Time Aware Closed Form Frame Slotted ALOHA Frame Length Optimization

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***Abstract*—Calculating the optimal frame length for Frame Slotted ALOHA in RFID systems is a critical issue as it highly affects the reading efficiency, and hence the reading time. Most previous studies have focused mainly on the conventional definition of the reading efficiency, which is the ratio between the number of successful slots and the total number of slots (frame length). However, the duration of the slots in RFID systems depends on whether the slot is idle, successful, or collided. Some other state-of-the-art studies have focused on optimizing the frame length taking into consideration the differences in slot durations. However, they do not deliver a closed form solution for the optimum frame length in terms of the differences in slots durations. Therefore, this paper proposes a closed form solution for the optimum frame length for FSA by optimizing the Time-Aware Framed Slotted ALOHA (TAFSA) efficiency, which considers the differences in the slot durations. Simulations indicate that the proposed solution gives the most accurate results with respect to the exact solution. Moreover a gain of approx. 10% in terms of reading time wrt. the classical algorithm using parameters of the ISO 18000-6C UHF-RFID standard. However, the results can also be applied to other systems based on Frame Slotted ALOHA.**

I. INTRODUCTION

Over the recent years, the number of applications that use Radio-Frequency Identification Systems (RFID) has increased, and their number is expected to further grow in the near future. One main application is the area of logistics, where e.g. hundreds of tags (transponders) may be closely placed on pallets. This naturally requires fast RFID readers (interrogators), in order not to slow down the delivery process of the actual goods. Commonly used RFID standards in the area of logistics (e.g. ISO 18000-6C [1]) is based on TDMA (time division multiple access), which leads to a certain probability of tag-collisions on the communications channel. As the tags are of low price and simple design, they neither can sense the channel nor communicate with the others. Moreover, they are identified once during the reading process [1]. Hence, the readers are responsible for coordinating the network, and for the avoidance of collisions using anti-collision algorithms.

According to the previously published RFID work, Frame Slotted Aloha (FSA) [2] is the most widely used anti-collision protocol for RFID systems due to its simplicity and robustness. In FSA, the communication timing between the reader and the tags is divided into TDMA frames, each frame includes a specific number of slots. During the reading process, each active tag randomly assigns itself to one of the available slots in a frame. Therefore, each slot can take one of the three different states: 1) Successful Slot: Only one tag chooses this slot, is fully identified, and then deactivated by the reader within the following frames. 2) Collided Slot: Multiple tags reply, resulting in a collision. The collided tags normally remain in their active state and retry their transmission in the next frame. 3) Idle Slot: No tag responds and the slot remains unused.

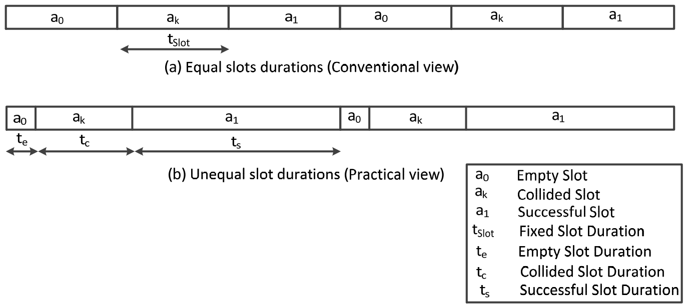


Figure 1: Equal and unequal views of slots in Frame Slotted ALOHA with frame length $L = 6$.

Increasing the reading speed can directly be translated into the maximization of the number of successful slots wrt. the number of idle or collided slots. Based on the Random Access Theory, for a given number of tags n, the expected number of empty E, successful S, and collided C slots in each frame with a length of L slots can be expressed by the following equations [3]:

$$E = L\left(1 - \frac{1}{L}\right)^n, \; S = n\left(1 - \frac{1}{L}\right)^{n-1}, \; C = L - E - S \tag{1}$$

The conventional definition of the expected reading efficiency η_{conv} is given by the ratio between the expected number of successful slots S in a frame and the frame length L [4]:

$$\eta_{conv} = \frac{S}{L} \tag{2}$$

Based on (1) and (2), this results in the conventional efficiency:

$$\eta_{conv} = \frac{n}{L}\left(1 - \frac{1}{L}\right)^{n-1} \tag{3}$$

The main goal for optimizing the FSA algorithm is finding the optimal frame length L, which maximizes the reading efficiency η_{conv}. Based on (3), the reading efficiency η_{conv} is maximized when $L_{opt} = n$ as shown in [4]. In [5], [6] the authors proposed another formula for the optimal frame length that minimizes the total census delay, i.e $L_{opt} = \frac{n}{ln(2)}$. Moreover, [3] computes the optimum frame length empirically, which minimizes the reading time which almost matches the results in [5], [6]. However, in practice efficient RFID readers can quickly identify the type of a slot (i.e. idle, successful, or collided). Hence, the durations of the different slot types are not identical, which reduces the overall reading time. Figure

1 shows two frames, each one with a frame length of $L = 6$ slots. The first frame in (a) presents the conventional view of the frame with equal slots durations t_{Slot} for all slot types. The second frame in (b) presents the behavior of the real RFID slots behavior. Here, the slot duration depends on the slot type. In the recent years, some research groups concentrated on optimizing the frame length in the case of non-equal slot durations: [7], and [8], proposed a numerical solution for the optimal frame length. This method depends on searching for the optimal frame length which maximizes the reading efficiency. Moreover, this searching depends also on the tag to reader data rate, which makes the searching process more complicated. [9] optimized the mean number of resolved tags in unit time by taking into consideration the different slot durations. However, this approach bases on a complex multidimensional table look-up, which is relatively time consuming. [10] proposed to search for the optimum frame length that minimizes the mean time needed to resolve a bunch of tags. However, the author reached to a recursive Bellman-equation, which is complex to be applied in systems with real time restrictions. In this paper, we propose a novel closed form solution for the optimum frame length in FSA for RFID systems. The proposed solution gives a direct relation between the frame length L, and the number of tags n in the reading area. Furthermore, it includes a factor representing the different slot durations.

This paper is organized as follows: Section II presents the proposed closed form for the optimal frame length based on the Time-Aware FSA efficiency. Next, section III shows how theoretically we calculate the slots duration constant for the ISO 18000-6C protocol in addition to a real measurements example of one collided and empty slot duration. Finally, section IV gives numerical results proofing the validation of the proposed formula compared to the numerical solution, and shows the improvements of the new optimization criterion, before we conclude in section V.

II. PROPOSED OPTIMAL FRAME LENGTH FOR UNEQUAL SLOT DURATIONS

For calculating the proposed optimal Time-Aware frame size L_{TA}, which takes into consideration the different slot durations, we firstly have to define the Time-Aware reading efficiency η_{TA}. Let the Time-Aware reading efficiency be the ratio between the total successful time and the total frame time:

$$\eta_{TA} = \frac{t_s \cdot S}{t_e \cdot E + t_s \cdot S + t_c \cdot C}, \tag{4}$$

where $t_s \cdot S$, $t_e \cdot E$, and $t_c \cdot E$ are respectively the expected total successful, idle, and collided times. Furthermore, S, E, and C are the expected numbers of successful, empty and collided slots, and t_s, t_e, t_c are respectively the successful, idle, and collided slot durations. The next step is to derive the new optimum frame length L_{TA} under the Time-Aware environment. L_{TA} can be optimized by finding the value of L which maximizes the Time-Aware reading efficiency. This is achieved by differentiating the reading efficiency in (4) with respect to the frame length L and equate the result to zero:

$$\frac{\partial \eta_{TA}}{\partial L} = 0 \tag{5}$$

According to (1), E, S, and C are a function of L. Taking into account that t_e, t_s, t_c are constants for a given system specification, we get:

$$\frac{(t_eE + t_sS + t_cC)t_s\frac{\partial}{\partial L}(S) - t_sS\frac{\partial}{\partial L}(t_eE + t_sS + t_cC)}{(t_eE + t_sS + t_cC)^2} = 0 \tag{6}$$

After multiplying both sides by the denominator and dividing by t_s (non-zero constant), the equation can be simplified to:

$$(t_eE + t_cC)\frac{\partial}{\partial L}(S) + t_sS\frac{\partial}{\partial L}(S) = S\frac{\partial}{\partial L}(t_eE + t_cC) + t_sS\frac{\partial}{\partial L}S \tag{7}$$

After subtracting the term which is multiplied by t_s, the equation finally results in:

$$\{t_eE + t_cC\}\frac{\partial}{\partial L}(S) = S\frac{\partial}{\partial L}\{t_eE + t_cC\} \tag{8}$$

Then, substituting the values of E, S, and C from (1) leads to:

$$\begin{aligned}&\left\{\underbrace{t_eL\left(1-\frac{1}{L}\right)^n}_{E} + t_c\underbrace{(L - \left(1-\frac{1}{L}\right)^{n-1}(L-n-1))}_{C}\right\} \\ &\times\frac{\partial}{\partial L}\underbrace{n\left(1-\frac{1}{L}\right)^{n-1}}_{S} \\ &= \underbrace{n\left(1-\frac{1}{L}\right)^{n-1}}_{S} \\ &\times\frac{\partial}{\partial L}\left\{\underbrace{t_eL\left(1-\frac{1}{L}\right)^n}_{E} + t_c\underbrace{(L - \left(1-\frac{1}{L}\right)^{n-1}(L-n-1))}_{C}\right\}\end{aligned} \tag{9}$$

By simplifying the result, the final exact equation for the proposed Time-Aware frame length is given by the implicit equation:

$$\left(1 - \frac{n}{L_{TA}}\right) = (1 - C_t)\left(1 - \frac{1}{L_{TA}}\right)^n, \tag{10}$$

where n is the number of tags, and C_t is the slot duration constant defined as $C_t = \frac{t_e}{t_c}$ with $0 < C_t \leq 1$, as $t_e \leq t_c$ in practical applications. (10) shows the exact relation between the proposed Time-Aware frame length L_{TA} and the number of tags n, which takes into consideration the time difference in the slot durations.

Unfortunately, (10) is an implicit equation. We will now derive an approximate, but explicit equation. (10) can be also expressed as:

$$\left(1 - \frac{1}{\beta}\right) = (1 - C_t)\left(1 - \frac{1}{\beta n}\right)^n, \tag{11}$$

where $\beta = \frac{L_{TA}}{n}$. As we are focusing on systems with many tags we can use the approximation

$$\lim_{n\to\infty}\left(1 - \frac{1}{\beta n}\right)^n = e^{-\frac{1}{\beta}}, \tag{12}$$

which simplifies (10) to:

$$\left(1 - \frac{1}{\beta}\right) = (1 - C_t)\, e^{-\frac{1}{\beta}}. \tag{13}$$

Analysis of (10) indicate that the relevant values for $\beta = \frac{L_{TA}}{n}$ are in the region close to one. Hence, we can develop a Taylor series for $e^{-\frac{1}{\beta}}$ around one which leads to:

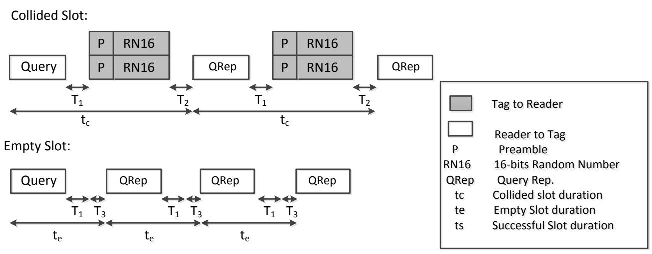


Figure 2: Slot durations during tag inventory rounds for the ISO 18000-6C standard

$$e^{-\frac{1}{\beta}} \simeq 1 - \frac{1}{\beta} + \frac{1}{2\beta^2} \tag{14}$$

After substituting (13) and additional simplifications we get:

$$\beta^2 C_t - \beta C_t + 0.5(C_t - 1) = 0 \tag{15}$$

By solving (15), and rejecting the negative solution we finally obtain:

$$L_{TA} = \frac{n}{2}\left(1 + \sqrt{\frac{2}{C_t} - 1}\right) \tag{16}$$

The proposed equation gives a linear relation wrt. the number of tags n, and includes the slot duration constant C_t, which can be easily varied as a function of the transmission rate and the working standard.

III. SLOT DURATION CONSTANT CALCULATION FOR THE ISO 18000-6C PROTOCOL

In this section, we will discuss in details how we calculate the slot duration constant C_t from the physical layer parameters. Figure 2 shows the timings of collided and empty slots. Each slot contains different sequences of reader to tag commands and tag replies. Based on the EPCglobal C1 G2 standard [1], the slot duration constant is

$$C_t = \frac{t_e}{t_c}, \tag{17}$$

where the empty slot duration t_e is given by:

$$t_e = T_{QRep} + T_1 + T_3. \tag{18}$$

Here, T_{QRep} is the query repeat command time:

$$T_{QRep} = T_{FS} + T_{command}, \tag{19}$$

with, $T_{FS} = 3.5 \cdot T_{ari}$, $T_{command} = 6 \cdot T_{ari}$, and $T_{ari} = \frac{DR}{2.75} T_{pri}$. By substituting in (19) we get

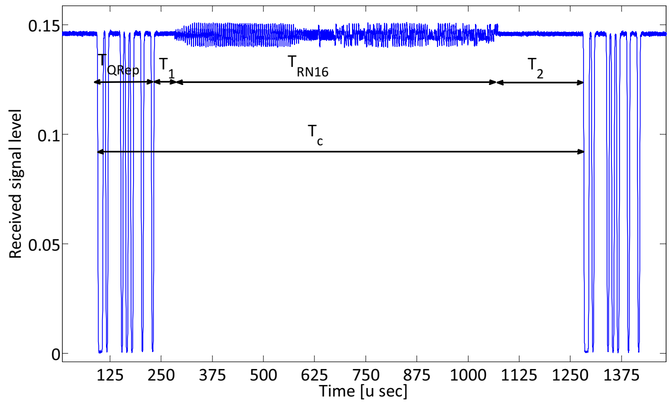
$$T_{QRep} = 3.5 \cdot DR \cdot T_{pri}, \tag{20}$$

where T_{ari} is reader symbol duration, $T_{pri} = \frac{1}{BLF}$, BLF is the tag backscatter link frequency and DR is the so-called divide ratio constant that can take the two values $DR = 8$ or $\frac{64}{3}$. Finally, M equals to 1, 2, 4, or 8, which represents the modulation types FM0, Miller 2, 4, or 8, respectively. T_1 is the time from the reader transmission to the tag response, which can be expressed as:

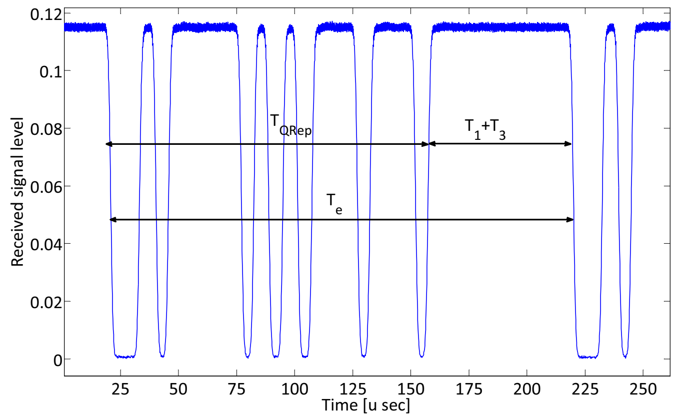
$$T_1 = \max\{DR \cdot T_{pri}, 10 \cdot T_{pri}\} \tag{21}$$

Table I: Available slots duration constants C_t of the EPCglobal C1 G2 standards

Divide Ratio: DR	Modulation: M	Pilot Length: n_p	C_t
8	1	0	0.47
		12	0.41
	2	4	0.35
		16	0.28
	4	4	0.23
		16	0.18
	8	4	0.14
		16	0.1
64/3	1	0	0.7
		12	0.65
	2	4	0.57
		16	0.5
	4	4	0.43
		16	0.35
	8	4	0.3
		16	0.22



(a) Collided slot timing



(b) Empty slot timing

Figure 3: Slots durations measurements, $f_s = 8\,\text{MHz}$, tag Backscatter Link Frequency $BLF = 160\,\text{kbps}$

Next, T_3 is the time that the reader waits after T_1 before issuing another command. As it has no constraints, it can be assumed to be zero. After substituting (20) and (21) in (18), t_e can be expressed as:

$$t_e = T_{pri} \cdot (3.5 \cdot DR + \max\{DR, 10\}). \tag{22}$$

Next, the collided slot duration t_c is given by:

$$t_c = T_{QRep} + T_1 + T_2 + T_{RN16}, \tag{23}$$

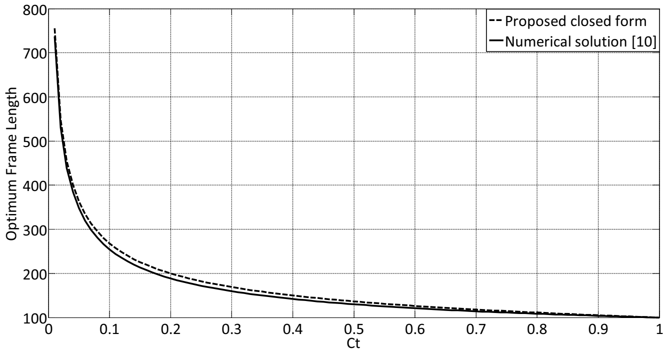


Figure 4: Optimum frame length L_{TA} as a function of the slot duration constant C_t ($n = 100$ tags). The conventional case with identical slot durations corresponds to $C_t = 1$.

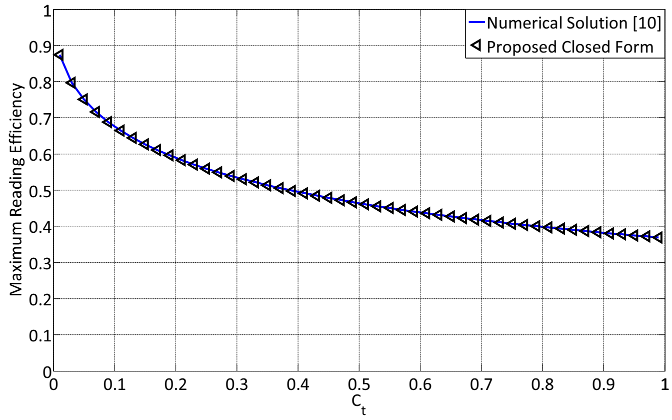


Figure 5: Maximum reading efficiency

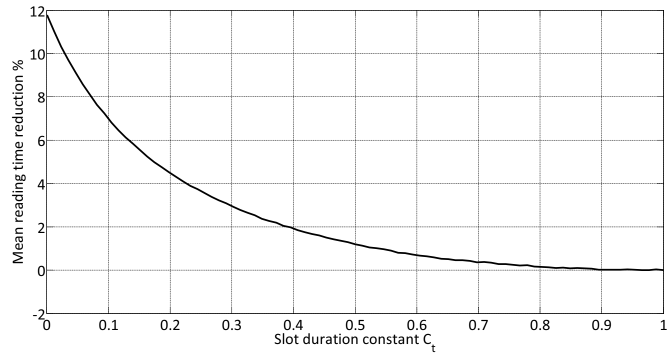


Figure 6: Percentages of saving time using the proposed TAFSA for an ideally known number of tags (1000 iterations for each step)

where T_2 is the reader response time starting from the end of the tag response, $T_2 = 6 \cdot T_{pri}$, and T_{RN16} is the duration of 16 bits temporary data, 6 bits preamble, n_p pilot tones, i.e. $T_{RN16} = (22 + n_p) \cdot T_{pri}$. Therefore, t_c can be expressed as:

$$t_c = T_{pri} \cdot (3.5 \cdot DR + \max\{DR,\, 10\} + 6 + 22 \cdot M + n_p \cdot M)\,. \quad (24)$$

From equations (22) and (24), the final expression of C_t is:

$$C_t = \frac{3.5 \cdot DR + \max\{DR,\, 10\}}{3.5 \cdot DR + \max\{DR,\, 10\} + 6 + 22 \cdot M + n_p \cdot M}\,. \quad (25)$$

Table I shows the values of the slots durations constant of the EPCglobal C1 G2 standards. According to table I, the slot duration constant C_t varies from 0.1 to 0.7, and this affects the optimum frame length directly.

Figure 3 shows an example of a real measurements for slots durations using a Universal Software Radio Peripheral (USRP B210) [11]. In these measurements, we used sampling frequency of $f_s = 8\,\mathrm{MHz}$, because the total RFID bandwidth in the European system is $4\,\mathrm{MHz}$, tags Backscatter Link Frequency $BLF = 160\,\mathrm{kbps}$. Furthermore, we used the modulation type Miller $M = 4$ with extended pilots, $n_p = 16$. According to figure 3, the slot duration constant $C_t = 0.18$, which verify the theoretical results in table I.

IV. SIMULATION RESULTS

Figure 4 shows the behavior of the proposed frame length formula in (16) compared to the numerical solution in [10] for the complete range the slot duration constant C_t for $0 < C_t \leq 1$. In the simulation, we used a fixed number of $n = 100$ tags. According to figure 4, the proposed equation approaches the numerical solution proposed at [10] in the full range of C_t with a very small bias comes from the Taylor series approximation in (14). Figure 5 shows a the maximum reading efficiency using the proposed frame length formula in (16) and the numerical solution of the frame length proposed in [10]. According to figure 5, the proposed formula gives identical results with the numerical solution. However, unlike the complex table look-up presented in [10], our approach only is based on a linear equation, which is a function of the number of tags n.

Figure 6 shows simulation results for the reading time reduction of the proposed optimal Time-Aware frame length L_{TA} wrt. the classical optimal frame length $L = n$ as a function of the slot duration constant C_t. These simulations assume a perfect knowledge of the number of tags n. According to the figure, $C_t = 0$ means that the idle slot duration time t_e is quite small wrt. the collided slot duration time t_c. In this case, the proposed Time-Aware frame length can reduce the average reading time by up to 12% compared to the conventional optimization criterion. With $C_t = 1$, which means that the slot durations are of identical length, we obtain the efficiency of the classical optimization, i.e. $L = n$. According to practical example in section III, we have a slot duration constant $C_t = 0.18$. Based on (16), the optimum frame length should be $L_{TA} = 2n$. In this case we can expect an average reading time reduction of $5\,\%$.

In practice, the number of tags in the interrogation region is unknown. Hence, the anti-collision algorithms in real RFID systems consist of two stages: The first stage estimates the number of tags in the interrogation area $\hat{n}$. The second stage calculates the optimal frame length L_{opt} based on $\hat{n}$ for maximizing the reading efficiency. Figure 7 shows the mean reduction of the reading time using the proposed Time-Aware frame length for some well-known tag estimation algorithms using the value of the slot duration constant $C_t = 0.18$. The main issue of these simulations is to show the practical effect on the reading time by working with the proposed frame length using different tag estimation algorithms. Each curve presents the mean reduction

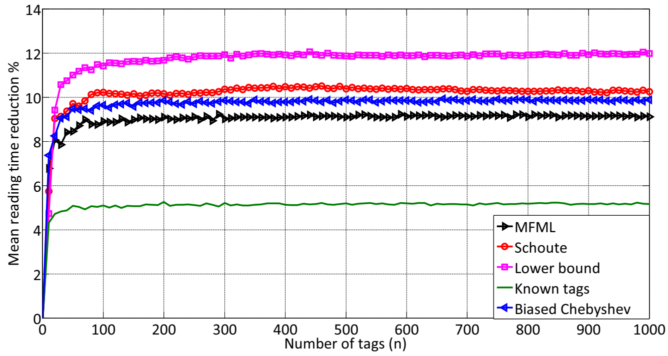


Figure 7: Percentages of saving time using the proposed TAFSA for different anti-collision algorithms (1000 iterations for each step)

of the reading time between the proposed frame length and the conventional frame length using the same estimation algorithm. When a simple tag estimation technique is used like Lower bound [3] or Schoute [12], we can reduce the reading time in the order of 10 to 12 %, and we gain around 9 % for better estimation algorithms like MFML [13] and Biased Chebyshev [14]. According to figure 7, in case of better estimation algorithms, the mean reading time reduction approaches the curves assuming perfect knowledge of the number of tags. As a result, the newly proposed closed form algorithm provides additional improvements wrt. the classical optimization algorithm when the tag estimation provides inaccurate results.

V. Conclusion

This paper proposes a novel closed form solution for the optimum frame length in unequal slot duration FSA. The theoretical derivations lead to a new optimization criterion that can be easily implemented in RFID readers. The proposed frame length equation gives the most accurate results compared to the exact solution, and the numerical methods. However, we propose a direct linear relation with the number of tags in the reading area. The proposed optimization method reduces the average reading time by 5 % in case of a perfect knowledge of the number of tags. In realistic systems, where the number of tags has to be estimated, the gain reaches up to 12 %.

The future work will especially focus on additional improvements, if the exact number of tags is unknown, and the initial frame size is optimized.

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