RFID-Env: methods and software simulation for RFID environments

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Abstract

Purpose – The purpose of this paper is to present the results of an analytical and experimental research for the development of an innovative product designated RFID environment (RFID-Env). This software is designed for the use of professionals in computer systems and plant engineering who are engaged in research and development (R&D) of ultra high frequency (UHF) passive radio frequency identification (RFID) systems as applied to the management and operation of logistic supply chains.

Design/methodology/approach – The RFID-Env makes it possible to simulate on computer screens a complete RFID-Env by processing user data on the technical and physical characteristics of real or virtual RFID-Envs. Information outputted can include descriptions of the performance to be expected from a given configuration and detailed reports as to whether that particular configuration will succeed in reading all the RFID tags flowing through a defined system.

Findings – The paper shows the models and methods on how these simulations can be performed, and this is the major scientific contribution of this work, i.e. what are the logical and physical models that enable the development of software simulators for RFID-Envs.

Research limitations/implications – This work will be continued to introduce more consideration of the physical environment, such as the interferences produced by the tagged products themselves by scattering the radio frequency (RF) signals, and the models, positioning and focusing of the antennas. New RF prediction models shall be created along the continuation of this paper, with the purpose to rise the amount of environments that can be simulated.

Practical implications – The product is intended for use by developers in computer sciences, and by engineers doing R&D for the solution of RFID problems, and makes it possible to simulate a complete range of virtual RFID-Envs so that R&D can proceed in a non-factory atmosphere.

Originality/value – There are only a few related papers that consider in an isolated form some of the problems approached here, but it was not found models that proposed as an integrated form all the processing to an RFID-Env simulation like here presented.

Keywords Computer applications, Communication technologies, Information systems, Information services, Information management, Innovation

Paper type Technical paper

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1. Introduction

The major challenge for industry in logistic chains is the need to constantly optimize processes so as to produce goods or services as quickly and efficiently as possible, at the right place and precisely as desired by the clients (Reyes and Jaska, 2007). Nowadays, the variety of products offered in the market place adds to the complexity of managing the flow of information along the production supply chain and obliges manufacturers to introduce new technologies to facilitate the logistic operations (Ngai *et al.*, 2007). The technology of radio-frequency identification (RFID) is attracting attention and interest from industry and commerce because it can potentially simplify processes and improve the efficiency of automatic product identification (Borriello, 2005).

The main component of the RFID technology is the intelligent tag, which is attached to some product. The information electronically identified in the tag is read by electromagnetic devices and passed to a radio transmitter where an RF carrier transmits it to a possibly distant receiver, called a reader or an interrogator, capable of interpreting and registering the information (Floerkemeier and Sarma, 2009).

The RFID technology can be used in many different ways and the fields of application for then is growing exponentially (Spekman and Sweeney, 2006). Among the improvements that it can provide in logistic operations, Prado *et al.* (2006) emphasize:

- greater availability of products;
- better profit margins due to cost reductions;
- improved worker operational efficiency;
- reduction in inventory losses;
- reduction in stock levels;
- reduction of the technical assistance cost; and
- better industrial or commercial layouts for installations.

Bendavid *et al.* (2006) agree with these improvements and state that if conventional business processes are compared with those of the RFID technology, the impact of this new technology, specifically at the strategic level, includes:

- the development of new business models;
- the integration of activities; and
- the re-engineering and automation of older processes, thus facilitating B2B (business to business) commerce.

But the use of RFID equipment and the integration of these devices with the business information system face some challenges as well, as discussed in the next sections of this paper. One of the major problems refers to the physical configuration of the environment where RFID equipment is installed (Jo *et al.*, 2009). Problems like magnetic interference and maximum reading distance of tags may render the design of RFID environments (RFID-Envs) more difficult or even unfeasible. This paper proposes methods and models for enabling the simulation of RFID-Envs. The literature on the subject contains a few related papers that consider some of the problems approached here in an isolated way, but the authors could not find in the literature the integration of such models into a single framework as the paper proposes.

The remaining of the paper is organized as follows. Section 2 presents an overview of RFID and challenges for their use. Section 3 presents related work. Section 4 describes the methodology and procedures used in the research. Section 5 describes the proposed software system and shows the main models that allow conducting simulations and an experimental simulated application. Section 6 demonstrates the obtained results, describing the considered physical parameters and the type of environments that can be simulated, such as a "conveyor mode" or a "portal mode". Finally, Section 7 lists some conclusions.

2. Overview and challenges for use of RFID

Hassan and Chatterjee (2006) consider that the RFID system is made up basically of three elements which are:

(1) the tags;

(2) the electromagnetic and data readers; and

(3) a series of computer programs.

Landt (2005) agrees with this definition and adds that the operation of the RFID system depends on an electronic tag that is attached to each product and has a unique digital identity. This identity is known as the product code or EPC – electronic product code. When the tag is requested by the external electronic reader, the data recorded in the tag's memory are recovered and transmitted. This memory consists of an integrated circuit or microchip and has the capacity to store a considerable amount of information, such as, among others:

- the electronic code of that particular product;
- the product reference number;
- the respective production data;
- delivery date;
- expiration period; and
- information on the supplier (Atkinson, 2004).

Although there are many promising applications of RFID technology in the supply chain, many technological difficulties prevent the large-scale use of this system (Spekman and Sweeney, 2006). This technology has functional problems that have been widely discussed by the software developers and production engineers. These difficulties have been instigating constant research in order to improve the technology. These problems are:

- collisions caused by simultaneous communication of two or more tags readouts;
- electromagnetic interference;
- insufficient RF carriers range;
- difficulties in finding the ideal positioning; and
- the number of antennas required for the electronic readers (Myung and Lee, 2006; Hassan and Chatterjee, 2006; Cheng and Jin, 2007).

Considering these problems, this paper presents the results of an experimental research conducted to obtain data for the development of an innovative product: RFID-Env Software Simulation. This product is designed to be used by computer system applications scientists and research and development (R&D) engineers working on RFID problems. The main feature of this product is to simulate a complete RFID-Env away from the factory floor. Curtin *et al.* (2007) proposed an interesting questions list to be answered at the moment of an RFID systems adoption. Among the issues to be examined, it is included: how does the radio interference, caused by physical items, impact in the usage of the RFID in a business context? Which are the other ways of interference that may prevent reading multiple items simultaneously? What are the limitations for the tags reading in a mobile environment? How fast can an item travel and still achieve an accurate tag reading? What is the physical proximity margin of error? What is the rate of technical advancement in terms of RFID signal fidelity over longer distances? Our objective in this paper is, through the methods and models presented and through the implementation of these methods and models in the software RFID-Env, to objectively answer the important questions above.

3. Related works

The results presented in this paper are not available in the literature. There are many citations on the bibliography that analyze and propose theoretic-mathematical models about RF propagation characteristics. Other authors present the RF estimation models based in different types of environments, mainly external, such as urban areas with big or little distances. However, it was not found estimation models that considers the main environments and ways that RFID systems can be used, except, preliminarily in Gakhar *et al.* (2008) and Floerkemeier and Sarma (2009), reported next.

As an example, Nikitin and Rao (2006) present a meticulous study about RFID signal propagation, considering many logical and physical characteristics; nevertheless, they do not present the use of environment models.

Malison *et al.* (2008) present a specific study about the influence of the human body over RF propagation in RFID devices. The environment is not considered, except by the fact that RFID tags will be close to the human body in movement.

Gakhar *et al.* (2008) is the closest related work. It presents the creation of an RFID propagation model to only one use case, the most simple as possible: one antenna positioned exactly in front of a tag, directly viewed without obstacles between the devices. This tag is attached in a plastic tray, over a metal table. Tests were performed varying the distances between the antenna and the tag and the angulation between the tag and the antenna. It was considered the environment influences, such as the metal of the tray support table, the floor and the walls surrounded. It was not considered on the test the anti-collision protocols.

Floerkemeier and Sarma (2009), two scientists from Auto-ID Lab (MIT), among the main authors in the RFID area, presented the RFID simulation engine. This is a tool that simulates in discrete events the functioning of the anti-collision algorithms and, in a theoretical way considering only one RF propagation model, the physical aspects of the RFID system operation. This paper does not cite how the anti-collision protocols were implemented, an important part to an RFID system simulation.

None of the related papers show a set of methods and models for the simulation as the ones here presented. In this work, it is presented the models of RF as well as the restrictions imposed by the anti-collision algorithms of the signals transmitted by the tags.

4. Methodological procedures

This paper proposes a series of computation model of computation (MoC) models to the development of RFID-Env simulation systems. In Vincentelli *et al.* (2000) as well as

Marcon *et al.* (2002), it is seen that a MoC is a models composed by a system with hardware and software components, allowing object abstractions, applied to allow the reasoning about way the system works. The modeling of a computer system includes a describing formalism used by the designers to define the system functionalities. Many software systems, such as the simulator here presented, perform tasks in a parallel or concurrent way.

Edward Lee, a fellow from Institute of Electrical and Electronic Engineers, said:

> [...] in concurrent systems, modules consist of relatively autonomous agents that interact through messaging of some sort. The rules of interaction of the agents, the semantics of the composition, are what we call the MoC (Girault *et al.*, 1999; Buck *et al.*, 1994).

The development of RFID-Env was based on the high-level abstract models and is able to represent all the parameters, therefore developers can configure the tests in any situation that best suits the environment to be simulated. The software includes a library of communication protocols (anti-collision protocol library) that covers the four main ISO standards for the ultra high frequency (UHF) and EPC Generation 2 area (ISO 18000-6), which are:

(1) ALOHA LST.

(2) ALOHA FST.

(3) Btree.

(4) Random slotted (Q algorithm).

Moreover, the protocol library has the Calculated Q proposal, which is an improved edition of the random slotted, the most recent version of the ISO and EPC standards. The software was written in the Java programming language and the developers can extend the reading coverage, by using new communication protocols. The proper operation of the RFID-Env was confirmed by performing under many test conditions, with the different protocols proposed by the ISO.

Owing to a combination of the tag size, the reading capacity at distances around 5 m, the reading area control by adjusting the antenna direction, the interrogator configuration, a major part of the efforts to use RFID in the supply chains and consumer goods control is directed to the UHF passive tags (ISO 18000-6) (Hassan and Chatterjee, 2006; Curtin *et al.*, 2007; Borriello, 2005; Weinstein, 2005). For this reason, our development was concentrated on the physical characteristics and anti-collision algorithms used in these tags.

In the simulated environment, the models took into account the tag's anti-collision communication protocol, the amount of tags to be read in a specified period of time, the environment temperature, the distance between the tags and the reader's antennas, the speed the tags passed by the readers and, finally, the electromagnetic interferences generated by the environment. To use the RFID-Env, the operator simply enters the physical and technical characteristics of the environment. Then, the simulator generates reports predicting whether, for that particular configuration, all the tags will be read correctly or not.

The system was studied and improved by researchers from the Center of Technological Innovation from Vale do Paranhana. This is one among several centers in belonging to the Program of Technological Innovation, promoted by the Government of the State of Rio Grande do Sul in Brazil. These centers are promoters of innovation and are located in the main regions of the State of Rio Grande do Sul, Brazil. The program was created by partnerships between a number of public and private institutes of the State of Rio Grande do Sul and it integrates human, financial and technological resources into a statewide system for the development of science, technology and innovation. This initiative was performed by the Office of the Secretary of State for Science and Technology of Rio Grande do Sul, in 1989, the program for the establishment of centers of technological innovation is today the largest R&D network in the state (Jung *et al.*, 2007).

5. The system

The design strategy of the first MoC to be presented describes, in high level, the general behavior of our RFID-Env simulator through a finite state machine (FSM). FSMs have been widely used to describe and analyze intricate control sequences. Because of their finite nature, FSMs yield better to analysis and synthesis than alternative control models, such as sequential programs language with "if-then-else" and "goto". In the example, using an FSM, a designer can enumerate the set of reachable states to verify that a particularly dangerous state cannot be reached. The same situation may be impracticable in a richer language (Girault *et al.*, 1999). The Figure 1 shows the model's four main states:

(1) *Environmental characteristics design (ECD)*. The system is on this state while the user configures the physical characteristics from the system environment to

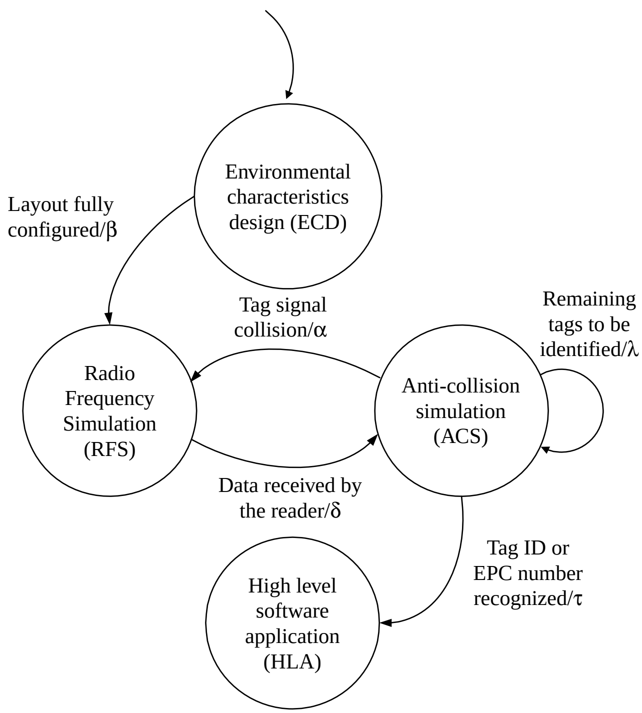

Figure 1. State diagram of the RFID-Env – proposed design strategy

be simulated. Type and amount of the tags on the environment, distances, moving speed and materials are described by the user at this moment.

(2) *RF simulation (RFS)*. State that evaluates, in each time span, which tags in the environment are inside the action radius of the reader's equipment antenna. Another important question to be considered is that, eventually, tags will be accessible to the reader, but that does not mean the opposite is true, in other words, one tag may be reached by the reader's signal, but, in the reverse path, the tag may not be able to make its signal reach with the minimal necessary quality to the reader's antenna. The RFS state will be active each time that one or more tags are present in the environment and have not been identified by the anti-collision simulation (ACS) state. Basically, the RFS state passes to the ACS state all detected tags. The ACS state identifies a single tag each time and returns the system control to the RFS. These states alternate with each other until all tags in the environment have been identified. Owing to the signal collision sent by the tags, a same tag may be detected more than once on the RFS state, until the ACS state identifies it as a single tag between the others in the environment.

(3) *ACS*. The state receives from the RFS state the signal of the tag(s) presented in the environment. In the case of existing more than one tag in the environment, the anti-collision process is started, and many changes between the ACS and RFS state will be necessary, until the anti-collision process of the tag's group has been completely finished. Eventually, a tag that, in the beginning of the anti-collision process, has been responding to the RFS process is not accessible through RF during the ACS process. The RFS process stops passing the signal from this tag to the ACS process at this moment; this will prevent the complete reading of this tag information. This situation, for instance, is possible in environments where the tags are moving, or there is a transit of materials or the presence of electromagnetic interferences.

(4) *High-level software application (HLA)*. This is the final state of the software simulator, it happens when the identified tag information is passed to the user's application high-level software.

As shown in Figure 1, each elliptic node represents a state and each arc represents a transition. The arc without a state source points represents the initial state of the system, i.e. state ECD.

According to Lee and Lee (1998) an FSM M is a tuple of the form:

$$M ::= <I, O, Q, q0, T> \tag{1}$$

where:

I	is a set of input events.
O	is a set of output events.
Q	is a finite set of states.
$q0 \in Q$	is the initial state.
T	is a set of transitions.

An event is a named variable that is either present or absent. Each transition $t \in T$ is:

$$t ::= <qs, guard/action, qd> \qquad (2)$$

where:

$qs \in Q$ is the source state.

A guard g is a Boolean expression generated by the following grammar:

$$g ::= true | false | e | \neg g \,|\, g \oplus g \,|\, g \otimes g \qquad (3)$$

where $e \in I$. The evaluation of an event e is either "true" or "false" when the event is either present or absent. The operators $\neg$, $\oplus$ and $\otimes$ correspond to the Boolean operators "not", "or" and "and", respectively:

- An action lists a subset of the output events., i.e. an action a is:

$$a ::= nil \,|\, b \qquad (4)$$

$$b ::= e \,|\, b, b \qquad (5)$$

where $e \in O$ and "," distinguishes two events in the action:

- $qd \in Q$ is the destination state.

In one reaction of the FSM, a subset of the events in I are present. One transition is triggered when its guard is true under the current input events. The FSM goes to the destination state of the triggered transition, and emits each output event in the action of the triggered transition, making these output events present. If the action is nil, it means that no output event is emitted. An action only lists the output events to be emitted, and thus all other output events are absent.

Each transition links a source state with a destination state and is labeled by "guard/action". Thus, for Figure 1, I = {"Layout fully configured", "Tag signal collision", "Data received by the reader", "Remaining tags to be identified", "Tag ID or EPC number recognized"}, $O = \{\beta, \alpha, \delta, \lambda, \tau\}$, $Q = \{ECD, RFS, ACS, HLA\}$, $q0 = ECD$ and T = {<ECD, Layout fully configured/β, RFS>, <RFS, Tag RF signal detected/δ, ACS>, <ACS, Tag signal collision data/α, RFS>, <ACS, Remaining tags to be identified/λ, ACS>, <ACS, Tag recognized/τ, HLA>}, where:

β is the complete set of environmental data, like type and quantity of tags and antennas, distances, material interferences, etc.

α is *a* request command to new detection RF.

δ is the RF signal detected.

λ is the remaining of anti-collision process data.

τ is the tag ID or EPC number recognized.

The initial model shown in Figure 1 is hierarchical, in other words, it foresees the existence of other specific model, being, therefore, a hierarchical concurrent FSMs (HCFSMs). The internal models will describe the physical level simulation forms (RF) and the logical level simulations (anti-collision). HCFSMs are models that allow a state of the FSM to be refined into another FSM, i.e. a set of substates. This characteristic enables many internal simulation models to be implemented in an independent way, making the system flexible according with its specificity (Lee and Lee, 1998). On the next section, it will be discussed simulation forms to the RFS and ACS states, and the internal models already developed to these tasks. Figure 2 shows the HCFSM proposal to the RFID-Env Simulator software.

Figure 2 shows the FSM already shown on Figure 1, but now with FSM slaves that can be used to the two main states of RFID Simulator here presented. The states are the physical simulation (RFS) (master) and logical (RFS) of an RFID system states. In fact, each slave state is a complete FSM and it should be detailed for a better understanding. For this paper scope, some of the slave states already developed will be detailed as an overview of the system.

5.1 Models (slaves) to a physical (RFS) and logical (ACS) simulation

There are many RF propagation simulation models, and many standardized protocols (and the respective models) to the solution for a tag emitting signal collision problem. From the proposal of a HCFSM to the RFID-Env, many internal models (slaves) will allow appropriate simulations for each type of use case.

5.2 Physical level communication simulation (RFS)

According to Sarkar *et al.* (2003) the basic wireless network physical environment can be simulated through RF propagation models. RF propagation models are formulas that allow the accurately estimation of the signal parameters for mobile systems. Since site measurements are expensive, propagation models have been developed as a suitable, low-cost, and convenient alternative. For Tam and Tran (1995), propagation models provide the estimation of the signal strength and time dispersion in many RF environments. These data are valuable in the design and installation of radio systems. RF propagation models can be generated from experiments using real physical environments and/or from theoretic-mathematical models. The basic value to be computed in an RF propagation model is the path loss (PL), which is the measure of the average RF attenuation suffered by a transmitted signal when it arrives at the receiver, after having a path of several wavelengths. It is defined by equation (6):

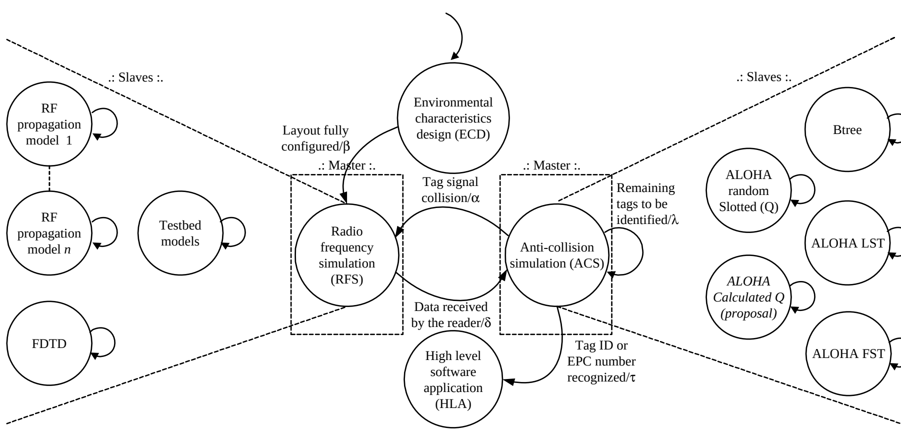

Figure 2.
HCFSM of the RFID-Env, with master and slave states identified

$$PL(dB) = 10 \log \frac{p_t}{P_r} \tag{6}$$

where P_t and P_r are the transmitted and received power, respectively.

Channel modeling is required to predict PL and to characterize the impulse response of the propagating channel. In a free space, the power reaching the receiving antenna – which is separated from the transmitting antenna by a distance d – is given by the Friis free-space equation (7):

$$P_t = \frac{\mathrm{Pr} * Gr * Gt * \lambda^2}{4\pi \mathrm{d}^2} \tag{7}$$

Typical values that can be used by the Friis' RFID system model are the following (Sweeney, 2005):

(1) *Interrogator*:
- Pr – Interrogator equipment power (between 23 and 30 dBm).
- Gr – Interrogator antenna gain (6 dBi).

(2) *Tags*:
- Pt – Tag received power (requires a minimal power of − 10 dBm, or 100 microwatts).
- Gt – Antenna gain (only 1 dBi).

(3) *RF and environment*:
- λ – wavelength signal (33 cm at 915 MHz).
- d – distance between interrogator and tag.

There are other RFS methods, such as FDTD (finite-difference time-domain) based and modeled using real experiments, both approaches developed in this paper. In Koos *et al.* (2006), it is seen that industrial and research design of novel RF components, heavily depends on the reliability and accuracy of mathematical modeling algorithms. A very general tool for simulating RF environments is the FDTD method. FDTD directly describes Maxwell's equations in the time domain. It is thus a robust method that contains a minimum amount of implicit assumptions. Basically, through the usage of FDTD method it is possible to develop software tools that allow the simulation of radiating elements and the interaction of electromagnetic waves with the several materials that compose an environment (Sullivan, 2000). One of the internal models developed to the RFS state uses the FDTD method, and through the results of this method it is possible to simulate which tags of the environment can be read in a determined time span, accomplishing with the RFS state tasks from the RFID-Env software.

For the creation of models based on real experiments, our group also made a great amount of tests in the real use RFID system environments (Plates 1 and 2). These experiments enable the creation of propagation models based on the tests results, because the results in environments with similar material tend to repeat (these models are RF propagation models shown in our HCFSM).

Plate 1.
Testbed to formulate a shopping metal cart model

Note: Inside the metal box there is a base with a tag to verify the tags reading possibility in this kind of situation – on the right of the photo there is a RFID reader antenna

Plate 2.
Testbed to formulate a maximum distance reading model

Note: On the left, a base with a tag and on the right a base with an RFID reader antenna

5.3 Logical level communication simulation (ACS)

Anti-collision protocol is a fundamental part to the well functioning of RFID systems because it allows the reader to identify and communicate even when there is more than one tag in the environment. RFID tags send and receive signals in the same shared frequency, and this causes a collision of signals emitted by the tags. This problem constitutes a big deal that demands communication channel sharing techniques. Such techniques are implemented by "anti-collision protocols". The current protocols standardized by ISO and EPCglobal are based mainly on two generic strategies:

(1) channel sharing by time (ALOHA algorithms); and

(2) tags identification by reader-machine questioning, generically called "tree-based or binary tree protocols" (Shih *et al.*, 2006).

The first version (the type *A* version) of the ISO 18000-6 anti-collision protocol was based on ALOHA protocol. In the review process of the first version by ISO, the protocol received the fast slot mode (FST) operation mode, and the older version began to be identified in the ISO standard as long slot mode (LST). The basic operation mode of these protocols consists in placing the tag transmissions in rounds and slots. A round is composed by a number of slots. Each slot has sufficient time duration for the interrogator to receive the answer from a tag. The FST version of ISO 18000-6 A standard specifies a complement to the functioning of the LST anti-collision algorithm. This complement is optional, being on the criterion of the manufacturer to configure its tags to use the FST mode. Basically, the new mode intends to make the algorithm faster, reducing stages comparing to the older version.

In the ISO 18000-6 type B devices, the standardized anti-collision protocol is the Btree, based on binary tree protocols. This protocol always has only one transmission slot available for all the tags, the zero slot and the tags randomly select values that will make them to come closer or farther from the zero value. When a tag reaches zero in their slot counter, it will be able to transmit. The collisions happen when more than one tag reaches the value of zero in their slot counter at the same stage of the algorithm execution. Empty slots happen when none of the tags have zero in their slot counter. The amount of readings performed by the interrogator (i.e. the amount of interactions with slot zero) provides the amount of slots used by Btree for the reading of all the tags in the environment.

Finally, we have the random slotted anti-collision protocol (EPCglobal, 2005) used by the last version of the UHF standards (ISO 18000-6 C and EPCglobal Generation 2). As well as in Btree and in both standard 18000-6 Aloha algorithms (LST and FST), the base of the random slotted algorithm (also called *Q* algorithm) is on the generation of a random number method for a slot counter in order to be stored in the tag. In accordance with the interrogator instructions, the value of the counter slot is decreased in the tags. When this counter reaches zero in any tag, this initiates the communication. However, the random slotted algorithm possesses important evolutions when compared to the Btree and ALOHA:

- The possibility of a tag to work simultaneously with more than one interrogator by the use of sessions.
- A more precise functionality to adjust the total number of slots (the *Q* value of the algorithm) available to the transmission of the tags. The algorithm possesses the functionality to adjust the number of slots available to the tags during the anti-collision process.

When the RFID-Env software is simulating the ISO 18000-6 standard types A reading, B and C tags, and the respective anti-collision communication protocols, it respects the manner in which these devices work – there are processes involving the interrogator operation and others related to the tags functioning. Some few processes were implemented specifically for the simulation. For example, the process that generates the unique code identifier denominated UID (unique identifier) on each tag. In a typical real-life system, the tags already have a UID value at the moment that the protocols are executed, while in the RFID-Env, a random number generator produces an initial simulated UID numbers and allocates to each tag the corresponding simulated UID value. This can vary between 16 bits (in the ISO 18000-6 C) and 64 bits (in the ISO 18000-6 B) (ISO/IEC 18000-6, 2006a, b).

During the process of identifying the tags, the protocol may use only a portion of the data contained in the tag's memory. In the ISO 18000-6 A, a sub identifier of 40 bits is transmitted. However, in the ISO 18000-6 B, the whole UID of 64 bits is sent, and in the ISO 18000-6 C a random value of 16 bits, exclusively for the anti-collision process, called RNI6, is sent out.

According to the tag type standardized by ISO to be simulated on the software, the respective slave model of the anti-collision protocol will be started by the master state ACS. For instance, Figure 3 shows a complete FSM of one of the Aloha Calculated Q slave, which implements the random slotted anti-collision protocol (or the *Q* algorithm). In this protocol, the type C UHF tags, which are in the anti-collision process, shall implement an arbitrate state. The state arbitrate can be considered as a "holding state" for the tags that are participating in the current inventory round, but whose slot counters did not hold nonzero values yet. A tag in arbitrate shall decrement its slot counter every time it receives a QueryRep command, whose session parameter matches

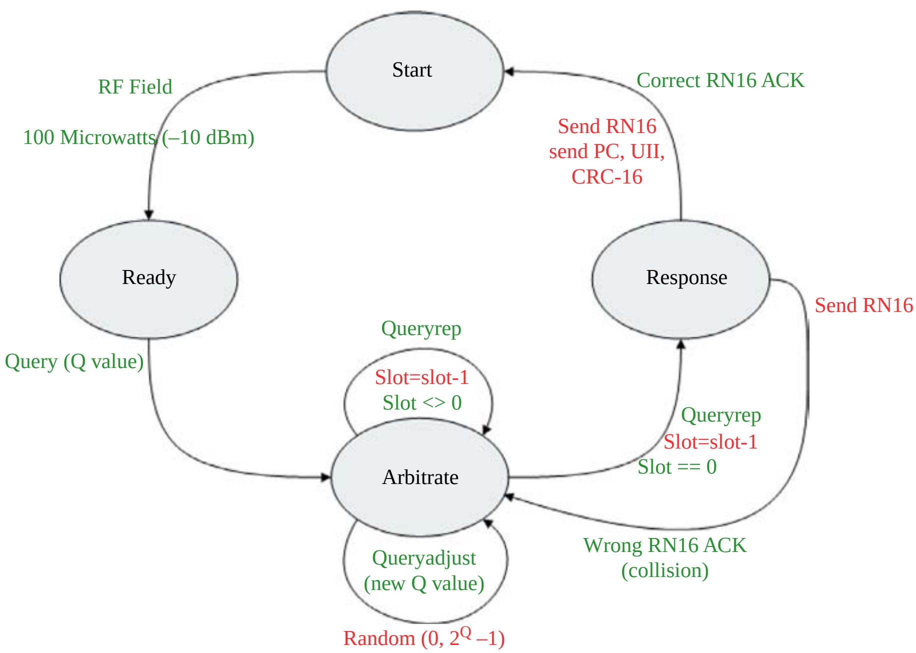

Figure 3.
Slave FSM of ACS state to simulate Aloha Calculated Q protocol

the session for the inventory round currently in progress, and it shall move to the response state and reply an RN16 when its slot counter reaches zero (i.e. that time can communicate with the reader).

The work (Azambuja *et al.*, 2008) provides a detailed explanations about this FSM, as well as explanations of the other FSMs for each slave state of the ACS.

The work environment of the RFID-Env is divided into three windows: simulator, single mode and portal mode. On the initial screen (Figure 4), the user specifies which anti-collision protocol he wishes to test, the number of tags in the environment, and according to the protocol selected, the user provides some specific parameters such as the starting sizes of the frames in ALOHA type protocols used by the ISO 18000-6 A and C standards. The user also may select the total number of executions (to facilitate the generation of average statistics of the results) and the printout format (which is generated in text file).

On the initial screen, there is a (optional) selection box denominated advanced Selection, where the user can select the system operational mode to be simulated: single mode or portal mode. If the user only wants to test the algorithms functioning, without interference of the physical environment, this option may be ignored. For tests where the constructive characteristics of the tags (for example, whether the tag base material is plastic or wood) and where the environmental characteristics, such as the amount of the antennas, tag speed, temperature or other variables are considered, the user must, in this case, select either the single or portal mode.

Figure 5 shows the portal mode screen enabled after selection of the advanced simulation by the user and the option corresponding to this mode.

As soon as the user inputs the number of tags presented in the environment, the UID generation process is executed and a unique code is attributed for each tag of the virtual environment. The environment is generated in the RAM memory and the five main stages for the simulation process are shown in Figure 6.

When the execution starts, the user is requested to input the number of tags to be simulated (see stage 1 in Figure 6). With this information, the software creates a slot in the memory where the values will be stored for each tag (stage 2). When this is

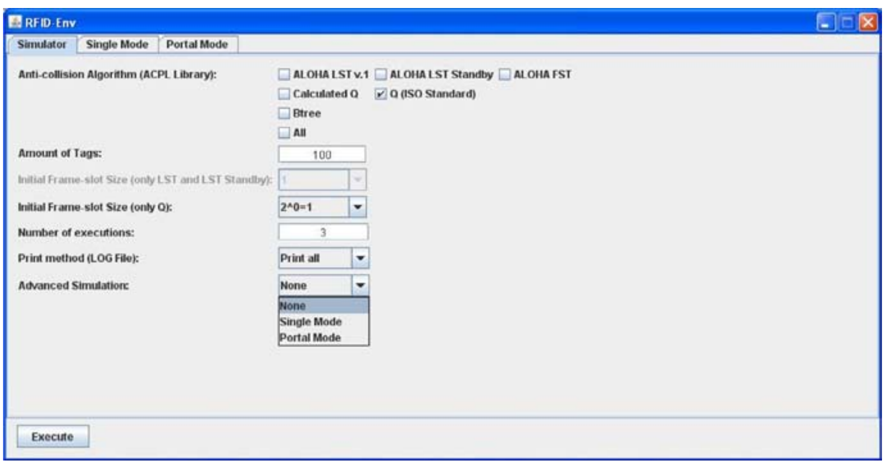

Figure 4.
Initial window of the RFID-Env and selection of the type of environment

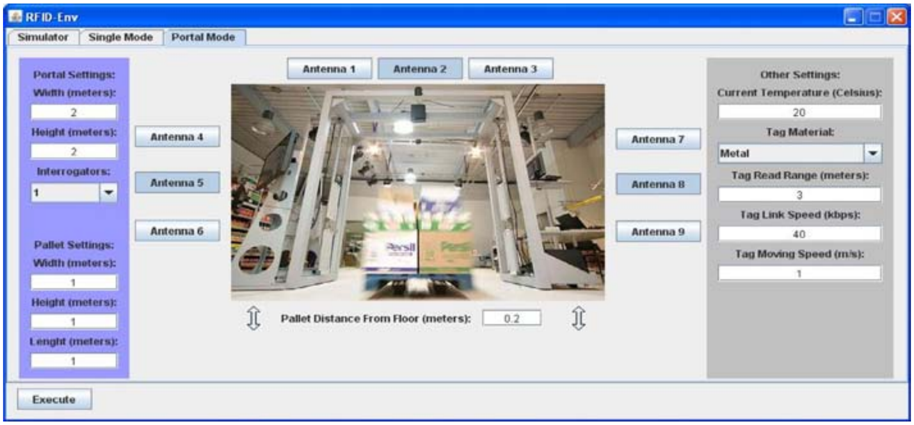

Figure 5.
Portal mode screen of the RFID-Env

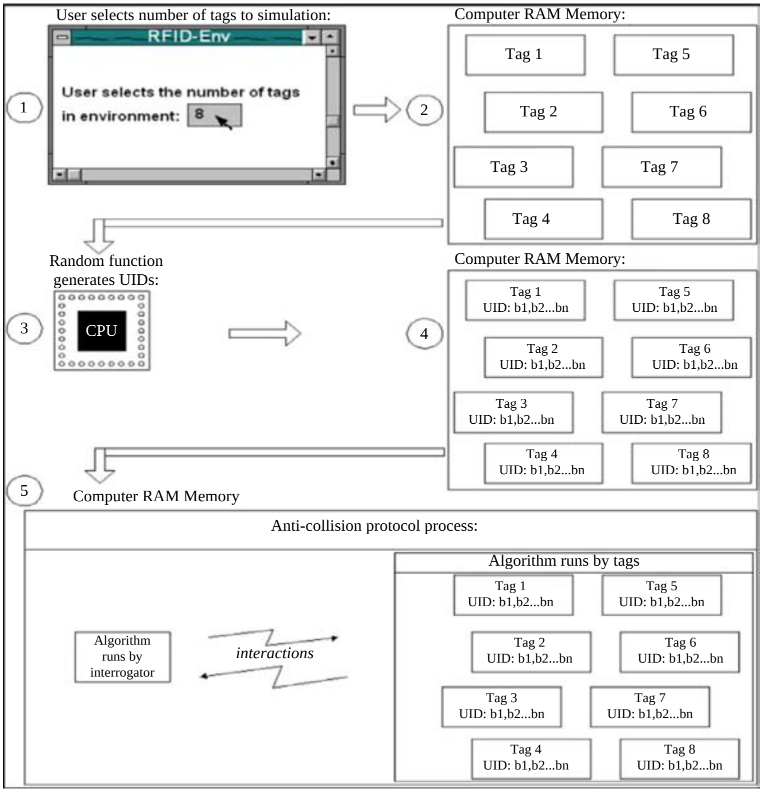

Figure 6.
Simulation environment and the initial stages of RFID-Env operation

complete, the generation process of the UID for the tags starts (stages 3 and 4). By last, at the stage 5, the process that runs the specific anti-collision algorithm protocol to be simulated is initiated and begins to interact with the tags, while, at the same time, the interrogator process starts up.

5.4 Experimental operation

Having obtained the inputs on the type and the amount of RFID tags, the system performs a simple simulation where the tags are read for testing the anti-collision protocols. As an example, we will demonstrate the report of a ten tags reading simulation using the ISO 18000-6 B (Btree anti-collision protocol) standard. The algorithm utilized by the Btree has a determinant difference in relation to the ALOHA-based protocols – it does not include the concept of the communication frame size (round size) (ISO/IEC 18000-6, 2006a).

In the other three ISO protocols, although the dimensions for the initial round sizes are required, the Btree approach eliminates this necessity. This algorithm has an advantage over the algorithms used by the ISO 18000-6 A LST and FST standards. While in those standards the algorithms return a very low performance when reading more than 256 tags (because this is the maximum round size), the Btree does not suffer from this limitation (ISO/IEC 18000-6, 2006a, b; Shih *et al.*, 2006). By contrast, the Btree uses a concept where the first iterations of the algorithm, that is, the first communications between the tags and the reader, tend to generate many collisions, as it can be seen in the RFID-Env utilization example presented below.

When the number of tags to be simulated is provided, the RFID-Env executes the algorithms and generates the outputs and totals for the final simulation results at the end of the report (Figure 7).

```
-----------------|BTREE|----------------
--Iteration #1, Tags that replied:
E0E069FEC02185EC20 | E0B4909015F4627A76
E08C1013BF9FCB2BAE | E059592730460AF424
E0BB6B2EA85B402E70 | E0D49AC0DD20AEE2E7
E041E50008FC2F6965 | E096E4892AAEA7DCF9
E03783A6E0D9449A7D | E0A77048EDBEF83434
--Iteration #2, Tags that replied:
E059592730460AF424 | E0BB6B2EA85B402E70
E0D49AC0DD20AEE2E7 | E041E50008FC2F6965
E096E4892AAEA7DCF9 | E03783A6E0D9449A7D
E0A77048EDBEF83434
--Iteration #3, Tags that replied:
E041E50008FC2F6965 | E03783A6E0D9449A7D
E0A77048EDBEF83434
--Iteration #4, Tags that replied:
E0A77048EDBEF83434
--Iteration #5, Tags that replied:
E041E50008FC2F6965 | E03783A6E0D9449A7D
                    ...
--Iteration #11, Tags that replied:
No tag replied
                    ...
--Iteration #27, Tags that replied:
E08C1013BF9FCB2BAE
---------- Performance Report ---------
Tags: 10
Iterations: 27
Iterations with tag collision: 13
Iterations with no tag reply: 4
```

Note: With 13 collisions, four empty slots and a total of 27 slots used for communication of ten RFID tags

Figure 7. Btree protocol execution report

When the number of simulation tags is given, RFID-Env executes the simulation generating a report with iterations and performance summary.

Figure 7 shows that during the first iteration, all the ten tags try to transmit their information, generating many signal collisions. After the first frustrated transmission, all tags randomly select zero or one value. Tags that generated one increment in their slot counter will only retransmit when their slot counter reaches the zero. Tags that generated zero do not need to increment their slot counter and keep having the opportunity to retransmit on the next iteration.

If more than one tag randomly select zero (which happens in the second iteration of Figure 7), again these tags randomly select a new zero or one value, while the ones that already had one in their slot counter (the other three tags in the environment) increment once again this value. These steps are repeated, until only one tag has randomly selected zero and all the others had randomly selected one, which happened in the iteration no. 4. This characteristic of many collisions on the first Btree iterations is proper of this protocol.

The final report of Figure 7 shows that the algorithm execution needs 27 iterations for ten tags reading, considering that 13 slots had tags collision and four slots without any tag transmission.

6. Results

6.1 Physical parameters considered by the RFID-Env system

This section presents the physical parameters considered by the RFID-Env, as well as the way they are analyzed and the influence of these parameters on the final results of the simulations.

6.1.1 Maximum reaches for reading, speed and total exposition time. The maximum distance for proper reading changes, on the tag side, because of the following main factors:

- tag speed;
- the material on which the tag antenna is assembled; and
- the presence of spurious magnetic and physical interference in the environment.

On average, the UHF tags can operate at distances of 5 m between the tag and the interrogator antenna, at the same time the average can vary between 3.65 and 10.66 m according to the frequency of operation and the tag material (Cheng and Jin, 2007).

The RFID-Env system considers these values in the following manner: given the average read reach distance of the tags system to be simulated and the movement speed of the tagged product, it is possible to calculate the total time each tag is exposed to the interrogator. From the values of reading speeds found in the references in ISO/IEC 18000-6 (2006a, b), and the amount of bits to be read from each tag, the following formula can be solved:

$$\textit{total exposition time} >= [\textit{time to read}(y \text{ bits}*\text{n tags})] \quad (8)$$

where:

total exposition time	total exposition time of the tag group at the reach of the interrogator reading distance.
y bits	amount of bits of each tag.
n tags	amount of tags to be read.

In order to calculate the total time that each tag is exposed to the interrogator, it is first necessary to determinate the maximum reading reach to the right and to the left of the interrogator antenna. Considering the situation of an environment based on a conveyer belt moving from left to right and with an antenna pointed directly to the tags, it can be seen that a point exists (T1 on Figure 8) where the tags enter the leading edge of the interrogator reading range. Point T2 is the exact front center of the interrogator and is at half of the distance traveled by the tag within its reading area. As a corollary, one can say that a point T3 also exists to the right of T2, where the tag moves out of the reading range of the interrogator. It is the sum of these two distances that provides the total exposure in meters (m) of the tag group to the reader. Dividing this value by the travel per second (m/s) of the tag movements, one can obtain the total time of exposure. This is the *total exposition time* cited in the formula (8) in which the interrogator should succeed in reading all the bits of all the tags on each of the moving packages.

RFID-Env users need to supply some sort of simple information about the environment, especially once this is generally known in advance. Figure 9 shows the input screen in the single mode, where the following information is required:

- temperature;
- tag material;
- maximum reading reach;
- tag reading speed;
- the tags movement speed; and
- frontal distance between the interrogator antenna and the tags, that is the distance (c) or the minor cathetus of the rectangular triangle shown in Figure 8.

It should be noticed that the calculation of the total time necessary for reading a group of tags is made after the complete tag group reading simulation, with the anti-collision protocol selected on the initial RFID-Env screen. Given the total number of slots necessary for reading the tags group, the simulator will calculate:

$$t\_total = total\_number\_of\_slots \times each\_slot\_reading\_time \quad (9)$$

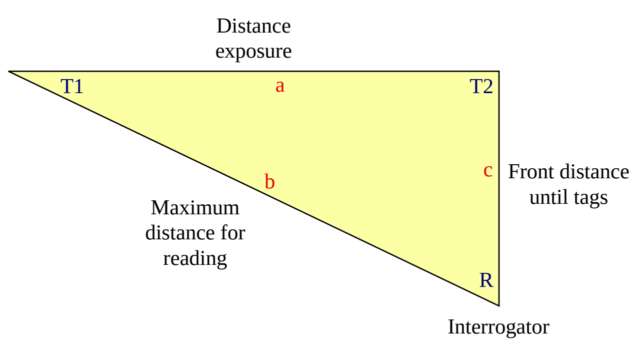

Figure 8.
Calculation of the time and exposition distance

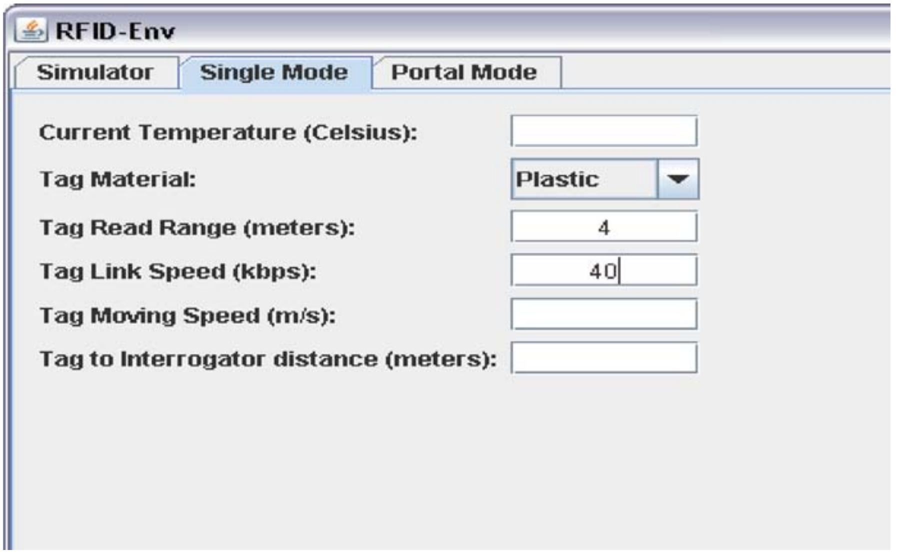

Figure 9.
Data for the analysis of the environment in single mode

where:

t_total	total necessary reading time of the group of tags.
total_number_of_slots	number of slots generated in the simulation.
each_slot_reading_time	amount of bits to be read in each tag divided by reading speed value of the tags.

With the information acquired in the single mode interface, the RFID-Env can calculate the distance of the cathetus (a), considering the fact that the maximum tag reading distance is the length of the hypotenuse (b). The frontal distance between the interrogator antenna and the tags refers to the cathetus distance (c). This environment configuration represents a geometric situation in the shape of a rectangular triangle, which measurements may be calculated using the Pythagoras' theory. In Figure 8, the formula used by the RFID-Env for calculating the cathetus length (a) is the following:

$$a^2 = b^2 + c^2 \qquad (10)$$

The interface of Figure 9 shows the type of material selected (plastic) and the maximum distance of 4 m, typical for this material. According to the material selected by the user, the reading distance value of that material is shown in the tag read range box. However, as this value may vary from one to another manufacturer and, for other physical reasons, this distance is merely suggested by the RFID-Env, the user can change this value to the more convenient distance. This feature allows the user to set the system in order to fit with the appropriate field, lining up with the technical information provided by his/her tag supplier. Also, the same functionality applies to the speed of reading the tags – the RFID-Env suggests a speed of 40 kbit/s (kilobit per second), which is a normal value in many types of tags. Moreover, it can be changed by the users, based on their technical tag's information.

Given this information, the RFID-Env may predict situations where it is physically impossible to read a stated number of tags. An example is given in the report generated by the RFID-Env and is shown on Figure 10 – where the information supplied by the user is:

- maximum reading distance (hypotenuse) of 4 m;
- reading speed 40 kbit/s;
- tag movement of 5 m/s; and
- frontal movement (cathetus *c*) of 2 m.

This data referred to a group of 1,000 tags (for example, a box containing 1,000 products moving on a conveyer belt) using the ISO 18000-6 protocol. With this configuration, the RFID-Env could figure out that it was a possibility that the system could not work.

Some solutions for the problem detected by the simulator and shown in Figure 10 could be:

- change the communication protocol to reduce the number of necessary slots;
- reduce the number of tags to be read "simultaneously" (i.e. the number of tags in one package);
- slow down the transport speed;
- change the distance between the tags and the reader; or finally
- a combination of some or all the options above.

6.1.2 Temperature. The environmental temperature has a deep effect on the time that the registers can maintain storage of the 0 and 1 logic values. Basically, the registers can increase the storage time when the temperature falls below 25°C, but when the mercury rises above that level, the registers start to lose storage capacity by more than 8 s. Moreover, the operation may cease altogether at some temperatures and the RFID-Env is designed to consider this factor. Thus, if the user specifies a value outside of the temperature limits supported by typical circuits, a signal of alert is generated by the RFID-Env and it informs the user of this fact.

As the development work continues on the RFID-Env, the instrument will be enabled to take into consideration the time that the register values can be maintained at different temperatures. This information may be related with values such as the reading speed of each tag, the length of time that the value is exposed to the electronic

```
-------------------|ISO 18000-6 C Protocol |-----------
-- Performance Report –
Tags: 1,000
Slots needed for all tags to reply: 2,822
Slots withtag collision: 727
EmptySlots (with no tag reply): 1,095
Total required timeto read all tags: 2.82 seconds (worst case)
Calculated Total Exposition Time: 1.38 seconds
-------------------------------------------------------
With this configuration the group of tags could not be fully read.
-------------------------------------------------------
```

Figure 10.
RFID-Env red alert – reading impossible for physical reasons

reader, the number of tags present in the environment, and by last the physical interferences which result in the tags being without power for brief periods of time. Because of these relationships, the environmental temperature may strongly influence the simulation results.

6.2 RFID-Env: environment type configuration

Taking into consideration some of the typical environments in which RFID systems are installed, the RFID-Env user can simulate the reading of a tag group in three ways:

(1) by ignoring possible variations in the environment (simulator mode);
(2) conveyer belt mode with an antenna (single mode); and
(3) portal mode for pallets (portal mode).

The process of simulation starts in the main window as is shown in Figure 4. If the user only wants to simulate the operation of one or more anti-collision protocols, without considering the physical variations of the environment, only this interface shall be used. While still in the main window, it is possible to visualize the selection field for the type of environment:

- none (simulation without environmental variables);
- single mode; or
- portal mode.

The respective tabs are activated or not according with the mode selected.

If a user desires to test a conveyer belt environment, he/she should select the single mode. This will activate the respective window and will request specific information to that kind of environment such as:

- temperature in celsius degrees;
- type of material in which the RFID chip and the tag antenna are assembled;
- read speed in kbit/s of the tag in use in the environment;
- product movement speed on the conveyer belt in meters per second; and
- the frontal distance (meters) between the antenna and the conveyer belt.

As soon as the type of the tag's material is selected, the corresponding value in meters will appear in the box provided for the typical value of read reach (between the antenna and the tag) for that type of material.

For example, when the user selects glass, the number 2 will appear in the box, the number 4 for plastic and so on. These values are typical for many manufacturers (Cheng and Jin, 2007). In any case, these values are suggested by the RFID-Env system as a reference guide to the user, and he/she can easily change it to reflect the real values obtained from the manufacturer's technical specifications for the tags actually being used.

6.2.1 Portal mode – amount of antennas versus measurements of portal and pallets. As is shown in Figure 5, the RFID-Env portal mode is designed to simulate environments with portals in the shape of tunnels, which the pallets and other transporter packages can pass through. In addition to the information required for the single mode (distances, temperature, and read speed) the portal mode needs the dimensions of the portal and of the pallets carrying the ticketed products. The user should input also the number of interrogators and antennas in the portal. Usually, each interrogator is limited to four antennas.

Concerning to the antennas located in the portal, the user may select the position of each one (up to a limit of eight antennas simultaneously if the option of two interrogators was chosen). The simulator should be fed with the approximate direction of the antennas in relation to the total of tags to be read, assuming that all the ticketed packages are uniformly distributed over the transporter. This means that the user selects an antenna in each face of the portal (left, right, and upper), so the simulator will consider that n tags are distributed facing these three directions equally, which would mean $n/3$.

From the measurements of the portal and the pallet, the simulator can determinate the lateral and superior distances between the pallet and the interrogator antennas, selected as active by the user. In the current version of the RFID-Env, the portal mode operates in the same way as the single mode, but with the difference that in the portal mode, the number of tags measured is divided by the number of active antennas. This division is performed by the simulator in accordance with the number of directional antennas located in each part of the portal, as described in the previous paragraph. The lateral antennas work in the exactly same way as in the single mode, but the upper antennas, although they also work in the shape of a "rectangular triangle", its view is of a "rectangular triangle" seen from different angle (from up to down). It is clear, the advantage of a greater number of antennas in the portal: an increase in the range of action in many directions and a reduction in the total number of tags captured by each antenna. For the situation shown in Figure 10 (where the simulator detects that it is impossible to read the tags in that environment), one can make a simple calculation, where, for instance, the 1,000 tags are now divided between, let say, eight antennas (two readers). This would reduce drastically the number of simultaneous readings required from the system.

As the development of the RFID-Env continues, the parameters of the portal mode analysis will be amplified, for instance, by a more detailed consideration of the focus and positioning of the antennas and the type of antenna itself. Antennas are available with characteristics designed to operate over greater distances, operating in a straight line or reading wider angles. Greater attention will also be given to the physical characteristics of the ticketed products and the interference that these materials can cause by scattering the RF signal. It is known that the products in the center of the pallet present the greatest reading difficulties due to the interference re-transmitted from the surrounding products.

7. Conclusions

This paper describes the results of an experimental research, with the goal to develop an innovative product – the RFID-Env (RFID-Env Software Simulation). This product is intended to be used by developers in the computer sciences area, and by engineers working at R&D for the solution of RFID problems. Moreover, with this product is possible to simulate a complete range of virtual RFID-Envs, so the R&D can proceed in a non-factory atmosphere.

The functionality and the applications of the software RFID-Env were demonstrated showing how the product allows the simulation of the four RFID protocols operation, standardized by ISO 18000-6, the types A LST and FST, the type B, and the type C. This paper also shows the predominant model that controls the main functioning logic of the simulator, also, the strategies that allow the performance of this task, certainly not a trivial one.

The experimental application demonstrated that this new product can help RFID systems potential users to select the protocol which will best attend the system characteristics they intend to implement.

Considering the physical characteristics of an environment proposed for the RFID technology implementation, such as the speed of the tags in relation to the interrogators, the distances, the number of antennas in the location and the number of tags to be read simultaneously, the RFID-Env is able to avoid the waste of money, by showing that a particular standard or environmental configuration under consideration, will in fact supply or not the necessities of a particular situation.

This work will be continued by introducing more considerations about the physical environment, such as the interferences produced by the tagged products themselves, by scattering the RF signals and the models, positioning and focusing of the antennas. New RF prediction models shall be created along the continuation of this paper, with the purpose to increase the amount of environments that can be simulated.

References

Atkinson, W. (2004), "Tagged: the risks and rewards of RFID technology", *Risk Management Journal*, Vol. 51 No. 7, pp. 12-19.

Azambuja, M., Marcon, C. and Hessel, F.P. (2008), "Survey of standardized ISO 18000-6 RFID anti-collision protocols", *Proceedings of the Second International Conference on Sensor Technologies and Applications* (*SENSORCOMM '08*), *Cap Esterel, France*, IEEE Conference Publishing Services, Los Alamitos, CA, pp. 468-73.

Bendavid, Y., Castro, L., Lefebvre, L.A. and Lefebvre, É. (2006), "Explorando los Impactos de la RFID en los Procesos de Negocios de una Cadena de Suministro", *Journal of Technology Management and Innovation*, Vol. 1 No. 4.

Borriello, G. (2005), "RFID: tagging the world", *Communications of the ACM Journal*, Vol. 48 No. 9, pp. 34-7.

Buck, T., Ha, S., Lee, E.A. and Messerschmitt, D.G. (1994), "Ptolemy: a framework for simulating and prototyping heterogeneous systems", *International Journal of Computer Simulation*, Vol. 4, pp. 155-82 (special issue on "Simulation software development").

Cheng, T. and Jin, L. (2007), "Analysis and simulation of RFID anti-collision algorithms", *IEEE The 9th International Conference on Advanced Communication Technology* (*ICACT2007*), *Phoenix Park, Korea*, pp. 697-701.

Curtin, J., Kauffman, R. and Riggins, F. (2007), "Making the MOST out of RFID technology: a research agenda for the study of the adoption, usage and impact of RFID", *Information Technology and Management*, Vol. 8, pp. 87-110.

EPCglobal (2005), *EPC™ Radio-frequency Identity Protocols Class-1 Generation-2 UHF RFID Protocol for Communications at 860 MHz – 960 MHz Version 1.0.9*, EPCglobal, Houston, TX, 31 January, pp. 94.

Floerkemeier, C. and Sarma, S. (2009), "RFID Sim – a physical and logical layer simulation engine for passive RFID", *IEEE Journal Transactions on Automation Science and Engineering*, Vol. 6 No. 1, pp. 33-43.

Gakhar, S., Feldkamp, J., Perkins, M., Rensheng, S. and Reddy, C.J. (2008), "Engineering RFID systems through electromagnetic modeling", *IEEE International Conference on RFID, Las Vegas, NV*, EUA, IEEE Conference Publishing Services, Los Alamitos, CA, pp. 344-9.

Girault, A., Lee, B. and Lee, E.A. (1999), "Hierarchical finite state machines with multiple concurrency models", *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, Vol. 18 No. 6, pp. 742-60.

Hassan, T. and Chatterjee, S. (2006), "A taxonomy for RFID", *Proceedings of the 39th IEEE Hawaii International Conference on System Sciences, Hawaii*, pp. 1-10.

ISO/IEC 18000-6 (2006a), *Information Technology Automatic Identification and Data Capture Techniques – Radio Frequency Identification for Item Management Air Interface – Part 6: Parameters for Air Interface Communications at 860-960 Mhz*, ISO/IEC, Geneva.

ISO/IEC 18000-6 (2006b), *Information Technology – Radio Frequency Identification for Item Management – Part 6: Parameters for Air Interface Communications at 860 MHz to 960 Mhz. Amendment 1* (*2006-06-15*)*: Extension with Type C and Update of Types A and B*, ISO/IEC, Geneva.

Jo, M., Youn, H.Y., Cha, S. and Choo, H. (2009), "Mobile RFID tag detection influence factors and prediction of tag detectability", *IEEE Sensors Journal*, Vol. 9 No. 2, pp. 112-9.

Jung, C.F., Caten, C.S. and ten Ribeiro, J.L.D. (2007), "Inovação em produtos e processos a partir da parceria entre o setor público e o privado: o Programa de Pólos Tecnológicos do RS", *Proceedings of the VI Congresso Brasileiro de Gestão de Desenvolvimento de Produto, Belo Horizonte, Brazil.*

Koos, C., Fujii, M., Poulton, C.G., Steingrueber, R., Leuthold, J. and Freude, W. (2006), "FDTD-modelling of dispersive nonlinear ring resonators: accuracy studies and experiments", *IEEE Journal of Quantum Electronics*, Vol. 42 No. 12, pp. 1215-23.

Landt, J. (2005), "The history of RFID", *IEEE Potentials*, Vol. 24 No. 4, pp. 8-11.

Lee, B. and Lee, E.A. (1998), "Hierarchical concurrent finite state machines in Ptolemy", *Proceedings of the International Conference on Application of Concurrency to System Design 1998, Fukushima, Japan*, pp. 34-40.

Malison, P., Promwong, S., Sukutamatanti, N. and Banpotjit, T. (2008), "Indoor measurement and modeling of RFID transmission loss at 5.8 GHz with human body", *Proceedings of the 5th IEEE International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology, Krabi*, pp. 421-4.

Marcon, C.A.M., Calazans, N.L.V. and Moraes, F.G. (2002), "Requirements, primitives and models for systems specification", *Proceedings of the 15th Symposium on Integrated Circuits and Systems Design* (*SBCCI'02*)*, Porto Alegre, Brazil*, p. 323.

Myung, J. and Lee, W. (2006), "Adaptive splitting protocols for RFID tag collision arbitration", *Proceedings of MobiHoc'06, Florence, Italy*, pp. 202-13.

Ngai, E.W.T., Cheng, T.C.E., Au, S. and Lai, K.H. (2007), "Mobile commerce integrated with RFID technology in a container depot", *Decision Support Systems*, Vol. 43, pp. 62-76.

Nikitin, P.V. and Rao, K.V.S. (2006), "Theory and measurement of backscattering from RFID tags", *IEEE Antennas and Propagation Magazine*, Vol. 48 No. 6, pp. 212-8.

Prado, N.R.S.A., Pereira, N.A. and Politano, P.R. (2006), "Dificuldades para a adoção de RFID nas operações de uma cadeia de suprimentos", *Proceedings of the XXVI ENEGEP – Encontro Nacional de Engenharia de Produção, Fortaleza, Brazil.*

Reyes, P. and Jaska, P. (2007), "Is RFID right for your organization or application?", *Management Research News*, Vol. 30 No. 8, pp. 570-80.

Sarkar, T.K., Zhong, J., Kyungjung, K., Medouri, A. and Salazar-Palma, M. (2003), "A survey of various propagation models for mobile communication", *IEEE Ant. Prop. Magazine*, Vol. 45, pp. 51-82.

Shih, D., Sun, P., Yen, D. and Huang, S. (2006), "Taxonomy and survey of RFID anti-collision protocols", *Computer Communications – The International Journal for the Computer and Telecommunications Industry*, Vol. 29 No. 11, pp. 2150-66.

Spekman, R.E. and Sweeney, P.J. II (2006), "RFID: from concept to implementation", *International Journal of Physical Distribution & Logistics Management*, Vol. 36, pp. 736-54.

Sullivan, D.M. (2000), *Electromagnetic Simulation Using the FDTD Method*, Wiley-IEEE Press, New York, NY.

Sweeney, P. (2005), *RFID: For Dummies*, Wiley, Indianapolis, IN.

Tam, W.K. and Tran, V.N. (1995), "Propagation modelling for indoor wireless communication", *Electronics & Communication Engineering Journal*, Vol. 7 No. 5, pp. 221-8.

Vincentelli, A.S., Sgroi, M. and Lavagno, L. (2000), "Formal models for communication-based design", in Palamidessi, C. (Ed.), *CONCUR 2000 – Concurrency Theory*, Lecture Notes in Computer Science, Vols 1877/2000, Springer, Berlin, pp. 29-47.

Weinstein, R. (2005), "RFID: a technical overview and its application to the enterprise", *IEEE IT Professional*, Vol. 7 No. 3, pp. 27-33.

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