An Enhanced Multiple-Feedback Algorithm for RFID MAC Protocols

You-Chang Ko¹, Sumit Roy², Choong-Ho Cho³, and Hyong-Woo Lee⁴

¹ *Solution Business Division, Samsung Networks Inc., Seoul, S. Korea*
youchang.ko@samsung.com

² *Dept. of Electrical Engineering, University of Washington, Seattle, WA 98195*
sroy@u.washington.edu

³ *Dept. of Computer & Information Science, Korea University, Jochiwon, S. Korea*
chcho@korea.ac.kr

⁴ *Dept. of Electronics & Information Engineering, Korea University, Jochiwon, S. Korea*
hwlee@korea.ac.kr

Abstract— This paper introduces two new tree-based anti-collision schemes using multiple feedback symbols for uplink tag random access of emerging radio frequency identification (RFID) networks. To this end a uplink(UL) time slot requires an extra time portion called voting field in addition to the packet payload to obtain a slot based estimate for the number of contending tags. As a function of the voting field length we examine MAC efficiency improvements in terms of UL throughput, and compare it with the conventional binary tree based RFID MAC in ISO 18000-6 Type B standard.

I. INTRODUCTION

The radio frequency identification (RFID) network itself has two principal components: a) the reader/interrogator and b) objects with attached tags/transponders. The primary metric for evaluation of an RFID network is rate of acquiring tag information by the reader upon querying. While physical layer air interface parameters such as data transmission rate in downlink(DL, reader-to-tag)/uplink(UL, tag-to-reader) clearly impact the *tag read rate*, the impact of the multiple access protocol (and specifically the anti-collision component) is the focus of this work. The great majority of the plethora of anti-collision schemes in the RFID MAC arena that have been proposed thus far, have been categorized into two primary types – framed Aloha[7],[8] and *m*-ary splitting algorithm (MSA)[3]-[6],[9],[10], where both schemes are designed to broadcast a *single* feedback symbol for packet access result to a UL time slot. MSA can be further classified into two categories depending on the sequence of collision resolution process (CRP): *depth-first-search* MSA(DMSA)[3]-[6] and *breadth-first-search* MSA(BMSA)[9],[10]. In this paper we introduce a novel anti-collision principle called *multiple feedback algorithm* (MFA) based on [3], and propose its *enhanced* version (EMFA) into RFID MAC protocols. The (E)MFA running on top of the DMSA¹ skeleton structure utilizes a novel approach in which the reader broadcasts

multiple feedback symbols for a UL time slot. To this end a UL time slot requires an extra time portion called *voting field* in addition to the packet payload to obtain a slot based estimate for the number of contending tags. Fig. 1 illustrates the slot structure of the conventional schemes and the (E)MFA in a half duplex shared medium. Consider the *x*-th time slot (S_x) in a TDMA uplink frame. Then the length of a UL time slot in conventional schemes(T_{c_slt}) is set exactly the same as the packet duration (T_{pkt}) for which a slot based *single* feedback – a ternary type random variable (Q), i.e., *Empty*, *Success* or *Collision* – is implicitly or explicitly broadcast via downlink (DL) channel according to DMSA protocol as seen in Fig. 1-a. In contrast that of (E)MFA UL slot(T_{m_slt}) consists of two parts as shown by Fig. 1-b: T_{pkt} and the voting field duration ($d\Delta\tau$) each of duration $\Delta\tau$; an additional signal pulse placed at random within the d bins is sent during this period. The reader measures voting mini-slots corresponding to a data packet S_x . In case of a packet collision (i.e. multiple tags choosing the same UL slot), the slot is split subsequently into m slots for collision arbitration as needed, where $m (\geq 1)$ is a variable chosen depending on the size of d . There are two distinct advantages of the (E)MFA idea over *ISO 18000-6 Type B* (ISOB) standard [1] that uses a *fixed* binary splitting size. Firstly, an estimate of the number of contending sources is available via observation of the voting min-slots corresponding to a UL data slot; this allows choice of *dynamic splitting size per slot* and enhanced MAC efficiency. Secondly, even with multiple packets ($n \geq 2$) access within a UL slot S_x (i.e. a collision), some mini-slots will carry a singleton signal with high probability implying that the corresponding data packet(s) are guaranteed to be successfully received in the very next retransmission.

Clearly, larger d implies that more chances for a mini-slot to contain a singleton signal are available, as well as that more accurate estimate of the number of contending sources is achieved. On the other hand, increasing the voting field will ultimately lead to throughput degradation as the overhead increase starts to negate any gains from the accurate estimate of collision events. The actual throughput is thus a function of

¹ [4]-[6] are the special case of DMSA where $m = 2$, a *fixed* binary tree MAC, whereas MFA[3] is the special case of DMSA where m is *dynamic* per collided slot.

Fig. 1 The UL time slot structure for conventional schemes (a) and (E)MFA (b) in a half duplex shared medium

the ratio $\gamma_m = \Delta\tau / T_{pkt}$. There exist two major shortcomings in the previous MFA[3]: firstly, the extra slot time portion ($d\Delta\tau$) was neglected in calculating the UL throughput. So it was not clear how much *practical* gain could be expected from the MFA. Secondly, information of a binary type feedback symbol for each $\Delta\tau$ is not sufficient for dynamic splitting size for a collided slot: a feedback for v_i is either *silent* meaning no occupation of signal or *not silent* meaning at least one signal occupation. This issue will be discussed more specifically in the following section. In this paper, taking $d\Delta\tau$ time into consideration we develop new analytical models for MFA and EMFA. Our mathematical results are also supported by simulation results. In particular in order to better facilitate the dynamic splitting size, EMFA uses a ternary type feedback symbol (W) rather than a binary one (V) for v_i . We examine the value of d that optimizes UL throughput for both MFA and EMFA and the achieved gain from them over ISOB, the baseline protocol.

We organize the remainder of the paper as follows. Section II illustrates the MAC protocols structure of the MFA and EMFA in depth. In chapter III, analytical models for MFA, and EMFA are derived. In section IV, the maximal throughput and gain as a function of γ_m via analytical and simulation results are discussed. Finally we draw our conclusion in section V.

II. (ENHANCED) MULTIPLE FEEDBACK ALGORITHM: (E)MFA

A. MFA

A slot duration (T_{slt}) in MFA consists of two parts: packet duration T_{pkt} , and voting field $d\Delta\tau$, where a tag that transmitted its packet to S_x sends an additional signal pulse at random within one of the d mini-slots. In MFA, then, the reader broadcasts a feedback couple $\{U, V\}$ at the end of each slot according to DMSA protocol: U for the sensing result of T_{pkt} is a binary feedback defined as (1) and V for the sensing results of $d\Delta\tau$ is a binary d -tuple random variable, $(V_1, V_2, \dots, V_d)$ defined as (2). Thus as long as $U = 1$ the S_x needs to be split promptly into m according to the DMSA protocol as defined by (3). Then the collided packets in S_x will be retransmitted in an orderly fashion within m slots via d -bit sequence in V . Fig. 2-a illustrates an example of collision resolution process in MFA with dynamic splitting. Suppose that four packets – pkt_1, pkt_2, pkt_3 , and, pkt_4 – are to be sent in slot S_x with three mini-slot ($d = 3$); two of them (pkt_2 and pkt_3)

send their voting signal to v_1 and the rest (pkt_1 and pkt_4) to v_3 and v_2 , respectively. The corresponding feedback for S_x $\{U, V\}_x$ is $\{1, (1, 1, 1)\}$. In the next retransmission, pkt_2 and pkt_3 are supposed to compete again at S_{x+1} : because the $\{U, V\}_{x+1}$ is $\{1, (1, 0, 1)\}$ they can be identified in the following retransmission. Slot splitting is no longer required in S_{x+2} , S_{x+3} , S_{x+4} , and S_{x+5} since $U = 0$. At the beginning of an inventory session the reader broadcasts the command including the size of d and the exponent q that sets the size of *initial contention window* (f_0) to 2^q , where $q = 0, 1, 2, \dots$. Fig. 2-b shows the logical procedure of a MFA tag in transmitting the packet. e_i denotes the number of silent mini-slots prior to v_i right before a non-silent mini-slot: the tag retransmitted pkt_2 to S_{x+1} and sent a corresponding voting signal to v_3 sets its transmission counter(t_c) to 2 instead of 3 after receiving feedbacks. Once an identification session starts *Step B* and *Step C* keep alternated in a tag until $U = 0$.

$$U = \begin{cases} 0, & \text{if Empty or Success} \\ 1, & \text{otherwise,} \end{cases} \quad (1)$$

$$V_{i,x} = \begin{cases} 0 \text{ (Empty)}, & \text{if } v_i \text{ is silent} \\ 1 \text{ (Nonempty)}, & \text{if } v_i \text{ is not silent.} \end{cases} \quad (2)$$

$$m_x = \sum_{i=1}^d V_{i,x} \quad (3)$$

B. Enhanced MFA

In EMFA, a binary d -tuple random variable, V is redefined by W with a *ternary* d -tuple random variable, $\{W_1, W_2, \dots, W_d\}_x$ for S_x feedback as (4). The U for T_{pkt} in (1) is no longer used since tags can infer the result from the information in W only. We assume that the reader channel sensing capability is sensitive enough to distinguish the signal multiplicity reliably even in each v_i .

$$W_{i,x} = \begin{cases} 0 \text{ (Empty)}, & \text{if no signal arrives at } v_i, \\ 1 \text{ (Success)}, & \text{if a single signal arrives at } v_i, \text{ and} \\ 2 \text{ (Collision)}, & \text{if more than one signals arrive at } v_i. \end{cases} \quad (4)$$

Fig. 3-a illustrates the difference how dynamic slot splitting for a collided slot S_x is performed between MFA and EMFA. We use the same scenario of four packets voting

[Step A] The start of a session

- Set transmission counter (t_c) at random within $[1, f_0]$.
- Go to **Step B**.

[Step B] Transmitting packet and extra signal

- Decrease t_c by 1.
- if ($t_c = 0$)
 - Transmit packet immediately to the current time slot (S_x).
 - Send an extra signal at random within $[1, d]$ mini-slots attached to S_x .
 - Save the chosen mini-slot index (i), where $1 \leq i \leq d$.
- end
- Go to **Step C**.

[Step C] Receiving Feedbacks

- Check U .
- if ($U = 0$)
 - if (the tag transmitted packet to S_x)
 - Leave the session.
 - else
 - Go to **Step B**.
- end
- else // collision
 - if (the tag transmitted packet to S_x)
 - Set t_c to $i - e_i$.
 - else
 - Increase t_c by m_x via Formula (3).
- end
- Go to **Step B**.
- end

b) UL channel access process in an MFA tag
Fig.2 The functional logic flow in a MFA tag

result as the S_x in Fig. 2-a. Then W_x should be $\{2, 1, 1\}$. It is obvious that pkt_2 and pkt_3 in MFA are destined to be collided again at their next retransmissions to S_{x+1} . However those in EMFA get a chance to choose one of two split slots – S_{x+1} and S_{x+2} – due to the fact that $v_1 = 2$. A tag that transmitted its packet to the S_x needs to check the *slot collision decision function* (C_x) as defined by (5). If $C_x = 0$ the tag leaves the session. Otherwise ($C_x = 1$) the tag needs to identify its retransmission time according to the other mini-slot feedbacks in $W_{i,x}$. We define $s_{i,x}$ and $c_{i,x}$, the number of, respectively, successful and collided mini-slots up to the v_i in S_x to where the extra signal was sent by the tag as (6). Then the packet

TABLE I
PROPERTIES OF TREE BASED RFID ANTI-COLLISION SCHEMES

Tree Based Anti-collision Schemes			Splitting Size	Degree of Dynamic
Root	Variation	Tag estimation		
MSA	DMSA	default	$m = 2, 3, 4, \dots$	session variable(static)
		MFA	$m = [1, d]$	slot variable
		EMFA	$m = [2, 2d]$	slot variable
	BMSA[9]	collision rate per frame	$m = [2, k]$, where $k \geq 3$	frame variable

[Step A] The start of a session

- Set transmission counter (t_c) at random within $[1, f_0]$.
- Go to **Step B**.

[Step B] Transmitting packet and extra signal

- Decrease t_c by 1.
- if ($t_c = 0$)
 - Transmit packet immediately to the current time slot (S_x).
 - Send an extra signal at random within $[1, d]$ mini-slots attached to S_x .
 - Save the chosen mini-slot index (i), where $1 \leq i \leq d$.
- end
- Go to **Step C**.

[Step C] Receiving Feedbacks

- Check the collision decision function C_x via Formula (5).
- if ($C_x = 0$)
 - if (the tag transmitted packet to S_x)
 - Leave the session.
 - else
 - Go to **Step B**.
- end
- else // collision
 - if (the tag transmitted packet to S_x)
 - Set t_c via Formula (7).
 - else
 - Increase t_c by m_x via Formula (8).
- end
- Go to **Step B**.
- end

b) UL channel access process in an EMFA tag
Fig. 3 The functional logic flow in an EMFA tag

transmission counter, $t_c(W_{i,x})$ for a tag that sent an extra signal to v_i in S_x is defined by (7) where $rand[A, B]$ is the function that chooses a random number between A and B inclusive. Using (6) the splitting size for a collided S_x ($C_x = 1$) is given by (8). Fig. 3-b depicts the logical procedure for an EMFA tag in transmitting the packet. Once an identification session starts **Step B** and **Step C** keep alternated in a tag until $C_x = 0$. Hence in (E)MFA m_x is a slot variable, whereas d is a session variable. The properties of tree based RFID anti-collision schemes are summarized in Table 1.

$$C_x = \begin{cases} 0, & \text{if } \sum_{i=1}^d W_{i,x} < 2 \\ 1, & \text{otherwise} \end{cases} \quad (5)$$

$$\begin{cases} s_{i,x} = \sum_{a=1}^i W_{a,x}, & \text{such that } W_{a,x} = 1 \\ c_{i,x} = \sum_{a=1}^i W_{a,x}, & \text{such that } W_{a,x} = 2 \end{cases} \quad (6)$$

$$t_c(W_{i,x}) = \begin{cases} s_{i,x} + 2c_{i,x}, & \text{if } W_{i,x} = 1 \\ rand[s_{i,x} + 2c_{i,x} - 1, s_{i,x} + 2c_{i,x}], & \text{if } W_{i,x} = 2 \end{cases} \quad (7)$$

$$m_x = s_{d,x} + 2c_{d,x} \quad (8)$$

III. ANALYSIS OF THE SYSTEMS

In order to estimate the number of contending sources, consider the situation where unknown number n (≥ 2) tags choose the same UL slot along with d mini-slot voting signals. The distribution of the n voting signals in the d mini-slots is therefore multinomial as (9)

$$M(b_1, b_2, \dots, b_d; n) = \binom{n}{b_1, \dots, b_d} \prod_{i=1}^d p_i^{b_i} = \frac{n! d^{-n}}{\prod_{i=1}^d b_i!} \quad (9)$$

where the d bins contain $b_1, \dots, b_d$ signals respectively such that $\sum_{i=1}^d b_i = n$ and $p_i = 1/d$ (each mini-slot is chosen equally). The first term in the middle equation is multinomial coefficient defined by $n! / \prod_{i=1}^d b_i!$. The number of all possible outcomes of the vector $(b_1, \dots, b_d)$ is ${}_dH_n (= {}_{d+n-1}C_n)$, i.e., the number with repetitions of arrangements of n objects into d bins. Let $N(n)$ denote the number of *additional* UL time slots that are required to resolve an initial n -packet collision. Note that $N(0) = 0$, $N(1) = 0$ serve as initial conditions since there are no collisions with either 0 or 1 packet access in a slot.

A. Analysis of MFA

Let $X = \Sigma V_i$ from (2), the random variable taking values in the range $[1, 2, \dots, d]$. Then $N(2)$, $N(3)$ can be deduced from (10), and thus $N(n)$ can be recursively computed as given by (11). For a given probability of $M(\cdot)$, X plus the additional number of slots required to resolve the subsequent collisions from b_1 to b_d are consumed after n tags cast a vote within d mini-slots. Our delay derivation for MFA yields the same results as Appendix A in [3]. However because an UL slot time in MFA contains an overhead portion as illustrated in Fig. 1-b we need to take the duration ($d\Delta\tau$) into consideration to estimate the practical gains from (E)MFA; hence the time slot duration (T_{m_slt}) is represented by $T_{pkt}(1 + d\gamma_m)$.

B. Analysis of EMFA

We denote $Y = \Sigma W_i$ the random variable for the size of splitting slots taking the range $[2, 3, \dots, 2d]$ for S_x whose $C_x = 1$. Then with the similar fashion with MFA $N(n)$ for EMFA can be recursively derived by (12). Therefore for a given probability of $M(b_1, \dots, b_d; n)$ $M(\varepsilon_1, \dots, \varepsilon_\alpha; b_1), \dots, M(\omega_1, \dots, \omega_\alpha; b_d)$, where α is 1 if $b_i < 2$, or 2 otherwise, the number of Y plus the additional number of slots to resolve subsequent collisions from $N(\varepsilon_1)$ to $N(\omega_\alpha)$ are consumed. Let us consider about initial packet loading factor (λ_0) i.e., packet arrival rate in a UL time slot. Then λ_0 is defined by np^* , where n is the total tag pool, and p^* is the probability that a tag in n is selected by the reader for an inventory session. Since once it is selected a tag transmits its packet with probability 1 within f_0 , λ_0 becomes np^*/f_0 . Then the number of packets arrival event can be represented by binomial random variable with parameters, n and p^*/f_0 . Thus we have $\bar{N}$ as (13). The first term of $\bar{N}$ means the initial frame length, and the second term is for the additionally required slots needed to serve the

collided tags in the first frame. Now we define normalized UL throughput (ρ_{UL}) for a CRP, which can be expressed by (14).

$$\begin{aligned} N(2) = & M(2, 0, \dots, 0; 2)[T_{m_slt} + N(2) + N(0) + \dots + N(0)] + \dots + \\ & M(0, 0, \dots, 2; 2)[T_{m_slt} + N(0) + \dots + N(0) + N(2)] + \dots + \quad (10) \\ & M(1, 1, \dots, 0; 2)[2T_{m_slt} + N(1) + N(1) + \dots + N(0)] + \dots + \\ & M(0, \dots, 1, 1; 2)[2T_{m_slt} + N(0) + \dots + N(1) + N(1)]. \end{aligned}$$

$$\begin{aligned} N(n) = & M(n, 0, \dots, 0; n)[T_{m_slt} + N(n)] + \dots + \\ & M(0, 0, \dots, n; n)[T_{m_slt} + N(n)] + \dots + \quad (11) \\ & M(n-1, 1, \dots, 0; n)[2T_{m_slt} + N(n-1)] + \dots + \\ & M(0, \dots, 1, n-1; n)[2T_{m_slt} + N(n-1)] \\ = & \sum_{\substack{0 \leq b_i \leq n, \\ 1 \leq i \leq d}}^{H_d} \left[M(b_1, \dots, b_d; n) \left\{ XT_{m_slt} + \sum_{i=1}^d N(b_i) \right\} \right] \end{aligned}$$

$$N(n) = \sum_{\substack{0 \leq b_i \leq n, \\ 1 \leq i \leq d}}^{H_d} M(b_1, \dots, b_d; n) \left[\sum_{\substack{0 \leq \varepsilon_j \leq b_1, \\ 1 \leq j \leq \alpha}}^{H_{b_1}} \left\{ M(\varepsilon_1, \dots, \varepsilon_\alpha; b_1) \times \dots \times \right. \right. \quad (12)$$

$$\left. \left. \left[M(\omega_1, \dots, \omega_\alpha; b_d) \times \left(YT_{m_slt} + \sum_{j=1}^{\alpha} N(\varepsilon_j) + \dots + \sum_{j=1}^{\alpha} N(\omega_j) \right) \right] \right\} \right]$$

$$\bar{N} = f_0 \left\{ T_{m_slt} + \sum_{l=0}^n N(l) P(l) \right\}, \text{ where } P(l) = \binom{n}{l} \left(\frac{p^*}{f_0} \right)^l \left(\frac{f_0 - p^*}{f_0} \right)^{n-l} \quad (13)$$

$$\rho_{UL} = \frac{\text{successful packet times}}{\text{total UL times}} = \frac{\lambda_0}{\bar{N}} \quad (14)$$

IV. PERFORMANCE EVALUATION

We assume that the packet length is 16-bit long as in [2], and the extra signal length is 1-bit ($\gamma_m = 6.25\%$) and 2-bit ($\gamma_m = 12.5\%$) long. The channel or air interface is assumed perfect, i.e. no packet losses. The lines and dots in Fig. 4 thru Fig. 7 represent analytical results and simulation results, respectively. As seen in Fig. 4 where $\gamma_m = 6.25\%$, a longer d on one hand increases throughput over the baseline protocol, ISOB (DMSA with $m = 2$), but on the other hand contributes progressively to increased overhead; eventually there is no gain beyond $d = 4$ or 5 for MFA (Fig. 4-a) and $d = 3$ or 4 for EMFA (Fig. 4-b) within $\lambda_0 = 10$. We notably observe the low λ_0 regions, i.e., approximately prior to 0.5 for MFA and 0.4 for EMFA, where (E)MFA is outperformed by ISOB. This is because packets are much less likely to be collided and the presence of the voting field only increases overhead. Beyond these points where collisions increasingly prevail, (E)MFA starts to yield the gain depending on the size of d . If γ_m gets bigger the optimal d for both schemes is decreased because the increased overhead portion overwhelms the gain sooner than the shorter γ_m . Thus the optimal d at $\gamma_m = 12.5\%$ is

a) MFA

b) EMFA

Fig. 4 Performance comparison of the normalized UL throughput between MFA (a) EMFA (b) when $\gamma_m = 6.25\%$

a) MFA

b) EMFA

Fig. 5 Performance comparison of the normalized UL throughput between MFA (a) EMFA (b) when $\gamma_m = 12.5\%$

decreased to 3 or 4 for MFA and to 2 or 3 for EMFA as shown by Fig. 5-a) and Fig. 5-b), respectively. A bigger γ_m also makes the break-even point where (E)MFA starts to achieve gain postponed; with $d = 3$ MFA starts to yield the gain beyond $\lambda_0 = 1.2$, whereas EMFA brings gain beyond $\lambda_0 = 0.7$. We also observe MFA that when $\gamma_m = 12.5\%$ it hardly increases the maximal throughput over ISOB. However EMFA can still be higher than it. Fig. 6 shows the maximal ρ_{UL} comparison with various sizes of f_0 . The maximal ρ_{UL} at $\gamma_m = 6.25\%$ for EMFA, MFA, and ISOB is, respectively, 0.52, 0.5, and 0.44, and the maximal gain from MFA and EMFA over ISOB is, respectively, 31% and 36% as in Fig. 6-a. The maximal ρ_{UL} at $\gamma_m = 12.5\%$ for EMFA, MFA, and ISOB is, respectively, 0.47, 0.44, and 0.44, and the maximal gain from MFA and EMFA over ISOB is, respectively, 8% and 17% as shown by Fig. 6-b. Therefore the overall performance of (E)MFA outperforms that of ISOB: especially it is more robust when offered load is high. In particular it is shown that EMFA is superior to MFA because 1) EMFA achieves higher ρ_{UL} through a broader range of λ_0 than MFA does, and 2) EMFA is less sensitive to the value of γ_m than MFA since the enhanced sensing result for a mini-slot facilitates a better

dynamic splitting size even with the smallest size of d (2). The Fig. 7-a and 7-b illustrate how splitting size in MFA and EMFA, respectively, adapts dynamically to increased λ_0 . The split size in (E)MFA dynamically changes as a function of λ_0 intensity adapting to slot based estimate, whereas it is fixed in ISOB regardless of λ_0 . As seen in the figures the splitting size in EMFA increases more proportional to λ_0 than that in MFA.

V. CONCLUSIONS

We have introduced a novel anti-collision principle – multiple feedbacks algorithm (MFA) – into RFID MAC protocols and proposed its enhanced version (EMFA). (E)MFA enables the reader to split the collided slot dynamically according to the slot based backlogged tag estimate. In order to examine the practical gain from (E)MFA we derived the optimal voting field size (d) for both schemes that yields the maximal UL throughput as a function of γ_m , ratio of mini-slot duration $\Delta\tau$ to packet duration T_{pkt} . As a result with the optimal d at $\gamma_m = 6.25\%$, MFA and EMFA achieve significant throughput gains (31% and 36%, respectively) relative to the conventional RFID spec. (ISOB)

a) The maximal ρ_{UL} when $\gamma_m = 6.25\%$

b) The maximal ρ_{UL} when $\gamma_m = 12.5\%$

Fig. 6 The comparison of maximal ρ_{UL} with various f_0 sizes in MFA and EMFA

a) MFA

b) EMFA

Fig. 7 Dynamic splitting size in MFA (a) and EMFA (b)

[1]. Since the real size of tag pool is unknown at the start of an inventory session, the initial tag loading factor λ_0 can be set conservatively; (E)MFA is shown to be more robust than ISOB in this situation. The value of γ_m is critical for (E)MFA performance; the bigger the value of γ_m the worse the performance is. Yet EMFA is less sensitive to γ_m than MFA since an enhance sensing feedback per mini-slot enables EMFA to take advantage of a better dynamic splitting size even with the smallest $d(2)$. In order to get DL gain, for a further study, (E)MFA can be run on top of *breadth-first-search m-ary splitting algorithm* (BMSA)[10], whereby DL time is greatly reduced.

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