A Centralized and Aligned Scheduler for passive RFID Dense Reader Environments working under EPCglobal standard

M. Victoria Bueno-Delgado, Pablo Pavon-Marino

Communications and Technology Information Department, Universidad Politécnica de Cartagena, Plaza del Hospital 1, 30202 Cartagena, Spain

Abstract

Passive RFID systems with several reader stations densely allocated close to each other are susceptible to reader collision problems. They are characterized by reader-to-tag and reader-to-reader interferences. Both degrade the system performance decreasing the number of tags identified per time unit. Although some proposals have been suggested to avoid/handle these collisions, most of them require extra hardware, do not make an efficient use of the network resources and are not compatible with the current standards and regulations. This paper proposes a centralized and aligned scheduler that optimizes the distribution of network resources (frequencies and time slots) among the readers in the network. Those readers with unidentified tags in their target region will have higher priority for receiving resources. The optimization problem is formulated as a Mixture Integer Programming problem. Results show that the method proposed provides higher network throughput and fairness than the EPCglobal Class-1 Gen-2 standard for dense reader environments. In addition, unlike previous works, the scheduling algorithm presented is compatible with EPCglobal standards and the European regulations, and can be implemented in real RFID systems with fixed and mobile readers.

Keywords: RFID, EPCglobal Class-1 Gen-2, Dense Reader Environment, anti-collision protocols

Email address: mvictoria.bueno@upct.es (M. Victoria Bueno-Delgado)

1. Introduction

Radio Frequency Identification (RFID) is increasingly being used to identify and track objects in supply chains, manufacturing processes and product traceability. In these scenarios, passive RFID technology is commonly preferred due to its low-cost, easy implementation and durability. Passive RFID systems are composed of a large number of tags and one or several readers. The former store relevant information about the items they are attached to (price, expiration date, etc.), do not incorporate battery and feed their circuitries from the energy of the electromagnetic waves emitted by the readers [1]. Readers are complex devices designed to be continuously transmitting electromagnetic waves for creating identification areas, where tags enter and leave, trying to send back their identifiers to the readers. The size and shape of an identification area depends on several factors: reader and antennas design (radiation pattern, gain, polarization, impedance, etc.), tag parameters (e.g. gain, matching features, IC sensitivity), external factors (ambient conditions, noise, etc.) and readers output power suited. However, for the sake of simplicity, in most of scientific literature readers checking areas are defined as perfect circumferences which radio only depends on the readers output power suited [2, 3, 4, 5]. In this work we also follow this assumption. In Europe the maximum reader transmission power at Ultra High Frequency (UHF) band is 3.2 Watts Effective Isotropic Radiated Power (EIRP) [6]. This value limits the maximum reader-to-tag read range (d_{RT}) and reader-to-reader interference range (d_{RR}) to a maximum of 10 and 1000 meters respectively in indoor scenarios [7]. Note that these values were obtained in [7] according to a specific configuration of tag and reader parameters (e.g. tag IC sensitivity about -11 dBm). Hence, any variation of these parameters could directly affect to the final value of d_{RT} and d_{RR}.

In some installations, one single reader is not enough to cover a specific identification area, or simply the final application requires the existence of more than one checking areas. For instance, in a supermarket, every product has a tag attached to it, and the product must be tracked in different zones: in the main door of the load/unload stock area, in the sells checkpoint area, in the supermarket exit door etc. That is, different readers must be deployed under the same RFID system to cover those specific areas (see Fig. 1); the so-called Dense Reader Environments (DRE). The performance of DRE is negatively affected by the reader collision problems, characterized by two types of collision [8]: Reader-to-Tag Collisions (RTC) and Reader to-Reader

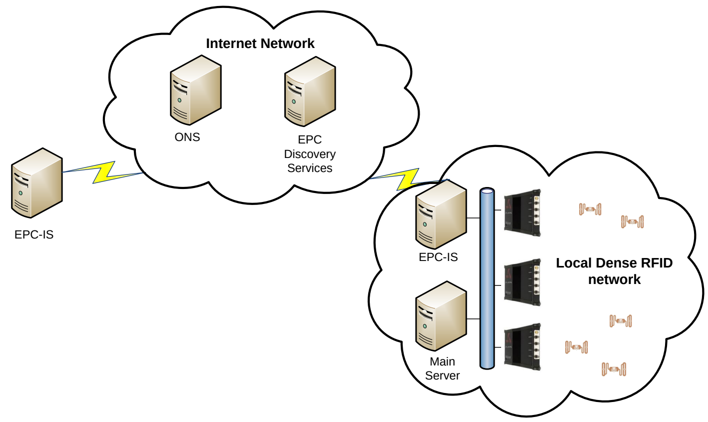

Figure 1: Network architecture of a RFID Dense Reader network connected to the EPC-global Network

Collisions (RRC). The former occur when two or more readers overlap their reader-to-tag read ranges (delimited by d_{RT}) and try to read the same tag simultaneously. In Fig. 2, if R and R' try to identify tag A, A receives electromagnetic energy from both readers at the same time. This is a source of RTC, even if both readers are operating at different frequency. Since tag A is a passive device, it has not the specific hardware to select a particular reader/frequency to transmit its data. Therefore, to avoid RTC, overlapping readers must be configured to operate non-simultaneously. RRC happen when the signal generated by one reader, interferes with the reception system of other reader, since they are at less than d_{RR} distance. This hinders the tag identification process: a reader can receive strong signals from neighbor readers, interfering with the weak tag signal. In Fig. 2, if R reads data from tag B and, at the same time, R' sends data to tag C, R' interferes with R. To avoid RRC effects, readers located in RRC range must operate at different frequencies and/or at different times.

This paper presents a resource allocation and scheduling model to assign transmission frequencies and time intervals to the readers in a passive DRE, so that (i) the RRC and RTC problems are eliminated and (ii) the model is compatible with the EPCglobal Class-1 Gen-2 [9] and EPCglobal Network standard [10]. This work is focused on a RFID network deployed in Europe. The scheduler is also compliant with the European regulation ETSI EN 302 208 [6]. Anyhow, this proposal could be easily adapted to work in any place, for being compliant with regulations in US, Japan, China, etc.

Our approach is based on a scheduling algorithm which is periodically executed by a central system, trying to fairly share the network resources among the readers, maximizing the network throughput. That means, maximizing the total amount of contention-free usable identification time in the readers. The resources allocation is formulated and solved as a Mixture Integer Programming (MIP) problem. This centralized approach is well suited to make use of the classical centralized infrastructure of a DRE, which commonly relies on a centralized server to store and process the upper-layer identification information, connected to each reader with a wired or wireless infrastructure (e.g. EPCglobal Network infrastructure [10]). Therefore, the model suggests an implementation of the algorithm as a new process integrated in this existing central element, and thus eliminating the need of extra control channels or specific hardware to coordinate the readers (e.g. like in [11, 13, 14]).

The rest of the paper is organized as follows. Section 2 addresses the DRE operation mode of current standards and regulations in commercial RFID systems. Section 3 introduces the related work. The algorithm proposed and the problem formulation is addressed in Section 4. Section 5 provides the simulation results and Section 6 concludes.

2. Standards and regulations in Dense Reader Environments

To minimize interferences and maximize tag identifications, DRE work under a common Physical and Medium Access Control (MAC) layer, defined by the standards and regulations. In this study we focus on a passive RFID system placed in Europe, where readers work at UHF band under the EPCglobal Class-1 Gen-2 standard [9] and ETSI EN 302 208 regulation [6]. Both are described separately in the next subsections. Finally, the operation mode of a commercial reader, which implements both, is described.

2.1. ETSI EN 302 208

ETSI EN 302 208 is the European regulation that defines the operating frequencies and system operation in passive RFID systems UHF band, from 865 to 868 MHz [6]. The regulation defines 15 work frequencies, each spanning 200 KHz although only 4 of them are available in Europe (frequencies 4, 7 9 and 11), each spaced 600 KHz apart. This amendment allows adjacent channels for tag responses (also called backscattering). The regulation also recommends that each reader selects a channel randomly and listens to it

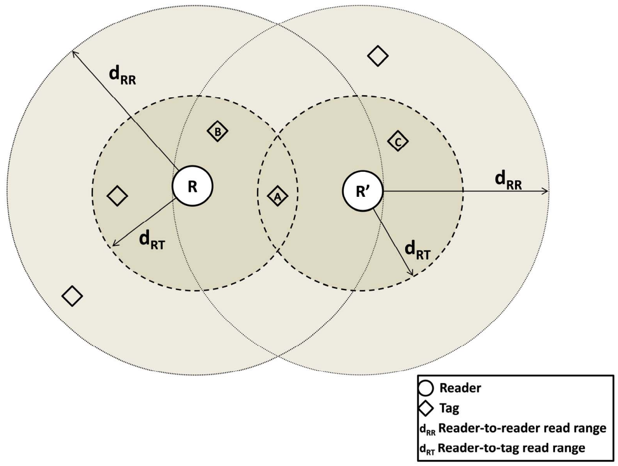

Figure 2: Readers interference ranges

during, at least 5 ms, following the Listen Before Talk (LBT) strategy. If the channel is free, the reader occupies it for up to 4 s. After this time, the channel must be free for, at least, 100 ms. This regulation is intended to mitigate the effects of RRC.

2.2. EPCglobal Class-1 Gen-2

EPCglobal Class-1 Gen-2 is the worldwide standard for passive RFID at 860-960 MHz [9]. It was stated as *de facto* standard for passive RFID in 2005 and, nowadays, it is implemented in most of passive RFID systems on the market. EPCglobal Class-1 Gen-2 defines the physical and Medium Access Control (MAC) layer management for RFID systems. In DRE, EPCglobal Class-1 Gen-2 suggests three different methods to minimize collisions, separating reader and tag transmissions spectrally. In Europe, the standard recommends the *Alternative-channel backscatter* method, where reader transmissions are located in a subset of the channels and tag responses are located in a different subset of the channels. Figure 3 shows the reader transmission using SSB-ASK modulation and tag backscatter on a 300 KHz subcarrier. In EPCglobal Class-1 Gen-2 readers randomly alternate among the four channels recommended by ETSI-EN 302 208 using the FHSS (Frequency Hopping Spread Spectrum) technique. As [6], EPCglobal tries to mitigate RRC effects.

2.3. EPCglobal Network

EPCglobal recommends a centralized and complex infrastructure to retrieve all data related to a product, which is read by a RFID system. This network infrastructure is the EPCglobal Network. It defines the procedure for collecting, sharing, and accessing dynamic information about the tags attached to items, when they pass throughout supply networks. From EPCglobal Network components [15], only the middleware placed in the main server of a local RFID network is the component of interest in this work (see Fig. 1). The middleware manages communication and data exchange among the readers in the network and the EPC Information Services (EPC-IS)[10], a public data base of the local network required to get the global visibility of products imposed by EPCglobal Network. The main server and the readers are connected by a wired or wireless network. The server exchange messages with readers to configure the RFID network, to require specific information, etc. These messages are classified into [16]:

- *Command Channels*: They follow a request/response pattern. That is, messages sent by the server requiring something must be answered by the reader and vice versa.
- *Alarm Channels*: These messages are asynchronous message sent from the reader to the server.
- *Notification Channels*: These messages are used by readers for delivery of tag data.

The Reader Management Specification [16], defined by EPCglobal Network, points out a set of conceptual objects and operations which enables the server to query the status of these objects. RFID developers make use of these objects to implement the reader's procedure to be compatible with the standard.

2.4. Reader operation mode under EPCglobal Class-1 Gen-2, ETSI EN 302 208 and EPCglobal Network

The operational mode of commercial readers in DRE is shown in Fig. 4. Consider a Dense RFID system with R readers. Every reader (r_i), $i = \{1, 2, \ldots, R\}$, switches on DRE mode, and randomly selects one of the F frequencies (channels) recommended by ETSI-EN 302 208 and it starts to listen to it. r_i listens the arbitrary channel f_j, $j = \{1, 2, \ldots, F\}$, at least 5 ms. If the channel is free, r_i takes f_j as its communication channel and starts

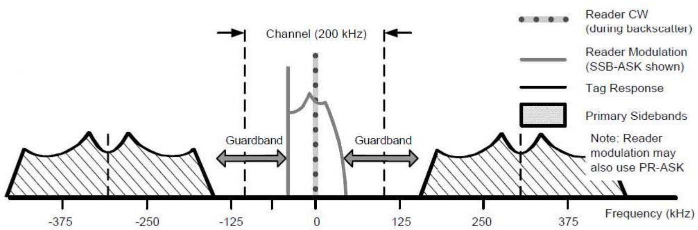

Figure 3: European 600 KHz channel. From EPCglobal standard specification, version 1.2.0-2008 [9]

its identification procedure, sending electromagnetic waves to create checking areas and sending *Query* packets [9] to identify tags in coverage. The tags identification procedure is carried by EPCglobal Class-1 Gen-2, studied in depth by authors in [17].

While r_i is executing the identification procedure, if it does not detect tags in coverage for at least 100 ms, r_i leaves f_j, because no tags are in range. Otherwise r_i continues the identification procedure up to T=4 s. After T time, r_i leaves f_j, it sends the information collected (number of tags identified) to the main server by means of a *Notification channel* message and it waits 100 ms to select a new frequency.

3. Related work

In this section the most relevant research proposals for coordinating readers in passive DRE are reviewed, emphasizing their requirements, problems and incompatibilities with EPCglobal Class-1 Gen-2. These mechanisms are commonly classified into centralized and distributed [12] and, under this classification, there are collision resolution methods based on power control, CSMA, FDMA, TDMA, etc. We follow this taxonomy to survey them.

3.1. Centralized algorithms

Centralized mechanisms are designed to be executed in a centralized device (server), which is connected to the readers through a wired or wireless network (see Fig. 1). The central server not only collects tag's identifications, but also may send and receive info to/from readers, managing and sharing the network resources with the aim of minimizing reader collisions.

There are centralized mechanisms based on TDMA, as the Neighbor Friendly Reader Anticollision (NFRA) [13], where a central server manages reader synchronization in a unique frequency, at 433 MHz, and only one frequency at UHF band is used for reader transmissions. NFRA is focused on maximizing throughput, while in [18] a slight modification of NFRA is proposed to also guarantee higher fairness. Both proposals are focused only on minimizing RRC, are not compatible with EPCglobal Class-1 Gen-2, and their implementation in a real DRE require the use of an extra wireless network at 433 MHz. In [19] the authors suggest a mathematical programming methodology as scheduler to coordinate DRE. The proposal only tries to optimize time distribution for the dual reader case in a single frequency. It is assumed that a centralized system computes the scheduler, but authors do not specify how it is done how the readers are informed about their assigned time, or its feasibility in a real RFID system. In [20] the authors propose the use of a non commercial hardware as centralized server which coordinates readers under a TDMA scheme in one channel, and also manages the reader-to-tag communication through a technique that multiplexes the reader request to specific tags. This technique is not compatible with the current standards. Besides, in the proposed multiplexing technique the readers have to share tags information among adjacent readers, but they do not specify how to do it. The authors also assume RRC do not happen in their simulations. In [21], a mechanism is proposed to control, in real-time, the overlapping of the reader-to-tag read ranges. Then, it decides to disconnect the interfering readers to reduce RTC. Naturally, this scheme can only be applied to those scenarios which admit the disconnection of a set of reader systems.

Other centralized techniques are based on pure FDMA or a combination of FDMA with power control, as in [22], where the authors propose a centralized server to distribute the frequencies among the readers in a FDMA scheme, so that readers which are closer to each other are allocated frequencies more separated from each other. The authors assume that there are as many frequencies as readers, without considering the frequency restrictions of the country regulations and standards. They also suggest reducing the reader output power to decrease the collisions. Naturally, this recommendation reduces the size of the checking areas. Besides, this recommendation is not possible in many real systems, where the identification region is strictly defined. In [23] the authors propose a similar approach, consisting of controlling the reader output power optimally with the aim of reducing RTC (but not considering RRC).

Other mechanisms combine FDMA and TDMA to solve the resource allocation problem, like HiQ [24], a hierarchical Q-learning mechanism based on the discovery of collision patterns among readers. Readers measure the instants of collision and broadcast this data, as well as the own channel and time period used, to adjacent readers via a common control channel. Then, each reader collets neighboring info to computes the best time period and channel for its next reading cycle using an artificial neural network, and transmits this information to a global server, which arbitrates among readers. The main drawback of this approach is that readers have to manage a large amount of information, and results depend on the quality of the neural network training. Besides, authors do not specify how readers communicate each other. RA-GA [25] is a FDMA-TDMA technique based on a heuristic method. It uses the SINR constraint of each reader to appropriately assign spectral and temporal resources. However, the use of a heuristic model involves that the solution may not be the global optimum. Besides, the authors do not describe in depth the algorithm to know if it fulfills the requirements of standards and regulations.

3.2. Distributed algorithms

In these schemes, readers communicate directly with their neighbors - usually by means of wireless links- and do not rely on a centralized device to make the allocation of the network resources. In some techniques, readers take decisions themselves, without considering neighboring info.

The most common distributed techniques are those based on carrier sense (CSMA) or LBT. Pulse [26], based on LBT, makes use of an auxiliary control channel to exchange reader control messages. Readers can listen simultaneously the control and the reading channel, but only transmit in one of them. Before powering the tags, readers check if some neighboring reader is on. When a reader is activated it continuously transmits beacons in the control channel before the tag reading process takes place. After a guard period without transmissions in both channels, the reader occupies the control channel filling it with beacons, and shortly afterwards it starts the tag reading process. In [27] a similar mechanism is suggested, but only for minimizing RRC, whereas [28] introduces another LBT aimed at RTC minimization. In the latter, a wireless sensor network is selected for reader-to-reader communications. This network is not used for sensing any particular parameter, thus resulting in extra costs. All of them, [26, 27, 28], only consider a single reading channel. DiCa [29] is another single channel distributed algorithm based on LBT and focused on RTC reduction. It proposes the use a control channel which doubles the range of the reading channel. When a collision with other reader is detected, DiCa decreases both channels range proportionally. Authors claim that this is an energy saving system. However, since the readers' energy consumption has a minor impact in system operation cost, it is questionable if the energy cost reduction obtained compensates the performance loss and extra hardware complexity.

Some strategies combine LBT and FDMA, as MCMAC [30]. In a MCMAC system with R readers, $R-1$ non-overlapping channels for reading and one control channel are used. The control channel is used to distribute the reading channels by means of a random access competitive algorithm. Although this approach can mitigate the effects of RRC, it does not solve the RTC. Besides, if the number of readers (R) is higher than the number of channels (F), MCMAC delays the operation of $R-F-1$ readers. In RAC-Multi [31], the data channels are separated into odd-and even-numbered channels to avoid adjacent channel interference between neighboring readers. First, only the odd-numbered channels are used, instead of randomly selecting a channel from all available channels. RAC-Multi also provides a control channel, a with channel separation from data channel.

Other distributed mechanisms are based on TDMA scheme, like DCS protocol [11], which is focused on mitigating RTC. In DCS, a single frequency is used, and the time is divided in fixed identification cycles, subdivided into time-slots (called *colors*). Readers randomly select a color in every cycle to identify tags. When two or more readers select the same color readers collide (RRC). Then, those colliding readers select a new color for the next cycle. Neighboring readers that selected the same color as colliding readers have to change color. Probabilistic DCS (PDCS) is proposed in [14] for increasing the low performance of [11]. In PDCS readers, after a collision, select a new color with a probability P, reducing the number of readers changing color. The authors in [11] also proposed Colorwave [32] with the aim of improving the low performance of DCS. In Colorwave the identification cycles have a variable number of colors. When RRC are too high, the number of colors per cycle increases, reducing the probability of RRC. In [33] a modification of Colorwave is proposed. The readers, after a collision, select the random number according to the number their neighbors, interference and read range. In [33] authors assume every reader can calculate the number of neighbors using a binary tree protocol in a short length slot. However, the use binary tree algorithms in DRE environments is not recommended, because the time every reader needs to obtain the number of neighbors depends on the number of neighbors, and, in most of cases, the time required is higher than the length of the slot suggested [34].

4. CASE: Centralized and Aligned Scheduler compatible with EPCglobal

The related work section points out the lack of a proposal that address both the RTC and RRC effects being also compatible with the existing standards and regulations. In this work we propose CASE, a centralized an aligned scheduler compatible with EPCglobal standard that is intended to mitigate RTC and RRC. Note that we focus the work on European regulation, but the proposal can be extended to the restrictions imposed by the the regulations of other areas. CASE is designed to be executed in the central server of a DRE under an EPCglobal Network infrastructure, managing and sharing the network resources. The aligned term in CASE comes from the network synchronization, which is also maintained by the mechanism through the central server.

To avoid both RTC and RRC effects, we base our approach on coordinating the readers in a combined TDMA and FDMA scheme. TDMA is applied to partition the time in reconfiguration intervals (frames). At the end of an interval each reader is allocated a transmission frequency and a time slot within the subsequent interval, so that it is free of RTC and RRC with the other readers. The scheduling of the resources targets two different goals: (*i*) maximizing the total amount of RRC and RTC contention-free time in the readers, and (*ii*) favor a fair distribution of the identification time among the readers, according to the necessities of each reader (*i.e.* the estimated number of unidentified tags in their target region [35]). After calculating the optimal allocation, the readers are appropriately configured following their standardized configuration interfaces. In this manner, legacy reader equipment can be used, and no modifications to the standards are needed.

The Dense RFID system is assumed to be composed of R readers, connected to a centralized device by means of a wired or wireless EPCglobal Network infrastructure. Readers are working under the EPCglobal Class-1 Gen-2 standard [9], in particular at UHF Europe band, allocated at 868 MHz. Readers collect information from tags in their target region and send it back to the central server periodically, following the EPCglobal Network procedure [10] and the messages enumerated in Section 2.3. The position of the readers is assumed to be known by the central server. In set ups based on fixed readers, this can be easily achieved without the need of extra hardware, while mobile readers would require an attached positioning system. Note that in indoor scenarios, the GPS technology is not an available solution for mobile readers, but there exist many indoor location techniques for RFID readers that could be applied [36, 37, 38].

We assume that all the readers can operate in any of the $F = 4$ frequencies recommended by ETSI-EN 302 208 regulation and EPCglobal standard. Anyhow, the model can be easily modified to coordinate dense RFID environments where some of the readers have simpler hardware, and are not able to tune its transmitter to some of the available frequencies. According to the ETSI EN 302 208 regulation, the time is divided into time intervals of $T = 4$ seconds of working time, followed by idle times of at least 100 ms. The working time in each channel is organized in a super-frame of $S = 1600$ consecutive time slots of a duration of 2.5 ms each (summing up 4 seconds). This time slot duration corresponds to one slot in EPCglobal readers, sufficient to read one tag identity [9][17]. At the end of a working period, each reader $r = 1, \ldots, R$ is responsible of communicating to the central server its priority for receiving new slots in the following T period, (V_r), and any update in the reader position. After receiving the updated information, the central server executes the resource allocation algorithm CASE, which assigns to each reader r (i) a working frequency f_r, (ii) a set of V_r consecutive working time slots granted to the reader in the next 4 seconds period.

The frequencies and time slots are allocated guaranteeing that neither RTC nor RRC effects are present in the system. The central system uses the readers' positions to calculate the constraints to the resource allocation that must be applied to guarantee contention-free assignments:

- If two or more readers are within two times the reader-to-tag range (d_{RT}) both RTC and RRC effects could appear. In this case, the assignment allows the readers to operate at the same or at a different frequency, but forbids the working time slots assigned to the two readers to overlap.
- If the distance among readers is larger than d_{RT} and shorter than the maximum RRC distance (d_{RR}) only RRC is susceptible to occur. In this case, the resource allocation permits the readers to share the same frequency, or have an overlapped time interval, but not both.

- If the distance between the two readers is higher than the maximum d_{RR}, the frequency and working time interval assignment of one reader is not constrained by the assignment of the other.

Among the contention-free possible solutions to the resource allocation problem, we are interested in those which maximize the total amount of working time slots granted (since it favors a higher amount of time slots devoted to identify tags), while trying to make an allocation of the working intervals, proportional to the reader requirements (represented by V_r). As an example, the scheduler intends to allocate a double amount of time slots to a reader with a double priority. This favors a more efficient use of the identification time, preventing large working intervals to be wasted on readers with a small number of tags to identify. During the working period, each reader arranges the time slots granted in a sequence of identification cycles, according to the EPCglobal Class-1 Gen-2 standard.

4.1. Problem formulation

In this Section we present the MIP formulation associated to the scheduling problem to be solved for the resource allocation.

Given Parameteres

R:	set of readers
F:	set of frequencies
S:	set of time slots per frequency channel
$d_{i,j}$:	distance between readers i and j, $i, j \in R$
V_r:	priority requested by reader r, $r \in R$
α:	allocation tuning factor

Find

$x_{r,f}$:	1 if reader r is allocated in frequency f, 0 otherwise
$k_{r,f,s}$:	1 if reader r is allocated in frequency f and time slot s, 0 otherwise
$y^+_{r,s}$:	1 if timeslot s is the first working interval of reader r, 0 otherwise
$y^-_{r,s}$:	1 if timeslot s is the last working interval of reader r, 0 otherwise
L :	continuous variable used for *maxmin* optimization of the resource allocation
M :	minimum number of slots assigned to each reader

Subject to

$$k_{r,f,s} \leq x_{r,f} \qquad r \in R, f \in F, s \in S \tag{1}$$

$$\sum_{f \in F} k_{r,f,s} \leq 1 \qquad r \in R, s \in S \tag{2}$$

$$k_{i,f_1,s} + k_{j,f_2,s} \leq 1 \\ i, j \in R, d_{i,j} \leq d_{RT}, f_1, f_2 \in F, s \in S \tag{3}$$

$$k_{i,f,s} + k_{j,f,s} \leq 1 \\ i, j \in R, d_{RT} < d_{i,j} \leq d_{RR}, f \in F, s \in S \tag{4}$$

$$k_{r,f,s} + k_{r,f,s-1} = y^+_{r,f,s} - y^-_{r,f,s} \\ r \in R, f \in F, s \in S - \{1\} \tag{5}$$

$$\sum_{s \in S} y^+_{r,f,s} \leq 1 \qquad r \in R, f \in F \tag{6}$$

$$\sum_{s \in S} \sum_{f \in F} k_{r,f,s} \geq M \qquad r \in R, V_r == 1 \tag{7}$$

$$\sum_{s \in S} \sum_{f \in F} k_{r,f,s} = M \qquad r \in R, V_r == 0 \tag{8}$$

$$L \leq \sum_{s \in S} \sum_{f \in F} k_{r,f,s} \qquad r \in R, V_r == 1 \tag{9}$$

Objective function

$$max \left[(1-\alpha) \sum_{r,f,s} k_{r,f,s} + \alpha \left(\sum_{r \in R} V_r \right) L \right] \tag{10}$$

The decision variables of the problem are: variables $x_{r,f}$, which determine the transmission frequency to be used by each reader: the variables $k_{r,f,s}$ represent the resource allocation to be designed, determining the slots and frequencies which are assigned to each reader. Variables $y^+_{r,f,s}$ take the value of 1 if the slot s in frequency f is the first time slot of the working interval of reader r. And $y^-_{r,f,s} = 1$ if the slot $s-1$ in frequency f is the last time slot of the working interval of reader r. Finally, the variable L is used to include a *maxmin* fairness criterium in the distribution of the resources among the readers. Its application in the formulation will be clarified later in this section. The constraints to the problem are: constraint (1) implies that a reader will be allocated at most one frequency. Constraint (2) ensures that if a reader is not allocated a frequency, it cannot use any time slot in that frequency. Constraints (3) forces the readers situated at a distance $d_{i,j} < d_{RT}$, to not overlap their time slot assignment. Then, mutual RTC and RRC are avoided between those readers. Constraints (4) guarantee that no RRC occurs between readers $i, j \in R$ situated at a distance $d_{RT} < d_{i,j} < d_{RR}$, because the readers are allowed to share frequency or time slot, but not both. The sets of constraints (5-8) are devoted to force the scheduler to allocate contiguous time slots to the readers. First, the sets of constraints (5-6) are included to force the variables $y^+_{r,f,s}$ and $y^-_{r,f,s}$ to have the appropriate meaning. In (5) we force $y^+_{r,f,s}$ variables to have a value of 1 if the reader r is active at frequency f and time slot s, but not at the previous time slot. Similarly, they force $y^-_{r,s}$ variables to have a value of 1 if the reader r is not assigned the time slot s, but was assigned the previous time slot. Constraint

(7) applies the same idea to the first time slot. They are separated since the first slot has no previous time slot. If the first slot $s = 1$ is active $y^{+}_{r,f,1}$ will take the value of 1, since it is the first slot of the working interval of the reader. In summary, constraints (5-8) make $y^{+}_{r,s} = 1$ if s is the first slot of a contiguous set of working time slots. Constraint (7) guarantees that at most 1 contiguous working interval is assigned to a reader. In other words, all the working time slots assigned to a reader are contiguous. Finally, constraint (9) implies that the decision variable L is the lowest proportion between the allocated time slots and the requested time slots of any reader $r \in R$. That is, is the proportion of granted resources observed by the reader which received the worst (lowest) proportion. The objective function to the optimization problem is shown in Equation (10). It intends to balance two desired targets: (i) make a resource allocation which maximizes the total amount of slots allocated, and (ii) enforce a fair distribution of the resources among the readers. To accomplish this, we use a composite objective function with two summands balanced by a weighting factor $\alpha \in [0, 1]$. The first summand favors the solutions which maximize the identification throughput: the total amount of slots dedicated to identify tags, irrespective of the readers they are assigned to. The second summand intends to maximize the decision variable L. This decision variable represents the *maximin* concept. It is defined as the lowest ratio L_r among all the readers $r \in R$, been L_r the ratio between the allocated time slots for reader r, and the requested time slots of reader r (V_r). In the objective function, the decision variable L is also weighted by the total demand $\sum_{r \in R} V_r$, so that if $\alpha = 0.5$, increasing the *maxmin* proportion of the allocation in 1 unit, would have the same benefit as increasing the throughput in $\sum_{r \in R} V_r$ time slots. The weighting factor α should be tuned according to the desired design criteria. In the limit, if $\alpha = 0$ only network throughput maximization is considered, while if $\alpha = 1$, only the *maximin* fairness of the resources allocation is optimized.

5. Performance evaluation

We evaluate the performance of CASE in terms of network throughput and fairness. In this work throughput is defined as the ratio of assigned resources (time slots) free of RTC and RRC with respect to the total amount of resources required by the system in a time interval. Fairness measures the fair distribution of the resources free of RTC and RRC among the readers in the network that need resources. E.g. 100% of fairness means all readers requiring resources are satisfied, guaranteeing a fair distribution, proportional to their needs.

Since most of the schedulers surveyed in Section 3 are not compliant with the standard, and focus only on minimizing RTC, or RRC, but not both, we evaluate and compare CASE with the scheduler implemented in commercial readers in Europe (explained in Section 2.4), that works under EPCglobal Class-1 Gen-2 under the European standard (*aka* EPC-ETSI), resulting a fair comparison.

We have implemented a RFID network simulator using the Matlab framework. The simulator permits to study the performance of centralized and distributed networks based on fixed and mobile readers. The simulation of the proposed algorithm has included the use of GAMS/CPLEX [39] due to the optimization problem has been solved in this platform.

5.1. Evaluation scenario

We consider a hypothetical but real scenario in Europe where a RFID system with several readers could be deployed. This is, for instance, a supermarket with different zones: a stock area, a products exhibition area, a a sells area and the exit area. This scenario requires a single RFID tracking system with several fixed UHF readers installed on it. We assume this dense RFID system composed by a set of R readers with a bi-static and omnidirectional antenna. Readers output power is set at the maximum value permitted in Europe, $P_{tx} = 3.2$ Watts EIRP [6]. As we discussed in Section 1, this value limits the reader-to-tag read range reader interference range to a maximum of d_{RT}=10 and d_{RR}=1000 m in indoor scenarios respectively [7]. That is, at $P_{tx} = 3.2$ Watts EIRP, RTC occurs when readers are placed at less than 20 m each other ($< 2 * d_{RT}$) and RRC at less than 1000 m each other ($< d_{RR}$).

From the initial scenario we evaluate two work installations: those with only fixed readers (static scenario), and those with, not only fixed, but also mobile readers (dynamic scenario). In the former, we evaluate an array deployment as shown in Fig. 5, setting d as the distance among adjacent readers. We avoid random deployments considering that readers in a RFID system are commonly installed in strategic zones to cover an specific area in a regular way, and an array deployment fulfills this requirement. In the dynamic scenario, the execution starts like static scenario in array deployment, and a 50% of readers will randomly move with a speed of 1 m/s, similar to the movement of a person's walking. The movement of mobile readers follows a Random Waypoint Model (RWM) [40].

Parameter	Description	Value
P_r	Reader output power	3.2 Watts EIRP
d_{RT}	Reader-to-tag read range	10 m
d_{RR}	Reader-to-reader interference range	1000 m
R	Number of readers	[2, 4, ..., 20]
t	time slot duration	2.5 ms
T	Time interval	4 s
S	Frame length duration	1600 slots
V_r	Priority Requested by reader	1
α	Allocation tunning factor	[0.1, 0.5, 0.9]
d	Distance between adjacent readers	[15, 500] m
v	Mobile readers speed	1 m/s

Table 1: Configuration parameters

All readers are connected to a central server by a wired or wireless connection. In both, CASE and EPC-ETSI, the central server collects tags info. But in CASE the central server also collects, every T=4 s, data sent by readers and schedule the resources allocation for the subsequent time interval T. Note that in the dynamic scenario, mobile readers also send their updated coordinates to calculate the relative distances among readers.

Table 1 summarizes the values of other configuration parameters that were introduced in Section 4. Note that different values of R and d have been evaluated in a fixed area to study the effect of the readers density in the throughput and fairness response. When d=15 m adjacent readers overlap their reader-to-tag and reader-to reader areas ($d < 2 * d_{RT}$ and $d < d_{RR}$), and RTC and RRC occurs. d=500 m involves that only RRC occurs. α has been tuned to evaluate the scheduler response according to the goal of the system: to maximize throughput (low values of α) or to maximize fairness (high values of α). Finally, with the aim of simplifying the evaluation, we assume that all readers in the network always require the maximum quantity of resources, that is, they always detect tags to identify in their coverage areas. It involves that V_r is configured to the maximum value.

5.2. Evaluation results

First, CASE and EPC-ETSI are evaluated under the static scenario and d=15 m. Figures 6 and 7 shows the results of throughput and fairness respectively. CASE is evaluated for different α values, to show the behavior of the scheduler according to the imposed fairness. As can be seen, in both schedulers throughput dramatically decreases when the number of readers increases. The reason comes from d value, that provokes readers are suffering, not only from RRC but also from RTC with their neighboring readers, showing a very harsh scenario. In all tests, results of CASE with α=0.1 are higher than EPC-ETSI, but, as α increases, the throughput becomes worse, due to the nature of the CASE scheduler. It forces to a fair resource allocation among readers, which provokes that sometimes free resources are not assigned.

Another strategy to solve the low throughput in this scenario could be to optimize the reader placement from an electromagnetic perspective, i.e. by optimizing the coverage of the identification area [41]. This method would permit to minimize the overlapping area with the both aims of reading a tag regardless its position and of minimizing the RTC. However, this solution involves working in a scenario where we are not forced to set the readers in specific places, nor work at maximum output power.

Fig. 7 shows the fairness response in both schedulers. EPC-ETSI shows the lowest fairness in almost all the tests, since it does not implement a fair assignment mechanism. In CASE, as α value increases, the fairness shows better response, being almost constant for all number of readers. When α=0.9, CASE shows the best fairness, but this result is open to misinterpretation, because the performance of the scheduler is the worst. In fact, when the number of readers is high, the scheduler is forced to assign a low quantity of slots per reader which, at the end, may be inefficient, because readers need as much slots as possible to identify the highest quantity of tags in coverage [17].

Figures 8 and 9 shows the results of throughput and fairness respectively under a static scenario and d=500 m. Note that in this scenario RTC does not occur because readers are placed at 500 m distance each other. As can be seen in Fig. 8, throughput in both schedulers is almost maximum when $R \leq 10$ because every reader can be allocated in a unique frequency, eliminating RRC. Note that, in contrast to CASE, EPC-ETSI does not reach 100% throughput with $R \leq 10$ due to its random nature of readers' frequency selection, that may provoke that two or more adjacent readers select the same frequency, as well as the listening and waiting times imposed by EPC-ETSI. When the number of readers increases, the throughput decreases in both schedulers, but is still quite high, being CASE with α=0.1 the best configuration. Note that there is a fluctuation in the results when R=12 and R=16. The reason comes from the way the readers are deployed. In the scenario considered readers are equally spaced in rows with four readers each one. When R=12, the throughput reaches its lowest value, due to the lack of frequencies free of RRC. When the number of readers increases up to R=16, the new readers in the network can make use of the frequencies without suffering RRC, since the distance among them and the readers in the first row is higher than d_{RR}.

Fig. 9 shows the fairness in the evaluated scenario. The lack of RTC in this scenario helps both schedulers to get a good fairness response in almost all tests, being CASE with α=0.9 the best strategy.

CASE and EPC-ETSI were also evaluated under the dynamic scenario with d=15 and d=500. The goal was to know the influence of portable readers carried by humans at 1 m/s speed in a DRE. The results were quite similar to the previous one, concluding that the CASE and EPC-ETSI performance in the evaluated scenarios is not affected by the readers mobility.

From the results we conclude that in those static and dynamic scenarios where RTC is affecting ($d < 2 * d_{RT}$), CASE with α=0.1 shows better throughput than EPC-ETSI, and a similar fairness. With higher values of α, the results in both schedulers are similar, but the network fairness is significatively higher in CASE. Hence, in harsh DRE, CASE improves EPC-ETSI. In those static and dynamic scenarios where RTC is not affecting ($d > 2 * d_{RT}$), EPC-ETSI shows a really good throughput, even when the number of readers is high, and other strategies like CASE does not add an outstanding improvement. However, the fairness of EPC-ETSI is significatively lower than CASE with a high number of R due to the lack of a mechanism to control the fairness in the system. Hence, in static and dynamic DRE free of RTC, if not only the throughput is an important issue, but also the fairness, CASE is also shown as an efficient scheduler.

5.3. Computational cost

Since the proposed optimization problem is solved in a centralized manner, the computation time is a relevant factor for practical use. In the performance evaluation addressed in the previous subsection we measured the computation time, executing the algorithm in a PC with Windows XP, 2.4 GHz CPU, 3GB RAM. Note that CASE execution involves to solve an optimization problem where some parameters are fixed, like number of frequencies or slots, but other parameters can change over time: readers priority (V_r), readers position (portable readers), number of readers (incoming or outgoing from work area), etc. The value of these parameters has a direct influence on the degree of complexity of the optimization problem to solve and the time needed to solve it.

In static scenarios with fixed V_r in all readers, and $d > 2 * d_{RT}$, the time needed by the PC to solve the optimization problem when $R \leq 10$ was negligible for all α values, while the time for $20 \leq R < 10$ was lower than 0.2 s. In those static scenarios with fixed V_r in all readers, and $d < 2 * d_{RT}$, the complexity of the problem increases, because RTC occurs, and the α parameter has a strong influence on the resource allocation solution. In this scenario, the time required to compute the algorithm was around 0.5 second for all cases. From these tests we conclude that in static scenarios, where the readers are fixed and their priorities are always the same, the resource allocation optimization problem can be solved once, before running the system, in order to work with a prefixed resource allocation configuration. In this way, the central server has not to spend time computing and solving the resource allocation problem.

In the dynamic case, the need of the mobile readers position over time increases the complexity of the optimization problem. The computation time required in these tests was as follows: in those scenarios where the initial position of readers is $d > 2 * d_{RT}$, the time required for all α values was also negligible for R <5, 0.3 s when $5 \leq R$ <12, and 0.5 when $12 \leq R \leq 20$. For those scenarios where $d < 2 * d_{RT}$ the computational time increased, as in the previous tests. In this case, the computation time was around 0.8 second for all cases.

The same scenarios were computed tuning the V_r value of every reader in the network. The computation time required with this new assumption suffered a strong increase in both scenarios, but even more in the dynamic case with $d < 2 * d_{RT}$, spending up to 3 seconds.

From the previous results where some parameters values change over time, we conclude that if the number of readers in the network is low, the computation time could be feasible for a further RFID implementation. Otherwise, a heuristic model may be implemented to reduce the computation time.

6. Conclusions

Several proposals have been suggested to avoid/handle reader collisions problems in Dense Reader Environments. Most of them require extra hardware, do not address both RTC and RRC problems, do not make an efficient use of the network resources or are not compatible with the current standards and regulations. In this paper we surveyed most of them and proposed a centralized and aligned scheduler that optimizes the distribution of network resources (frequencies and time slots) among the readers in a DRE network, being totally compatible with current European standard and regulations. Note that we focus the work on European regulation, but the proposal can be extended to the restrictions imposed by the regulations of other areas. The optimization problem was formulated as a Mixture Integer Programming problem. Results, considering scenarios with fixed and mobile readers, show that, in most of the cases, the method proposed provides higher network throughput and fairness than the EPC-ETSI strategy, which is based on EPCglobal Class-1 Gen-2 standard and the European regulation ETSI EN 302 208. The improvement of our proposal is even remarkable when the reader density increases. Finally, the computational cost has been evaluated, concluding that the proposed scheduling algorithm is feasible to be implemented in small-medium size RFID systems.

Acknowledgments

This work has been funded by the Spanish Ministerio de Innovacion y Ciencia by the National project CALM TEC2010-21405-C02-02 (subprograma TCM) and also 457 developed within the framework of Programa de Ayudas a Grupos de Excelencia de la Region deMurcia, funded by Fundacion Seneca,Agencia de Ciencia y Tecnologia de la Region de Murcia (Plan Regional de Ciencia y Tecnologia 2007/2010).

References

[1] Xiao, Y., Yu, S., Wu, K., Ni, Q., Janecek, C. and Nordstad, J., (2007) Radio frequency identification: technologies, applications, and research issues. Wireless Communications and Mobile Computing Journal, vol. 7, no. 4, pp. 457-472.

[2] Burkhart, M., Von Rickenbach, P., Wattenhofer, R., Zollinger, A., (2004) Does topology control reduce interference?, in Proc. ACM International Symposium on Mobile ad hoc networking and computing. New York, NY, USA: ACM, pp. 9-19.

[3] Kanj, I., Wiese, A., Zhang, F., (2010) Local algorithms for edge colorings in UDGs, in Graph-Theoretic Concepts in Computer Science, ser. LNCS, C. Paul and M. Habib, Eds. Springer Berlin / Heidelberg, vol. 5911, pp. 202-213.

[4] Moscibroda, T., Von Rickenbach, P., Wattenhofer, R., (2006) Analyzing the energy-latency trade-off during the deployment of sensor networks, in Proc. of IEEE International Conference on Computer Communications, pp. 1-13.

[5] Kuhn, F., Wattenhofer, R., Zollinger, A., (2003) Worst-case optimal and average-case efficient geometric ad-hoc routing, in Proc. of ACM international symposium on Mobile Ad Hoc Networking and Computing. New York, NY, USA: ACM, pp. 267-278.

[6] ETSI-EN 302 208-2, version 1.3.1, February 2010. Available on-line at: http://www.etsi.org

[7] Leong, K.S., Ng, M.L., Cole, P.H., (2005) The reader collision problem in RFID systems, in Proc. IEEE International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications, pp. 658-661.

[8] Yoon,W. and Vaidya, N. H., RFID reader collision problem: performance analysis and medium access, Wireless Communications and Mobile Computing Journal, in press.

[9] EPC Radio-Frequency Identify protocol for communications at 868-960MHz, version 1.2.0, October 2008. Available on-line at http://www.epcglobalinc.org/standards

[10] EPCglobal Network. Avaliable on line at: http://www.epcglobalus.org

[11] Waldrop, J., Engels, D.W., Sarma, S. E., (2003) Colorwave: an anti-collision algorithm for the reader collision problem, in Proc. IEEE Int. Conf. on Communications, Anchorage, Alaska, USA, pp. 1206-1210.

[12] Bueno-Delgado, M.V., Vales-Alonso, J., Angerer, C., Rupp, M., (2010) Study of RFID Schedulers in Dense Reader Environments, in Proc. IEEE International Conference on Industrial Technology, Via del Mar, Chile.

[13] Eom, J.B., Yim, S.B., Lee, T.J., (2009) An efficient reader anti-collision algorithm in dense RFID networks with mobile RFID readers, IEEE Transactions on Industrial Electronics, vol. 56, no. 7, pp. 2326-2336.

[14] Gandino, F., Ferrero, R., Montrucchio, B., Rebaudengo, M., (2011) Probabilistic DCS: An RFID reader to reader anti-collision protocol, Journal of Network and Computer Applications, vol. 34(3), pp. 821-832.

[15] Bi, H.H., Lin, K.J., (2009) RFID-Enabled Discovery of Supply Networks, IEEE Transactions on Engineering Management, vol. 56, no. 1, pp. 129-141.

[16] Reader Management Specification. Available on-line at: http://www.epcglobalinc.org/standards/rm

[17] Bueno-Delgado, M.V., Vales-Alonso, J., (2011) On the optimal frame-length configuration on passive RFID installations, Journal on Network and Computer Applications, vol.34(3), pp. 864-876.

[18] Ferrero, R., Gandino, F., Motrucchio, B., Rebaudengo, M., (2010) Fair Anti-Collision Protocol in Dense RFID Networks, in Proc. Third International EURASIP Conference on RFID Technology, La Manga del Mar Menor, Spain, pp. 101-105.

[19] Vales-Alonso, J., Bueno-Delgado, M.V., J.J. Alcaraz-Espin, (2011) Optimal Scheduling in dual Reaer RFID Environments, IEEE International Conference on RFID Technologies and Applications, Sitges-Barcelona (Spain), pp 479-485.

[20] Wang, D., Wang, J., and Zhao, Y., (2006) A novel solution to the reader collision problem in RFID system. in Proc. IEEE International Conference on Wireless Communications, Networking and Mobile Computing (WICOM), Montreal, Canada, pp. 1-4.

[21] Chen, N. K. Chen, J. L., Lee, C. C.,(2009) Array-based Reader Anti-Collision Scheme for Highly Efficient RFID Network Applications, Wireless Communication and Mobile Computing Journal, vol. 9, pp.976-987.

[22] Chung, H. B., Mo, H., Kim, N., Pyo, C., (2007) An advanced RFID system to avoid collision of RFID reader, using channel holder and dual sensitivities, Microwave and Optical Technology Letters, vol.49 (11), pp. 2643-2647.

[23] Kim, J., Lee, W., Kim, E., Kim, D., Suh, K., (2007) Optimized Transmission Power Control of Interrogators for Collision Arbitration in UHF RFID Systems, IEEE Communications letters, vol 11, no. 1, pp. 22-24.

[24] Ho, J., Engels, D., Sarma, S., (2006) HiQ: a hierarchical Q-learning algorithm to solve the reader collision problem, in Proc. of International Symposium on Applications and the Internet, Phoenix, Arizona, USA., pp 88-91.

[25] Seo, H., Lee, C., (2010) A new GA-based resource allocation scheme for a reader-to-reader interference problem in RFID systems, in Proc. of IEEE ICC, Cape Town, South Africa.

[26] Birari, S.M., Iyer, S., (2005) PULSE: A MAC Protocol for RFID Networks, in Proc. International Workshop on RFID and Ubiquitous Sensor Networks, Japan.

[27] Liu, L., Yan, D., Lai, X., Lai, S., (2008) A New Kind of RFID Reader Anti-collision Algorithm, in Proc. IEEE International Conference on Circuits and Systems for Communications, Shangai, China, pp. 559-563.

[28] Sungjun, K., Sangbin, L., Sunshin, A., (2006) Reader Collision Avoidance Mechanism in Ubiquitous Sensor and RFID Networks, in Proc. International Workshop on Wireless network testbeds, Experimental Evaluation and Characterization, L.A., USA, pp. 101-102.

[29] Kwang-il, H., Kyung-tae, K., Doo-seop, E., (2009) Distributed Tag Access with Collision Avoidance among Mobile RFID Readers, in Proc. International Conference on Computational Science and Engineering, Vancouver, Canada, pp. 621-626.

[30] Dai, H., Lai, S., Zhu, H., (2007) A Multi-Channel MAC Protocol for RFID Reader Networks, in Proc. International Conference on Wireless Communications, New York, USA, pp. 2093-2096.

[31] Shin, K., Song, Q., (2009) RAC-Multi: Reader anti-collision algorithm for multichannel mobile RFID networks, Sensors, vol. 10, pp. 84-96.

[32] Waldrop, J., Engels, D.W., Sarma, S. E., (2003) Colorwave: a MAC for RFID reader networks, in Proc. IEEE Wireless communications and networking conference, vol. 3, New Orleands, LA, USA, pp. 1701-1704.

[33] Shin, K. C., Park, S. B., Jo., G. S., (2009) Enhanced TDMA Based Anti-Collision Algorithm with a Dynamic Frame Size Adjustment Strategy for Mobile RFID Readers, Sensors Journal, vol. 9, pp. 845-858.

[34] Bueno-Delgado, M.V., Egea-López, E., Vales-Alonso, J., García Haro, J., (2009) Handbook of Enterprise Intregration, Radio Frequency Identification Technology, Auerbach Publications, CRC Press, pp. 429-466.

[35] Vales-Alonso, J., Bueno-Delgado, M.V., Egea-Lopez, E., Gonzalez-Castano, F.J., Alcaraz, J., (2011) Multiframe Maximum-Likelihood Tag Estimation for RFID Anticollision Protocols, Industrial Informatics, IEEE Transactions on , vol.7, no.3, pp.487-496.

[36] Tesoriero, R., Gallud, J., Lozano, M., Penichet, V., (2008) Using active and passive RFID technology to support indoor location-aware systems, IEEE Transactions on Consumer Electronics, vol. 54, no.2, pp. 578-583.

[37] Saad, S.S., Nakad, Z.S., (2011) A Standalone RFID indoor positioning system using passive tags, IEEE Transactions on Industrial Electronics, vol.58, no.5, pp.1961-1970.

[38] Liu, X., Peng, J., Liu, T., (2011) A novel indoor location system based on passive RFID technology, in Proc. of International Conference on Electronic and Mechanical Engineering and Information Technology, pp. 4285-4288.

[39] General Algebraic Modeling System, version 23.7.3. Available on-line at: http://www.gams.com

[40] Bettstetter, C., Wagner, C., (2002) The spatial node distribution of the random waypoint mobility model, in Proc. of German Workshop on Mobile Ad Hoc networks (WMAN), Ulm, Germany.

[41] Di Giampaolo, E.; Forni, F.; Marrocco, G., (2010) RFID-network planning by Particle Swarm Optimization, in Proc. of Fourth European Conference on Antennas and Propagation (EuCAP), pp.1-5.

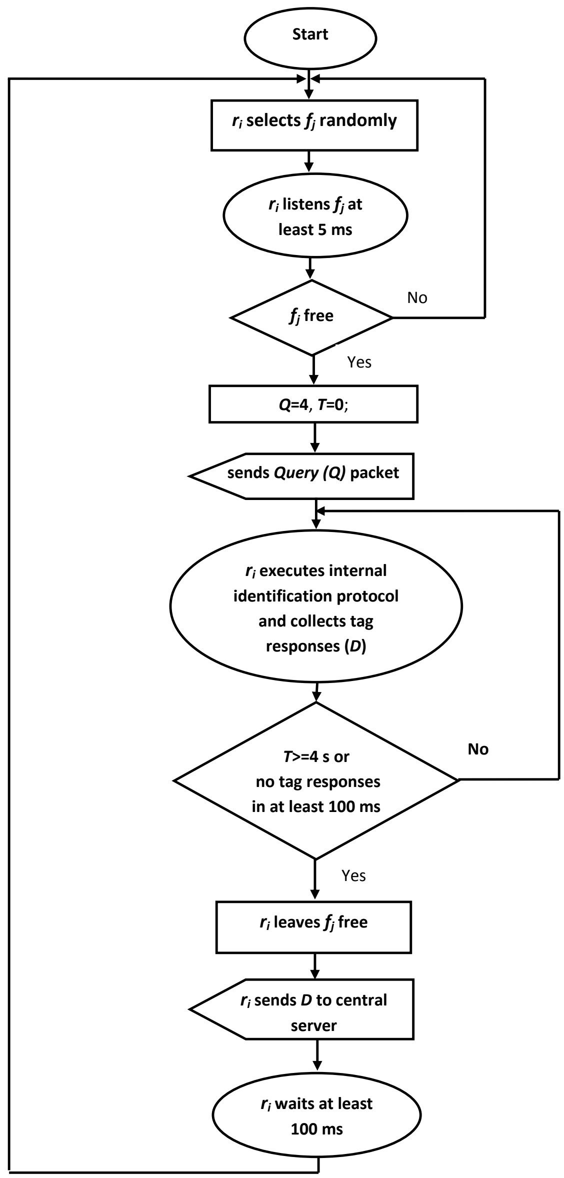

Figure 4: Operational mode of commercial readers in European DRE

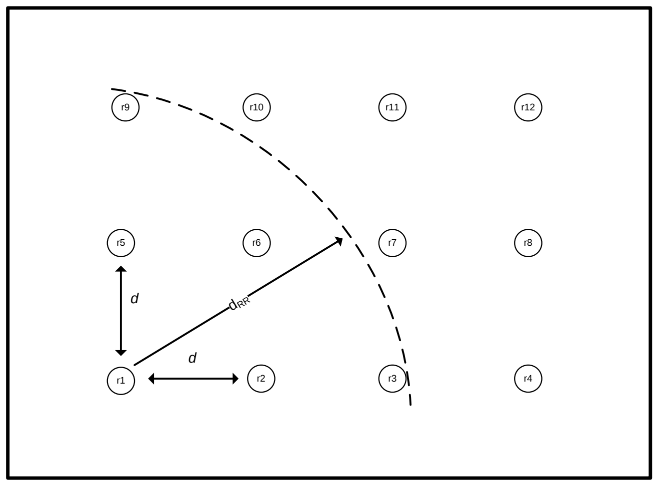

Figure 5: Example of RFID Dense Reader Environment in array deployment

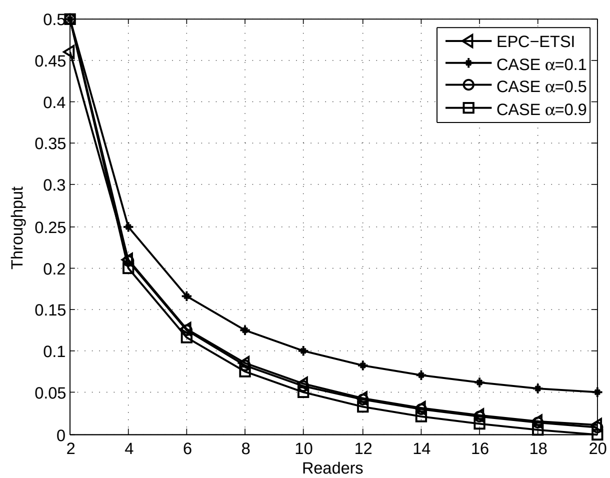

Figure 6: Network throughput of a static RFID system in array deployment and d=15 m

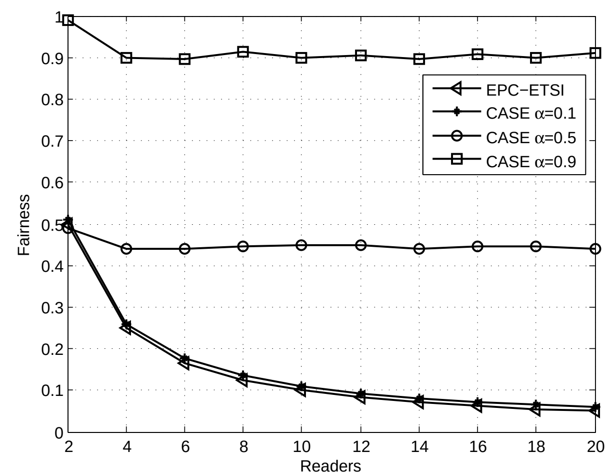

Figure 7: Network fairness of a static RFID system in array deployment and d=15 m

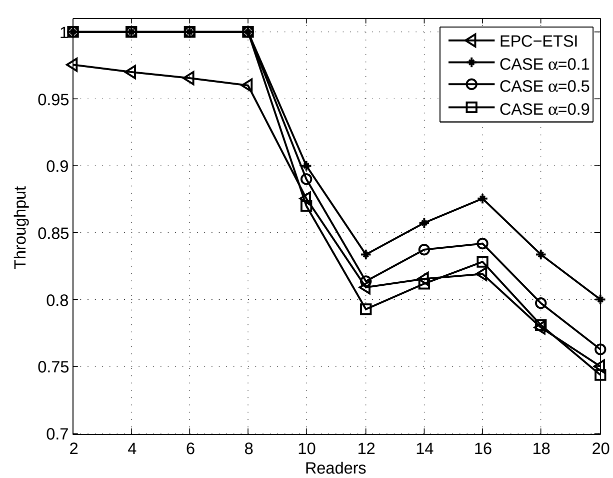

Figure 8: Network throughput of a static RFID system in array deployment and d=500 m

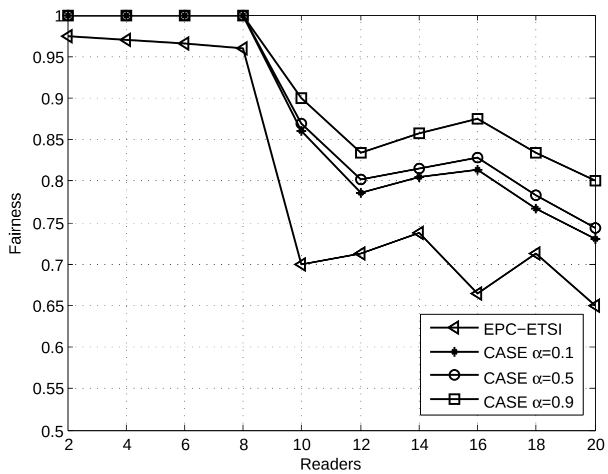

Figure 9: Network fairness of a static RFID system in array deployment and d=500 m