Early Frame Break Policy for ALOHA-Based RFID Systems

Petar Šolić, *Member, IEEE*, Joško Radić, *Member, IEEE*, and Nikola Rožić, *Life Senior Member, IEEE*

***Abstract*—Throughput of dynamic frame slotted ALOHA (DFSA) in radio frequency identification (RFID) systems depends on the tags quantity estimate. This paper shows how to apply the slot-by-slot (SbS) estimate approach, along with the policy for the early frame-break. Simulation results show noticeable throughput improvements.**

***Note to Practitioners*—RFID supply chain application relies on the fast tag identification. As already shown in the literature, maximizing the number of read tags in the unit of time is a challenging task. In this paper, we propose a method which can assure near optimal tag identification time while maintaining low computational burden at the implementation point of view.**

***Index Terms*—Dynamic frame slotted ALOHA (DFSA), early frame break, efficient tag estimate method (TEM), slot-by-slot (SbS) estimation.**

I. Introduction

RADIO frequency identification (RFID) based on the wireless communication between reader and tags has become the most popular technology for object tracking in indoor environments. For multiple tags identification, RFID systems widely use dynamic frame slotted ALOHA (DFSA) scheme [1]. In DFSA, RFID reader announces the size of the frame, i.e., the number of slots (in standard [2] denoted with Q, and limited to the power of 2, i.e., to the frame size $L = 2^Q$) which tags occupy randomly. Afterwards, the reader interrogates the frame in the slot-by-slot (SbS) manner. The slot interrogation procedure includes three possible scenarios that can happen. There can be a slot with a single tag response (*successful* slot), the slot with no tags in (*empty* slot), or there may be a multiple-tag response in the slot. The last scenario generally ends up with tags signals summed up in the channel and therefore impossible to decode (*collision* slot). An example of the ALOHA frame including empty, collision, and successful slots scenarios is shown in Fig. 1.

To increase the tag reading rate, it is crucial to increase the number of successful slots. Intuitively, the size of the frame will have a strong impact on the performance of the system.

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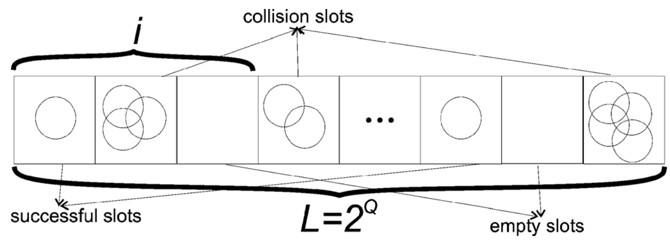

Fig. 1. Example of interrogating frame defined with $L = 2^Q$. i stands for the size of the part of the frame.

Reducing the size of the frame will increase the number of collisions, while a larger frame size will result in a larger number of empty slots. Calculations show that the throughput (η) for the equal slots duration, defined as the ratio of a number of successfully decoded slots (S) over L ($\eta = S/L$), is maximal when the number of slots of the frame equals the number of tags in the reader's read zone. In this case, the throughput is maximized and amounts about 37% [3]. Generally, the number of tags in the typical real environment is unknown, and therefore it has to be estimated. A number of previous works [3]–[5] present frame-by-frame (FbF) tag number estimate methods, which are based on the number of successful slots (S), empty slots (E), and the collision slots (C) experienced in the previous frame. To maximize the throughput, the authors in [6] present a maximum-likelihood (ML) SbS estimation method, with emphasize on the possible early frame break if it is of the wrong size according to its ML estimate. However, they do not give details on the policy of when to break the frame. In this paper, we propose the policy which is based on the application of the FbF tag number estimate method as the SbS estimate. To perform it, we use the low computational cost FbF method named the improved linearized combinatorial model (ILCM) [7]. The early frame break policy is based on the convergence of the FbF estimator, i.e., when it is not providing any new information from the incoming slots of the current frame. Once the convergence is obtained, we apply the frame break once the expected number of successful slots for the next frame is higher than that of the current frame. The presented scheme shows an improvement in terms of required time to identify all tags. Note that the given policy can be applied to the any of previous published FbF tag estimate methods, where presented results show that the performance depends on the estimator accuracy as well as its computational complexity.

This paper is organized as follows. In Section II, we provide the brief study on ILCM tag estimate method, the policy for the early frame break and state-of-the-art estimators in

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ALOHA-based RFID systems. Section III presents simulation results and concludes this paper.

II. SbS-Based Estimation and Frame Breaking Policy

To describe how to apply FbF estimation to the SbS basis, we apply the use-case scenario of ILCM FbF estimate method. In Section II-A, a brief explanation on how ILCM works is given. Section II-B is dedicated to the SbS estimation, and frame break policy. Finally, a brief overview of related works in the field is given.

A. ILCM

ILCM is the ML tag estimate [8], based on

$$p(E,S,C \mid n) = \frac{L!}{E!S!C!}\frac{N_S(n,S)N_C(n,S,C)}{L^n} \tag{1}$$

where $L = E+S+C$ is the frame size, $N_S(n,S)$ stands for the number of ways to distribute n tags to S slots, and $N_C(n,S,C)$ describes the number of ways in how to distribute the remaining $n - S$ tags to C slots. Denominator L^n stands for the total number of ways to distribute n tags in L slots. The multinomial coefficient $L!/(E!S!C!)$ describes the number of ways to permute E, S and C positions in the frame. Then the tag quantity estimate $\hat{n}$ is defined by $\arg\max_n\{p(E,S,C \mid n)\}$.

At the implementation point of view, relation (1) is computationally heavy and requires both specific hardware and software to complete the calculations. This is due to expansion of generating functions in Maclaurin series (due to term $N_C(n,S,C)$ which looks for *at least two* tags in the slot), finding the coefficients with required terms in an expansion, and repeating the process again for different numbers of tags n until a maximum is found. As a consequence, this process is energy-inefficient, especially in the context of mobile RFID readers [9].

Since the relation (1) is a complex counting formula, it was simplified in [7]. Simplification is possible since $\hat{n}$ and S are in a linear relationship if C is fixed. In addition, ILCM is derived to encompass multiple frames and allow estimate for any frame size, which provides $\hat{n}$ as the following linear relation:

$$\hat{n} = kS + l \tag{2}$$

where

$$\begin{aligned} k &= \frac{C}{(4.344L - 16.28) + \left(\frac{L}{-2.282 - 0.273L}\right)C} \\ &\quad + 0.2407\ln(L + 42.56) \\ l &= (1.2592 + 1.513L)\tan(1.234L^{-0.9907}C). \end{aligned} \tag{3}$$

B. SbS Estimation and Frame Break Policy

Since the slots within the frame can be considered to be mutually independent, it is possible apply FbF ILCM estimation (2) to the slot basis. Hereby reader estimates the number of tags after each slot denoted with index $1 \le i \le L$. Given (2),

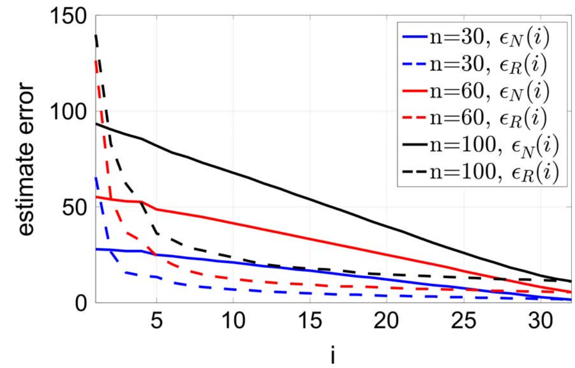

Fig. 2. Error in the tag number estimate for the part of the frame $L = 32$, for $N(i) = k'(i)s + l'(i)$ and $R(i) = N(i)2^Q/i$.

the estimated number of tags on the slot basis is then $N(i) = k'(i)s + l'(i)$, where $k'(i)$, $l'(i)$ are

$$\begin{aligned} k'(i) &= \frac{c}{(4.344i - 16.28) + \left(\frac{i}{-2.282-0.273i}\right)c} \\ &\quad + 0.2407\ln(i + 42.56) \\ l'(i) &= (1.2592 + 1.513i)\tan(1.234i^{-0.9907}c). \end{aligned} \tag{4}$$

Index i satisfies $i = e + s + c$, and e, s, c are the numbers of empty, successful, and collision slots for the part of the frame, respectively. For an all-collision scenario (i.e., $i = c$, and $e = s = 0$), we use (4) where, for $s = 0$, $N(i) = l'(i) = (1.2592 + 1.513i)\tan(1.234i^{-0.9907}i)$, resulting in a reasonable estimate if the number of tags is not too large. At the end of the interrogation frame, it holds that $i = L$. The smaller i is, the higher the error in estimate $\epsilon_N(i) = \mathcal{E}(|N(i) - n|)$ will be due to fewer slots information the reader has. Note that $\mathcal{E}(\cdot)$ stands for the expectancy operator. For example, $\epsilon_N(i)$ for $L = 32$ is shown in Fig. 2, where one can notice its linearity. Therefore, we consider estimator $R(i) = N(i)2^Q/i$, which gives exponential $\epsilon_R(i) = \mathcal{E}(|R(i) - n|)$. The exponential shape is of interest, since this enables us to consider cases when the estimator does not obtain any information from the incoming slots. This is what we call convergence of the estimator, defined with the condition $R(i) - R(i-1) \le 1$. The frame satisfying the convergence becomes the candidate for breaking.

Once the convergence is obtained, we look for the expected number of successful slots of the current frame of size $L_1 = 2^{Q_c}$ and proposed one $L_2 = 2^{Q_n}, Q_n = \text{round}(\log_2(R(i))$. Since tags occupy timeslots randomly, the probability that a single timeslot will be occupied by r of the total n tags is given by binomial distribution [3]

$$B_{n,1/L}(r) = \binom{n}{r}\left(\frac{1}{L}\right)^r\left(1 - \frac{1}{L}\right)^{n-r}. \tag{5}$$

Therefore, the probability of the successful slot is given as

$$p_s = B_{n,1/L}(1) = \frac{n}{L}\left(1 - \frac{1}{L}\right)^{(n-1)}. \tag{6}$$

The policy is to break the frame if the expected number of successful slots in the rest of the current frame $L_1 p_{s1} - s$, with

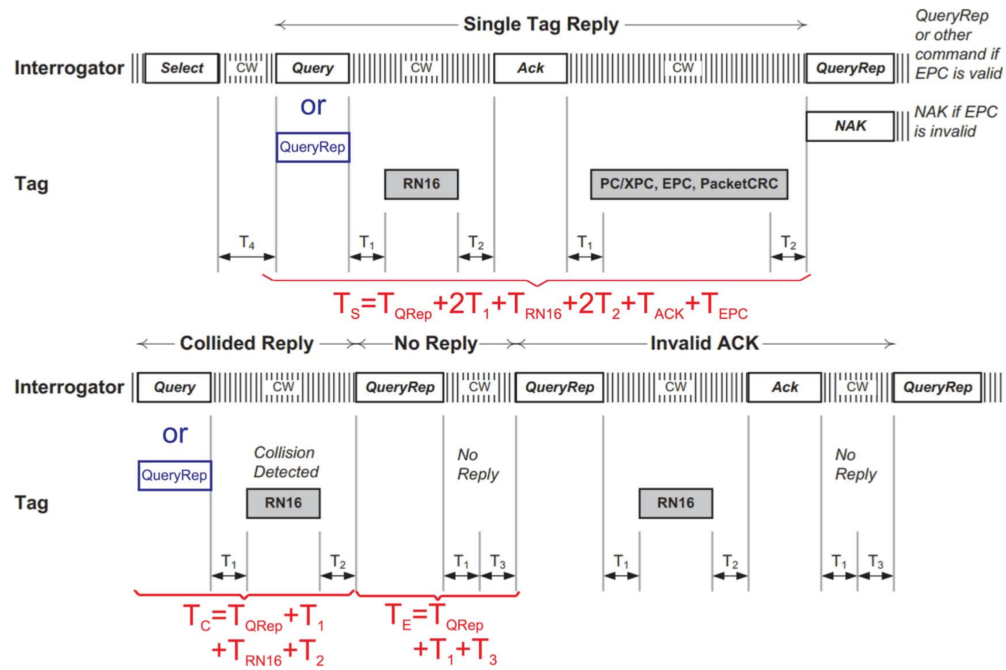

Fig. 3. Gen2 different slot type duration details.

$p_{s1} = B_{R(i),L_1}(1)$ less than the one expected in the new frame $L_2 p_{s2}$, where $p_{s2} = B_{R(i),L_2}(1)$. A complete procedure for early frame breaking is given in Algorithm 1.

Algorithm 1 ILCM SbS implementation

Require: Current Q denoted with Q_c.

Ensure: New Q denoted with Q_n.

$i = 0$, $Q_n = -1$

while $Q_n = -1$ **and** $i \leq 2^{Q_c}$ **do**
  $e, s, c = \text{ReadSlot}(), i = i + 1$
  $k'(i) = c/((4.344i - 16.28) + (i/(-2.282 - 0.273i)c) + 0.2407 \ln(i + 42.56)$
  $l'(i) = (1.2592 + 1.513i)\tan(1.234 i^{-0.9907} c)$
  if $k'(i) < 0$ **then**
    $k'(i) = 0$
  end if
  $N(i) = k'(i)s + l'(i)$
  $R(i) = N(i)2^{Q_c}/i$
  if $C = 0$ **then**
    $R(i) = s2^{Q_c}/i$
  end if
  if $i > 1$ **and** $R(i) - R(i-1) \leq 1$ **then**
    $L_1 = 2^{Q_c}$
    $Q_t = \text{find\_optimal\_Q}(R(i)), L_2 = 2^{Q_t}$
    $p_{s_1} = (R(i)/L_1)(1 - (1/L_1))^{(R(i)-1)}$
    $p_{s_2} = (R(i)/L_2)(1 - (1/L_2))^{(R(i)-1)}$
    if $(L_1 p_{s_1} - s) < L_2 p_{s_2}$ **then**
      $Q_n = Q_t$
    end if
  end if
end while
if $Q_n \neq -1$ **then**
  broadcast(Q_n)
else
  $Q_n = Q_c$
  broadcast(Q_n)
end if

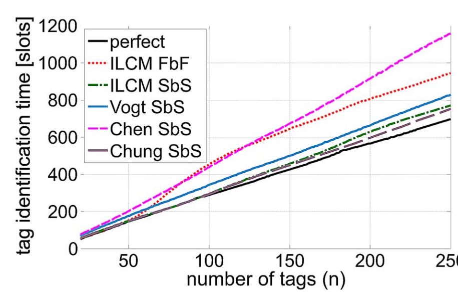

Fig. 4. Tag identification time (slots) for SbS mechanisms.

C. Tag Estimate Methods

The tag quantity estimate methods, based on the defining probability event space is well investigated in the literature. Unfortunately, the better estimation often comes at the expense of the computational burden. In this subsection we provide brief description of state-of-the art estimators. Note that the policy described in the previous subsection can be applied to any of the further described tag estimate methods.

The Vogt's [5] mean square error (MSE) estimate is given by

$$\hat{n}_{\text{vogt}} = \arg\min_n \left\| \begin{pmatrix} a_0 \\ a_1 \\ a_{\geq 2} \end{pmatrix} - \begin{pmatrix} E \\ S \\ C \end{pmatrix} \right\|^2 = \arg\min_n (a_0 - E)^2 + (a_1 - S)^2 + (a_{\geq 2} - C)^2 \quad (7)$$

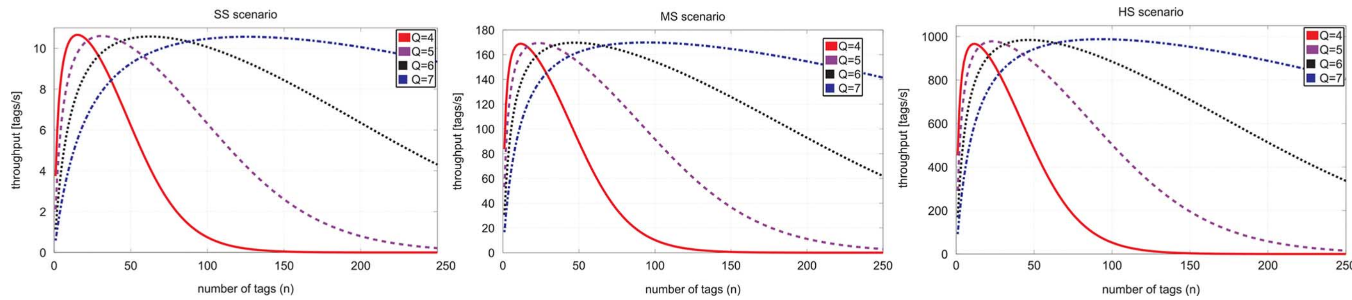

Fig. 5. Throughput (η_t) used for forming optimal Q-bins for timing specification of Gen2. Intersections of η_t for different Q form optimal Q for given n.

which defines the number of tags n that minimizes the distance between frame realization (E, S, C) and the expected number of empty, successful, and collision slots given from (5) as $a_0 = LB_{n,1/L}(0), a_1 = LB_{n,1/L}(1)$, and $a_{\geq 2} = L(1 - B_{n,1/L}(0) - B_{n,1/L}(1))$, respectively. Modification of Vogt frame estimate to the slot basis is done as explained in [6]. However, the problem in (7) is the $i = c$ scenario which gives minimum for $n \to \infty$, and cannot be efficiently implemented, since $i = c$ scenario for partial frame is likely. In such scenario [6] suggests usage of $\hat{n} = 2.39c(2^{Q_c}/i)$, where for $i = c$, it becomes frame depending constant $\hat{n} = 2.39(2^{Q_c})$.

Unlike Vogt method, Chen [10] recently presented an efficient SbS tag estimate method where $\hat{n} = (s + 2.39c)(L/i)$. Chen proposed frame break if the current frame size is of the different length than the estimated one. Further evaluation of this concept, based on the same estimate was given in [11]. Therein author discusses on which index of the partial frame (checkpoint) should be used before checking the frame appropriateness. This idea further reduces the computational costs of given method. However, [11] does not provide the way of choosing correct index.

The critique on existing tag estimate methods are provided in [12], where authors claim that formula

$$P(E, S, C) = \frac{L!n!}{E!S!L^n} \sum_{k=0}^{\min(n-S,C)} \sum_{v=0}^{C-k} (-1)^{k+v} \times \frac{1}{k!v!(n-k-S)!} \frac{(C-k-v)^{n-k-S}}{(C-k-v)!} \quad (8)$$

provides the best estimation because previously published works [3]–[6], [13] mainly contain errors due to their approaches which do not consider the slot type dependence. Considering authors simulations, and rationale described in the paper [12], we conclude that given formula provides the correct joint probability distribution of finding n tags among E, S, C slots.

III. Simulation Results

Simulations were conducted by implementing Gen2 [2] process of tag identification. Gen2 reader interrogates tags through rounds of identification containing multiple frames. The reader initiates the communication by broadcasting initial Q, and collided tags are moved to the next frame of the current round. Gen2 round does not end until there are collision slots. Results are obtained through Monte-Carlo experiments of 10 000 rounds of identification for each n, where $1 \leq n \leq 250$.

To compare our method with state of the art we consider Vogt [5], Chen [10], ILCM frame by frame [7], Chung *et al.* [12], and perfect estimate where $\hat{n} = n$. For the sake of fairness of simulations for Vogt and Chung *et al.* methods we apply the same policy for the frame break as for ILCM SbS, with $\hat{n} = 2.39(2^{Q_c})$ for $i = c$ scenario. Results that compare total slots required to identify all tags are given in Fig. 4. Results of Chen's method largely differs from the one presented in the original paper [10]. This is due to initial Q set to 4, while [10] results are for initial Q set to 6, 7, and 8. Moreover, we find that given method does not work fine for scenarios when initial tag quantity largely diverge from the initial frame size.

Further, Gen2 specifies timing details (depicted in Fig. 3) [2], which allows one to compute the total time consumption instead of the required number of slots. Number of read tags per second is highly dependent on the tag responses duration, defined with backscatter link frequency (BLF), the number of Miller modulated carrier cycles for each tag bit response (M), and the duration of empty slot, i.e., time $T3$ which denotes the time reader waits for issuing another command if the channel is idle. To consider total time, we choose 3 Gen2 reading modes named Slow Speed (SS), Middle Speed (MS), and High Speed (HS) mode. SS uses BLF $= 40$ kHz, $M = 8$, and $T3$ equals the duration of tag's RN16 response, i.e., $T3 = T_{RN16}$. MS uses BLF $= 340$ kHz, $M = 4$, and $T3 = T_{RN16}/3$, while HS uses BLF $= 640$ kHz, $M = 1$, and $T3 = 0.1Tpri$, $Tpri = 1/\text{BLF}$. Including timing details have the impact on selecting optimal frame size, which is not $Q = \log_2(\hat{n})$ anymore, and it should be derived from the timed throughput function ($\eta_t = S/t_L$ [tags/second]), where $t_L = ET_E + ST_S + CT_C + T_{\text{Query}}$. T_E, T_S, and T_C are durations of empty, successful, and collision slots, where T_{Query} is the duration of $Query$ command. Examples of η_t are given in Fig. 5. Intersections of η_t for different Q define optimal Q-bins, given in Table II. Results comparison from Fig. 6 shows that the method used by Chung *et al.* gives the least time to identify tags, but at the cost of computational burden. In order to ensure that estimation does not involve any latency to the real RFID reader, it is necessary for SbS algorithm to be executed within time T_2 (see Fig. 3), which Gen2 specifies to be minimum of $3Tpri$ or equivalent of 4.7 μs for BLF $=$ 640 kHz. If we consider Algorithm 1, its total cost in terms of Floating Point Operations (FLOP) is a constant value ($\mathcal{O}(1)$) of 667 FLOP (worst case), by using the FLOP costs as specified

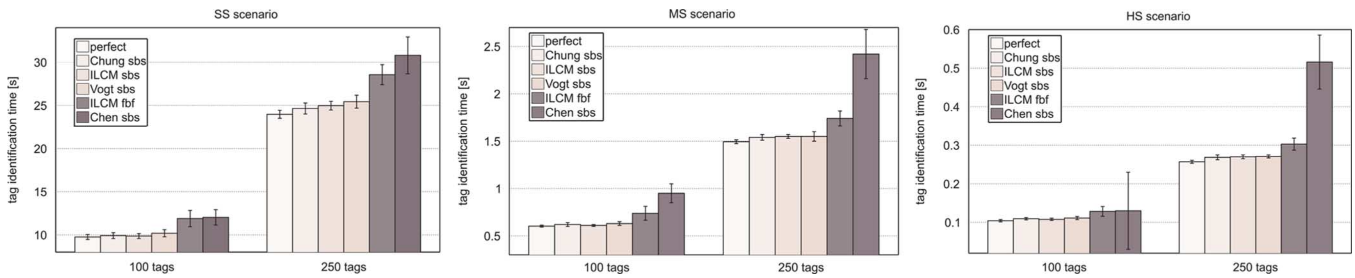

Fig. 6. Mean tag identification time and its standard deviation for given scenarios. Results are given from left to right in the legend order.

TABLE I
FLOATING POINT OPERATION COSTS [9] AND [13]

Operation	FLOP cost
Addition, subtraction, multiplication	1
Comparison operation	2
Division, square root	10
Exponential, logarithmic and trigonometric function	50
Factorial	100

TABLE II
Q-BINS FOR THREE DIFFERENT SCENARIOS IN GEN2 PROTOCOL

Q	SS scenario	MS scenario	HS scenario
0	$[0, 1]$	$[0, 1]$	$[0, 1]$
1	$[2, 2]$	-	-
2	$[3, 5]$	$[2, 3]$	$[2, 3]$
3	$[6, 10]$	$[4, 7]$	$[4, 7]$
4	$[11, 21]$	$[8, 16]$	$[8, 15]$
5	$[22, 43]$	$[17, 32]$	$[16, 31]$
6	$[44, 87]$	$[33, 65]$	$[32, 63]$
7	$[88, 174]$	$[66, 131]$	$[64, 128]$
8	$[175, 349]$	$[132, 263]$	$[129, 258]$
9	$[350, 700]$	$[264, 528]$	$[259, 517]$

in Table I, which for the 1 GFLOPS reader (10^9 Floating Points Operations Per Second) [13] gives the total time of 0.66 μs, and thus guarantees execution within the requested time. However, this may not be the case for the Vogt ($\mathcal{O}(n)$) method and the Chung *et al.* method ($\mathcal{O}(nC^2)$) since they highly depend on the number of tags and/or number of collision slots.

IV. CONCLUSION

In this paper, authors presented the policy for the early frame break in DFSA RFID systems. The policy is independent of the tag estimate method, and based on the FbF estimator convergence, i.e., when it is not learning any new information from the incoming slots. Once the convergence is obtained we consider braking the frame if the expected number of successful slots for the next frame is greater than one of the current frame. This policy can be applied to the any FbF estimator, where tag identification time depends on its accuracy. Once applied to the FbF estimator, we show that Chung method with the policy provides the least time for tag identification, however at the cost of computational burden. In order to ensure that latency caused by computational cost does not affect the system we suggested the usage of constant execution time ILCM tag estimate method. Using the proposed approach, one can consider the design of efficient readers that minimize tag identification time.

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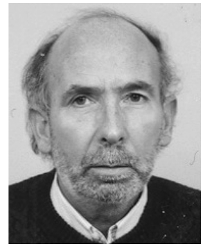

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