Section VII, we showed that with increasing tags, a sensor node using conventional Pure/Slotted Aloha consumes a large amount of energy, thus depleting its battery quickly. In contrast, a sensor node using Aloha variants with the fast mode feature is able to read a large number of tags. Hence, the choice of tag reading protocol determines how much energy can be used by a sensor node for reading tag, and how much is used for communications. In this respect, given the goal of this paper is to quantify the energy consumption of tag reading protocols and the maximum number of tags a sensor node can read, our results will be useful to application designers wanting to budget the use of a sensor node’s battery.

In the sections to follow, we first present our system model and research methodology before deriving the equations necessary to quantify the energy consumption of each tag reading protocol of interest.

III. RELATED WORK

To date, only EM Microelectronic [20] has analyzed and compared the reading delay of six Pure Aloha variants. Our work extends upon theirs in the following manner. First, we provide a detailed comparison that includes Slotted Aloha variants. Second, we analyze the energy consumption in every contention phase. Lastly, we provide a theoretical analysis of both Pure and Slotted Aloha based tag reading variants. Apart from [20], none have considered Pure and Slotted Aloha based tag reading protocols, especially the variants analyzed in this paper. Namboodiri et al. [22] compared the energy efficiency of tree based protocols with their proposed Framed Aloha based protocol. Similarly, Fernandes [8] compared the energy efficiency of tree search algorithms with Framed Aloha variants that use muting and varying frame sizes. The authors of [39] and [15] studied the energy consumed during collision resolution. In [16], the authors evaluated the energy consumption of Framed Slotted Aloha based tag reading protocols. Many works, e.g., [2][1][23][26][9][30][29], have analyzed the performance of Pure and Slotted Aloha protocols in conventional wireless networks. These works however are not focused on energy efficiency. Moreover, they only investigate the delay incurred by competing nodes rather than the delay incurred by the destination/reader to receive/read responses. Lastly, these works do not consider the variants studied in this paper.

This paper therefore aims to fill this gap by presenting a study of twelve variations of Pure and Slotted Aloha protocols. The following section details the parameters used to build the analytical model described in Section VI.

IV. SYSTEM AND ANALYTICAL 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 [33]. This device is chosen because it is specifically designed for sensor networks and has very low energy consumption during scanning compared to other RFID readers, see Table I.

The reader operates from a Lithium rechargeable battery (\( B \)) which has 0.48 Kilo-joules of energy (see Table III in the Appendix). The tag’s data rate is 26 kbps (ISO 15693). The power consumed during scanning (\( \psi \)) is 180 milli-watts.

The communications from a tag to the reader is modeled as a Poisson process [30]. Each tag responds on average \( \lambda \) times per second. The model requires independence among tag transmissions, which is supported by the lack of tag-to-tag communication capabilities. An RFID reader is assumed
to transmit energy until all tags are read. Note, although tags are energized at the same time, our analysis quantifies the energy consumption after the reading process has started, and hence tag responses are independent of the reader. This means, the number of tags that replies in a time interval depends only on their transmission time and are independent of any transmissions that occur in other time intervals.

In a Poisson process, the mean arrival time between tag responses is $\frac{1}{\lambda}$ [30], where $\lambda$ is the average duty cycle of tags. To understand the impact of $\lambda$, we study the energy consumed by anti-collision protocols when $\lambda = 20$ and $\lambda = 50$. These choices are representative values that are sufficiently far apart. Other values exhibit similar trends and do not affect our choices are representative values that are sufficiently far apart.

In our analysis, we omit the delay associated with energizing tags, and also propagation and processing delays. Further, our analysis assumes a noise free channel, i.e., packet losses are due to collisions only. The reader detects collisions when the CRC check fails, and it transmits an ACK only when an ID is received correctly. Finally, tag ID is 112 bits in size, which includes 16-bit s of CRC.

We assume that a tag waits for a duration of $t_{ACK}$ for an ACK after transmitting its ID. Thus, the delay incurred by a tag to transmit its ID and receive an acknowledgment is $T = T_{ID} + t_{ACK}$. From [20], the size of $t_{ACK}$ is six bits, hence $t_{ACK} = 0.23$ms when transmitted at 26 kbps.

We assume tags are passive, have no power source, static, and are used in read-only mode. Further, we assume tags’ antenna is never at 90 degrees with respect to the reader. Otherwise, tags become unreadable, and hence they do not contribute to the offered load. In other words, a reader is unaware of tags that are displaced by 90 degrees since they are not energized to participate in any communications [9][36].

Retransmission delays are bounded to $K$ random slots. According to [30] and [17], $K = 5$ is an optimum value for analysis. Increasing $K$ after protocols have reached maximum throughput results in higher transmission delays [19].

For Pure Aloha with fast mode, a reader sends a quiet command to silence tags temporarily. The quiet command is sent asynchronously, in a separate channel, as soon as an ID transmission is detected [20]. The duration and length of the quiet command, $t_{quiet}$, is 0.19ms and 5-bits respectively. A tag’s ID is validated by verifying its preamble, which consists of a predefined sequence of bits followed by synchronization bits. Based on [20], we conservatively assume that on average a reader sends a quiet command after a duration $T_f = T_{ID}/4$.

For Pure and Slotted Aloha with slow down mode, $\lambda'$ denotes a tag’s new response duty cycle after identification, where $\lambda' = \lambda r$. Here, $r$ is the magnitude by which a tag’s duty cycle is reduced. In our analysis, we assume $r = 3$ [20].

For protocols involving the early-end feature, an idle slot is only active for $t$ time. Following [3], we set $t = T_{IP}$, which includes the time required to sense for responses, and transmit SOF and EOF commands.
V. Research Methodology

As discussed in Section II-C, we need to determine the scanning duration or average delay incurred by a reader to read a tag. To do this, we calculate the delay incurred in the following phases, i) success, when tags are read successfully, ii) collision, due to simultaneous tags responses, and iii) idle listening, where the reader receives no responses. The delay in each phase is then multiplied by the scanning power to derive the energy consumption, and the battery lifetime of an RFID-enhanced sensor node.

To calculate a node’s battery lifetime, we evaluate the average number of tags a given battery can read in its lifetime. This can be determined by dividing the available battery energy with the average energy consumed to read a tag.

\[ N_p = \frac{B}{E} \]  

where \( B \) (Joules) is the capacity of a given battery, \( E = \psi D \) (Joules) is the average energy consumed to read a tag, \( \psi \) (Watts) is the power used during scanning, and \( D \) (seconds) is the average delay to read a tag from \( n \) tags.

Another important evaluation is the amount of energy wasted while reading \( n \) tags. We first compute the number of tags a battery can read in ideal conditions and then use the result to derive the battery wastage during tag reading. Under ideal conditions, i.e., instantaneous tag response and no collisions, a battery can read \( N_{\text{Ideal}} \) number of tags in its lifetime. Consequently,

\[ N_{\text{Ideal}} = \frac{B}{E_{\text{single-tag}}} \]  

where \( E_{\text{single-tag}} = \psi / T \) (Joules) is the energy consumed to read a tag. Subtracting Eq. 3 from 4 gives us the total number of transmissions which resulted in collisions and idle listening, so called “wasted” transmission opportunities,

\[ N_{\text{waste}} = N_{\text{Ideal}} - N_p \]  

Inserting Eq. 3 and 4 into 5, simplifying, and multiplying both sides by \( T \), we get,

\[ E_{\text{single-tag}} N_{\text{waste}} = B \left( 1 - \frac{T}{D} \right) \]  

The LHS of Eq. 6 gives us the average battery energy wasted \( B_{\text{waste}} \) (Joules) during tag identification. We can rewrite Eq. 6 to obtain,

\[ B_{\text{waste}} = B \left( 1 - \frac{T}{D} \right) \]  

With Eq. 2, 3 and 7 in hand, we can proceed to evaluate the energy efficiency of anti-collision protocols. Notice that the common term is \( D \). In Section VI, we will derive \( D \) for, 1) Pure and Slotted Aloha with and without muting, 2) Pure and Slotted Aloha with slow down mode, 3) Pure Aloha with fast mode; with and without muting, 4) Slotted Aloha with early-end; with and without muting, and 5) Slotted Aloha with early-end; with and without slow down.

After calculating \( D \), and applying Eq. 2, 3 and 7 to each protocol, we compare all protocols according to the following metrics, (i) average energy consumption in each phase of the reading process, (ii) the total energy used to read a set of tags, (iii) estimated battery lifetime, and (iv) the average energy wastage.

VI. Delay Equations

The average delay incurred by a reader to read a tag consists of two components:

1) Arrival delay. When reading starts, each tag transmits after a random delay. Since each tag’s transmission is Poisson distributed, there is a mean delay of \( 1/\lambda \) between consecutive transmissions. This is referred to as the arrival delay [30]. If there are \( n \) tags, then on average each tag takes \( \frac{1}{n\lambda} \) time to transmit its ID for the first time. Thus, for each tag, before it enters into contention, a reader experiences an average arrival delay of \( \frac{1}{n\lambda} \), denoted by \( D_{\text{Arrival}} \). Note, as muting, slow down, and fast mode features are only activated after contention starts, the arrival delay is the same for all protocols, except for those using the early-end feature, where idle slots are closed early.

2) Contention delay. This is the average contention delay incurred by a tag before it is successfully identified.

A. Pure Aloha and Slotted Aloha

We first derive the average delay to read a tag successfully from \( n \) tags. Following that, we evaluate the reader’s idle listening and collision delay.

1) Average delay to read a tag successfully: In [30], the authors presented a Pure and Slotted Aloha model to evaluate the average delay taken by a node to transmit a packet successfully given \( n \) competing users. In RFID systems, tags and the reader are analogous to competing nodes and destination node respectively. Therefore, as per [30], the average delay to transmit a tag ID successfully to a reader is,

\[ D_{\text{Success}} = T \left( 1 + \left( e^{xG} - 1 \right) \alpha \right) \]  

where \( x = 2 \) for Pure Aloha, and \( x = 1 \) for Slotted Aloha, \( G \) is the offered load, \( T \) is the message transmission time, and \( K \) is the number of retransmission intervals of duration \( T \) and \( \alpha = \left( \frac{K+1}{2} \right) \). For Pure/Slotted Aloha, \( G = G_A = n\lambda T \) [30]. Thus, the average delay to successfully transmit a tag ID is,

\[ D_{\text{Success,Tag}} = \left( D_{\text{Success}} \right)_{G=G_A} \]  

Equation 9 is derived as follows. For Aloha based protocols, during collisions, tags retransmit after a random time. In [30] and [19]’s analysis, the retransmission time is divided into \( K \) slots of duration \( T \), which is assumed to be uniformly distributed. Each tag retransmits at random during one of the next \( K \) random slots with probability \( 1/K \). This means tags will retransmit within a period of \( K \times T \) after experiencing a collision. On average, a tag will retransmit after a duration of \((K+1)/2\)T = \( \alpha \) slots.

The number of collisions before a tag successfully response is \( e^{xG_A} - 1 \), where \( e^{xG_A} \) denotes the average transmission attempts made before a successful identification. Since each collision is followed by a retransmission, we can calculate the
average delay before a successful tag response as \( (e^{xG_A} - 1)a \), followed by a single successful transmission of duration \( T \). In total, the average delay a tag takes to transmit its ID successfully to the reader is \( (e^{xG_A} - 1)aT + T = D_{\text{Success, Tag}} \).

With the contention and arrival delay in hand, the average delay a reader takes to read a tag successfully is,

\[
D_{\text{Success, PS}} = D_{\text{Success, Tag}} + D_{\text{Arrival}} = T \left[ 1 + (e^{xG_A} - 1)a \right] + \frac{1}{n \lambda} \tag{10}
\]

2) Average delay in idle listening: The idle listening delay is the sum of two values: \( D_{\text{Arrival}} \), and the average idle delay experienced by the reader during contention \( D_{\text{Idle, Reader}} \).

To derive \( D_{\text{Idle, Reader}} \), we use the following methodology. As we know, for Pure and Slotted Aloha, if the offered load is \( G_A \), the mean number of successful transmissions out of \( G_A \) is \( G_A e^{-xG_A} \), which corresponds to the throughput of Pure and Slotted Aloha [30]. \( G_A \) in terms of slots is computed as \( G_{\text{slots}} = G_A/T \). Therefore, if the offered load is \( G_{\text{slots}} = G_A/T \), the reader observes \( G_{\text{slots}} e^{-xG_{\text{slots}}} \) collision-free slots. Thus, if we have \( N_{\text{Idle, Tag}} \) slots for which a tag is waiting to transmit, a reader is idle only for \( N_{\text{Idle, Tag}} e^{-xN_{\text{Idle, Tag}}} \) slots. In the following paragraphs, we show how to compute \( N_{\text{Idle, Tag}} \) and \( D_{\text{Idle, Reader}} \).

In Eq. 11, the term \( e^{xG_A} \) denotes the average number of attempts made before a tag is identified. The corresponding average delay for these attempts is,

\[
D_{\text{Attempts, Tag}} = Te^{xG_A} \tag{12}
\]

The average delay incurred by a tag while waiting to transmit is determined by subtracting Eq. 12 from Eq. 9. In other words, \( D_{\text{Success, PS}} - D_{\text{Attempts, Tag}} \). In terms of slots, we have,

\[
N_{\text{Idle, Tag}} = \frac{D_{\text{Success, Tag}} - D_{\text{Attempts, Tag}}}{T} = (e^{xG_A} - 1)\beta \tag{13}
\]

where \( \beta = \frac{K-1}{T} \). Eq. 14 can also be interpreted as the number of slots where a reader observes no response, so called idle slots. Therefore, we have,

\[
D_{\text{Idle, Reader}} = TN_{\text{Idle, Tag}} e^{-xN_{\text{Idle, Tag}}} \tag{15}
\]

Finally, the average delay due to idle listening is,

\[
D_{\text{Idle, PS}} = D_{\text{Idle, Reader}} + D_{\text{Arrival}} = T \left[ (e^{xG_A} - 1)\beta e^{-x(e^{xG_A}-1)\beta} \right] + \frac{1}{n \lambda} \tag{16}
\]

Note, we use the same methodology to derive the idle listening delay of all protocols of interest.

3) Average delay in collisions: The average delay experienced by a reader due to collisions is,

\[
D_{\text{Collisions, PS}} = D_{\text{Success, PS}} - D_{\text{Idle, PS}} - T \tag{18}
\]

For each of the subsequent protocols, the average delay due to collisions is evaluated using Eq. 18, hence are omitted from discussion.

B. Pure and Slotted Aloha with Muting

When muting is used, the number of tags in a reader’s interrogation zone becomes smaller after each successive identification, and in turn reduces the offered load. If \( i \) out of \( n \) is the number of tags which are identified and then muted by the reader, then the offered load due to the remaining tags is given by,

\[
G_A(n-i) = (n-i)\lambda T \tag{19}
\]

As the number of muted tags increases from \( i = 0, 1, 2, 3, ..., n \), the offered load reduces to \( G_A(n), G_A(n-1), G_A(n-2), G_A(n-3), ..., G_A(0) \).

Therefore, the average offered load to the reader for Pure/Slotted Aloha with muting, \( G_B \), is given by,

\[
G_B = \lambda T \frac{\sum_{i=0}^{n-1} (n-i)}{n} \tag{20}
\]

Inserting \( G_B \) from Eq. 20 into Eq. 11, the average delay to read a tag using Pure/Slotted Aloha with muting is,

\[
D_{\text{Success, PS, Mute}} = \{D_{\text{Success, PS}}\}_{G_A=G_B} \tag{21}
\]

C. Pure and Slotted Aloha with Slow Down

When slow down is used, the duty cycle or mean transmission by a tag is reduced to \( \lambda' < \lambda \). Since \( \lambda \) is directly proportional to the offered load, slowed down tags contribute with a lower load compared to the remaining tags. Thus, in order to formulate the average delay of a tag with slow down mode, we need to calculate the offered load experienced by a reader with varying duty cycles. If there are \( j \) identified or slowed down tags, then the offered load due to these tags is,

\[
G_1 = j\lambda' T \tag{22}
\]

The remaining \( (n-j) \) tags will have an offered load equal to,

\[
G_2 = (n-j)\lambda T \tag{23}
\]

The combined offered load to the reader is then \( G_{\text{Tot}} = G_1 + G_2 \). In other words,

\[
G_{\text{Tot}} = j\lambda' T + (n-j)\lambda T \tag{24}
\]

\[
= T (j \lambda' + (n-j) \lambda) \tag{25}
\]

With each identified tag, the offered load reduces. This is represented in Eq. 27.

\[
G_C = \frac{\sum_{j=0}^{n-1} G_{\text{Tot}}}{n} = T \frac{\sum_{j=0}^{n-1} ((n-j) \lambda + j \lambda')}{n} \tag{26}
\]

In Eq. 27, \( \lambda' = \lambda \) indicates there is no change in a tag’s duty cycle after identification. In that case, Eq. 27 reduces to \( G_C = n \lambda T \), which is the same as \( G_A \) for Pure and Slotted Aloha without slow down. On the other hand, if \( \lambda' = 0 \) then Eq. 27 reduces to \( G_C = \lambda T \sum_{j=0}^{n-1} (n-j) \), which has the same form as \( G_B \) for Pure and Slotted Aloha with muting; as in Eq. 20 with \( j = i \). Therefore, conventional Pure and Slotted Aloha is a special form of Pure and Slotted Aloha with slow down.
when tags’ duty cycle is unchanged. Similarly, muting is a special form of slow down where tags’ duty cycle is zero.

Lastly, to simplify Eq. 27, \( \lambda' \) can be made an integral fraction of \( \lambda, \lambda' = \lambda/r \), thereby reducing a tag’s duty cycle by a factor of \( r \). In this case, Eq. 27 becomes,

\[
G_C = T\lambda \sum_{j=0}^{n-1} \left( n - j \left( 1 - \frac{1}{r} \right) \right) \frac{1}{n}
\]  

By inserting \( G_A = G_C \) in Eq. 11, we can evaluate the average delay to read a tag successfully using Pure Aloha with slow down mode. Similarly, Pure Aloha and Slotted Aloha with the slow down and muting features can be analyzed using the methodology presented in Section VI-B.

Note that we used an iterative approach to compute the offered load in order to maintain independence among tag transmissions. This is because in practice tags rely on ACK sent by the reader to slow down, and thereby nullify the independence assumption required by the Poisson model.

D. Pure Aloha (Fast Mode)

When fast mode is used, the reader inhibits other tags from transmitting by sending a quiet command in a separate channel after receiving a tag’s preamble successfully. Specifically, the reader spends \( T_f \) time determining whether the preamble is valid before transmitting a quiet command to other tags to stop them from transmitting.

In order to receive a tag ID successfully, a reader must not experience any collisions for a duration of \( T_f \) when receiving. Thus, the probability that no tag transmits in \( T_f \) is\(^1\),

\[
P_s[0, T_f] = \frac{G_D^0 e^{-G_D}}{0!} = e^{-G_D} \tag{29}
\]

Tag responses during \( T_f \) constitute the offered load to the reader. Therefore, the average offered load to the reader for Pure Aloha with fast mode is,

\[
G_D = n\lambda T_f \tag{31}
\]

In order to determine the average delay incurred to read a tag, we also need to determine the average retransmissions made by a tag before it is identified.

Using Eq. 30, the throughput of Pure Aloha with slow down is calculated as,

\[
S = G_D P_s = G_D e^{-G_D} \tag{32}
\]

The mean attempts taken by a tag to transmit its ID successfully is \( G_D/S \) or \( e^{G_D} \). From this, the average delay due to unsuccessful attempts is,

\[
D_{Attempts\_Failed} = T (e^{G_D} - 1) \alpha \tag{34}
\]

\( D_{Attempts\_Failed} \) corresponds to the number of attempts made before a tag manages to transmit its preamble successfully. The delay experienced by a reader to receive preamble correctly is therefore,

\[
D_{Preamble} = T_f + D_{Attempts\_Failed} = T_f + T (e^{G_D} - 1) \alpha \tag{35}
\]

After receiving a tag’s preamble, the reader silences the remaining tags and proceeds to receive the rest of the tag’s ID. The average delay to read a complete tag ID successfully is therefore,

\[
D_{Success\_fast} = D_{Preamble} + (T - T_f) + t_{quiet} \tag{37}
\]

Finally, adding the mean arrival delay experienced by the reader in Eq. 38, we have the average delay to receive a tag ID successfully for Pure Aloha with fast mode,

\[
D_{Success\_fast} = T \left[ 1 + (e^{G_D} - 1) \alpha \right] + \frac{1}{n\lambda} + t_{quiet} \tag{39}
\]

Idle listening delay can be obtained using a similar methodology to Pure/Slotted Aloha in Section VI-A and the final expression is,

\[
D_{Idle\_fast} = T \left[ (e^{G_D} - 1)\beta e^{-((e^{G_D} - 1)\beta)} \right] + \frac{1}{n\lambda} \tag{40}
\]

Finally, the delay due to collisions is computed as

\[
D_{Collisions\_PS} = D_{Success\_fast} - D_{Idle\_fast} - (T + t_{quiet}) \tag{41}
\]

Pure Aloha with fast mode can also include muting. In that case, we use the methodology presented in Section VI-B to analyze its performance.

E. Slotted Aloha Variants with Early End

The key consideration when the early-end feature is used is the reduction in the average delay to read a tag due to the early closure of idle slots. Let \( t < T \) be the duration after which a reader closes a slot if no responses are detected. Then, the average delay to read a tag in Slotted Aloha variants with early-end is,

\[
D_{Success\_E} = \{D_{Success\_PS}\}_{G=G_Y} - (T-t)\{N_{Idle\_PS}\}_{G=G_Y} \tag{42}
\]

where \( D_{Success\_PS} \) is given by Eq. 11. \( N_{Idle\_PS} \) is equal to Eq. 17 divided by \( T \), and \( G_Y = G_A \) for Slotted Aloha with early-end, \( G_B \) for Slotted Aloha with muting and early-end, and \( G_C \) for Slotted Aloha with slow down and early-end.

F. Putting It All Together

We now use Pure and Slotted Aloha without muting to show how Eq. 2, 3 and 8 are used to analyze the energy consumption and battery usage of each protocol of interest. We will use Eq. 2 to evaluate the energy consumption in each anti-collision
process phase. After that, we will use Eq. 3 and 8 to derive each protocol’s battery lifetime and wastage.

For Pure and Slotted Aloha, \(D_{\text{Success,PS}}\) is the average energy consumed to read one tag successfully, \(D_{\text{Collisions,PS}}\) is the average delay due to collisions, and \(D_{\text{Idle,PS}}\) is the average idle listening delay. Using Eq. 2, the energy consumption of each phase is,

\[
E_{\text{Success}} = \psi \times D_{\text{Success,PS}} \\
E_{\text{Collisions}} = \psi \times D_{\text{Collisions,PS}} \\
E_{\text{Idle}} = \psi \times D_{\text{Idle,PS}}
\]

Adding Eq. 44 and 45, we obtain the average energy wasted due to collisions and idle listening,

\[
E_{\text{Waste}} = \psi \times (D_{\text{Collisions,PS}} + D_{\text{Idle,PS}})
\]

To evaluate a reader’s battery lifetime, we insert \(D_{\text{Success,PS}}\) into Eq. 3 and 8 to obtain,

\[
N_{\text{Lifetime,Pure,Aloha}} = \frac{B}{\psi D_{\text{Success,PS}}}
\]

\[
B_{\text{Waste,Pure,Aloha}} = B \left(1 - \frac{T}{D_{\text{Success,PS}}} \right)
\]

For each protocol of interest, we repeat the above procedure to obtain their respective energy consumption equations. The resulting equations are presented in Table VI (see the Appendix).

**VII. RESULTS**

Using equations from Table VI, we compare, i) the average energy consumed to read one tag successfully, ii) the average energy wasted in collisions, iii) the average energy spent in idle listening, iv) battery efficiency, i.e., the number of tags a battery is able to read, and v) battery wastage.

**A. Average Energy Consumed to Read One Tag**

We first compare the energy consumption of Pure Aloha variants. Following that, we present our analysis of Slotted Aloha variants before comparing and contrasting them.

Figure 2 compares Pure Aloha variants. The energy consumption of conventional Pure Aloha is the highest because collisions consume the most energy due to its well known vulnerability period of \(2T\) [9].

Pure with slow down has a lower energy consumption than conventional Pure Aloha. The reason being slow down reduces the offered load to the reader, thereby reducing collisions.

Pure Aloha with muting further reduces the energy consumption of conventional Pure Aloha as muting silences a tag after identification, thereby removing the tag from contributing to the offered load of the system. As a result, muting variants have a lower energy wastage from collisions compared to slow down variants. Further, saturation is largely reduced.

Finally, Pure Aloha variants which employ fast mode achieve the highest energy savings compared to other protocols. This is due to the low energy wastage from collisions since a reader’s vulnerability period is reduced to \(T_f\), which increases system throughput (see Figure 7) and lowers energy consumption.

Figure 3 plots the results for Slotted Aloha variants. Slotted Aloha reduces the vulnerability period to \(T\) [9]. Similar to Pure Aloha, conventional Slotted Aloha shows an exponential rise in energy consumption with increasing number of tags. We see that the energy savings due to muting is higher compared to slow down as muting reduces the offered load significantly to reader by silencing tags, whereas slow down only reduces tags duty cycle.

Slotted Aloha variants with early-end have significantly lower energy consumption compared to other variants, notably when the number of tags is low. This is because less energy is consumed by idle listening; see Section VII-C for details. However, with increasing number of tags, the energy consumption of Slotted Aloha variants with early end gradually approaches variants without early-end support. This is because the probability of idle slots reduces with increasing tags, and hence diminishes the advantages provided by the early-end feature.

We now compare and contrast Pure and Slotted Aloha variants. The energy consumption of both Pure and Slotted Aloha variants, as depicted in Figures 2 and 3, is high when the number of tags is low, but reduces up to a given point with increasing number of tags. After that, the energy consumed starts increasing as the number of tags grows.

The above behavior can be explained by comparing the contention delay shown in Figure 5 with the arrival delay in Figure 4. We see that contention delay rises with increasing number of tags. On the other hand, arrival delay reduces with increasing number of tags. However, when the number of tags is low, the reader incurs a significantly higher arrival delay. Therefore, for low tag numbers, arrival delay constitutes a significant portion of the average delay incurred by a reader. On the other hand, when the number of tags is high, contention delay dominates.

**Fig. 2.** Average energy consumed to read one tag successfully for Pure Aloha variants, \(\lambda = 20, K = 5\), PA = Pure Aloha.

**Fig. 3.** Average energy consumed to read one tag successfully for Slotted Aloha Variants, \(\lambda = 20, K = 5\), SA = Slotted Aloha.

**Fig. 4.** Average Arrival Delay

Figures 6(a) and 6(b) compare Pure and Slotted Aloha protocols with \(\lambda\) values of 20 and 50. From the figures, we observe that Pure Aloha consumes the most energy because of its high vulnerability period. On the other hand, fast mode variants of Pure Aloha conserve a significant amount of energy because of its low vulnerability period. Specifically, Pure Aloha with fast mode and muting has the lowest energy consumption as it further mitigates collisions using muting.

Lastly, Figure 7 compares the throughput characteristics of Pure and Slotted Aloha variants. It can be observed that the
system throughput for Pure Aloha in fast mode is as high as Slotted Aloha variants. In addition, it can be observed that Pure Aloha protocols using the fast mode feature approach the maximum throughput when there is a large number of tags. Therefore, when protocols are operating at their maximum system efficiency, fast mode variants of Pure Aloha operate below their maximum system throughput. This means, given the same number of tags, Pure Aloha variants using fast mode experience more free channel times compared to other protocols, hence tags’ responses are less likely to collide.

### B. Average Energy Wasted in Collisions to Read One Tag

Figure 8(a) and 8(b) plot the average energy wasted due to collisions before a tag is read successfully. We observe that reducing \( \lambda \) significantly lowers energy consumption, especially when the number of tags is high. This is because, a lower value of \( \lambda \) reduces the offered load to the reader. However, when the number of tags is low, a higher energy consumption is observed for low \( \lambda \) values because of higher arrival delays.

Conventional Pure Aloha consumes the highest energy in collisions because of its high vulnerability period. However, Pure Aloha with fast mode and muting has the lowest energy wastage. This is because muting and fast mode both reduce collisions and therefore minimize energy consumption.

For Slotted Aloha variants, it can be observed that early end has no effect on energy wastage from collisions. This is because early ending slots does not reduce collisions. On the other hand, the muting and slow down features do reduce collisions, hence tag reading protocols employing both features achieve better energy efficiency.

Overall, conventional Pure Aloha and Slotted Aloha have the highest energy wastage from collisions, but those with fast mode have the best energy efficiency.

### C. Average Energy Consumed due to Idle Listening

Figures 9(a) and 9(b) show the average energy consumed from idle listening. The early end feature reduces energy consumption in idle listening significantly due to the early closure of idle slots.

Among Pure Aloha variants, conventional Pure Aloha consumes the lowest energy in idle listening. This is because there are the lowest number of idle slots due to a significant load offered by competing tags. On the other hand, Pure Aloha with fast mode consumes the highest energy. It is because, using fast mode, the reader inhibits competing tags to stop transmitting once a successful transmission is detected. This results in significant reduction in vulnerability period as compared to Pure Aloha. Due to this, the offered load to the reader is significant reduced resulting in a larger delay due to idle listening during the collision resolution process.

Similar to fast mode, muting and slow down variants increase energy wastage from idle listening, with fast mode resulting in the highest wastage. This is because the said features reduce the offered load and increase the probability of having idle slots. Hence, the reader is able to save a significant amount of energy due to less collisions albeit with a comparatively small energy wastage from idle listening.

### D. Battery Lifetime

Figures 10(a) and 10(b) show the battery lifetime of each protocol. Recall that the lifetime of a battery is the number of tags it can read when the same set of tags is read repeatedly. Among Pure Aloha variants, those with fast mode have the highest lifetime. On the other hand, conventional Pure Aloha has the worst battery life. The main reason for the performance discrepancy is that the use of fast mode reduces collisions significantly, thereby increasing the “goodput” of the system.

Among Slotted Aloha variants, those with muting and early end have the highest battery lifetime and conventional Slotted Aloha has the lowest lifetime.

Overall, Pure Aloha variants with the fast mode feature have long battery lifetime, in particular the variant incorporating...
both fast mode and muting. On the other hand, conventional Pure and Slotted Aloha have the least battery lifetime.

E. Battery Wastage

Figure 11(a) and 11(b) plot the energy wasted to read a tag successfully. Among Pure Aloha variants, those with fast mode and muting have the lowest battery wastage. For Slotted Aloha variants without early-end, Slotted Aloha with muting has the lowest energy wastage, and conventional Slotted Aloha has the highest wastage from idle listening. When early-end is used, the battery wastage for early-end variants of Slotted Aloha, Slotted Aloha with slow down, and Slotted Aloha with muting start to converge to variants without early-end. Among all Slotted Aloha variants, those incorporating muting and early-end have the lowest battery wastage.

Overall, muting, slow down, early-end and fast mode reduce battery wastage, with early-end having the highest impact when the number of tags is low. However, as the number of tags increases, those with fast mode have the lowest wastage.

VIII. CONCLUSIONS

In this paper, we have analyzed the energy consumption of twelve Aloha variants and determine their suitability for use in RFID-enhanced WSNs. We accurately modeled Aloha variants that use combinations of the early-end, slow-down, fast mode and muting feature. Based on our results, Pure Aloha with fast mode and muting consumes the lowest energy to identify a given number of tags. However, all the protocols studied are in-capable of efficient monitoring, thereby making them unsuitable for use in RFID-enhanced WSNs.

IX. ACKNOWLEDGMENT

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

APPENDIX

Table III summarizes the battery types used by sensor motes and RFID readers designed for WSNs. Table IV summarizes the system model parameters used in the equations of interest. Table V shows the offered load and throughput expression for the twelve protocols analyzed.
(a) \( \lambda = \lambda = \)
20, 50, \( K = K = \)
5

Fig. 11. Battery wasted from collisions and idle listening, PA = Pure Aloha and SA = Slotted Aloha.

### TABLE III
**Battery used in sensor nodes and RFID readers designed for sensor nodes**

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Usage (number of batteries used)</th>
<th>Voltage per battery (V)</th>
<th>Nominal capacity (mAh)</th>
<th>Energy stored (emf x capacity) (watt-hour)</th>
<th>Energy stored = (watt-hour x 3600) (joules)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkaline AA (AM-3P)</td>
<td>Imote sky (2), mica2 (2)</td>
<td>1.5</td>
<td>2870</td>
<td>4.305</td>
<td>15.79 Kilo-joules</td>
</tr>
<tr>
<td>Lithium Ion Rechargeable (CGR18650CF)</td>
<td>IMC9060-G RFID mobile reader from Symbol (3)</td>
<td>3.6</td>
<td>2250</td>
<td>8.1</td>
<td>29.16 Kilo-joules</td>
</tr>
<tr>
<td>Lithium Polymer Rechargeable (UBC008)</td>
<td>Integrated (mica2dot+ Skytek RFID reader (1))</td>
<td>3.7</td>
<td>120</td>
<td>0.442</td>
<td>1.59 Kilo-joules</td>
</tr>
<tr>
<td>Manganese Lithium Rechargeable (ML2020)</td>
<td>SkyeModule M1-Mini (1)</td>
<td>3.0</td>
<td>45</td>
<td>0.135</td>
<td>0.48 Kilo-joules</td>
</tr>
</tbody>
</table>

### TABLE IV
**Parameters Declaration**

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n )</td>
<td>Number of tags</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Mean number tag transmissions per second</td>
</tr>
<tr>
<td>( T )</td>
<td>Time taken by a RFID tag to transmit its ID and CRC</td>
</tr>
<tr>
<td>( t )</td>
<td>Duration after which slot is closed if no response received from tags</td>
</tr>
<tr>
<td>( G )</td>
<td>The offered load</td>
</tr>
<tr>
<td>( B )</td>
<td>Energy stored in a battery</td>
</tr>
<tr>
<td>( \psi )</td>
<td>RFID reader power consumption</td>
</tr>
<tr>
<td>( K )</td>
<td>Number of retransmissions slots of duration ( T )</td>
</tr>
<tr>
<td>( T_f )</td>
<td>Duration after which reader send quiet command in fast mode</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Tags new duty cycle in slow down mode</td>
</tr>
<tr>
<td>( r )</td>
<td>Factor by which tags duty cycle is reduced</td>
</tr>
<tr>
<td>( i )</td>
<td>Number of identified tags which are muted</td>
</tr>
<tr>
<td>( j )</td>
<td>Number of identified tags with reduced duty cycle</td>
</tr>
</tbody>
</table>

### TABLE V
**Offered Load and Throughput of Aloha Variants \( x = 1 \) for slotted Aloha and \( x = 2 \) for Pure Aloha variants.**

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Offered load</th>
<th>Notation</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>i) Pure/Slotted Aloha</td>
<td>( \lambda T ) ( n )</td>
<td>( G_A )</td>
<td>( G_A e^{-\lambda T n} )</td>
</tr>
<tr>
<td>i) Slotted Aloha with Early-End</td>
<td>( \lambda T ) ( n ) ( \frac{(n-1)}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} )</td>
<td>( G_B )</td>
<td>( G_B e^{-\lambda T n} )</td>
</tr>
<tr>
<td>i) Pure/Slotted Aloha with Muting</td>
<td>( \lambda T ) ( n ) ( \frac{(n-1)}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} )</td>
<td>( G_C )</td>
<td>( G_C e^{-\lambda T n} )</td>
</tr>
<tr>
<td>i) Slotted Aloha with Muting and Early-End</td>
<td>( \lambda T ) ( n ) ( \frac{(n-1)}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} )</td>
<td>( G_D )</td>
<td>( G_D e^{-\lambda T n} )</td>
</tr>
<tr>
<td>Pure Aloha with Fast Mode</td>
<td>( \lambda T ) ( n ) ( \frac{(n-1)}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} )</td>
<td>( G_E )</td>
<td>( G_E e^{-\lambda T n} )</td>
</tr>
<tr>
<td>Pure Aloha with Fast Mode and Muting</td>
<td>( \lambda T ) ( n ) ( \frac{(n-1)}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} ) ( \frac{1}{n} )</td>
<td>( G_F )</td>
<td>( G_F e^{-\lambda T n} )</td>
</tr>
</tbody>
</table>

### REFERENCES


TABLE VI

<table>
<thead>
<tr>
<th>Protocol Description</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure/Slotted Aloha Non-Muting, $G = G_A$</td>
<td>$E_{\text{Success}}^\psi = \psi T \left( 1 + \left( e^{G - 1} - 1 \right) \alpha + \frac{1}{\pi T} \right)$</td>
</tr>
<tr>
<td>Pure/Slotted Aloha Muting, $G = G_B$</td>
<td>$E_{1\text{idle}}^\psi = \psi T \left( e^{G - 1} - 1 \right) \beta e^{-(e^{G - 1} - 1)\beta} + \frac{1}{\pi T}$</td>
</tr>
<tr>
<td>Pure/Slotted Aloha Slow-Down, $G = G_C$</td>
<td>$E_{\text{Success}}^\psi = \psi T \left( 1 + \left( e^{G - 1} - 1 \right) \alpha + \frac{1}{\pi T} \right)$</td>
</tr>
<tr>
<td>Pure Aloha Fast mode, $G = G_D$</td>
<td>$E_{1\text{idle}}^\psi = \psi T \left( e^{G - 1} - 1 \right) \beta e^{-(e^{G - 1} - 1)\beta} + \frac{1}{\pi T}$</td>
</tr>
<tr>
<td>Pure Aloha with Fast Mode and Muting, $G = G_E$</td>
<td>$E_{\text{Success}}^\psi = \psi T \left( 1 + \left( e^{G - 1} - 1 \right) \alpha + \frac{1}{\pi T} \right)$</td>
</tr>
<tr>
<td>Pure Aloha with Fast Mode and Slow down, $G = G_F$</td>
<td>$E_{1\text{idle}}^\psi = \psi T \left( e^{G - 1} - 1 \right) \beta e^{-(e^{G - 1} - 1)\beta} + \frac{1}{\pi T}$</td>
</tr>
<tr>
<td>Slotted Aloha with Early End, $G = G_A$</td>
<td>$E_{\text{Success}}^\psi = \psi T \left( 1 + \left( e^{G - 1} - 1 \right) \alpha + \frac{1}{\pi T} \right) - (T - t) \left( \left( e^{G - 1} - 1 \right) \beta e^{-(e^{G - 1} - 1)\beta} + \frac{1}{\pi T} \right)$</td>
</tr>
<tr>
<td>Slotted Aloha with Early End and Slow Down, $G = G_C$</td>
<td>$E_{1\text{idle}}^\psi = \psi \left( e^{G - 1} - 1 \right) \beta e^{-(e^{G - 1} - 1)\beta} + \frac{1}{\pi T}$</td>
</tr>
</tbody>
</table>

Note: Dividing the above equations by $\psi$ gives the average delay in different anti-collision phases, which can then be used to evaluate battery lifetime $N_\text{Battery Life}$ and wastage $W_\text{Batter}$.


