Optimum frame-length configuration in passive RFID systems installations

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Abstract. Anti-collision mechanisms in RFID, including current standards, are variations of Aloha and Frame Slotted Aloha (FSA). The identification process starts when the reader announces the length of a frame (in number of slots). Tags receive the information and randomly choose a slot in that cycle to transmit their identifier number. The best performance of FSA always requires working with the optimum frame-length in each cycle. However, it is not a parameter easy to adjust in real RFID readers. In this work a markovian analysis is proposed to find the optimum value of frame-length for the current readers of the market. Besides, to validate and contrast the analytical results, a real passive RFID system has been used to get experimental results: the development kit Alien 8800. The experimental results match the analysis predictions.

1 Introduction

In passive RFID systems, the communication between readers and tags takes place in a shared communication channel. When the number of tags in coverage area is high, a medium access mechanism (MAC) is needed to minimize the collisions that happen by the simultaneous transmissions. Since passive tags hardware is too simple, the complexity of the anti-collision protocol must rely on the reader.

Anti-collision mechanisms in passive RFID, including current standards, are variations of Aloha and Frame Slotted Aloha (FSA) [1]. In FSA the time is divided into frames (identification cycles) and these are in its turn subdivided into slots.

The identification process starts when the reader announces the length of a frame or cycle (in number of slots). Tags in coverage receive the information and randomly choose a slot in that cycle to transmit their identifier number. The FSA throughput depends on the relationship between the number of tags to identify and the frame length. If the number of tags in coverage is much more higher than the number of slots, the identification time is considerable increased because a lot of collisions may occur and a potentially large number of cycles are necessary to all tags in coverage successfully dump their data. On the other hand, if the number of tags in coverage is low and the number of slots to compete is high, a lot of empty slots will succeed, and this also increases the identification time. The best performance of anti-collision protocols based on FSA always requires working with the optimum number of slots (frame-length) in each cycle. However, it is not a parameter easy to adjust in real RFID readers. Depending on the level of frame-length configuration, the readers available in the market can be classified as:

- Readers with static and fixed frame, without user configuration [2-6]. Identification cycles are fixed and set up by the manufacturer. It is not possible to modify by the user (it is usually fixed to 16 slots). Therefore, these readers are not able to optimize the frame-length.
- Readers with static and fixed cycle with user configuration [6-8]. Before starting the identification procedure the user can configure the frame length, choosing between several values, which depend on the manufacturer. Then, the identification cycle cannot be changed. If the user wants to establish a different value of frame-length, it is necessary to stop the identification procedure and restart with the new value of frame-length.
- Readers with dynamic cycle [6-8]. The user only configures the frame-length for the first cycle. Then the frame-length is self-adjusted trying to adapt to the best value in each moment, following the standard proposal [9].

We are interested in the testing scenario in which a fixed and known number of tags N enter in coverage simultaneously. The main goal of this paper is to comparatively study two different situations:

1. Systems based on a reader with static cycle length. A markovian analysis is proposed to find the optimum value of frame-length which minimizes the total identification time.
2. Systems based on a reader with a dynamic frame-length. We assume that the reader knows in every cycle the number of contending tags (not identified in previous cycles). Ideally, it is well-known that the frame- length must be made equal to the number of contending tags to maximize the system throughput. Nevertheless, the standard constraints the feasible frame-lengths to a reduced set of possibilities: the natural numbers power of two from 2^0 to 2^{15}. Our study explores this problem, to obtain the feasible frame-length which maximizes the throughput in each cycle, minimizing the total identification time.

The results permit to calculate the optimum value of the frame-length for the two types of readers shown above. Besides, to validate and contrast the analytical results, a real passive RFID system has been used to get experimental results: the development kit Alien 8800 [9]. Different frame-length values have been configured to get the total identification time with several populations of tags. The experimental results match up the analysis predictions.

The rest of the paper is organized as follows: Section 2 introduces a brief description about related works. Section 3 shows the markovian analytical study of the standard, oriented to readers with static frame. Section 4 describes the experimental results of the real passive RFID System used. Finally section 5 resumes the main conclusions extracted of this work.

2 Related work

A relevant set of performance studies has been conducted in the last years for anti-collision protocols based on FSA for passive RFID systems [10-18]. Most of them propose variations to the EPCglobal Class-1 Gen-2 standard or new algorithms to improve the frame adaptation. In [12] the authors propose that if the number of slots per frame and the number of tags in coverage is known, other standard parameters can be modified to reduce the identification time. However, nowadays it is not possible to find commercial readers which permit the tuning of those configuration parameters. In [13-14] the authors propose a set of anti-collision protocols that require extra hardware in the tags, which increases the final cost of the RFID systems.

Some works have proposed improvements of the adaptive frame algorithm of EPCglobal Class-1 Gen-2. Some of these add a heuristic to estimate the number of tags that compete in each cycle [15-18]. In this way, the reader is able to get a more accurate when has to establish the optimal frame-length in each cycle. However, these works do not take into account that, when these estimation algorithms are implemented with the standard EPCglobal Class-1 Gen-2, the optimum number of slots per cycle must be adjusted to the power-of-two values permitted by the standard. Therefore, the results of these works do not correspond to a real behavior of a commercial reader.

3 Performance Analysis

In this section we describe the markovian analysis for systems with a fixed length cycle. Our analysis is based on a variation of the analysis in [19]. The identification process of a RFID system is modeled as (homogeneous) Markov process $\{X_s\}$, where $\{X_s\}$ denotes the number of tags unidentified at the *s* identification cycle. Assuming *N tags* enter the coverage area of the reader, the state space of the Markov process is denoted as $\{N, N\text{-}1,\ldots, 0\}$.The probability distribution of μ_r indicates that the number of busy slots with exactly *r tags* is:

$$P_{K,N}(\mu_r = m) = \frac{\binom{K}{m} \prod_{i=0}^{m-1} \binom{N-ir}{r} G(K-m, N-mr, r)}{K^N} \tag{1}$$

where m=0,...,k and:

$$G(M,l,v) = M^l + \sum_{i=1}^{\left\lfloor \frac{l}{v} \right\rfloor} \left\{ (-1)^i \prod_{j=0}^{i-1} \left\{ \binom{l-jv}{v} \left(M-j\right) \right\} (M-i)^{l-iv} \frac{1}{i!} \right\} \tag{2}$$

In [19] all tags in coverage compete in every identification cycle. We modify and adapt the analysis proposed in [19] to the case of the EPCglobal Class-1 Gen-2 standard. Therefore, tags identified in a cycle will not compete in the following ones. The transition matrix H and transition probabilities are given by:

$$h_{i,j} = \begin{cases} P_{K,N-i}(\mu_1 = j-i), & i < j \leq i+K \\ 1 - \sum_{k=i+1}^{i+K} h_{j,k}, & i = j \\ 0, & otherwise \end{cases} \tag{3}$$

where $i = 0,\ldots,N$. We assume static scenario, where there are not new tag arrivals. Therefore, the Markov chain is absorbent. If the identification process starts in a non absorbent state v_i (there are not tags identified), the number of steps up to the absorbent state (average number of identification cycles) $\overline{D_{id}}$ is equal to the sum of the entries of the i-th row of D matrix, which is denoted by:

$$D = (I - F)^{-1} \tag{4}$$

D is the fundamental matrix of the absorbent chain. I is the identity matrix. F is the submatrix of H with non-absorbent states of transition matrix H (see [20]). Table 1 shows the analytical results with different values of number of slots per cycle ($K=2^Q$) and number of tags. This analysis has been computed with Matlab tool [21].

Table 1. Average number of identification cycles.

	Number of slots (*K*) = 2^Q				
***Tags*(*N*)**	**4**	**8**	**16**	**32**	**64**
10	8.2	3.67	2.44	1.89	1.54
20	60	8.56	4.11	2.76	2.15
30	630	19.6	6.15	3.60	2.61
40	8159	49.4	8.97	4.47	3.06
50	$1.1\ 10^5$	138	13.03	5.424	3.465
60	$1.6\ 10^6$	413.9	19.3	6.50	3.90
70	$2.5\ 10^7$	1304.2	29.41	7.76	4.32
80	$3.8\ 10^8$	4244.6	46.0	9.26	4.77
90	$6\ 10^9$	14127	73.81	11	5.23

As Table 1 shows, if we only compare the average number of identification cycles, as the number of slots per cycle increases, the results are better. However, this evaluation criterion is not significant because each identification cycle has not the same time duration. The duration depends on the number of slots per cycle, that is, the frame-length. Table 2 shows the same analysis results but measured as the average number of slots per frame. In this case, the average number of slots to identify all tags depends on, not only the number of tags that compete to be identified, but also the number of slots per cycle established.

Table 2. Average number of slots

	Number of slots (K)=2Q				
Tags(N)	**4**	**8**	**16**	**32**	**64**
10	32.8	29.36	39.04	60.48	98.56
20	240	68.48	65.76	88.32	137.6
30	2520	156.8	98.4	115.2	167.04
40	32636	395.2	143.52	143.04	195.84
50	$4.4\ 10^{5}$	1104	208.48	173.56	221.76
60	$6.4\ 10^{6}$	3311.2	308.8	208	249.6
70	10^{8}	10^{4}	470.56	248.32	276.48
80	$1.5\ 10^{9}$	$3.3\ 10^{4}$	736	296.32	305.28
90	$2.4\ 10^{10}$	$1.1\ 10^{5}$	$1.1\ 10^{3}$	352	334.72

It is important to emphasize that EPCglobal Class-1 Gen-2 can work in dynamic mode, where the number of slots (frame-length) can change cycle by cycle. An empty slot or a collision slot has not the same duration that a successful slot or a data slot. To check if the criteria assumed to evaluate if the total number of slots is adequate, we must show the results in terms of average identification time. This is calculated as:

$$\overline{T}_{total} \approx \overline{\mathrm{D}}_{\mathrm{id}} \cdot \left[\overline{k}_v \cdot T_v + \overline{k}_c \cdot T_c + \overline{k}_{id} \cdot T_{id} \right] \tag{5}$$

where $\overline{k}_v$, $\overline{k}_c$ and $\overline{k}_{id}$ are the average number of empty, collision and successful slots. T_v is the duration of an empty slot, T_c the duration of a collision slot and T_{id} is the duration of a slot with a valid data transmission. Since the slot length depends on the data length sent by the tag, we always suppose the maximum duration, it means, all tags always transmit a complete EPC code of 96 bits. The time slot depends on the parameters of the devices employed. In this work we use the default parameters of the standard specifications [9]. We observed the following results: T_i= 2.505·ms and T_v= T_c=0.575 ms. Since an empty and a collision slot have the same temporal duration, the equation (5) is simplified:

$$\overline{T}_{total} \approx \overline{\mathrm{D}}_{\mathrm{id}} \cdot \left[(\overline{k}_v + \overline{k}_c) \cdot T_c + \overline{k}_{id} \cdot T_{id} \right] \tag{6}$$

where,

$$\overline{k}_v + \overline{k}_c = \sum_{s=1}^{\overline{\mathrm{D}}_{\mathrm{id}}} \frac{(k_s - n_s)}{s} \tag{7}$$

k_s is the number of contention slots in the cycle s and n_s, $0 \leq n_s \leq N$, is the number of tags identified in each cycle s before the absorption ($\overline{D}_{id}$). The results of average identification time are shown in Table 3. If we compare Table 2 and 3, it can check that the criterion to evaluate the total number of slots is valid and the results are analogs. Since the number of operations involved in the last formulas (3) and (4) increase exponentially with the number of tags and slots, the use of them is limited to low values of competing tags (*N*). In order to extend the results of the above analysis, we have developed a simulator of RFID systems. The objective is to get the average number of slots when a potentially large number of tags compete to be identified. The simulator has been developed with the OMNeT++(*Objective Modular Network Test-*

bed in C++) tool. The following sections present the results obtained by means of simulation [22].

Table 3. Average identification time

	Número de *slots* (*K*) = 2^Q				
Tags(N)	**4**	**8**	**16**	**32**	**64**
10	0.0379	0.0354	0.0395	0.0494	0.0647
20	0.1742	0.0772	0.0738	0.0869	0.1110
30	1.5902	0.1476	0.1126	0.1198	0.1443
40	18.409	0.3011	0.1564	0.1555	0.1830
50	270.37	0.7223	0.2151	0.1910	0.2176
60	$2.06\cdot10^{3}$	2.0219	0.2914	0.2316	0.2498
70	$4.23\cdot10^{5}$	6.3209	0.3988	0.2732	0.2851
80	$94.5\cdot10^{6}$	19.758	0.5662	0.3209	0.3219
90	$71.2\cdot10^{8}$	65.765	0.8340	0.3753	0.3598

3.1 Scenario 1: Reader with static cycle

In the first scenario we simulate a system with a configurable reader with static cycle. It permits to configure the number of slots per cycle with the values of $Q \in [0,..., 15]$. We have simulated different population of tags in coverage. Fig. 1 shows the average number of slots per cycle, as a function of the number of tags in coverage. One curve is plotted for each value of *Q* parameter. Each curve defines an interval where the number of slots wasted to identify the population of tags is minimal with respect to the other curves. To get the optimum configuration, we have to check the limits of these intervals, that is, the intersection points with the other curves. From Fig 1 we get the Table 4 where we show the values of these intersections, and the *Q* value associated.

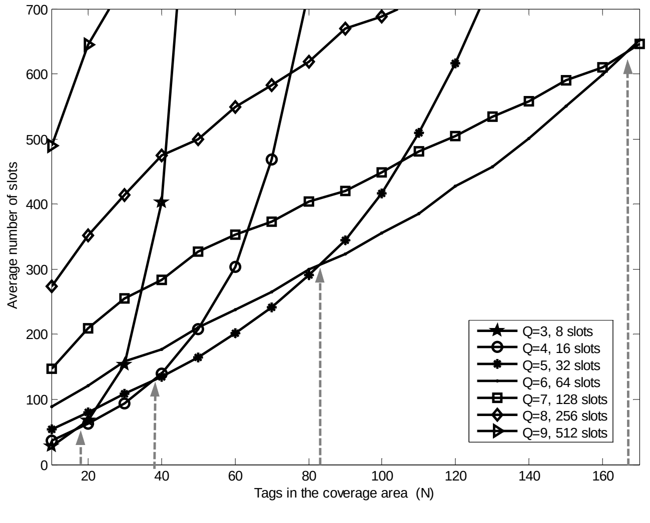

Fig. 1. Scenario 1. Identification rate vs number of tags for different values of *Q*.

Table 4. Optimum *Q* that minimizes the average number of slots

Optimal Q	*Number of slots (K)= 2^Q*	**Tags in coverage (*N*)**
1	2	$N \leq 4$
2	4	$4 \leq N < 8$
3	8	$8 \leq N < 19$
4	16	$19 \leq N < 38$
5	32	$38 \leq N < 85$
6	64	$85 \leq N < 165$
7	128	$165 \leq N < 340$
8	256	$340 \leq N < 720$
9	512	$720 \leq N < 1260$
10	1024	$1260 \leq N < 2855$
11	2048	$2855 \leq N < 5955$
12	4096	$5955 \leq N < 12124$
13	8192	$12124 \leq N < 25225$
14	16384	$25225 \leq N < 57432$
15	32768	$57432 \leq N$

3.2 Scenario 2: Reader with dynamic cycle

Currently, most of readers incorporate the adaptive algorithm proposed by the EPCglobal Class-1 Gen-2 standard [9]. This algorithm works to get the *Q* value that maximizes the identification rate, that is, the number of tags identified per slot. This result is useful in scenarios where the reader has *a priori* knowledge about the number of tags that compete in each cycle. In this case, we can get the *Q* value that maximizes the identification rate. We use the simulator to evaluate this metric, establishing the same value of tags competing in each cycle. Hence, we get the average identification rate for different *Q* values. From these simulations we get the Fig. 2 where we check that, for different values of *Q*, the maximum identification rate is 0.36, that is, the best theoretical value of FSA. To get a better view in Fig 2, we only show the values between $Q \in [2,...,7]$. From Fig 2 we extract the Table 5 where we indicate the optimum *Q* value that maximizes the number of identifications in a cycle. The limits established in each *Q* value are the intersections between two consecutives curves of *Q*.

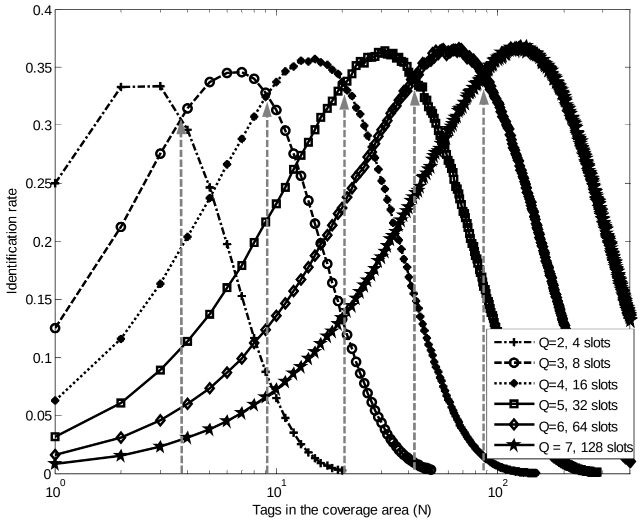

Fig. 2. Scenario 2. Identification rate vs number of tags for different values of *Q*.

Table 5. Optimum *Q* that maximizes the identification rate per cycle

Optimal Q	***Number of slots (K)= 2^Q***	***Tags* in coverage (*N*)**
1	2	$N \le 2$
2	4	$2 \le N < 4$
3	8	$4 \le N < 9$
4	16	$9 \le N < 20$
5	32	$20 \le N < 42$
6	64	$42 \le N < 87$
7	128	$87 \le N < 179$
8	256	$179 \le N < 364$
9	512	$710 \le N < 1430$
10	1024	$1430 \le N < 2920$
11	2048	$1430 \le N < 2920$
12	4096	$2920 \le N < 5531$
13	8192	$5531 \le N < 11527$
14	16384	$11527 \le N < 23962$
15	32768	$23962 \le N$

4. Experimental results: RFID system Alien 8800

An experimental validation of the results has been conducted. We have used the passive RFID kit Alien 8800 [9]. It works with EPCglobal Class-1 Gen-2 and its FSA anti-collision protocol in UHF band (868-929MHz). The kit is composed by two circular polarization antennas, installed face to face, at two meters of distance. One acts as transmitter and the other one as receiver. The reader only permits to choose among $Q \in [4,..., 7]$. For each *Q* value and different populations of tags we have measured the total identification time because this is the only parameter that the Alien reader gives us. Each experiment has been repeated up to 100 times. The results are shown in table 6. The experimental results are close to the analysis and simulation results. We have to take into account that the ambient conditions can affect to the final experimental results.

Table 6. Average identification time in experimental results.

	Number of *slots* (*K*) = 2^Q			
Tags(N)	**8**	**16**	**32**	**64**
10	0.041	0.042	0.067	0.089
20	0.091	0.089	0.911	0.142
30	0.157	0.139	0.143	0.163
40	0.340	0.172	0.192	0.189
50	0.823	0.243	0.201	0.241
60	2.021	0.311	0.253	0.279
70	5.213	0.414	0.298	0.296
80	12.25	0.697	0.348	0.349
90	53.66	0.921	0.394	0.379

5. Conclusions

In this work we analyzed the optimum configuration of frame-length (*Q* parameter) in different RFID readers, attending to the population of tags to identify. We have studied two operation modes in RFID readers that correspond to the readers of the real market: readers with fixed cycle and readers with frame-length adjusted dynamically. Our results show that there are significant differences between the two scenarios studied. For instance, if we work with a reader with static cycle and we set *Q*=5, we get that the better response will be with a population of tags between 20 and 42. On the contrary, in a reader with dynamic cycle, the same *Q* value determines that the population should be between 38 and 85 tags.

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