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Characterization of the Identification Process in RFID Systems

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1. Introduction

Radio Frequency Identification (RFID) is increasingly being used to identify and track objects in supply chains, manufacturing process, product traceability, *etc*. These environments are characterized by a large number of items which commonly flow in conveyor belts, pallets and lorries, entering and leaving logistic installations. In these scenarios the RFID systems are installed as follows: one or more readers are placed in a strategic place, creating checking areas. The tags, attached to items, enter and leave the checking areas (traffic flow). The goal of RFID in these applications is to guarantee the communication with the tags as quickly and reliably as possible, ensuring that all tags are identified before they leave the checking areas (Finkenzeller, 2003).

One of the main problems related to RFID in these applications is that both readers and tags share the RF spectrum. Hence, when two or more tags/readers transmit simultaneously a collision occurs. The collisions diminish the system performance, producing a delay in the identification, and may cause tags leaving the workspace unidentified. The parameter that measures the rate of unidentified tags is the *Tag Loss Ratio* (TLR). Depending on the application, even a TLR = 10^{-3} may be disastrous and cause thousands of items lost per day.

The collisions resolution on RFID has been extensively studied during the last years, for active and passive RFID systems. In active RFID, the collision resolution is not only mandatory to reduce the identification time, but also to decrease the tag energy consumption in order to maximize the batteries lifetime. In this case, tag hardware permits to put forward sophisticated anti-collision mechanisms. Nevertheless, this complex hardware also entails high-cost-devices and, in the end, the tag price becomes the dominant factor in the final deployment.

On the other hand, in passive RFID, the extreme simplicity of the tags is a hard constraint for the design of new collision resolution methods. However, the low-cost-price of passive tags is its most attractive characteristic which permits to think about a massive adoption in a near future. Several proposals have been conducted during the last years with the aim at minimizing the collision problems in passive RFID systems, suggesting new anti-collision protocols that, *a priori*, outperform the current standards. Most of these studies have been

addressed assuming *static* scenarios, that is, populations of tags that enter the workspace and stay there until all of them are identified, computing throughput (rate of identified tags per time unit), and the mean identification time. Although these results provide us insight into the performance of the algorithms, do not help to discern the conditions and phenomena which render to have uncontrolled tags (tags which are not identified when they leave the workspace) in *dynamic* scenarios, *i.e.,* scenarios where tags are entering and leaving the workspace.

In this chapter the analysis of the identification process is addressed either in static (section 4) and dynamic scenarios (section 5). In the former, the mean identification time is computed for the standard EPCglobal Class-1 Gen-2 anti-collision protocol (*Framed-Slotted-Aloha,* FSA). For the latter scenario, the rate of unidentified tags is also derived for the standard. Both studies are focused on the *Medium Access Control* (MAC) layer. Before, section 2 describes the identification process in RFID, Section 3 overviews MAC solutions presented in the scientific literature, including the current standard. A brief classification of the current passive RFID readers in the market is also introduced.

2. Identification process overview

Passive RFID technology has been inevitably selected in the majority of the industrial systems with a large number of identification objects. Several reasons can be adduced: The main one is the extremely low-cost of the tags (prices below 0.10 €), as well as lack of maintenance for the tags, reusability, easy installation, *etc*.

Passive RFID systems are installed in industrial environments to collect, automatically and transparently, the information regarding the items that enter and leave the workspace. The information is stored and managed by means of specialized middleware and software. Thus, updated information can be managed in real-time, decreasing the time to recognize, find, locate and manage items, therefore, improving facilities. Besides, RFID makes product traceability possible, which is an important issue in some industrial sectors.

As stated in the introduction, passive RFID system consists of one or more readers or interrogators placed in strategic zones and a potentially large population of cheap and small devices called tags or transponders. The readers transmit electromagnetic waves continuously, creating checking areas. Tags enter and leave the checking areas. To simplify the description in this chapter a passive RFID system with only one reader is assumed (see Fig. 1).

Passive tags are composed by an antenna, a simple electronic circuitry and a minimum amount of memory where it stores some information about the object (*e.g.* standard codes, history of transactions, expiration date). Since passive tags do not incorporate their own battery, they obtain the energy from the electromagnetic waves emitted by the reader (backscatter procedure) (Finkenzeller, 2003). This energy activates the electronic circuitry of the tag, which delivers a signal response with its carried data. Nevertheless, the simplicity of the tags limits their operative range, varying from some centimetres to a pair of meters.

The uplink and downlink communication between the reader and the tags share the RF spectrum. When several tags are in the coverage area at the same time, collisions may occur as a result of simultaneous transmissions. Hence, *Medium Access Control* (MAC) protocols are needed to handle/avoid collisions, but the extreme simplicity of the tags constraints the design of suitable anti-collision protocols. Complex or sophisticated behaviour can only exist in the reader system.
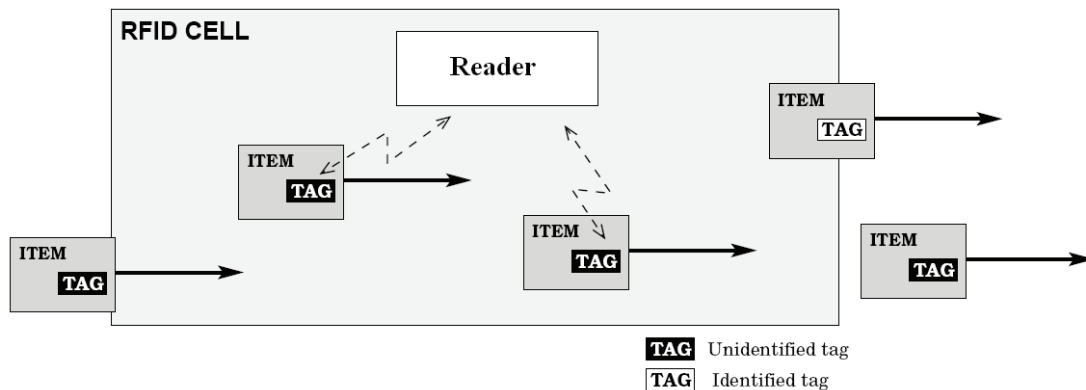
Fig. 1. Passive RFID scenario

During the last decade some standards have been proposed, not only for clarifying the specifications of hardware on passive tags and readers, but also for setting the anti-collision procedure to handle/avoid collisions (ISO, 2003) (EPC, 2004). Since 2005, the standard EPCglobal Class-1 Gen-2 for passive RFID has been the most extended and adopted by the manufacturers. However, it has been outperformed by new anti-collision algorithm proposals. Most of these studies have been addressed assuming *static* scenarios, that is, blocks of tags entering the checking area and staying there until all of them are successful identified. Disappointedly, actual RFID systems may involve a flow of tags entering and leaving the workspace (see Fig. 1). In these scenarios, the collision resolution is not only mandatory to reduce the identification time and to improve the system throughput, but also for minimizing the number of unidentified tags that leave the workspace, that is, the TLR.

3. The collision problem: Anti-collision mechanisms for RFID

Several multiple-access techniques and anti-collision protocols have been developed with the aim of minimizing colliding signals. The anti-collision procedures are focused on the Physical and MAC layer. We review these procedures in the following subsections.

3.1 Anti-collision protocols at Physical layer
At physical layer, FDMA, TDMA, SDMA, CDMA and CSMA have been the alternatives most studied (Finkenzeller, 2003). Albeit they can not be used directly in RFID because the following problems:
• *Frequency Division Multiple Access* (FDMA). The channel is divided into different sub-channels and the users are allocated different carrier frequencies. In RFID systems, this technique adds a cost to the readers, because they must provide a dedicated receiver for every reception channel. On the other hand, tags should be able to distinguish between different frequencies and to select the sub-channels of interest. Only active tags add the previous functionality.
• *Time Division Multiple Access* (TDMA). The channel is divided into time slots that are assigned to the users. One of the most important problems of this technique is the users must be synchronized to send their information in the slot selected. This technique can be applied directly to RFID. For passive RFID systems, the tag's simplicity requires the reader controls the synchronization (centralized). For active RFID system, the

synchronization can be centralized or the tags can control the synchronization themselves (distributed).

- *Space Division Multiple Access* (SDMA). This technique reuses certain resources, such as channel capacity in spatially separated areas. This technique can be applied to an RFID system as follows: in a scenario with two or more readers, the read range of each one is reduced but compensated by forming an array of antennas, providing then a large coverage area. The main drawback is the high implementation cost of the complicated array antennas system.
- *Code Division Multiple Access* (CDMA). It consists of using spread-spectrum modulation techniques based on a pseudo random code to spread the data over the entire spectrum. CDMA is the ideal procedure in many applications, e.g. navigation systems, GPS, *etc.* However, in RFID systems, this technique means more complex hardware in the tags and hence, higher cost.
- *Carrier Sense Multiple Access* (CSMA). This technique requires the tags to sense the channel traffic before sending their information. If there is no traffic, the tag starts to send. This mechanism can be only used with active tags because passive tags cannot monitor the channel.

Many of these solutions are not cost-effective due to the extra complexity of the tag. This is why solutions to the collision issue are usually sought at the MAC layer, tackling the burden of the algorithm at the reader equipment. Besides, new reactive procedures are being explored. Namely, those which extract useful information from colliding signals at Physical layer:

- The application of *Radar-Cross-Section* (RCS) has been proposed in the field of RFID by (Khasgiwale *et al.*, 2009). The number of collided tags is detected by means of the analysis of the RCSs. Then, *Minimum Distance Detector* (MDD) mechanism is used to decode colliding signals. Notice that this technique may only be useful for collisions where only two tags are involved. Indeed, this mechanism has been only simulated using ISO 18000-6C as the underlying standard (ISO, 2003).
- Constellations analysis computes IQ constellations produced by additive simultaneous tag responses, and determines symbol decoding regions of transmissions. This technique has been described for *Low Frequency* (LF) RFID systems in (Shen *et al.*, 2009) and for *Ultra High Frequency* (UHF) in (Angerer *et al.* 2009).

Although these techniques are still immature, the authors point out their feasibility and compatibility with current standards and tags.

3.2 Anti-collision protocols at MAC layer

When a number of tags/readers are presented simultaneously in the coverage area an appropriate *Medium Access Control* (MAC) protocol is needed to handle/avoid collisions caused by simultaneous transmissions. Collisions in RFID occur in a number of ways:

- Case of a single reader-multiple tags collisions. Multiple tags are in the reading range of the same reader and respond simultaneously. The reader detects the electromagnetic wave but is unable to interpret the signal received.
- Case of multiple readers-single tag collisions. Only one tag is in the read range of multiple readers. The interferences occur when the signal from a neighboring reader collides with the tag transmission.
- Case of reader-reader collisions. Multiple readers configured to work within the same frequency band, interfere each other and thus a collision occurs.

Discussion of these three types of collisions would require a complete volume. Therefore, in this chapter, an overview of the single reader-multiple tags collisions is presented, as well as the most relevant anti-collisions proposals.

3.2.1 Tree-based tag anti-collision protocols

Tree-based anti-collision protocols put the computational burden the reader. The reader attempts to recognize a set of tags in the coverage area in several interrogation cycles. Each interrogation cycle consists of a *query* packet, sent by the reader, and the response of tags in coverage. If a set has more than one tag, a collision occurs. When a collision occurs, the mechanism splits the set into two subsets using the tags identification numbers or a random number. The reader keeps on performing the splitting procedure until each set has one tag. Tree-based protocols are not efficient when the number of tags to recognize is large due to the lengthy identification delay (see Fig. 2).

Tree based anti-collision protocols have been extensively studied during the last years (Hush & Wood, 1998; Jacomet *et al.*, 1999; Law *et al.* 2000; Shih *et al.*, 2006; Myung & Lee 2006).

3.2.2 Aloha protocols

Aloha protocols are classified into four main groups. The first one is the *Pure-Aloha* (Leon-Garcia & Widjaja, 1996) protocol which is the simplest anti-collision scheme for passive tags with read-only memory. The second group is the *Slotted Aloha* protocol (Weselthier, 1988) Slotted Aloha protocol is based on Pure-Aloha. A tag can transmit only at the beginning of a slot. Therefore, packets can collide completely or not collide at all. The mechanism is as follows: the reader sends a packet announcing the number of slots (K) that tags can compete to use. Each tag receives the data and generates a random number between [0, *K-1*]. The result is the slot where the tag must transmit their identification number.

Slotted-Aloha outperforms Pure-Aloha at the cost of requiring a reading system that manages slotted time synchronization. The third group, Frame-Slotted-Aloha (FSA), is a variation of Slotted-Aloha. In FSA, the time is divided into discrete time intervals but slots are confined in consecutive frames, also called cycles. Each frame has a length of a fixed number of slots (see Fig. 3). FSA has been implemented in many commercial products and has been standardized in ISO/IEC-18000-6C (ISO, 2003) and in EPCglobal Class-1 Gen-2 (EPC, 2004).

In FSA, when the number of tags is much larger than the number of slots, the identification delay increases considerably. On the other hand, if the number of tags is low and the number of slots is high, many empty slots can occur, which leads to increased identification time.

In Dynamic FSA, the number of slots per frame is variable. Tags randomly choose a slot within the frame to send their information to the reader. When a frame finishes, an identification cycle concludes and the reader, following some rules, makes a decision about whether to increase/decrease/maintain the number of time-slots per frame in the next identification cycle.

According to (Schoute, 1983), the optimum throughput in a cycle of a DFSA protocol is achieved if the number of tags N equals the number of slots K in that cycle, and this throughput is given by $e^{-1} \approx 0.36$. Since the number of tags in range per cycle is commonly unknown, first the reader must estimate the number of tags that are going to compete per cycle, possibly through the statistical information collected on a cycle-by-cycle basis or any

heuristic methods. Then, the reader adjusts the frame size to guarantee the maximum throughput and minimize the identification delay. The main anti-collision DFSA algorithms for RFID applications have been comprehensively studied in ((a) Bueno-Delgado *et al.*, 2009).
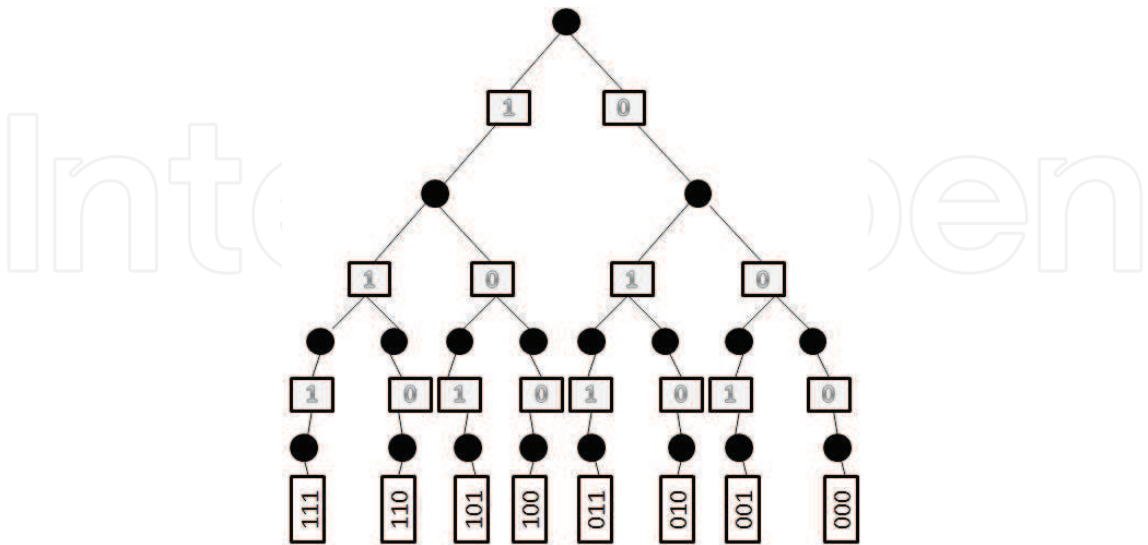

Fig. 2. Tree-based protocol procedure

3.3 EPCglobal Class-1 Gen-2

EPCglobal is an institution focused on the development of industry-driven standards for the Electronic Product Code (EPC) to support the use of Radio Frequency Identification (RFID). Regarding passive RFID, EPCglobal provides the EPCglobal Class-1 Gen-2 standard.

EPCglobal Class-1 Gen-2 is called "the worldwide standard for RFID systems" because it has been implemented to satisfy all the needs of the final customer, irrespective of the geographic location. For passive RFID systems, EPCglobal Class-1 Gen-2] is considered the *de facto* standard. It includes a set of specifications for the hardware of the passive tag and the hardware and software in the reader systems (which carry the true system complexity). After its publication in year 2005, it has been widely adopted by RFID systems manufacturers. Many commercial RFID systems have been implemented following this standard.
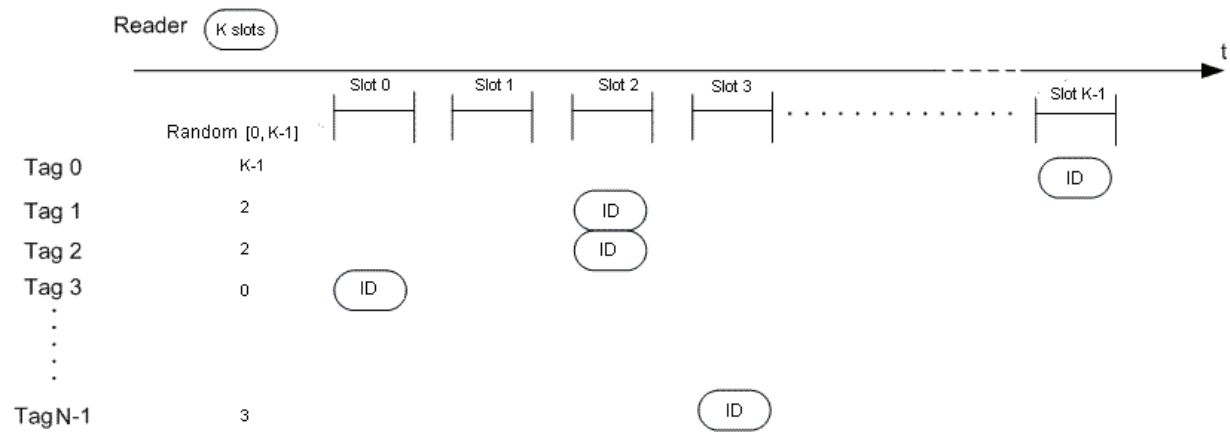

Fig. 3. Frame Slotted Aloha procedure

EPCglobal Class-1 Gen-2 works at UHF band (860MHz-930MHz). It proposes an anti-collision mechanism based on a variation of FSA. Fig. 4 illustrates EPCglobal Class-1 Gen-2 operation.

At a first stage the reader system is continuously monitoring the environment to detect the presence of tags by means of *Broadcast* packets. Tags in the coverage area are excited by the electromagnetic waves of the reader and send a reply immediately, producing a multiple collision. The reader detects the collision and starts the identification cycle. During each identification cycle, the time is structured as one frame, which is itself divided into slots, following a FSA scheme.

EPCglobal Class-1 Gen-2 shows two configuration alternatives:

- Fixed frame-length procedure: All identification cycles (frames) have the same value (number of slots). It is common to find commercial systems with this configuration.
- Variable frame length procedure (denoted as frame-by-frame adaptation). The number of slots per frame can be changed by the reader in each identification cycle. The reader decides if increase, decrease or maintain the number of slots per frame in function of some criteria.

In the following subsections both procedures are overviewed, as well as the implementation status of current readers.

3.3.1 Fixed frame length procedure

An identification cycle starts when the reader transmits a *Query* packet, including a field of four bits with the value $Q \in [0,...,15]$, stating that the length of the frame will be of 2^Q slots. Tags in coverage receive this packet and generate a random number r in the interval $[0, 2^Q-1]$. The r value represents the slot within the frame where the tag has randomly decided to send its identification number ID=r. Inside each frame, the beginning of a slot is governed by the reader by transmitting the *QueryRep* packet, excepting the slot 0, which is automatically initiated by the *Query* packet. The tags in coverage use an internal counter to track the number of transmitted *QueryRep* packets since the last *Query* packet, and then recognize the slot when they should transmit.

When the moment arrives, the tag transmits its identification number ID, which corresponds to the random value r calculated for contention, which is also equal to the slot number in the frame. After transmitting its ID, three actions can follow:

- If more than one tag has chosen the same slot, a collision occurs which is detected by the reader. Then, the reader reacts initiating a new slot with a *QueryRep* packet (see slot 0 in Fig. 4). The tags which transmitted their ID assume that a collision occurred, and must update their counter value to 2^Q-1. That means that they will not compete again in this identification cycle.
- If the reader receives the ID correctly, and this coincides with the slot number within the frame, then it responds with an *Ack* packet. All tags in coverage receive the packet but only the identified tag answers with a *Data* packet, e.g. an EPC code.

  If the reader receives the *Data* packet, it answers sending a *QueryRep* packet, starting a new slot. The tag identified will finish its identification process (see slot 1 in Fig. 4).
- If the reader does not receive a correct *Data* packet within a given time, it considers the time-slot has expired, and sends a *Nack* packet. Again, all tags in coverage receive it, but only the tag in the identification reacts by updating its counter value to 2^Q-1. Thus, this tag will not contend again in this identification cycle (see slot 3 in Fig. 4). After this, the

reader will send a new *Query* or *QueryRep* packet to start a new frame or slot respectively.

Finally, when a cycle finishes, a *Query* packet is sent again by the reader to start a new identification cycle. Tags unidentified in the previous cycle will compete again, choosing a new random *r* value.

3.3.2 Variable frame length procedure

The fixed frame length EPCglobal Class-1 Gen-2 standard provides a low degree of flexibility. If the Q value selected is high and the number of tags in coverage is low, many empty slots appear in the frame. On the contrary, if the Q value is low and the number of tags is high, many collisions arise. To mitigate this problem the standard proposes a variable frame length procedure (EPC, 2004) that selects the Q value in each cycle by means of some arbitrary function. ((a) Bueno-Delgado *et al.*, 2009) analyzes the different variable frame length algorithms. Since current readers usually implement only the fixed frame length procedure, in this chapter we focus exclusively on it.
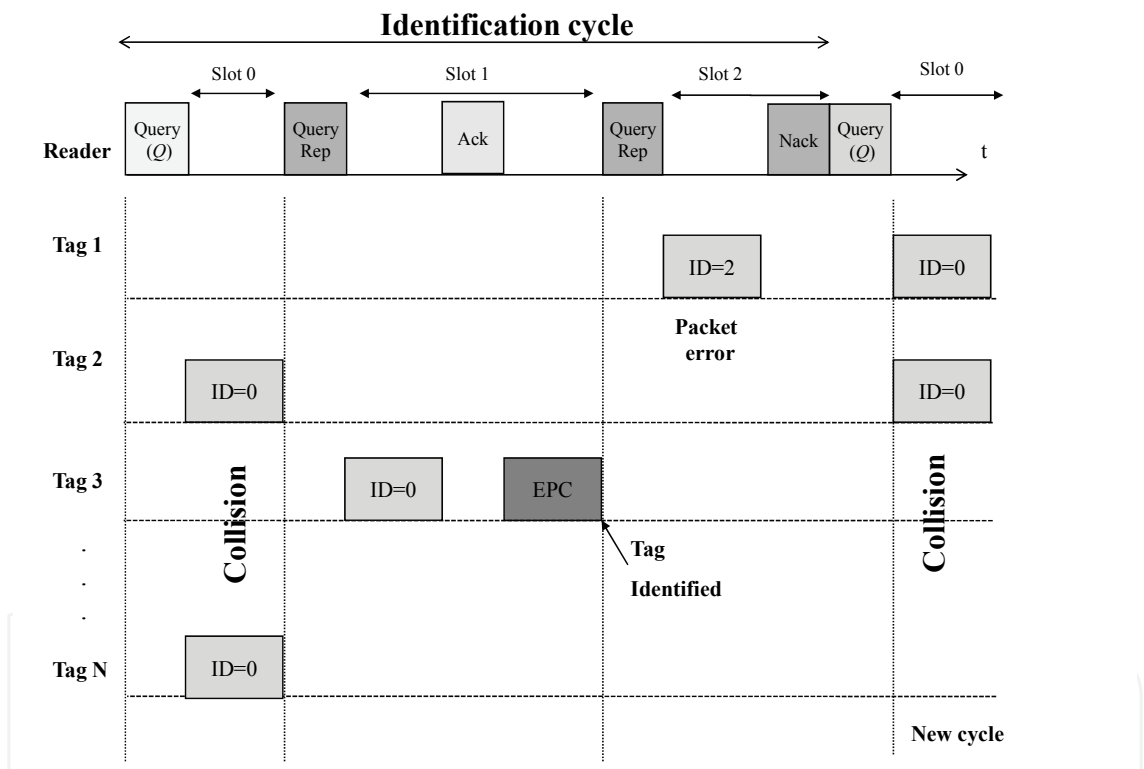

Fig. 4. EPCglobal Class-1 Gen-2 identification procedure

3.3.3 EPCglobal Class-1 Gen-2 in the market

The current UHF RFID readers available in the market implement the worldwide standard EPCglobal Class-1 Gen-2. Some of them only permit to work with one of the two procedures explained before. Besides, some readers do not permit to configure the initial frame-length (the Q value) or only some certain values which can influence directly to the final system performance. Depending on the level of frame-length configuration, the readers can be classified as follows:

- Readers with fixed frame length, without user configuration (Symbol, *on-line*; ThingMagic, *on-line*; Mercury4, *on-line*; Caen, *on-line*; Awid, *on-line*; Samsys, *on-line*). 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 fixed frame length with user configuration(Samsys, *on-line*; Intermec, *on-line*; Alien, *on-line*). 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 variable frame length (Samsys, *on-line*; Intermec, *on-line*; Alien, *on-line*). 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 (EPC, 2004).

4. Identification process in *static* scenarios

S*tatic* scenarios are characterized by a block of tags (modeling a physical pallet, box, *etc.*) that enter the checking area and never leave. Two related performance measures are commonly considered: The identification time, defined as the *mean* number of time units (slots, cycles, seconds, *etc.*) until all tags are identified, and the system throughput or efficiency, defined as the inverse of the mean identification time, *i.e.*, the ratio of identified tags per time unit.

4.1 Markovian analysis

The identification process in a *static* scenario is determined by the number of remaining unidentified tags. Thus, the identification process can be modeled as a homogeneous (*Discrete Time Markov Chain*) DTMC, X_c, where each state in the chain represents the number of unidentified tags, being *c* the cycle number. Thus, the state space of the Markov process is {*N, N-1,…, 0*}. Fig 5 shows DTMC state diagram from the initial state, $X_0=N$. The transitions between states represent the probability to identify a certain quantity of tags *t* or, in other words, the probability to have (*N-t*) tags still unidentified.

The transition matrix *P* depends on the anti-collision protocol used and its parameters. For EPCglobal Class-1 Gen-2, the parameter *K* denotes the number of slots per frame (frame length). To compute the matrix *P*, let us define the random variable μ_t, which indicates the number of slots being filled with exactly *t* tags. Its mass probability function is (Vogt, 2002):
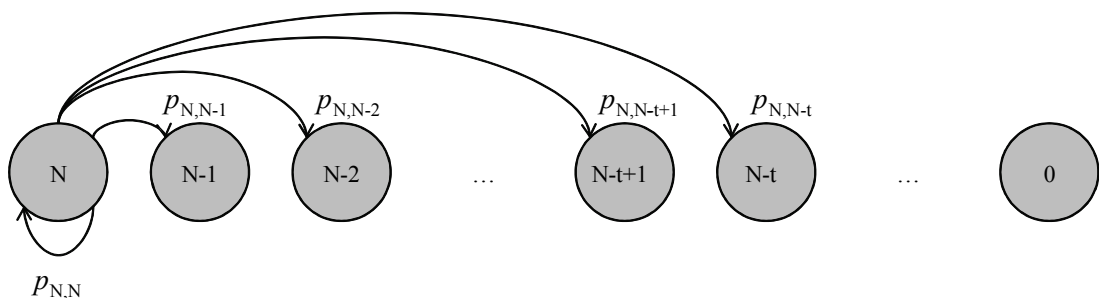

Fig. 5. Partial Markov Chain

$$\Pr_{K,N}(\mu_t = m) = \frac{\binom{K}{m} \prod_{i=0}^{m-1} \binom{N-it}{t} G(K-m, N-mt, t)}{K^N} \tag{1}$$

Where $m=0,...,K$ and:

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

Since the tags identified in a cycle will not compete again in the following ones, then the transition matrix P is ((b) Bueno-Delgado *et al.*, 2009):

$$p_{i,j} = \begin{cases} \Pr_{K,i}(\mu_1 = i-j) & , i-K \le j < i \\ 1 - \sum_{y=i-1}^{i-K} p_{i,y} & , i = j \qquad \text{for } i = 1,...,N. \\ 0 & , otherwise \end{cases} \tag{3}$$

The chain has a single absorbing state, $X_c=0$. The mean number of steps until the absorbing state is the mean number of identification cycles ($\bar{c}$). It can be computed by means of the fundamental matrix, D, of the absorbing chain (Kemeny, 2009):

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

As usual, I denotes the identity matrix, and F denotes the submatrix of P without absorbing states. Then,

$$\bar{c} = \sum_{j \in B} D_{Z,j} \tag{5}$$

Where B is the set of transitory states, and Z is the absorbing state.

In addition, using the physical and FSA standard parameters (Table 1 enumerates the typical EPCglobal parameters) is possible to transform the identification time to seconds as follows: T_{id} is the duration of a slot with a valid data transmission (EPC code). T_v and T_c is the duration of an empty and collision slot, respectively. Then, the identification time in seconds is approximated by:

$$\bar{T}_{total} \approx \bar{c} \cdot \left[\bar{k}_v \cdot T_v + \bar{k}_c \cdot T_c + \bar{k}_{id} \cdot T_{id} \right] \tag{6}$$

$\bar{k}_v$, $\bar{k}_c$ and $\bar{k}_{id}$ denote the average number of empty, collision and successful slots, respectively. These variables depend on the particular FSA algorithm and its configuration, and on the population size. For instance, setting M=4 (see Table 1), T_{id}=2.505 ms and $T_v=T_c$=0.575 ms. Since an empty slot and a collision slot have the same duration, the previous equation can be simplified:

$$\bar{T}_{total} \approx \bar{c} \cdot \left[(\bar{k}_v + \bar{k}_c) T_c + \bar{k}_{id} \cdot T_{id} \right] \tag{7}$$

Since,

$$\overline{k}_v + \overline{k}_c \approx K \cdot \overline{c} - \overline{k}_{id} \tag{8}$$

Then,

$$\overline{T}_{total} \approx \overline{c} \cdot \left[(K \cdot \overline{c} - \overline{k}_{id}) T_c + \overline{k}_{id} \cdot T_{id} \right] \tag{9}$$

Different populations of tags and Q values have been considered and the identification time has been measured. Fig. 6 shows the mean number of slots required to identify each tag population.

4.2 System throughput

The throughput (th) can be computed from the previous Markov analysis, just as the inverse of the identification time. Another way is described in this section. Let us remark that, obviously, the result of both methods is equal, and the second one is provided for completeness. Given N tags, and K slots, the probability that t tags respond in the same time-slot is binomially distributed:

$$\Pr(t) = \binom{N}{t} \left(\frac{1}{K}\right)^t \left(1 - \frac{1}{K}\right)^{N-t} \quad \text{for } t=0,...,N \tag{10}$$

Then, $Pr(t=0)$ is the probability of an empty slot, $Pr(t=1)$ the probability of a successful slot, and $Pr(t \geq 2)$ the probability of collision:

$$\Pr(t = 0) = \left(1 - \frac{1}{K}\right)^N \tag{11}$$

$$\Pr(t = 1) = \frac{N}{K}\left(1 - \frac{1}{K}\right)^{N-1} \tag{12}$$

$$\Pr(t \geq 2) = 1 - \Pr(t = 0) - \Pr(t = 1) = 1 - \left(1 - \frac{1}{K}\right)^N \left(1 - \frac{N}{K-1}\right) \tag{13}$$

Since every identification cycles is composed by K slots, the throughput per slot is computed as follows:

$$th = K \cdot \Pr(t = 1) = N\left(1 - \frac{1}{K}\right)^{N-1} \tag{14}$$

4.3 Optimum Q configuration

As seen in the previous sections, the identification performance depends on the number of tags competing and on the frame length. The best throughput performance occurs when there are as many competing tags as slots in the frame, $N=K$, yielding a maximum

Parameter	Symbol	Value
Electronic Product Code	EPC	96 bits
Initial Q value	Q_0	4
Reference time interval for a data-0 in Reader-to-Tag signaling	TARI	12.5us
Time interval for a data-0 in Reader-to-Tag signaling	DATA0	$1.0 \cdot$ TARI
Time interval for a data-1 in Reader-to-Tag signaling	DATA1	$1.5 \cdot$ TARI
Tag-to-Reader calibration symbol	Trcal	64us
Reader-to-Tag calibration symbol	RTcal	31.25us
Divide Ratio	DR	8
Backscatter Link Frequency	LF	DR/Trcal
Number of subcarrier cycles per symbol in Tag-to-Reader direction	M	1,2,4,8
Reader-to-Tag rate	Rtrate	64Kbps
Tag-to-Reader Rate	Trrate	LF/M
Link pulse-repetition interval	T_{pri}	1/LF
Tag-to-Reader preamble	T→R Preamble	$6\ T_{pri}$
Tag-to-Reader End of Signaling	T→R EoS	$2\ T_{pri}$
Delimiter		12.5us
Reader-to-Tag Preamble	R→T Preamble (RTP)	Delimiter+DATA0+TRcal+Rtcal
Reader-to-Tag Frame synchronization	R→T FrameSync	RTP –Rtcal
Time for reader transmission to tag response	T_1	Max(RTcal, 10 T_{pri})
Time for tag response to reader transmission	T_2	$5\ T_{pri}$
Time a reader waits, after T_1, before it issues another command	T_3	$5\ T_{pri}$
Minimum time between reader commands	T_4	$2 \cdot$ Rtcal
Query packet	22 bits	22 bits
QueryAdjust packet	9 bits	9 bits
QueryRep packet	4 bits	4 bits
Ack packet	18 bits	18 bits
Nack packet	8 bits	8 bits

Table 1. Typical values of EPCglobal Class-1 Gen-2 parameters

throughput of $1/e \approx 0.36$ (Schoute, 1983). For EPCglobal Class-1 Gen-2, K can not be set to any arbitrary natural number, but to powers of two, *i.e.* $K=2^Q$, for $Q \in [0, \dots, 15]$. For every N value, the value of Q that maximizes the throughput has been computed in ((b) Bueno-Delgado, 2009). Fig. 7 shows the results, and Table 2 summarizes them.

The former optimal configurations are useful for variable length readers. Readers with fixed frame length can be optimized as well, setting the best value of Q for a given population size. Notice that both criteria are different: the first one optimizes the reading cycle by cycle, whereas the second one minimizes the whole process duration. These values have been calculated by means of simulations in ((b) Bueno-Delgado, 2009), and are also shown in Table 2.

5. Identification process in *dynamic* scenarios

Many real RFID applications (*e.g.* a conveyor belt installation) work in *dynamic* scenarios. For this type of systems, the performance analysis must be linked with the *Tag Loss Ratio.* This parameter measures the rate of unidentified tags in an identification process and, depending on the final application, even a low TLR (*e.g.* TLR=10⁻³) may be disastrous and cause thousands of items lost per day. In this section, the TLR is computed for a RFID scenario similar to the one depicted in Fig. 1. There is an incoming flow of tags entering the coverage area of a reader (RFID cell), moving at the same speed (*e.g.*, modeling a conveyor belt). Therefore, all tags stay in the coverage area of the reader during the same time.

Every tag unidentified during that time is considered lost. As in the previous analysis, once acknowledged, a tag withdraws from the identification process. This problem has been studied previously in (Vales-Alonso *et al.,* 2009). Thereafter, the following notation and
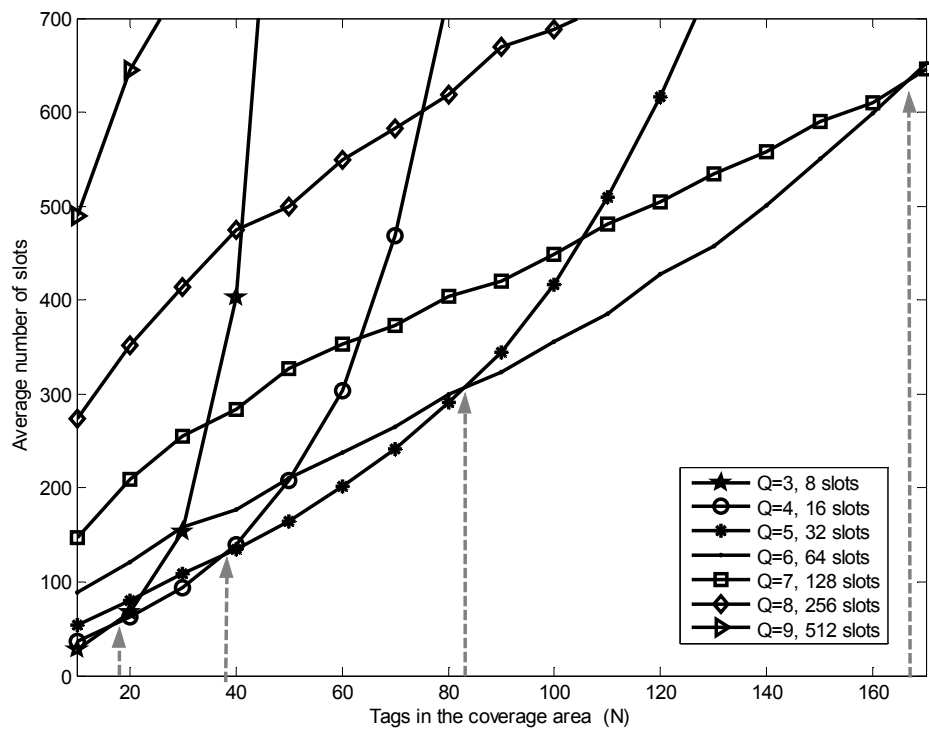

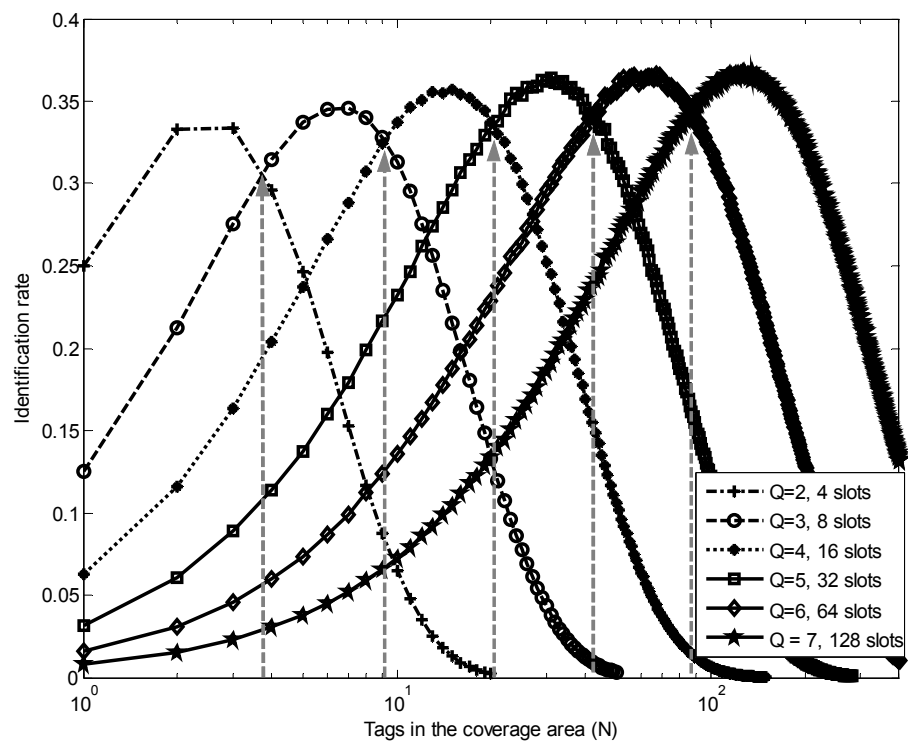Fig. 6. Mean identification time (in number of slots) vs. *N,* for different *Q* values

Fig. 7. Throughput (Identification rate) vs. *N* for different *Q* values

Optimal *Q*	Cycle by cycle optimization		Whole process optimization	
	Number of slots (K)= 2^Q	Tags in coverage (N)	Number of slots (K)= 2^Q	Tags in coverage (N)
1	2	$N \leq 2$	2	$N \leq 4$
2	4	$2 \leq N < 4$	4	$4 \leq N < 8$
3	8	$4 \leq N < 9$	8	$8 \leq N < 19$
4	16	$9 \leq N < 20$	16	$19 \leq N < 38$
5	32	$20 \leq N < 42$	32	$38 \leq N < 85$
6	64	$42 \leq N < 87$	64	$85 \leq N < 165$
7	128	$87 \leq N < 179$	128	$165 \leq N < 340$
8	256	$179 \leq N < 364$	256	$340 \leq N < 720$
9	512	$364 \leq N < 710$	512	$720 \leq N < 1260$
10	1024	$710 \leq N < 1430$	1024	$1260 \leq N < 2855$
11	2048	$1430 \leq N < 2920$	2048	$2855 \leq N < 5955$
12	4096	$2920 \leq N < 5531$	4096	$5955 \leq N < 12124$
13	8192	$5531 \leq N < 11527$	8192	$12124 \leq N < 25225$
14	16384	$11527 \leq N < 23962$	16384	$25225 \leq N < 57432$
15	32768	$23962 \leq N$	32768	$57432 \leq N$

Table 2. Throughput Maximization

conventions are used: a row vector is denoted as $\vec{V}$, the i-th component of a vector is denoted $(\vec{V})_i$, and $\sigma(\vec{V})$ denotes the sum of the values of the components of a vector $\vec{V}$.

For the sake of simplicity, let us assume tags remain C complete cycles in the reading area. Then, once a tag has entered the coverage area, it should be identified in the following C identification cycles. Otherwise (if it reaches the cycle $C+1$), tag is lost.

A truncated Poisson distribution, with parameter λ, has been selected as the arrival process in the system:

$$a(t) = \frac{\lambda^t}{t! \sum_{i=0}^{H} \frac{\lambda^t}{i!}}$$

(15)

For $t=,...,H$, being H the maximum number of tags entering per cycle.

The former assumptions allow to express the dynamics of the system as a discrete model, evolving cycle by cycle, such that,

- Each tag is in a given reading cycle in the set [$1,...,C$]
- After a cycle, identified tags withdraw from the identification process.
- After a cycle, each tag unidentified and previously in the i-th cycle moves to the ($i+1$)-th cycle.
- If a tag enters cycle $C+1$, it is considered out of the range of the reader, and, therefore, lost.
- At the beginning of each cycle, up to H new tags are assigned to cycle 1, following a truncated Poisson distribution.

For any arbitrary cycle, the evolution of the system to the next cycle only depends on the current state. Thus, a DTMC can be used to study the behavior of the RFID system. Next section describes this model.

5.1 Markovian analysis

Based on previous considerations, the system can be modeled by a homogeneous discrete Markov process X_c, whose state space is described by a vector $\vec{E} = \{e_1, ..., e_{C+1}\}$, where each $e_j \in [0,...,H]$, representing the number of unidentified tags in the j-th cycle. The following figures illustrate the model. They describe the state of the system for two consecutive cycles, showing tags entering and leaving the system, in both identification and no identification scenarios. Therefore, e_j is the number of tags which are going to start their j-th identification cycle in coverage. e_1 component also represents the number of tag arrivals during the previous identification cycle (which do not contend since they have not received a *Query* packet yet). Finally, component e_{C+1} indicates the number of tags lost at the end of the identification cycle, since tags leave coverage area after $C+1$ cycles.

In addition, let us define the mapping Ψ as a correspondence between the state vector and an enumeration of the possible number of states:

$$\Psi : [0,...,H] \times^{(C+1)} \times [0,...,H] \rightarrow \left[1,...,(H+1)^{C+1} \right]$$

$$\vec{E} = \{e_1, e_2,...,e_{C+1}\} \rightarrow \Psi : (\vec{E}) = 1 + \sum_{j=1}^{C+1} e_j H^{j-1}$$

(16)

This allows defining i-th state in our model as the state whose associated vector is given by Ψ^{-1}. Let us denote $\vec{E}_i$ as the vector associated to i-th state, *i.e.*, $\vec{E}_i = \Psi^{-1}(i)$. Finally, let e_{ij} denote to the j-th component of the $\vec{E}_i$ state vector.

The goal is to describe the transition probability matrix P for the model, from every state i to another state j. The stationary state probabilities is computed as $\vec{\pi} = \vec{\pi}\ P$. Let us denote λ_j as the average incoming unidentified tags to cycle j, which can be computed as:

$$\lambda_j = \sum_{j=1}^{(H+1)^{C+1}} e_{ij}\vec{\pi}_i \tag{17}$$

Obviously, λ_1 is the average incoming traffic in the system and λ_{C+1} is the average outgoing traffic of unidentified tags. Then, TLR can be calculated as:

$$TLR = \frac{\lambda_{C+1}}{\lambda_1} = \frac{\sum_{i=1}^{(H+1)^{C+1}} e_{i(C+1)} \cdot \vec{\pi}_i}{\lambda_1} \tag{18}$$

To build the transition probability matrix P let us define the auxiliary vectors $\vec{L}_i$ and $\vec{U}_i$ as:

$$\vec{L}_i = \{e_{i1},...,e_{iC}\} \tag{19}$$

$$\vec{U}_i = \{e_{i2},...,e_{i(C+1)}\}$$

That is, the $\vec{E}_i$ state vector without either the last or the first component. Let us define the *outcome* vector as:

$$\vec{O}^{ij} = (\vec{L}_i - \vec{U}_j) = \{o_1^{ij}...o_C^{ij}\} \tag{20}$$

Figures 8 and 9 graphically show this computation. To construct the transition matrix let us define the function $id(i,j)$ that operates on an outcome vector $\vec{O}^{ij}$ providing the number of identified tags in a transition from a state i to a state j:

$$id(i,j) = \vec{O}^{ij} \cdot \vec{1}' \tag{21}$$

Notice that, for $\vec{E}_i$ and $\vec{E}_j$, if $e_{ik} < e_{j(k+1)}$ for some $k=1,...,C$, such transition is impossible (new tags cannot appear in stages other than stage 1). These impossible transitions will result in $id(i,j)$ providing a negative value. The random variable $s(K,N)$ indicates the number of contention slots being filled with a single tag. The *mass probability function* of $s(K,N)$ has been computed in (Vogt, 2002) (see equation (1) and (2)). Henceforth, let us denote $Pr\{s(K,N)=k\}$ as $s_k=(N,K)$.

As stated in section 4.2, using FSA, up to K tags may be identified in a single identification cycle. Therefore, possible cases range from $id(i,j)=0$ to $id(i,j)=K$. The probability of $id(i,j)$ successful identifications is uniformly distributed among the contenders, whose distribution depends on the particular state, and hence the transition probability. From equations (1) and (2) and the previous definitions, the transition matrix P can be computed as follows:

$$p_{i,j} = \begin{cases} a(e_{j1})s_0(K,N) & ,id(i,j) = 0 \\ \\ a(e_{j1})\dfrac{\prod_{k=1}^{C}\binom{e_{ik}}{o_k^{ij}}}{\binom{N}{id(i,j)}}s_{id(i,j)}(K,N) & ,id(i,j) \in [1,K] \\ \\ 0 & ,otherwise \end{cases}$$

(22)

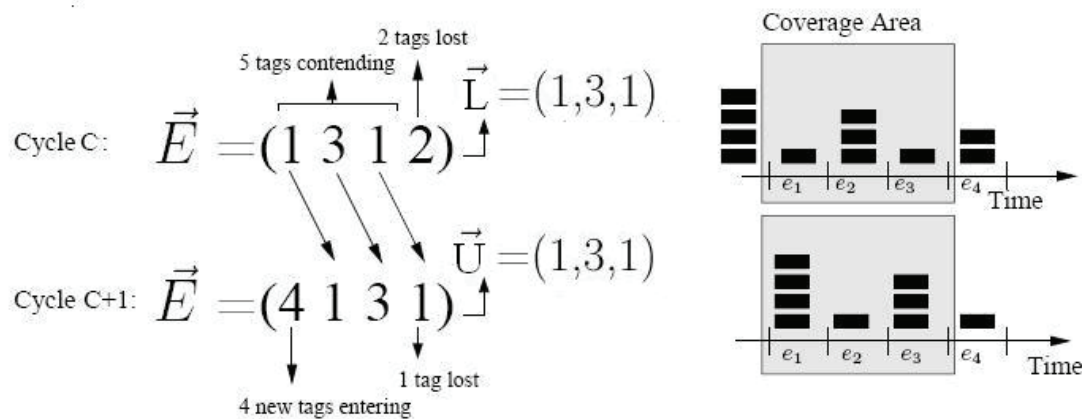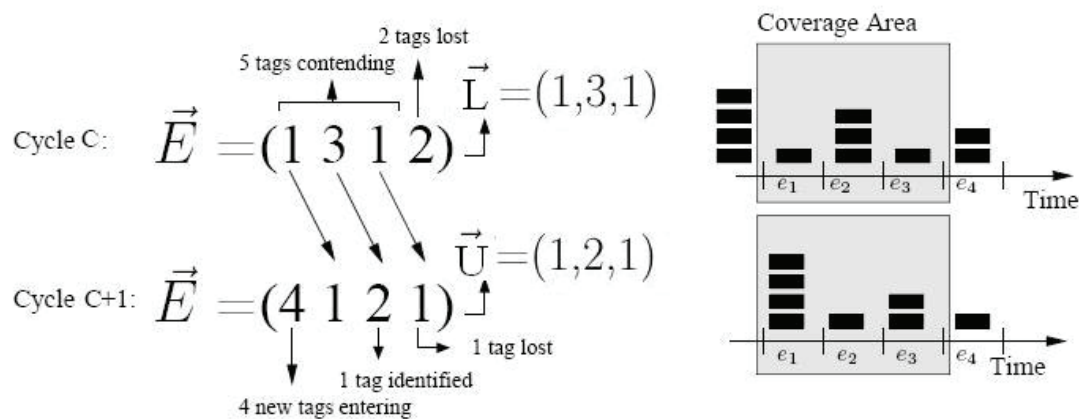Fig. 8. Representation of the transition state. Case 1: No identification

Fig. 9. Representation of the transition state. Case 2: Identification

5.2 Experimental evaluation: a postal mail control system

From a practical point of view, TLR evaluation may become critical in some realistic scenarios. As an example, this section evaluates a postal mail control system, where mails are carried over conveyor belts for distribution, with an attached tag.

Two configurations for the mail sojourn times of 2 and 3 identification cycles have been considered, for a frame length of K=8 slots. The slot time is assumed to be 4 ms based on parameters shown in Table 1. Therefore, the time sojourn is around 64 ms for C=2 and 100 ms for C=3. λ range spans from 1 to 7. Results are provided in figures 10 and 11. As expected, for a fixed C, TLR increases as the maximum number of arrivals H increases. In addition, for the parameters analyzed, keeping fixed H decrements TLR if C grows, because there are more opportunities for identification. For example, the maximum number of tags for H = 6 and C=2 is 12 tags, whereas for H = 6 and C=3 there might be up to 18 tags.

The main issue of the previous analysis is that it becomes computationally unfeasible for moderate values of H and C. In this case, simulation is mandatory. Figure 12 shows simulations performed for λ=[10,...,60] and H = [3; 6]. In this case, envelopes sojourn time is close to 800ms. We can observe that, if we set H=3, TLR reaches 10^{-4} and does not vary, independently of the λ value. On the other hand, with H=6, the TLR reaches up to 10^{-3}. It means that, one out of a thousand envelopes will be lost, showing the impact in the final system.

In summary, last section allows the evaluation of TLR for different protocol parameters, such as the number of slots, the arrival process, the time in coverage (conveyor belt velocity), *etc*.
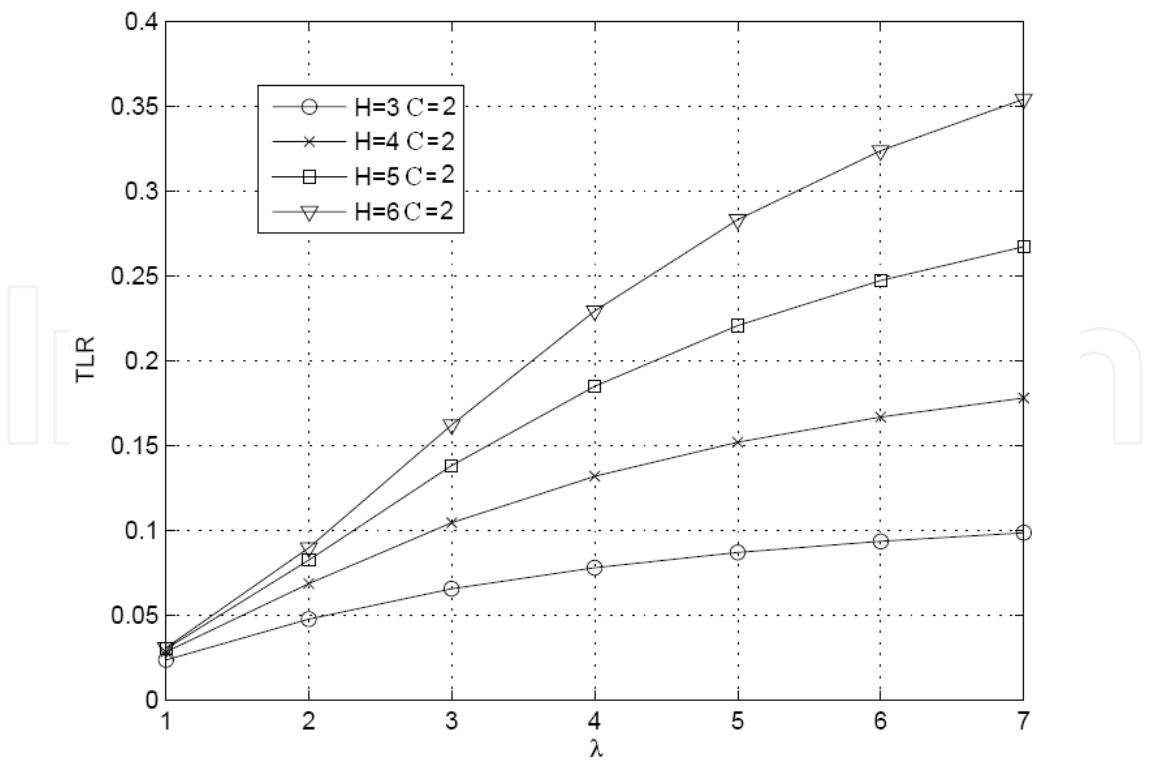

Fig. 10. TLR results for FSA with 8 slots and Poisson arrivals. C=4, and H=3 to H=6
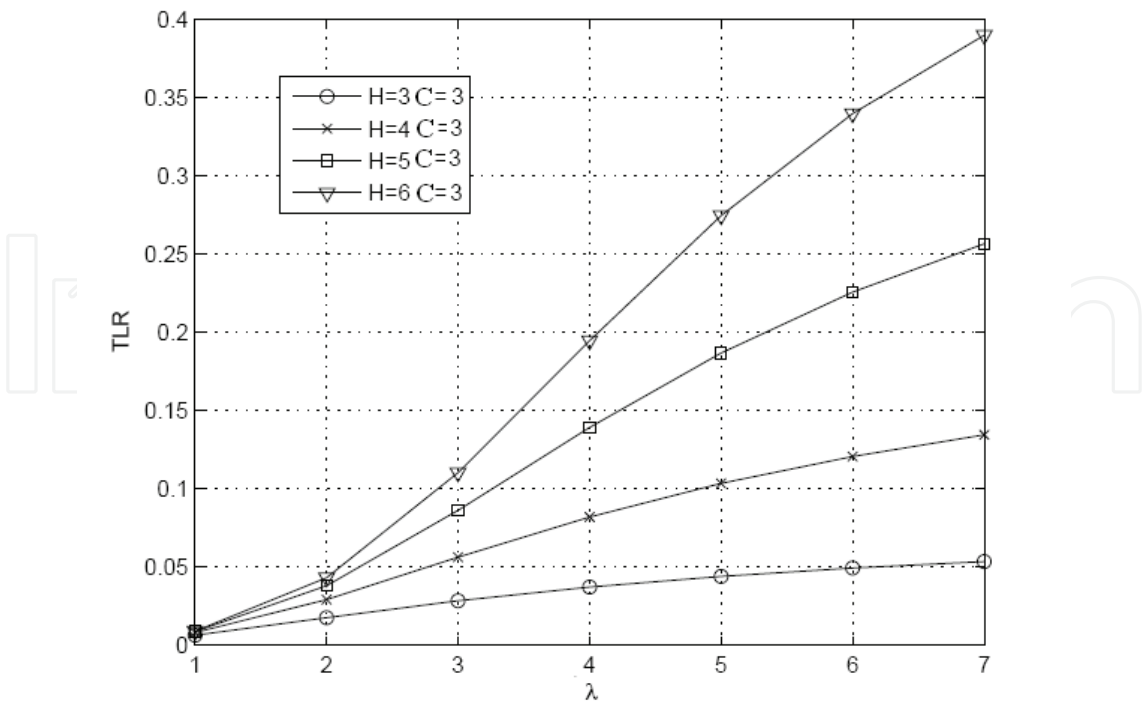
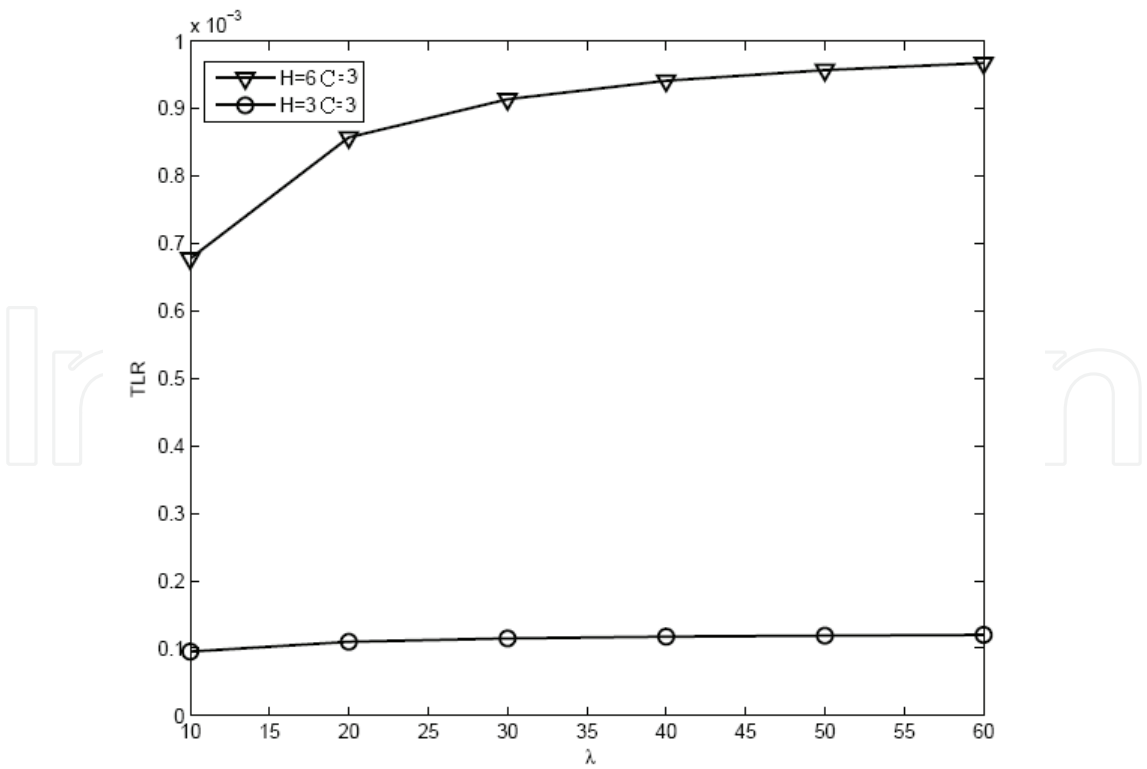Fig. 11. TLR results for FSA with 8 slots and Poisson arrivals. C=5, and H=3 to H=6

Fig. 12. TLR results for FSA with 64 slots and Poisson arrivals, C=4 and H=3, H=6

6. Conclusions and open issues

This chapter has presented an overview of the RFID identification process and how the RFID systems work in *static* and *dynamic* scenarios. The latter are common in traceability, inventory control, *etc.* Studying the identification process is mandatory to minimize the items that leave the checking areas unidentified. Since collisions are the main factor that produces delay in the RFID identification process, the chapter overviews this phenomenon in the *Medium Access Control* (MAC) layer. The study has been been addressed for passive RFID protocols due to their high market penetration.

The lack of standardization has traditionally been one of the limiting factors for the adoption of RFID technology. This situation has undergone an evolution during the last years, since the EPCglobal Class-1 Gen-2 standard have been widely accepted by RFID companies. The more relevant and adopted EPCglobal specifications have been described along the chapter, in particular, its physical and its anti-collision protocol.

The performance analysis of the identification process has been introduced. On the one hand, the analysis has been focused on *static* scenarios, where identification time has been computed, as well as system throughput. On the other hand, the identification process analysis of *dynamic* scenarios has been oriented to determine the *Tag Loss Ratio*. Configuration of actual implementations of RFID systems could make use of the results achieved to improve their identification process quality.

Finally, some open issues related to identification procedure have not been addressed yet: the analytical characterization of DFSA algorithms, more complex incoming traffics for dynamic systems, as well as considering another types of collisions, such as reader to reader. The study of these issues will be important in the research field of RFID for the next years.

7. Acknowledgments

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