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# On the optimal configuration of framed slotted ALOHA

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## Abstract

The primary task of RFID readers is to identify multiple objects as quickly and reliably as possible with minimal power consumption and computation. One issue addressed in this study is the manner in which RFID systems adopting the framed slotted ALOHA (FSA) protocol should be configured so that the minimum identification delay can be achieved with a preassigned confidence level. We first formalize two optimization problems associated with the configuration of passive RFID tag identification processes, i.e., the determination of two key parameter values—termination time and frame size. Next, by considering a comparative RFID system, which well approximates the original system, we establish closed-form formulas for the aforementioned parameters. Furthermore, through asymptotic analysis, we investigate the asymptotic behavior of the optimal parameter values as functions of number of tags and confidence level. Through numerical comparisons, we verify the effectiveness of the proposed solutions.

**Keywords:** RFID, Framed slotted ALOHA, Passive RFID tags, Anti-collision protocols

## 1 Introduction

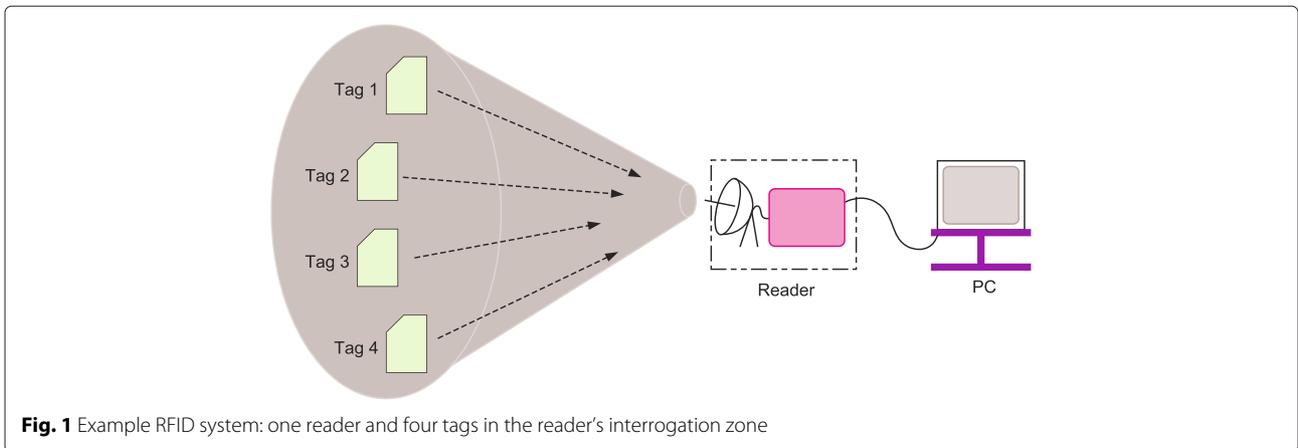
The radio frequency identification (RFID) market was worth US\$8 billion in 2013, up from US\$7 billion in 2012, and grew to US\$9 billion in 2014. The IDTechEx forecast is that it will be worth approximately US\$30 billion in 2024 [1]. In particular, rapid growth is being witnessed in such applications as apparel tagging in the retail sector, RFID-based ticketing in public transport systems, and tagging of animals (such as pets and livestock). It is noteworthy that recent renewed interest in RFID suggests that low-cost passive RFID tags will play an important role in the Internet of Things (IoT)—the network of interconnected things/devices which are embedded with sensors, software, network connectivity and necessary electronics that enables them to collect and exchange data [2–5]. In order for objects to interface with the existing Internet, they must have some means to connect to it: it is envisioned that RFID technology, which provides efficient wireless object identification, will bridge this gap between physical world and the virtual world, although other means are also being used, including old-fashioned barcodes, QR (quick response) codes, and wireless communication technologies such as Bluetooth and WiFi [2–5].

It is worth noting that the primary source of the RFID market growth is passive RFID tags, primarily because of their low-cost, zero maintenance requirements, and ease of large-scale deployment [1, 2, 5–7].

RFID systems usually consist of readers (also called interrogators) and tags (or transponders) (Fig. 1). A typical system has a few readers, either stationary or mobile, and many tags, which are attached to objects such as pallets, cartons, and bottles. A reader communicates with the tags in its wireless range and retrieves the identification (ID) codes that they emit. Among three types of commercially available tags—passive, semi-passive, and active—the passive tags are the least complex and therefore the cheapest. They have no internal power source, but use the electromagnetic field transmitted by a reader to power their internal circuits.

Collisions resulting from simultaneous tag responses are one of the key issues in RFID systems. Collisions lead to losses in bandwidth and energy, and increase tag identification delays. Hence, anti-collision algorithms are required to minimize these collisions. The task of designing anti-collision protocols is rendered more challenging because the tags are required to be simple, cheap, and sufficiently small [7–9]. Among several anti-collision protocols proposed thus far, the framed slotted ALOHA

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**Fig. 1** Example RFID system: one reader and four tags in the reader’s interrogation zone

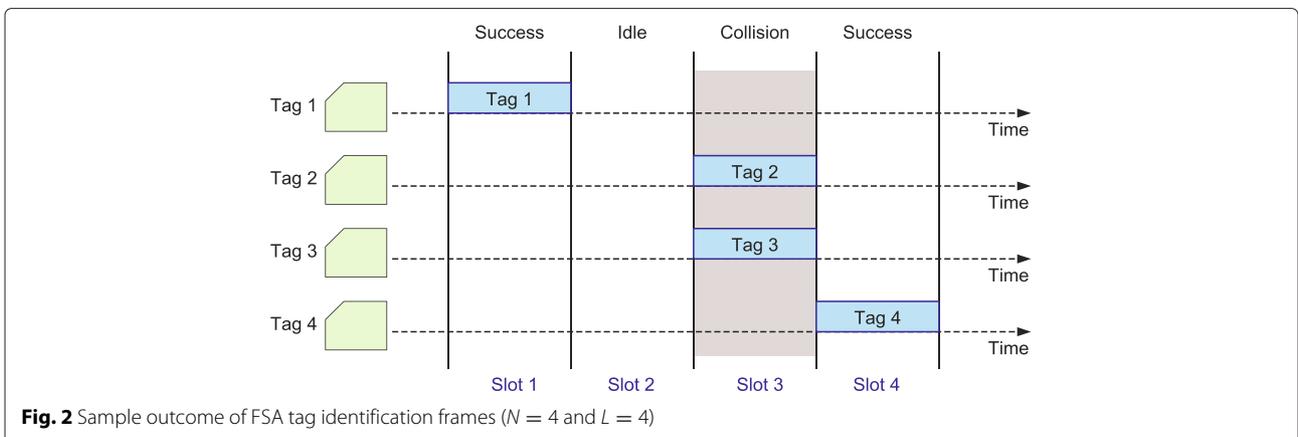
(FSA) protocol is the most widely used owing to its performance and simple implementation [6–11]. For example, RFID tags of Type A of ISO/IEC 18000-6 and 13.56 MHz ISM band EPC Class 1 use the FSA protocol, and Type B of ISO/IEC 18000-6 and 900 MHz EPC Class 0 use the binary search protocol [6, 10, 12].

Consider a passive RFID tag identification process with  $N$  passive tags in the reader’s interrogation zone. The overall tag-reading procedure can be outlined as follows [6, 9–11, 13, 14]. At the beginning of each FSA frame, the frame size, i.e., the number of time slots,  $L$ , for the upcoming FSA frame is broadcast to the tags, and during the reading frame every tag transmits its ID in the randomly chosen time slot. Meanwhile, the reader retrieves the IDs that are successfully transmitted by tags while collecting statistics on the number of slots filled with zero, one, or multiple tag responses; a slot with multiple tag responses implies a collision within the slot (see Fig. 2). The tag reading procedure is repeated frame to frame in the same manner until the reader terminates the process.

Basically, RFID readers are required to identify multiple objects as *quickly and reliably* as possible, with

minimal power consumption and computation. These performance requirements can be quantified in terms of *identification delay* and *confidence level*. One issue addressed in this study is the manner in which RFID systems adopting the FSA protocol should be configured so that the minimum identification delay can be achieved, while all the tags in the reader’s interrogation zone can be identified with a probability no lower than a given confidence level  $\alpha$  (this probability is hereafter referred to as the *probability of successful identification*). For instance, a confidence level of  $\alpha = 0.99$  implies that, if the tag reading procedure is carried out 100 times, then the reader is required to successfully identify all the tags in its interrogation zone, at least in 99 cases, on average.

Formally, we consider two problems associated with the configuration of tag identification processes. The first problem is to determine the so called *termination time*,  $T_\alpha$ , for given number of tags  $N$ , frame size  $L$ , and confidence level  $\alpha$ . We need to find an appropriate value of  $T_\alpha$  such that when the process terminates at the end of the  $T_\alpha^{th}$  frame, the probability of successful identification is no lower than a given confidence level  $\alpha$ . Once



**Fig. 2** Sample outcome of FSA tag identification frames ( $N = 4$  and  $L = 4$ )

$T_\alpha$  is determined for a given frame size  $L$ , the identification delay  $\tau_\alpha$  can be computed as  $\tau_\alpha = L \times T_\alpha$ . Because  $T_\alpha$  and  $\tau_\alpha$  are functions of  $L$ , the second problem can be defined as determining the optimal frame size  $L_{opt}$  that minimizes  $\tau_\alpha$ .

To the best of our knowledge, no closed-form solution to the two foregoing problems is currently available, primarily because closed-form expressions for parameters  $T_\alpha$  and  $L_{opt}$  do not exist, and they can be computed numerically only for small values of  $N$ . In this study, by considering a comparative (imaginary) RFID system which well-approximates the original system, and for which closed-form expressions for the aforementioned parameters are available, we establish closed-form formulas for the termination time, identification delay, and optimal frame sizes. Furthermore, through asymptotic analysis, we derive concise formulas and show how the optimal parameter values roughly behave as functions of number of tags  $N$  and confidence level  $\alpha$ .

In reality, the number of tags  $N$  is unknown to the reader and the reader should estimate it using an appropriate tag estimation function, utilizing the (aforementioned) collected statistics at the end of each frame. The tag estimate, namely  $\tilde{N}$ , is again utilized in computing the appropriate frame sizes to be used for the subsequent frames. In this scenario, frame size  $L$  is adjusted according to  $\tilde{N}$  at appropriate time instances (e.g., on a frame-by-frame basis) during the identification process. Consequently, the so-called dynamic FSA (DFSA) protocol [6, 7, 15–17] is more realistic than FSA. However, in this work, we assume that the frame size is fixed throughout the identification process in order to facilitate our discussion, because our interest is focused primarily on the optimal parameter configuration of the FSA protocol for a given  $N$ , i.e., we consider the situation after  $N$  or  $\tilde{N}$  is determined. In addition, we assume that each tag transmits its ID once every frame, regardless of whether the previous transmissions were successful; i.e., the muting function [6, 7] is not available. Therefore, the results herein are not restricted only to the FSA protocol.

The rest of this paper is organized as follows. Two problems associated with the RFID tag identification processes are formulated in the next section. In Section 3, we introduce important research results related to our work that were reported in previous studies, and briefly discuss the problems therein. In Section 4, our approach to the solution of the tag identification problems is introduced. In Section 5, we validate the accuracy of the practical formulas based on the proposed solutions through numerical comparisons. In Section 6, we establish concise formulas through asymptotic analysis and investigate the asymptotic behavior of the optimal parameter values as functions of number of tags  $N$  and confidence level  $\alpha$ . Finally, Section 7 concludes the paper.

## 2 Tag identification problems

In this section, we formalize two problems related to the optimal configuration of the FSA protocol for passive RFID tag identification. We consider only the cases where the tags are not informed by the reader about the outcome of each reading frame. Therefore, in the case of multiple reading frames, each tag transmits its ID once every frame regardless of whether the previous transmissions were successful.

Suppose  $N$  tags are present in the interrogation zone. Without loss of generality, we assume that each tag has been assigned a sequential identification number, say, from 1 to  $N$ , for later use. Let  $\mathcal{E}_t$  and  $\mathcal{E}_t^i$  denote the event that all tags are identified through the end of the  $t^{\text{th}}$  reading frame and the event that the tag with a sequential number  $i$  is identified throughout the  $t$  reading frames, respectively. Because  $\mathcal{E}_t = \bigcap_{i=1}^N \mathcal{E}_t^i$ , the probability of successful identification through  $t$  consecutive reading frames, i.e.,  $\mathcal{P}_{id}^t$ , is given by

$$\mathcal{P}_{id}^t \triangleq \mathbf{P}[\mathcal{E}_t] = \mathbf{P}\left[\bigcap_{i=1}^N \mathcal{E}_t^i\right].$$

We first observe that  $\mathcal{P}_{id}^t$  is a non-decreasing function of frame size  $L$ ; i.e., larger FSA frame sizes imply less competition among tags for time slots, but this has a drawback of prolonged identification delay. On the other hand, as we execute more FSA frames for tag identification, the probability of successful identification increases because a larger number of FSA frames implies more chances (time slots) of ID transmission for tags, i.e.,  $\mathcal{P}_{id}^t \leq \mathcal{P}_{id}^{t+1}$ . This inequality also follows from the fact that  $\mathcal{E}_t \subseteq \mathcal{E}_{t+1}$ ,  $t = 1, 2, \dots$ . In other words, the probability of successful identification increases as the tag ID reading process proceeds from frame to frame.

The primary objective of tag readers is to identify all the tags present in the interrogation zone with a probability greater than or equal to a preassigned confidence level  $\alpha$  in the shortest time. Therefore, we first need to know when to terminate the reading process such that the probability of the readers failing to identify all the tags is less than  $1 - \alpha$ . In this respect, the first problem can be stated as follows.

**Basic tag identification problem (BIP)** For a given number of tags  $N$ , FSA frame size  $L$ , and confidence level  $\alpha$ , determine the process termination time  $T_\alpha$  such that

$$\mathcal{P}_{id}^t < \alpha, \quad t < T_\alpha \quad \text{and} \quad \mathcal{P}_{id}^t \geq \alpha, \quad t \geq T_\alpha. \quad (1)$$

Thus,  $T_\alpha$  can be expressed as

$$T_\alpha \triangleq \min \{t = 1, 2, \dots : \mathcal{P}_{id}^t \geq \alpha\}. \quad (2)$$

If we terminate the reading process at the end of the  $T_\alpha^{th}$  frame, the identification delay  $\tau_\alpha$  is given by

$$\tau_\alpha = L \times T_\alpha \quad (\text{in time slots}). \quad (3)$$

It is worthwhile to determine the optimal frame size  $L_{opt}$  that minimizes  $\tau_\alpha$ . The optimization problem associated with the tag identification process can be stated as follows.

**FSA optimization problem (FOP)** For  $N$  tags and a given confidence level  $\alpha$ , determine the optimal frame size  $L_{opt}$  such that the identification delay  $\tau_\alpha$  is minimized.

Therefore, the optimal frame size  $L_{opt}$  and the minimum identification delay  $\tau_\alpha^*$  can be expressed as

$$L_{opt} \triangleq \arg \min_{L=N, N+1, \dots} L \times T_\alpha \quad (4)$$

$$\tau_\alpha^* = (L \times T_\alpha) \Big|_{L=L_{opt}}, \quad (5)$$

where for a function of  $L$ , i.e.,  $f(L)$ ,  $\arg \min_{L=N, N+1, \dots} f(L)$  denotes the value of  $L$  maximizing  $f(L)$  among  $L = N, N+1, \dots$ . Further, we denote the termination time for  $L = L_{opt}$  as  $T_\alpha^*$ .

### 3 Related work

In this section, we discuss some representative past studies on the optimal configuration of the FSA protocol and explain some problems associated with these studies.

Before seeking a straightforward solution for BIP and FOP, we consider the value of  $L$  that maximizes the normalized throughput as a candidate for the optimal frame size. For slotted ALOHA with  $N$  tags and frame size  $L$ , the average throughput  $U$ , i.e., the expected number of tags successfully identified during an FSA frame, is given by

$$U = N \left(1 - \frac{1}{L}\right)^{N-1}$$

and the normalized throughput  $U_{norm}$  is given by

$$U_{norm} = \frac{N}{L} \left(1 - \frac{1}{L}\right)^{N-1}.$$

Normalized throughput  $U_{norm}$  represents the utilization of FSA slots in the identification process and can be interpreted as the probability that a slot has a single transmission during an FSA frame. Normalized throughput is maximized at  $L = N$ .

Floerkemeier [18], Chen et al. [19, 20], and Bueno-Delgado et al. [21] proposed using  $L = N$  as the optimal frame size. Similarly, Huang [22] suggested the formula  $L_{opt} = 1/(1 - e^{2 \ln 2/N})$ . On the other hand, Lee et al. [12] derived the formula  $L_{opt} = 1/(1 - e^{-1/N})$ . It should be noted that all these results have one commonality: they are obtained in terms of normalized throughput or system efficiency and are *not optimal* with

respect to the optimization problem addressed in this work.

Zhen et al. [9] proposed setting the optimal frame size according to

$$L_{opt} = H \cdot N,$$

where  $H$  takes values in  $[1., 1.4]$  and is typically set to 1.4, based on the results of their experiments. The authors of [9] also proposed a simplified method of estimating termination time  $T_\alpha$ , but the definition of  $T_\alpha$  therein is given by

$$T_\alpha \triangleq \min\{t = 1, 2, \dots : \mathbf{P}[\mathcal{E}_t^1] \geq \alpha\},$$

which is quite different from (2) in that the probability of individual successful transmission  $\mathbf{P}[\mathcal{E}_t^1]$  is used instead of  $\mathcal{P}_{id}^t$ . Therefore, we can expect that the value of  $T_\alpha$  obtained according to [9] will be much smaller than the actual value.

On the other hand, Khandelwal et al. [23] proposed using  $L_{opt} = 1.943 \eta \times N$ , where  $\eta = \log(H/N)/\log(1 - 1/N)$  and  $H$  represents the number of slots with no tag response. Vogt [13] provided a frame size table listing recommended values for several ranges of  $N$ , as presented in Table 1, which are supposed to yield lower identification delays for a given tag range. For example, when  $N = 12$ , a frame size of 32 is considered optimal. Kim [24] considered the asymptotic regime, i.e., the case where  $N$  is very large, and derived the formula  $L_{opt} \approx N/\ln 2$  in the context of maximizing the probability of successful identification for a fixed identification delay. On the other hand, in [25], a similar asymptotic result is provided for optimal frame sizes such that the identification delay can be minimized under the constraint that each tag transmits successfully with a probability no lower than a certain value  $\alpha'$ .

**Markov chain (MC) analysis** The problems BIP and FOP can be solved by modeling the tag identification process as a discrete-time Markov chain (DTMC)  $\{X_t, t = 1, 2, \dots\}$ , where  $X_t$  denotes the number of identified tags until the end of  $t^{th}$  frame [13]. We now summarize the approach (for more details, the reader is referred to [13]). The  $(N + 1) \times (N + 1)$  transition matrix  $Q = [q_{ij}]$  ( $i, j = 0, 1, \dots, N$ ), associated with  $\{X_t, t = 1, 2, \dots\}$ , is given by

$$q_{ij} = \begin{cases} 0 & \text{for } j < i \\ \sum_{r=0}^i \mathbf{P}[\mu_1 = r] \binom{i}{r} / \binom{N}{r} & \text{for } j = i \\ \sum_{r=j-i}^j \mathbf{P}[\mu_1 = r] \binom{N-i}{j-i} \binom{i}{r-j+i} / \binom{N}{r} & \text{for } j > i, \end{cases}$$

**Table 1** Frame sizes for tag estimates suggested in [13]

$L$	16	32	64	128	256
Low( $N$ )	1	10	17	51	112
High( $N$ )	9	27	56	129	$\infty$

where  $\mu_1$  is the random variable representing the number of slots occupied by exactly one tag during a reading frame. The probability mass function associated with  $\mu_1$  is given as follows. For  $m = 0, 1, \dots, \min\{L, N\}$ ,

$$\mathbf{P}[\mu_1 = m] = L^{-N} \binom{L}{m} \frac{N!}{(N-m)!} G_{L,N}(m),$$

and

$$G_{L,N}(m) = (L-m)^{N-m} + \sum_{k=1}^{N-m} \left[ (-1)^k k! \binom{L-m}{k} \binom{N-m}{k} \times (L-m-k)^{N-m-k} \right].$$

If we set the row vector  $\mathbf{q}_t = (\mathbf{P}[X_t = 0], \mathbf{P}[X_t = 1], \dots, \mathbf{P}[X_t = N])$ , then we have

$$\mathbf{q}_t = \mathbf{q}_0 \cdot Q^t, \quad t = 0, 1, \dots$$

with  $\mathbf{q}_0 = (1, 0, \dots, 0)$ . Therefore,  $\mathcal{P}_{id}^t$  can be computed as

$$\mathcal{P}_{id}^t = \mathbf{P}[X_t = N] = \mathbf{q}_t(N). \quad (6)$$

The solutions for BIP and FOP are obtained as follows. Suppose there are  $N$  tags and the confidence level is given by  $\alpha$ . For each  $L$  ( $L = N, N+1, \dots$ ), we first compute  $\mathcal{P}_{id}^t$  ( $t = 1, 2, \dots$ ) using (6) and then  $T_\alpha$  and  $\tau_\alpha$  are determined from (2) and (3). The optimal frame size  $L_{opt}$  corresponds to the value of  $L$  that yields the smallest value of  $\tau_\alpha$ . It is noteworthy that although MC analysis provides a means of computing exact values of  $L_{opt}$  and  $T_\alpha$ , the computation is extremely complicated and sometimes intractable for large values of  $N$ .

#### 4 Proposed solutions for the tag identification problems

In this section, we first derive a closed-form solution for  $T_\alpha$  and then proceed to the solution of the optimization problem introduced in Section 2.

The difficulty in obtaining a solution for the optimization problem is because a closed-form expression for the probability of successful identification  $\mathcal{P}_{id}^t$  in general does not exist. The numerical computation of  $\mathcal{P}_{id}^t$  is possible through MC analysis only for some small values of  $N$ . However, we can establish the closed-form expression for the probability of individual successful transmission  $\mathbf{P}[\mathcal{E}_t^1]$ , which is given by

$$\mathbf{P}[\mathcal{E}_t^1] = 1 - (1 - (1 - 1/L)^{N-1})^t.$$

In order to circumvent the difficulty with the computation of  $\mathcal{P}_{id}^t$ , we consider an imaginary RFID system, which operates as follows. For each frame of fixed size  $N$ , distinct time slots are allocated to  $N$  tags in a dedicated fashion and each tag can transmit with probability  $\rho \triangleq (1 - 1/L)^{N-1}$  or can be blocked with probability  $1 - \rho$ .

In this system, the probability that  $N$  tags are successfully identified at the end of  $t^{\text{th}}$  frame, namely  $\tilde{\mathcal{P}}_{id}^t$ , is given by

$$\tilde{\mathcal{P}}_{id}^t = (1 - (1 - \rho)^t)^N = (\mathbf{P}[\mathcal{E}_t^1])^N. \quad (7)$$

It is noteworthy that if we assume that the events  $\{\mathcal{E}_t^i, i = 1, 2, \dots, N\}$  are mutually independent, though this assumption is not generally true, then  $\mathcal{P}_{id}^t = \tilde{\mathcal{P}}_{id}^t$ . In order to examine how close  $\tilde{\mathcal{P}}_{id}^t$  gets to  $\mathcal{P}_{id}^t$ , we compared  $\tilde{\mathcal{P}}_{id}^t$  with  $\mathcal{P}_{id}^t$  for  $N = 4, 8, 16, 32$  (and  $L = 6, 12, 23, 46$ , respectively, according to the asymptotic formula  $L_{opt} = N/\ln 2$  suggested in [24]), as shown in Fig. 3. The exact values of  $\mathcal{P}_{id}^t$  were numerically obtained using the MC analysis described in Section 3. From the numerical comparison results, we can derive the following observations.

- (O1) Overall,  $\tilde{\mathcal{P}}_{id}^t \leq \mathcal{P}_{id}^t$  for  $N = 4, 8, 16, 32$ , and  $t = 1, 2, \dots$
- (O2)  $\tilde{\mathcal{P}}_{id}^t$  approaches  $\mathcal{P}_{id}^t$  very fast as  $t$  (the number of frames read) increases.
- (O3)  $\tilde{\mathcal{P}}_{id}^t$  gets closer to  $\mathcal{P}_{id}^t$  as  $N$  becomes larger.

In this work, we propose using  $\tilde{\mathcal{P}}_{id}^t$  as a replacement of  $\mathcal{P}_{id}^t$  for the solution of BIP and FOP—hereafter, we use the notations  $\tilde{T}_\alpha$  and  $\tilde{L}_{opt}$  for the solutions of (2) and (4) when  $\tilde{\mathcal{P}}_{id}^t$  is used instead of  $\mathcal{P}_{id}^t$ . The observation (O1) has an important implication that it secures the reliability constraint in (1) because  $\alpha \leq \tilde{\mathcal{P}}_{id}^t \leq \mathcal{P}_{id}^t$  for  $t = \tilde{T}_\alpha$ , even if we use  $\tilde{\mathcal{P}}_{id}^t$  instead of  $\mathcal{P}_{id}^t$  in (2) and (4).

The termination time  $\tilde{T}_\alpha$  can be determined by substituting (12) in (2); i.e.,  $\tilde{T}_\alpha$  is the minimum value of  $t$  satisfying

$$(1 - (1 - \rho)^t)^N \geq \alpha;$$

thus we obtain

$$\tilde{T}_\alpha = \lceil \ln(1 - \alpha^{1/N}) / \ln(1 - \rho) \rceil, \quad (8)$$

where the ceiling operator  $\lceil x \rceil$  represents the smallest integer no smaller than  $x$ . Thus, the corresponding identification delay, denoted by  $\tilde{\tau}_\alpha$ , is given by

$$\tilde{\tau}_\alpha = L \lceil \ln(1 - \alpha^{1/N}) / \ln(1 - \rho) \rceil. \quad (9)$$

The optimal frame size  $\tilde{L}_{opt}$  that minimizes  $\tilde{\tau}_\alpha$  can be computed by combining (4) and (8):

$$\tilde{L}_{opt} = \arg \min_{L=N, N+1, \dots} L \lceil \ln(1 - \alpha^{1/N}) / \ln(1 - \rho) \rceil. \quad (10)$$

The optimal termination time  $\tilde{T}_\alpha^*$  and the corresponding minimum identification delay  $\tilde{\tau}_\alpha^*$  can be computed by substituting  $L = \tilde{L}_{opt}$  in (8) and (9), respectively.

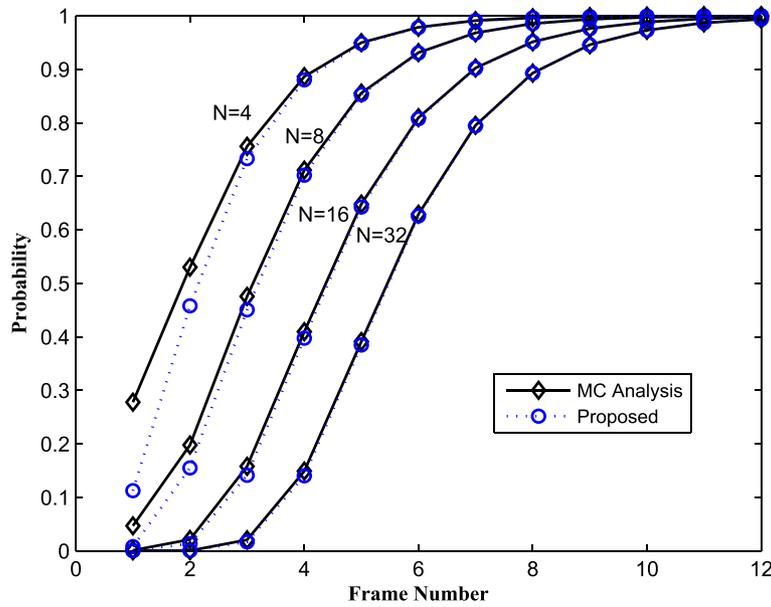


Fig. 3 Probability of successful identification for MC analysis and the proposed approach

### 5 Numerical comparison results

To validate the accuracy of the proposed solutions, we computed termination time  $\tilde{T}_\alpha$  and optimal frame sizes  $\tilde{L}_{opt}$  using our practical formulas (8) and (10) for various values of  $N$  and  $\alpha$ , and attempted to verify that  $\tilde{T}_\alpha$  and  $\tilde{L}_{opt}$  indeed correspond to the solutions of BIP and FOP. The exact values of  $T_\alpha$  and  $L_{opt}$  were computed using the MC method and MATLAB. It should be noted that the computation of exact values is restricted to some small values of  $N$ , because of the arithmetic overflow errors associated with the calculation of  $N!$  (and  $L!$ ) pertaining to the MC analysis.

First, we attempted to show that (8) can be adopted as a solution of BIP. For several values of  $\alpha$  ( $\alpha = 0.9, 0.92, 0.98, 0.995$ ), we computed  $T_\alpha$  according to (8) ( $N = 4, 8, \dots, 24$  and for each  $N$ ,  $L = N, N + 1, \dots, [N/\ln 2] + 7$  with the operator  $[x]$  representing the integer closest to  $x$ ) and compared them with the exact values. Figures 4, 5, 6, and 7 show a comparison of the exact values with those obtained by (8) for  $\alpha = 0.9, 0.92, 0.98, 0.995$ , respectively. They demonstrate that the values obtained using (8) exactly coincide with those using the MC method in most cases. Note that discrepancies between proposed values and exact ones are found only in four cases (out of total 344 cases):  $(N, L) = (4, 9)$ ,  $(12, 16)$ , and  $(24, 33)$  for  $\alpha = 0.9$  (Fig. 4) and  $(N, L) = (16, 24)$  for  $\alpha = 0.92$  (Fig. 5). For instance, in Fig. 4, when  $(N, L) = (4, 9)$ , the proposed value of  $T_\alpha$  is 4 (computed according to (8)) as opposed to the exact value 3 (computed according to the MC analysis). In other words,

concerning the solution of the problem BIP for  $(N, L) = (4, 9)$ , i.e., at least how many reading frames (each frame consisting of nine time slots) need to be executed in order to identify four tags with the probability of failing to identify all the tags no more than 0.1?, the proposed solution suggests four reading frames are required, while the exact value of  $T_\alpha$  is three. Similarly, for the remaining three cases, the proposed values of  $T_\alpha$  are greater than the exact values by 1. These results indicate that very rarely (only in four cases out of total 344 cases in the experiment), the proposed values can differ from the exact ones and the proposed approach tends to slightly overestimate  $T_\alpha$ , as can be expected from the observation (O1) in Section 4. Further, it is noteworthy that discrepancies between proposed values and exact ones disappear very fast as  $\alpha$  increases (e.g., for  $\alpha \geq 0.98$ ). This can be deduced from the fact that a larger value of  $\alpha$  necessitates an increase in  $T_\alpha$ , combined with the observation (O2).

Second, we attempted to show that the solution of FOP can be easily obtained from (10). For  $\alpha = 0.9, 0.92, 0.98$ , and  $N = 8, 10, \dots, 32$ , we computed  $\tilde{L}_{opt}$  according to (10) and compared the results with the exact values of  $L_{opt}$ . Figures 8, 9, and 10 show comparisons of the exact values of  $L_{opt}$  and  $\tilde{T}_\alpha^*$  with those obtained using (8) and (10) (i.e.,  $\tilde{L}_{opt}$  and  $\tilde{T}_\alpha^*$ ) for  $\alpha = 0.9, 0.92, 0.98$ , respectively (in these figures, the left y-axis represents “optimal frame sizes,” while the right y-axis represents “termination time”). Note that the proposed values differ from the exact values only in three cases (out of total 39 cases):  $N = 12, 24$  for  $\alpha = 0.9$  (Fig. 8) and  $N = 16$  for  $\alpha = 0.92$  (Fig. 9) while

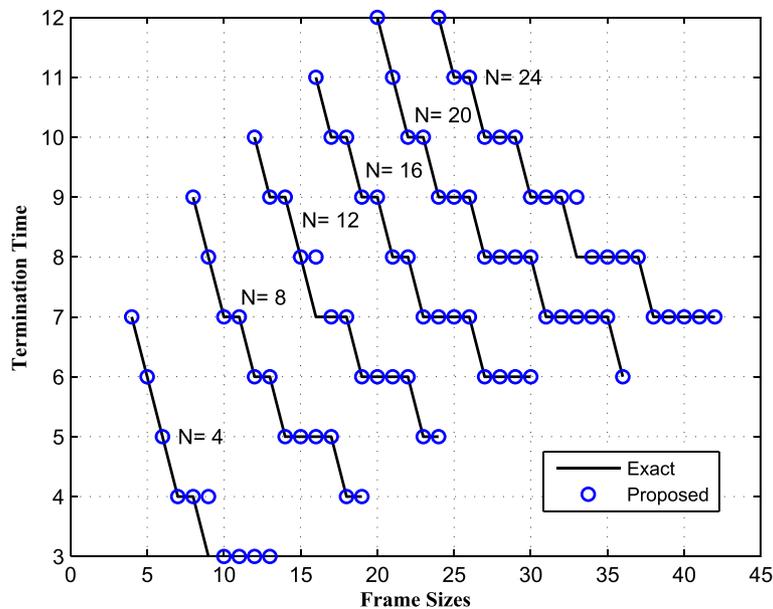


Fig. 4 Termination time for MC analysis and the proposed approach ( $\alpha = 0.9$ )

no discrepancies are found for  $\alpha = 0.98$  (Fig. 10). On the other hand, Figs. 11 and 12 compare the corresponding values of identification delay  $\tau_\alpha$  (i.e.,  $L_{opt} \times T_\alpha^*$  vs.  $\tilde{L}_{opt} \times \tilde{T}_\alpha^*$ ) as well as the values of the probability of successful identification  $\mathcal{P}_{id}^t$ , computed using the MC analysis, for the optimal parameter set  $(L_{opt}, T_\alpha^*)$  and the proposed parameter set  $(\tilde{L}_{opt}, \tilde{T}_\alpha^*)$ , for  $\alpha = 0.9, 0.92$ , respectively (in these figures, the left  $y$ -axis represents “identification delay,”

while the right  $y$ -axis represents “probability of successful identification”). At this time, a question naturally arises: Is it secure to use  $(\tilde{L}_{opt}, \tilde{T}_\alpha^*)$  instead of  $(L_{opt}, T_\alpha^*)$ , with respect to the reliability constraint  $\mathcal{P}_{id}^t \geq \alpha$  in (1)? For instance, when  $N = 12$  and  $\alpha = 0.9$ ,  $(\tilde{L}_{opt}, \tilde{T}_\alpha^*) = (19, 6)$ , while  $(L_{opt}, T_\alpha^*) = (16, 7)$  (Fig. 8). Figures 11 and 12 indicate that, even if  $(\tilde{L}_{opt}, \tilde{T}_\alpha^*) \neq (L_{opt}, T_\alpha^*)$ , the corresponding identification delays for the parameter sets  $(\tilde{L}_{opt}, \tilde{T}_\alpha^*)$  and

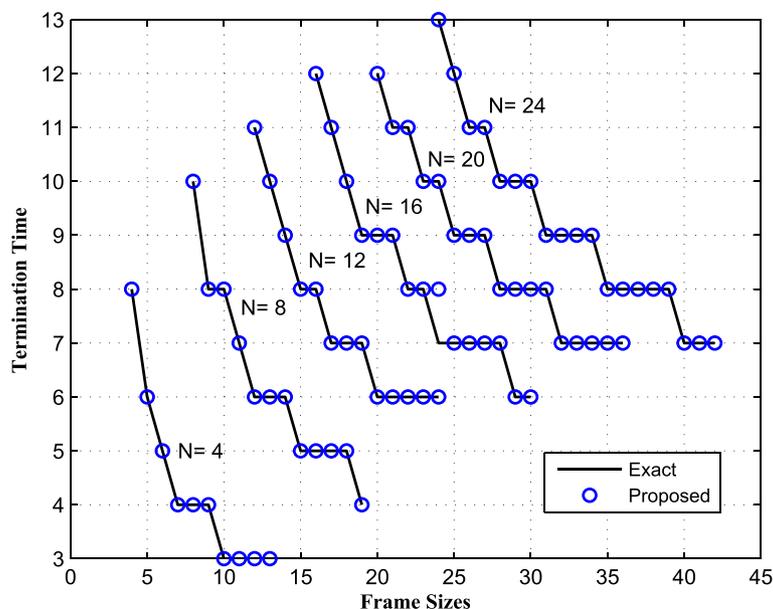
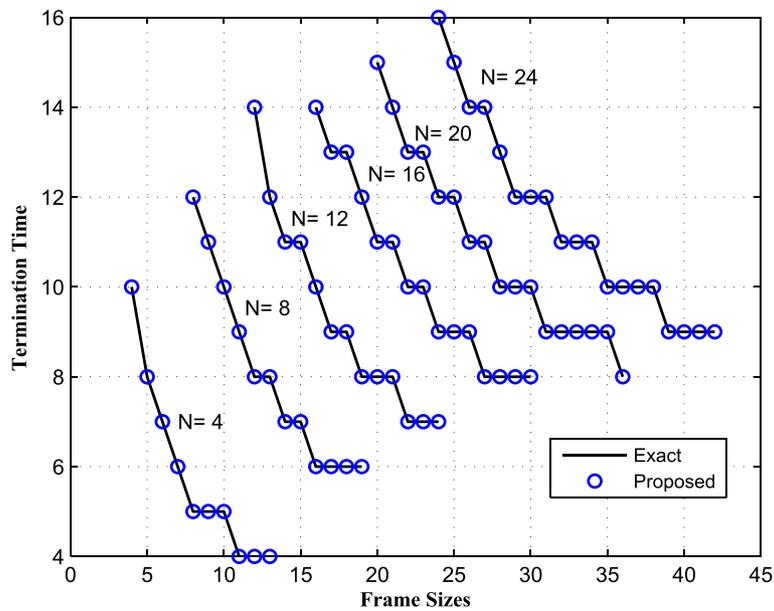


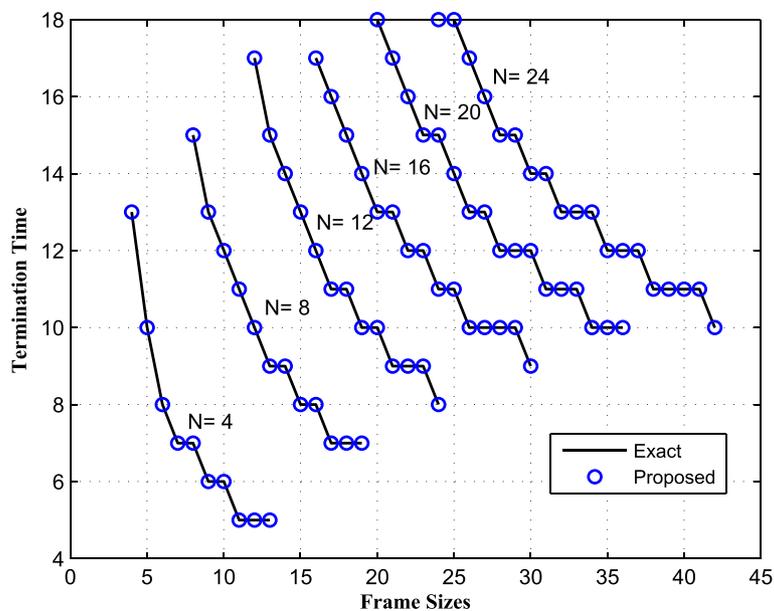
Fig. 5 Termination time for MC analysis and the proposed approach ( $\alpha = 0.92$ )



**Fig. 6** Termination time for MC analysis and the proposed approach ( $\alpha = 0.98$ )

$(L_{opt}, T_{\alpha}^*)$  almost coincide and  $\mathcal{P}_{id}^t$  for  $(\tilde{L}_{opt}, \tilde{T}_{\alpha}^*)$  is slightly greater than that for  $(L_{opt}, T_{\alpha}^*)$  in all the three cases, thereby satisfying the reliability constraint. For instance, when  $N = 12$  and  $\alpha = 0.9$ , the identification delays for  $(\tilde{L}_{opt}, \tilde{T}_{\alpha}^*)$  and  $(L_{opt}, T_{\alpha}^*)$  are 114 and 112 (in time slots), respectively, while the corresponding values of  $\mathcal{P}_{id}^t$  are 0.9078 and 0.9004, respectively (Fig. 11).

In summary, these results indicate that our practical formulas (8) and (10) can be effectively employed as the solutions of BIP and FOP. Very rarely, the formulas (8) and (10) yield parameter values deviating from the optimal values, but still, these values can be safely adopted, producing similar identification delays with a higher level of identification reliability.



**Fig. 7** Termination time for MC analysis and the proposed approach ( $\alpha = 0.995$ )

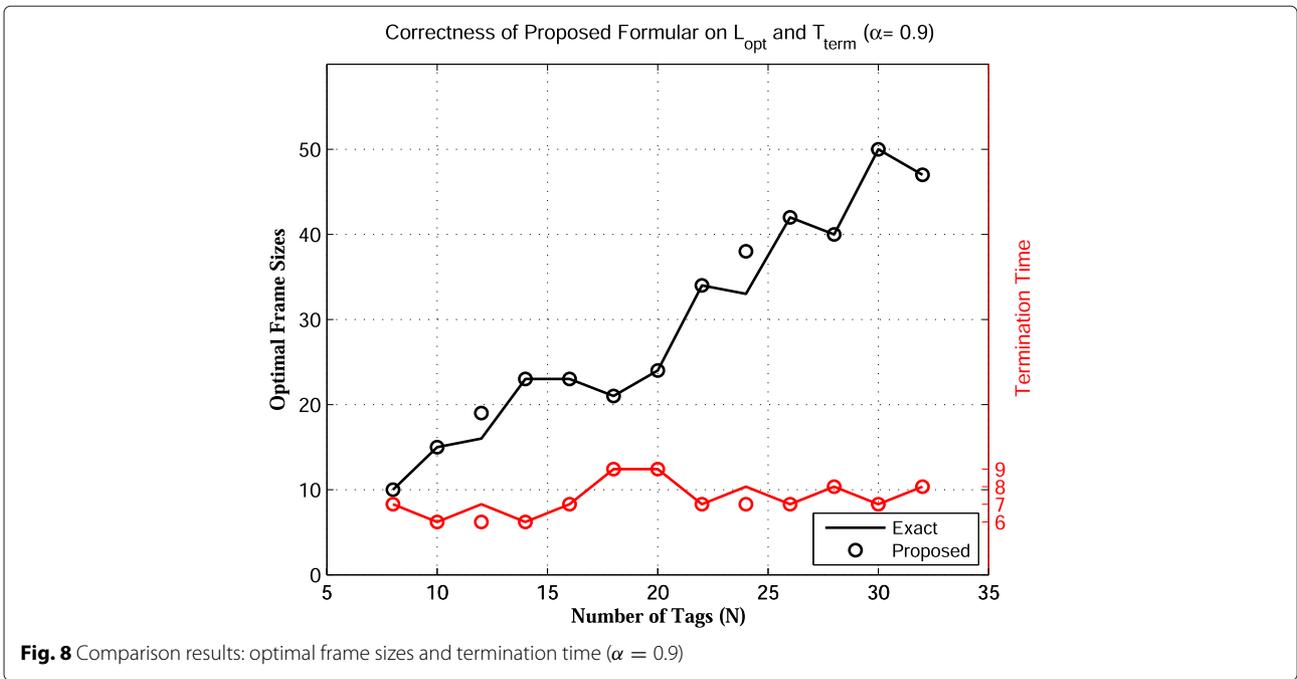


Fig. 8 Comparison results: optimal frame sizes and termination time ( $\alpha = 0.9$ )

### 6 On the asymptotic behavior of optimal frame size and termination time

In this section, we investigate how the optimal frame size and termination time roughly behave as a function of tag number  $N$  and confidence level  $\alpha$ , in the asymptotic regime (i.e., for large  $N$ ), as the formulas (8) and (10) are somewhat complicated. Throughout we assume that  $N$  is large.

Adopting the asymptotic result proposed in [24], for large  $N$ , the optimal frame size, denoted by  $\bar{L}_{opt}$ , is given by

$$\bar{L}_{opt} = \lceil N / \ln 2 \rceil. \tag{11}$$

According to Corollary 2 in [24], the probability of overall transmission failure of a specific tag (i.e.,  $1 - \mathbf{P}[\mathcal{E}_t^1]$ ) is

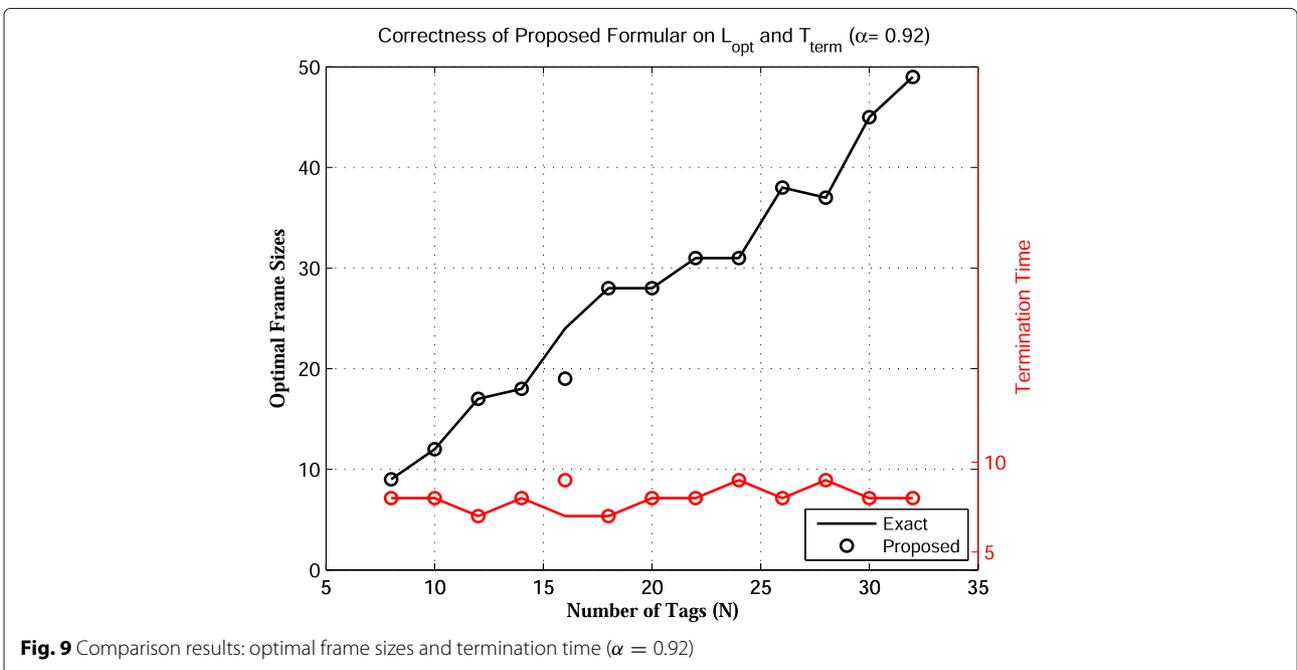


Fig. 9 Comparison results: optimal frame sizes and termination time ( $\alpha = 0.92$ )

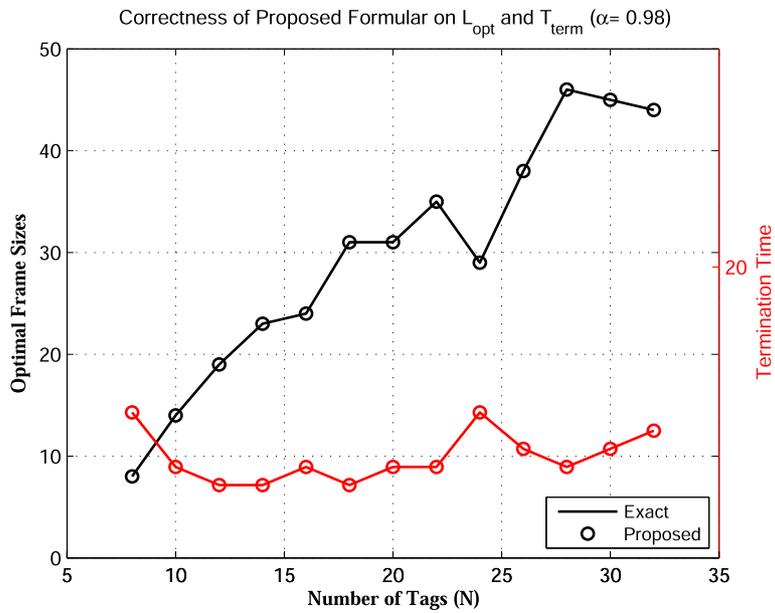


Fig. 10 Comparison results: optimal frame sizes and termination time ( $\alpha = 0.98$ )

reduced by half for every reading frame if the FSA frame sizes are set according to (11), i.e.,

$$\mathbf{P}[\mathcal{E}_t^1] \approx 1 - 2^{-t}, \quad t = 1, 2, \dots$$

Considering again the imaginary RFID system established in Section 4, the probability of successful identification in this system, denoted by  $\bar{\mathcal{P}}_{id}^t$ , for large  $N$ , is given by

$$\bar{\mathcal{P}}_{id}^t \approx (\mathbf{P}[\mathcal{E}_t^1])^N \approx (1 - 2^{-t})^N \tag{12}$$

and the asymptotic termination time  $\bar{T}_\alpha^*$  can be obtained by substituting (12) in (2) so that

$$\begin{aligned} \bar{T}_\alpha^* &= \min \{ t = 1, 2, \dots : (1 - 2^{-t})^N \geq \alpha \} \\ &= \lceil -\log_2 (1 - \alpha^{\frac{1}{N}}) \rceil. \end{aligned} \tag{13}$$

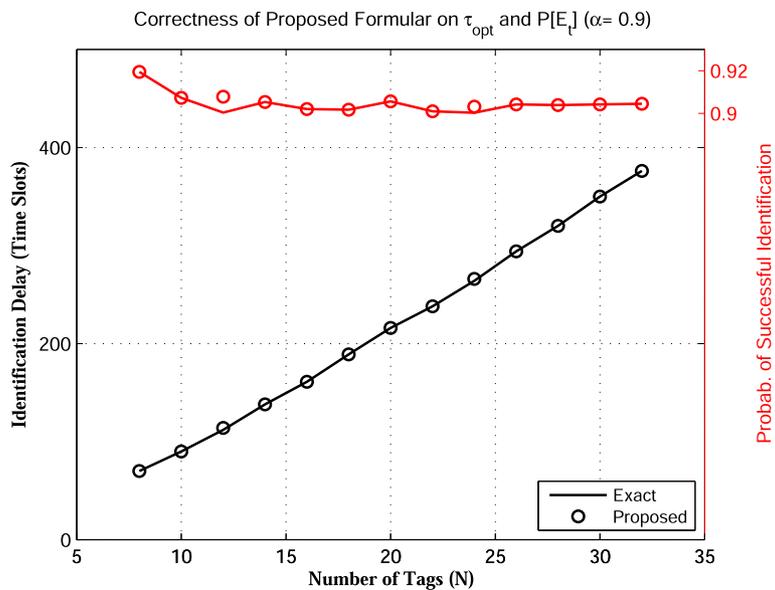
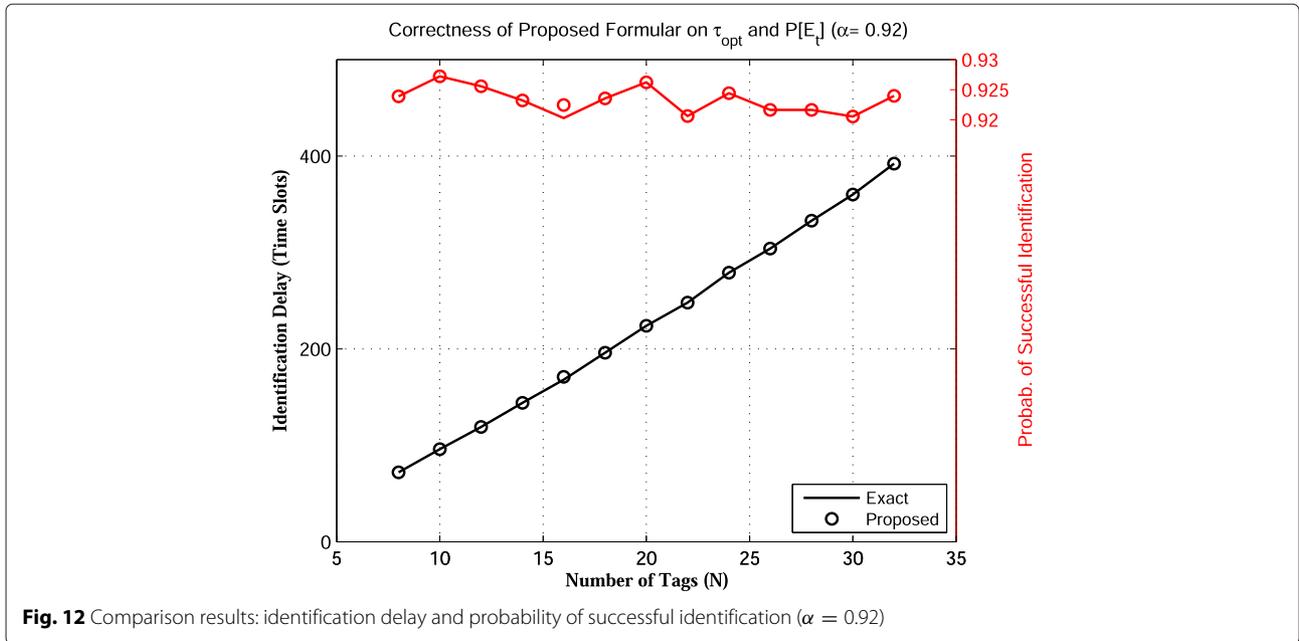


Fig. 11 Comparison results: identification delay and probability of successful identification ( $\alpha = 0.9$ )



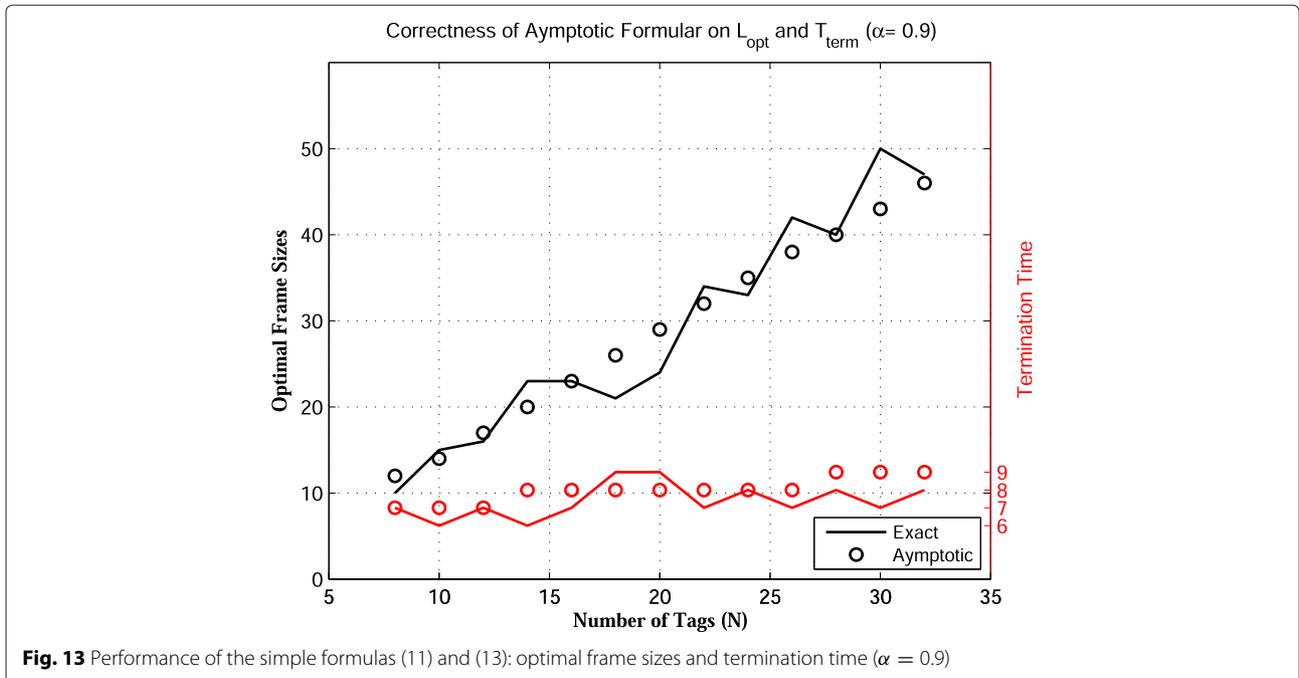
Set  $\epsilon \triangleq 1 - \alpha$ , termed *level of identification failure*. Using the fact that  $\alpha^{1/N} = (1 - \epsilon)^{1/N} \approx 1 - \epsilon/N$  for small  $\epsilon$  by the Taylor-series expansion, we can simplify  $\bar{T}_\alpha^*$  as

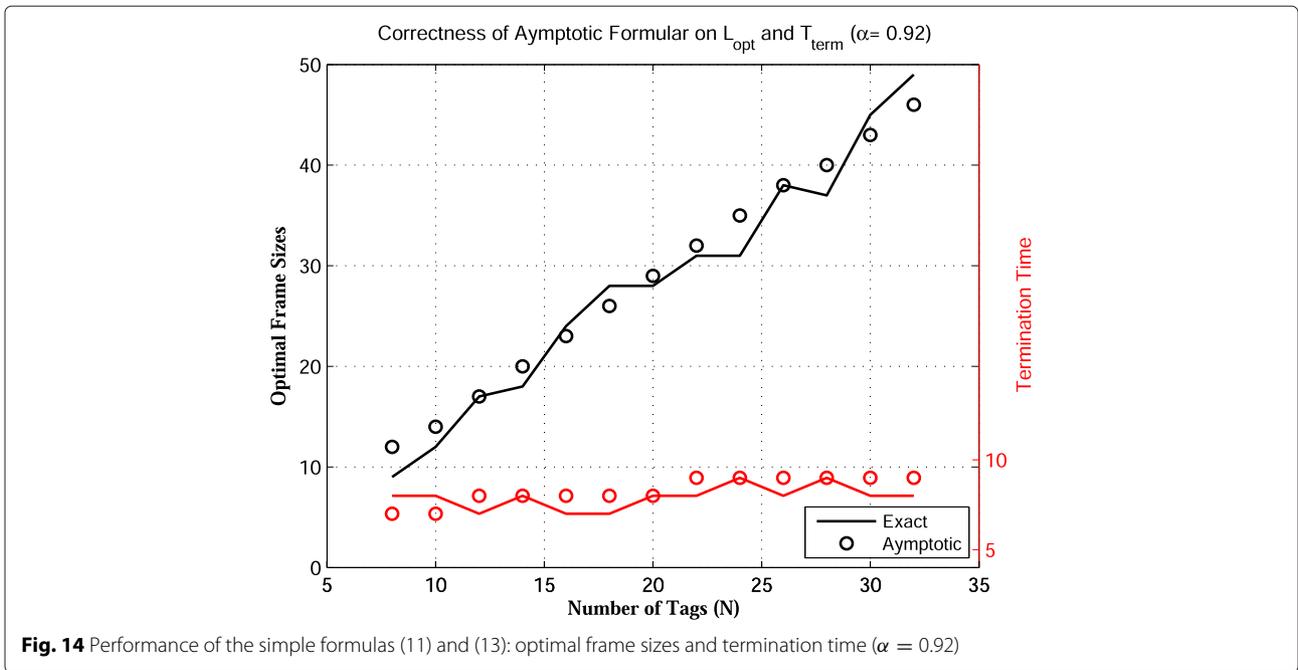
$$\bar{T}_\alpha^* \approx \lceil \log_2 N + \log_2(1/\epsilon) \rceil \quad \text{for } \epsilon \approx 0. \quad (14)$$

From (11) and (14), we can state the following facts on the asymptotic behavior of optimal frame size and termination time.

**Corollary 1** *In the optimal configuration of RFID systems adopting the FSA protocol,*

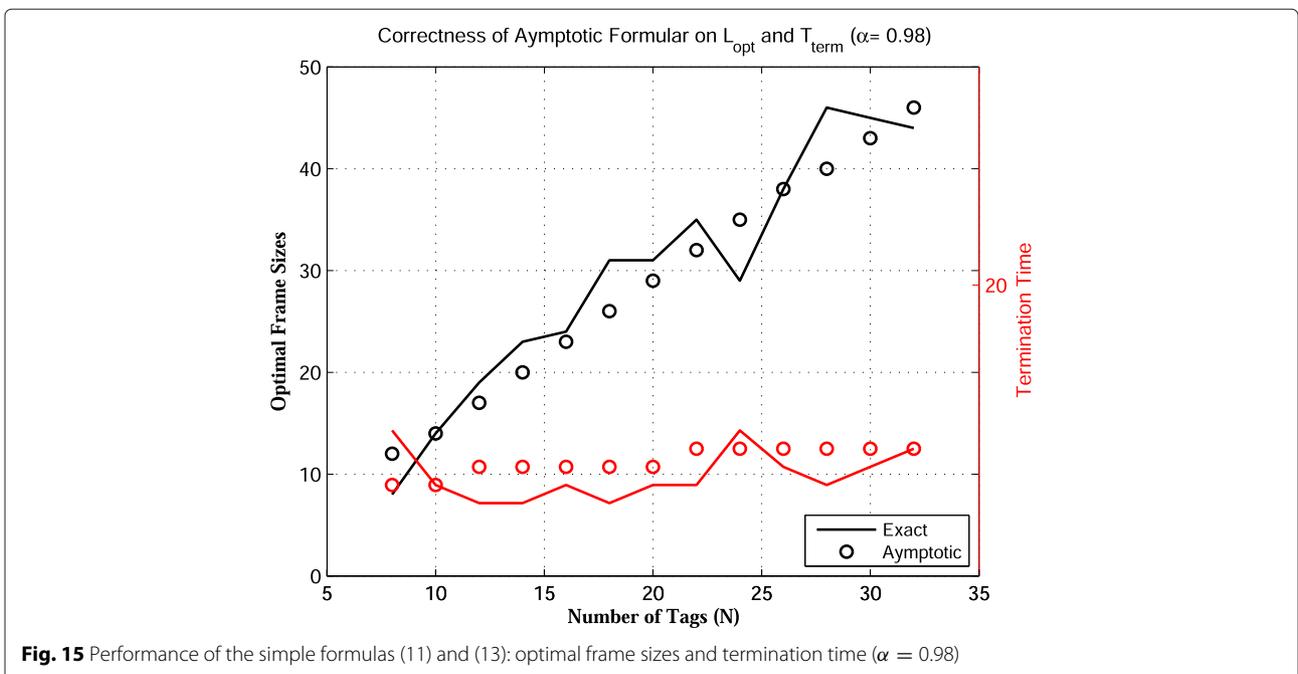
- (i) *the optimal frame size  $L_{opt}$  depends only on  $N$  and increases linearly as a function of  $N$ ;*
- (ii) *the optimal termination time  $T_\alpha^*$  depends on  $N$  and  $\alpha$ , and increases logarithmically either as a function of  $N$  or as a function of  $1/\epsilon$ .*

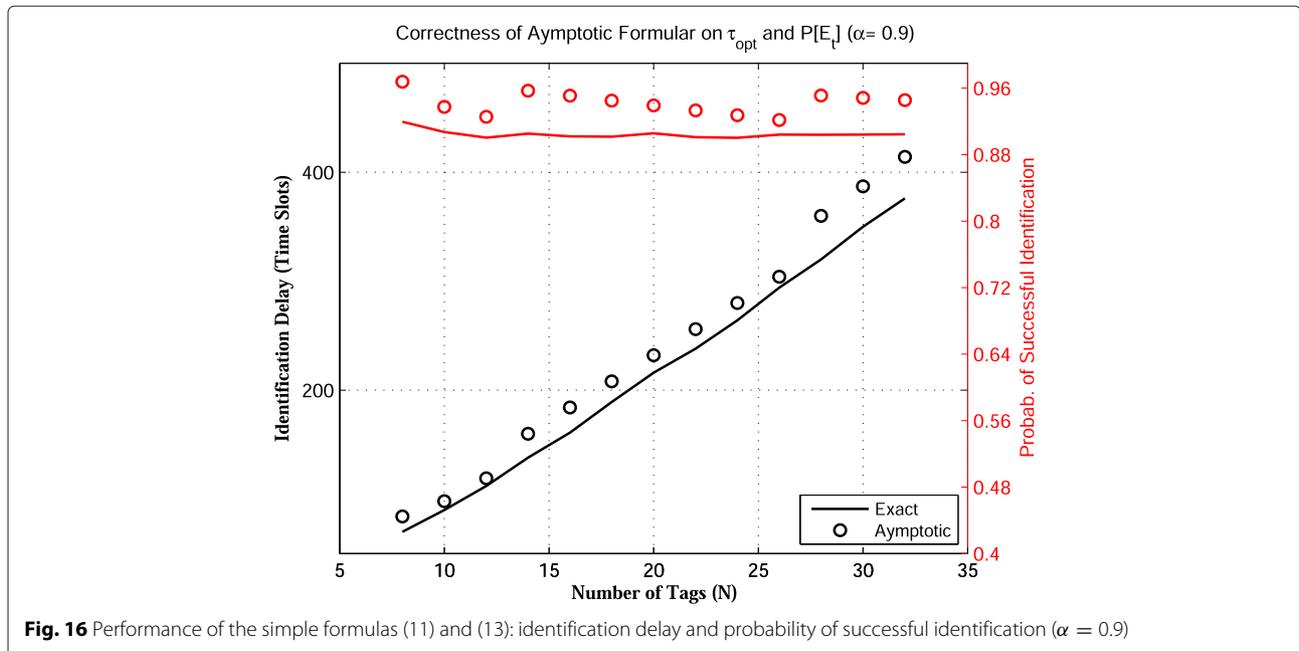




Through numerical comparisons, we examined the effectiveness of the asymptotic formulas (11) and (13) in the optimal configuration of the FSA protocol. Figures 13, 14, and 15 compare  $\bar{L}_{opt}$  and  $\bar{T}_\alpha^*$  with the exact values of  $L_{opt}$  and  $T_\alpha$  ( $N = 8, 10, \dots, 32$ ), for  $\alpha = 0.9, 0.92, 0.98$ , respectively, while Figs. 16, 17, and 18 depict the corresponding values of identification delay

$\tau_\alpha$  and the probability of successful identification  $\mathcal{P}_{id}^t$  (computed using the MC analysis) for the asymptotically optimal parameter set  $(\bar{L}_{opt}, \bar{T}_\alpha^*)$  and the optimal parameter set  $(L_{opt}, T_\alpha^*)$ , for  $\alpha = 0.9, 0.92, 0.98$ , respectively. We can observe that  $(\bar{L}_{opt}, \bar{T}_\alpha^*)$  well approximates  $(L_{opt}, T_\alpha^*)$ , while the values of  $\tau_\alpha$  and  $\mathcal{P}_{id}^t$  for  $(\bar{L}_{opt}, \bar{T}_\alpha^*)$  are slightly greater than the exact values (i.e., these parameter values



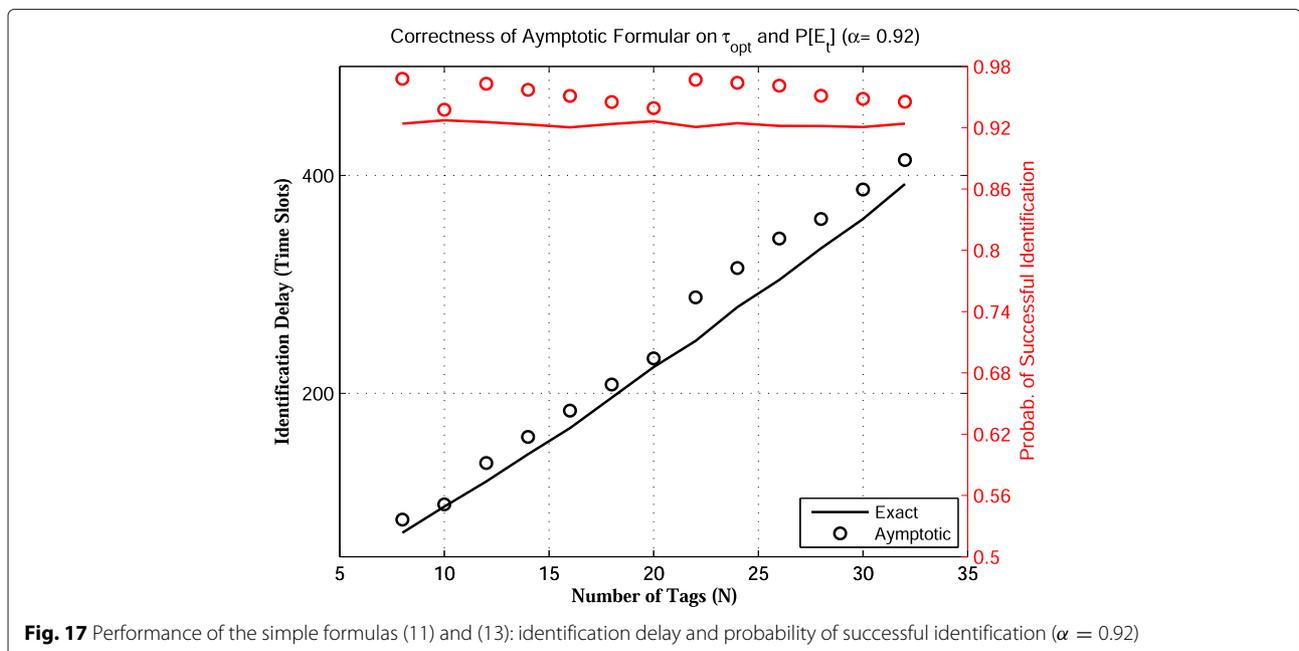


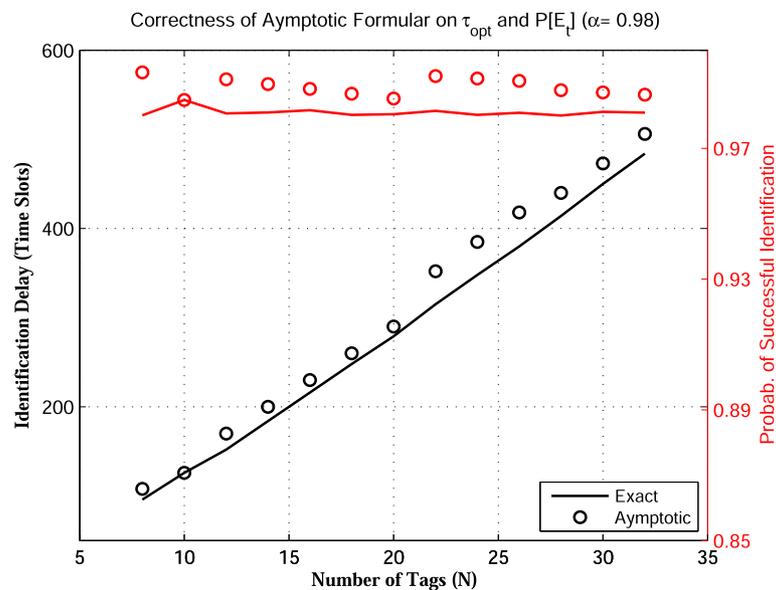
are safe to use because the reliability constraint is always satisfied).

In summary, these results suggest that the simple formulas (11) and (13) (or (14)) can be employed effectively in determining the optimal values of frame sizes and termination time associated with the FSA protocol. It is worth noting that  $\bar{P}_{id}^t$  given by (12) slightly underestimates the probability of successful identification, thereby resulting in longer identification delays; however, the differences are not significant.

### 7 Conclusions

In this paper, we discussed several problems regarding the optimal configuration of the FSA protocol for passive RFID tag identification; the performance requirement is to minimize the identification delay while meeting a preassigned confidence level. We first formalized two problems concerning the optimal configuration: (1) the determination of the appropriate termination time under the constraint that the probability of successful identification should be no lower than a given confidence level





**Fig. 18** Performance of the simple formulas (11) and (13): identification delay and probability of successful identification ( $\alpha = 0.98$ )

$\alpha$ , and (2) the determination of optimal frame sizes for the minimal identification delay. By considering a comparative RFID system, which turned out to be a fine approximation of the original system, we derived closed-form formulas for determining the optimal values of the key parameters. Additionally, through asymptotic analysis, we obtained concise formulas which demonstrate: (1) the optimal frame size increases linearly as a function of number of tags, and (2) the optimal termination time increases logarithmically, either as a function of number of tags or as a function of  $1/\epsilon$  (where  $\epsilon$  stands for level of identification failure).

#### Competing interests

The author declares that he has no competing interests.

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