On the Implementation of a Multi-Reader Radio Frequency Identification (RFID) Architecture

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***Abstract*— Radio Frequency Identification (RFID) systems are one of the enabling technologies for the ubiquitous computing paradigm. At the moment, the EPCglobal organization leads the development of industry-driven standards for this field and has settled the EPC "Gen 2" as a reference standard. In this paper, we analyze the anti-collision procedure of EPC "Gen 2" to find the time needed to identify a population of tags, by means of the finite Markov-chain of the system. In addition, a UHF multi-reader prototype based on time division multiple access (TDMA) scheme is evaluated in this work. In this TDMA scheme, the reader time-slot duration is allocated according to the computations obtained from our analytical study. The main conclusions derived from this implementation are summarized in this work.**

I. Introduction

Radio Frequency Identification (RFID) systems are one of the enabling technologies for the ubiquitous computing paradigm [1]. Their foreseen application range spans from replacement of barcode systems to location of large cargo ships with many containers. Matching such a broad range of applications, there is also a wide range of different RFID technologies. All of them share a common architecture: a basic RFID cell consists of a *reader* device (master or interrogator) and a set of RFID tags, which reply to the queries or enforce the commands from the interrogator. RFID are classified according to the source of energy of the tags: passive ones do not have a battery and obtain the energy from the reader signal, whereas active ones have their own battery. Passive tags are inexpensive and very simple, usually read-only devices, and they range typically from centimeters to a couple of meters. Active tags are more complex devices, with more sophisticated capabilities (usually integrating a microprocessor and memory) and they can be read and written from distances in excess of 100 meters. Whereas passive RFID systems are the most employed and have been studied for years [2], [3], [4], active RFID systems have been devoted little attention, and only recently a standard has been available [5].

In both cases, there are two issues related to interference between devices. First, the *tag collision* problem: in a RFID cell, if multiple tags are to be identified simultaneously, messages from tags may collide and cancel each other. Second, the *reader collision* problem: it arises when several readers are in coverage range and may interfere each other. A common solution proposed to this problem is to assign different frequencies or timeslots to readers in range, as in the classical Frequency Assignment Problem, usually studied in cellular networks.

To solve the tag collision problem, an anti-collision mechanism is needed. Since, in a typical application, items (with attached tags) enter and leave the reader coverage area, the goal of this mechanism is to communicate with the tags as quickly and reliably as possible to ensure that all tags have been identified. An additional goal for active tags is to save energy in order to maximize the battery lifetime. Therefore, the tag identification problem deals with identifying multiple objects with minimal delay and power consumption, line-of-sight independence and scalability. Unlike classical medium access protocols, channel utilization and fairness are not usually major concerns in RFID systems.

RFID anti-collision protocols are usually very simple, mainly due to the limitations of the devices, and most of them fall into the following categories [2]:

- *Splitting algorithms*. The set of tags to be identified is splitted in disjoint smaller subsets until the number of tags in a subset becomes one. It is done either by the tags selecting a random number or by the reader sending a string that matches only a subset of tags identification number (ID). Algorithms of this type can be viewed as a tree search.
- *Probabilistic algorithms*. The other major family of protocols is based on Framed Slotted ALOHA [6]. In this case, after receiving a signal from the reader, the tags randomly select a slot out of K (the frame length) and send their ID. This mechanism is very simple, but when the number of tags is large, it needs to adapt the frame length (K) [3] to dynamically achieve the desired performance.

At the moment, the EPCglobal organization leads the development of industry-driven standards for this field and has settled the EPC "Gen 2" as a reference standard [7]. With minor changes, EPC "Gen 2" has chosen Framed Slotted ALOHA as an anti-collision procedure and suggests a specific algorithm for frame length adaptation.

We are implementing an access control system using RFID.

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In such a system, people wearing ID cards (passive RFID tags) are to be identified as they pass through a door. Unlike ideal systems, in a practical implementation there is no direct line of sight between tags and reader, which hinders the identification process [8]. It is necessary to place additional antennae to perform redundant readings, which causes the reader collision problem. To solve it we use two readers that alternatively scan the tags, that is, Time Division Multiple Access (TDMA) for multi-reader scanning. In this paper we show the design process of the system. First, we evaluate the EPC "Gen 2" anti-collision procedure in a single cell scenario using a simple analysis to derive the average time needed to identify a population of tags. This time is used to set the duration of a timeslot for the TDMA reader access. Finally we show our prototype implementation as a case study and describe the problems found.

The rest of this paper is organized as follows, section II briefly discusses related work. In Section III we evaluate the EPC "Gen 2" anti-collision procedure to estimate the average number of cycles needed to identify all the tags present in a coverage cell. The protocol has been evaluated with and without frame adaption, by simulation and analysis respectively. Section IV shows a prototype of our system and the choices made in its implementation. Finally, section V concludes and describes possible future works.

II. Related Work

Most of the anti-collision protocols focus on passive RFID tags [2]. In this case, the limitations of the device usually impose the use of very simple protocols, all the burden of the identification process lying on the reader. The proposals fall into the following categories: splitting algorithms or probabilistic protocols. In the first group, a well known protocol, called QT memoryless [2] exemplifies its operation: the reader sends a string prefix and all the tags whose ID match that prefix reply. The reader appends a new digit to the string prefix subsequently. If there is no collision in the response, a tag has been identified. This type of algorithms can be viewed as a tree search and are deterministic, meaning that all tags are identified with probability one within a bounded time. However, this time can be very long, depending on the length of the tag IDs and the number of them to identify.

In the second group, framed slotted ALOHA is practically an unanimous choice. For instance, the I-Code protocol [3] as well as the EPC "Gen 2" protocol [7]. The latter, which is expected to be a *de facto* standard, is to be used with both active and passive tags. Besides, EPC suggests a procedure to adapt the frame length.

Framed slotted ALOHA has been extensively studied [6], but as classical MAC protocols, focusing on the channel utilization and access delay. In RFID, on the contrary, the appropriate performance metric is identification delay. Vogt [3] analyses the identification process of framed slotted ALOHA as a Markov chain and derives two procedures to dynamically adapt the frame length. It assumes that tags are not acknowledged and all the tags participate in every identification round. In this paper, we use a slightly modified analysis, considering that identified tags do not keep on participating, since EPC "Gen 2" states that the tags retire after being acknowledged.

The arrangement and alignment of tags and reader cause a variety of practical problems as shown in reference [8]. In this paper, we show a practical solution to the problem of line-of-sight between reader and tags.

The reader problem has been commonly addressed as a Frequency Assignment Problem, whose solution usually involves a graph coloring algorithm, either centralized or distributed [2]. Our problem is more specific and does not need such sophisticated algorithms.

III. Evaluation of EPC "Gen 2" anti-collision procedure

In this section, we evaluate the average time needed to identify a population of tags. Since we use TDMA with two readers, this time is necessary to set the duration of each reader scan period, that is, the TDMA timeslot duration. Although our reader is capable of reading several tag formats, we have evaluated the EPC procedure, since it is probably going to be the standard in the near future.

EPC "Gen 2" specifies frame slotted ALOHA as an anti-collision procedure. The operation is as follows: a population of N tags starts the identification process after receiving a collection command (called *Query* in [7]) from the interrogator. This command indicates the frame length with the parameter Q, where the number of available slots is $K = 2^Q$. Nodes select a slot to send their ID. If two or more nodes select the same slot, a collision occurs. If no collision occurs in that slot, the tag is acknowledged by the interrogator. We refer to the *Query* command and all the available slots as an *identification cycle*. The nodes acknowledged in an identification cycle do not participate in the following ones.

As shown in [3], the identification process can be modeled as a (homogeneous) Markov process $\{X_s\}$, where X_s denotes the number of tags *unidentified* at the s identification cycle. Thus, the state space of the Markov process is $\{N, N-1, \ldots, 0\}$. The probability distribution of the random variable μ_r that equals the number of slots being filled with exactly r tags:

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

where $m = 0 \ldots K$ and

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

Let us recall that all the acknowledged tags in a cycle withdraw from contention. Therefore, the transition matrix H

TABLE I

AVERAGE NUMBER OF IDENTIFICATION CYCLES VERSUS NUMBER OF TAGS

Slots / Tags	10	20	30	40	50	60	70	80	90	100
4	8.2	60	630	8159	$1.1\ 10^{05}$	$1.6\ 10^{06}$	$2.5\ 10^{07}$	$3.8\ 10^{08}$	$6.0\ 10^{09}$	$9.6\ 10^{10}$
8	3.67	8.56	19.6	49.4	138.0	413.9	1304.2	4244.6	14127	47797
16	2.44	4.11	6.15	8.93	13.03	19.3	29.41	46.0	73.81	121.3
32	1.89	2.76	3.60	4.47	5.424	6.50	7.76	9.26	11.0	13.2
64	1.54	2.15	2.61	3.06	3.465	3.90	4.32	4.77	5.23	5.72

and transition probabilities are given by

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

where $i = 0 \ldots N$. Where $i = 0 \ldots N$, and $i = 0$ corresponds to N tags unidentified, $i = 1$ corresponds to $N-1$ tags, and so on. Since this is an absorbing Markov chain, the average number of identification cyles equals the average number of steps to absorption, which is given by

$$\vec{t} = F\vec{c} \quad (4)$$

where $\vec{t}$ is a column vector and t_s is the expected number of steps (cycles, in our case) before the chain is absorbed given that the chain starts in state X_s, F is the *fundamental matrix* of H and $\vec{c}$ is a column vector all of whose entries are 1 (see [9]). Thus, if the starting state is X_1, that is, all the N tags to be identified, the average number of cycles to identify all the tags is t_1.

Table III shows the average number of cycles versus number of tags (N) for different frame lengths. It shows that with a fixed framed length, the number of cycles increases exponentially with the number of tags. The actual duration of an identification cycle depends on the number of slots used and several other parameters like the transmission rate and the packet length [7], among others. In addition, according to the specification [7] empty slots and slots with collision are shorter than slots with correct packets. We provide an approximation of the average identification in Figure 1, assuming that the duration of all the slots is the same and it equals 2.505 ms, which is the time needed for the correct identification of a single tag at 40 Kbps [7]. Thus, this is a conservative estimate, since empty and collision slots are actually shorter (0.575 ms).

A simple approach like frame slotted ALOHA does not scale well and needs a frame adaptation mechanism. The specification also suggests a mechanism for frame adaptation, though it leaves this open to vendors. The suggested mechanism operation is as follows: the reader checks the result of every slot in a frame. For each empty slot, the Q parameter (recall that $K = 2^Q$) is decreased c units ($0.1 < c < 0.5$); for each slot with collision, Q is increased c units; and no change occurs when there is a success. The final value of Q is rounded and sent in the next $Query$ packet to indicate the number of slots to be used. This procedure has been simulated.

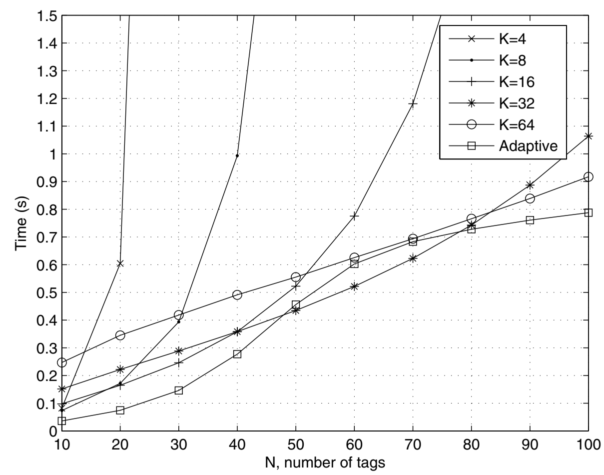

Fig. 1. Average identification time versus number of tags

The results are shown in Figure 1. With this procedure the reader is able to stabilize the protocol as the number of tags increases.

In our system people pass through a door, which obviously limits the number of tags present. Thus, we can assume that no more than 20 people are expected to be in range simultaneously. For this value, it does not worth including a frame adaptation procedure and it should be enough to use a frame of 8 or 16 slots as seen in Fig. 1. With this set up, 200 ms should be enough to identify all the tags, and so this is also the duration we will use for the TDMA timeslot at the readers.

IV. EXPERIMENTAL SETUP

In this section we describe a prototype of our access control system. Physically, it consists of an identification gate that allows only one person to cross at a time. Due to antenna size constraints, the system employs UHF RFID bands. This leads to an antenna placement problem: in order to detect tags with a high probability of success, the antenna should be located in front of the entrance, as shown in figure 2 (we asssume that users will wear RFID tags on their chests, so that the RFID reader signal will easily reach the tags regardless of the orientation of the user). However, this placement is not feasible because the antenna becomes an obstacle (especially if the user is driving an indoor vehicle).

To avoid this problem the antenna must be mounted at a door jamb, pointing at the area in front of the entrance (with

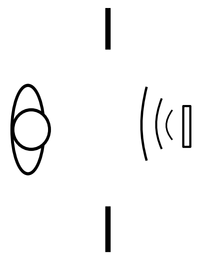

Fig. 2. Antenna in front of the entrance. It becomes an obstacle.

a 45-degree orientation with respect to the door's plane, as shown in figure 3). With this layout, the reader can detect users that advance straight ahead or face the antenna while crossing the door. However, if the user rotates slightly (figure 3) or hides the tag with his arm (which may be quite natural while walking), his body will block the UHF signal.

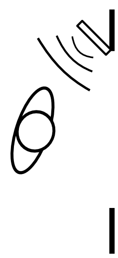

Fig. 3. A single antenna at the door jamb. Depending on user orientation, his body may block the RF signal.

An obvious solution is a layout with two antennae, one on each side. At the time this paper was written, UHF readers with two (or more) RF ports were expensive, large and power-hungry. This led us to a different aproach: external antenna switching. The idea is quite simple: the auxiliary CPU that controls the RFID reader connects the only RF port to one of the antennae before initiating each RFID scan.

We decided to employ a mechanical RFID switch for its near-zero insertion loss. It may be argued that mechanical switches have a limited operational life. We used a model with an estimated life of 10 million cycles, which, considering scan slot lengths, corresponds to some 1,380 working hours before replacing the units. Nevertheless, this lifespan can be greatly extended by combining the system with a movement sensor. In any case, high-quality splitters or electronic switches are out of the question for their high insertion loss (3dB typically).

This approach is feasible when the scanning rate is fast enough, so that half the succesful lectures in two seconds suffice to detect a user (this is roughly the time it takes a user to leave the detection range at walking speed). This represents a worst case situation when only one of the antennae can reach the tag.

Figure 4 illustrates the block diagram of the system, and figure 5 shows the current prototype: a main board (1), based on an ARM microcontroller, which controls a Sirit Infinity 9311 UHF reader with default settings (3) and the mechanical RF switch (2).

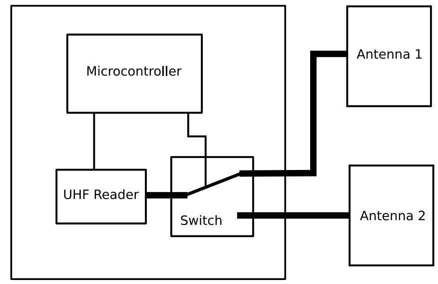

Fig. 4. Block diagram of the system.

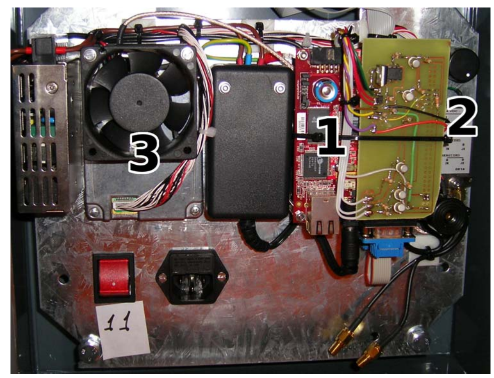

Fig. 5. Prototype.

There are two aspects that determine the reading speed: the time to perform a scan, and switching stabilization. In the prototype, the former is ∼200 ms and the latter is ∼20 ms. This yields 4-5 readings per second. It is important to note that the reader tries several tag formats per antenna: ISO 18000-6a, ISO 18000-6b, EPC0 and EPC1, i.e. four scans per switch position. Disabling some of the formats increases speed up to 5-6 readings per second. Taking into consideration that it takes two seconds to cross the detection area, there are four (eight) opportunities to read the tag in the worst (best) case. In our tests, this was enough to achieve a virtual 100% success.

V. Conclusion

In this paper we describe implementation issues that arise when using RFID as an access control system. In our system, people wearing ID cards (passive RFID tags) are to be identified as they pass through a door. We have placed two anntenae to perform redundant readings, which causes the reader collision problem. To solve it we use Time Division Multiple Access (TDMA), that is, we use two readers that alternatively scan the tags. We first use a simple analysis to derive the average time needed to identify a population of tags, which is used to set the duration of a timeslot for the TDMA reader access, and finally show our prototype implementation as a case study. We have evaluated the EPC "Gen 2" anti-collision procedure to estimate the average number of cycles needed to identify all the tags present in a coverage cell. The protocol has been evaluated with and without frame adaption, by simulation and analysis, respectively. We also show a prototype implementation of the system.

As future work we plan to extend the analysis to derive the average identification time when a frame adaptation mechanism is used, and to test the prototype in different scenarios involving a higher number of tags present simultaneously.

VI. Acknowledgment

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