A Comparative Study of RFID Schedulers in Dense Reader Environments

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Abstract- **In realistic deployments, several readers may be placed in the same area, forming a, so-called, *dense reader environment*. These scenarios are susceptible to suffer *Reader Collision Problems*, characterized by Reader-to-Tag and Reader-to-Reader interferences. Both affect network throughput, decreasing the overall number of tags identified per reader. This paper reviews the mechanisms proposed to mitigate the Reader Collision Problems. Besides, the constraints of these techniques are pointed out. The mechanisms have been evaluated to study the efficiency of the resources allocation.**

I. INTRODUCTION

Radio Frequency Identification (RFID) is increasingly being used to identify and trace objects in supply chains, manufacturing process, *etc*. These environments are characterized by a large number of items which commonly flowing on conveyor belts, inside pallets or boxes, and so on, entering and leaving facilities. Passive RFID is a low-price technology for identification of multiple items by means of a wireless communication. A typical passive RFID environment is composed by a large number of tags and one or more readers. The former store relevant information about the items they are attached to (price, expiration date, *etc.*), do not incorporate battery and are powered by means of the electromagnetic waves energy emitted by the readers. Readers are more complex devices. They are installed in checking areas and they continuously transmit electromagnetic waves to feed tags. The tags that cross these areas send their information back to the readers.

In large realistic installations several readers are commonly deployed in the same area, so-called *dense reader environments* (multiple readers in mutual range). In these scenarios, the rate of tags identified per reader is limited by the Reader Collision Problems, namely:

- Reader-to-Tag Interferences (RTI) that take place when two or more readers, independently of the working frequency, transmit at the same time, overlapping their read ranges (reader-to-tag range) and powering the same tag. For instance, in Fig. 1, if *R* and *R'* are feeding tag *A* simultaneously, tag is not able to produce a correct response to any of the readers.
- Reader-to-Reader Interferences (RRI) occur when two or more readers, working at the same frequency, are in mutual range. When one reader powers a tag within its reader-to-tag range it can receive stronger signals from other readers, interfering with the weaker signal from the tag. For example, in Fig. 1, tag *B* cannot be read by *R* if at the same time *R'* tries to read the tag *C*.

Current standards [1, 2] propose some solutions to reduce collision issues, but exclusively focused on minimizing RRI. On the other hand, a number of papers [3-8] deal with minimization of the RTI, but without considering reader-to-reader ones. Besides, most of the proposals require extra hardware, do not make an efficient use of the time/frequency resources, and even some of them are incompatible with the current standards.

This work reviews these regulations and the proposals in the scientific literature. The performance of the different mechanisms is studied for common reference scenarios, in order to provide comparative results of the efficiency in the allocation of resources.

The rest of the paper is organized as follows: In Section II the description of the reader collision environments is shown. In Section III, a review of the current regulations and standard is introduced. In Section IV, the most relevant research proposals are shown. Section V shows the performance results of the proposals and standards. Section VI concludes and suggests the key properties for future schedulers.

II. READER COLLISION ENVIRONMENTS PROBLEM DESCRIPTION

Dense reader environments are characterized by a RFID system composed by two or more readers, independently of the topology. Typically, these readers are connected to a central device (server) by means of a wired (Ethernet) or wireless network (WiFi, 3G, *etc.*). They are continuously monitoring tags within their reading range.

The reader coverage area depends on the reader output power. In Europe, this value reaches 2W [1] and guarantees a reader-to-tag range up to 10 m., while causes interferences among readers up to 1000 m [9]. Therefore, output power determines interference ranges:

a) If two or more readers are within two times the reader-to-tag range (*e.g.* 20 m for 2 W output power), either part or the whole reading area overlaps, preventing tags operation. Hence, both RTI and RRI are present. In this case, readers operation should be allocated at different working times.

b) If the distance among readers is between the previous range and the maximum RRI distance (*e.g.*, 1000 m for 2 W output power) only RRI appears. Readers operation can be multiplexed either in frequency or in time.

c) If distance among readers is larger than maximum RRI distance, they will not suffer interferences.

	Freq. =	**Freq ≠**
Work time =	*d >1000 m*	*d >20 m*
Work time ≠	*Any distance*	*Any distance*

Table 1. Concurrent 2 Watt readers configuration restrictions

Table 1 summarizes the distance (*d*) and concurrent operation possibilities in the 2 W output power case.

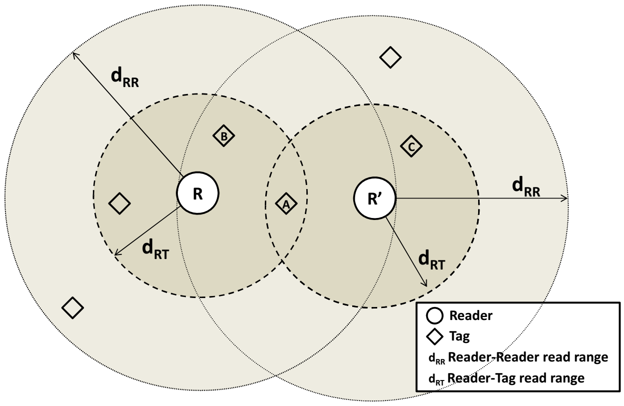


Figure. 1. Reader collision problems

III. Regulations and Standards

Some RFID regulations and standards propose mechanisms to work in *dense reader environments*. They have been designed to reduce RRI, but not aimed at RTI. All of them are based on *Frequency Division Multiplexing Access* (FDMA) scheme, allocating readers in different frequencies.

ETSI EN 302 208 [1] is a European regulation that works dividing the frequency band into 15 sub-bands (channels). In Europe, at maximum power (2 W), only ten channels are available while the remaining five are used as guard bands. Readers listen to a determined sub-band carrier during a fixed time before accessing to it, following the *Carrier Sense Multiple Access* (CSMA) mechanism, which is also called *Listen Before Talk* (LBT). If the sub-band is free, the readers start to transmit into. Then, the sub-band is used for up to 4 s, after which it must be free for at least 100 ms.

EPC global Class-1 Gen-2 UHF Protocol [2] divides the spectrum into ten different sub-bands. In contrast to [1], the readers randomly alternate (every 0.4 s) between bands, following the *Frequency Hopping Spread Spectrum* (FHSS) technique, which permits to reduce the collision probability. Readers do not listen to the channel before accessing to it. The reader transmissions are restricted to operate in even-numbered sub-bands and tag backscatter in odd-numbered sub-bands. Hence, only 5 channels are available to reader-tag communications.

IV. Research Proposals

In the next sections the most relevant research proposals are studied, emphasizing their requirements, problems and incompatibilities with current standards. Since these mechanisms are commonly classified into centralized and distributed ones, this classification is followed.

A. Centralized mechanisms

In this case a centralized master is in charge of reader coordination. It communicates with the readers using a wired or wireless link, and synchronizes the readers. It checks the requirements of each reader, and distributes the available resources among them, that is, it schedules the operation of the readers.

In [3] a centralized device is suggested to coordinate not only the resources (authors assume a single channel), but also intends to control communication between tags and readers. However, the mechanism proposed is unfeasible if the tag identities are *a priori* unknown (as they are in fact). Besides, the authors assume that RRI cannot occur.

In [10], the authors propose a FDMA mechanism to cope with RRI, which spatially reuses the same channels to minimize interference. Far away readers are assigned to the same channels, whereas if they are close channels are exclusive. In case the number of nearby readers surpasses the available channels, some of them are not allocated. The authors also recommend reducing the reader output power to decrease the interferences; nevertheless this solution would decrease the reading range.

In [4], the readers are allocated in only one channel. The centralized mechanism detects overlapping reading areas in real-time, and may disconnect some reader to reduce the RTI. Information about the number of competing tags is required, as well as the physical distribution of the readers, which is assumed to be static.

In [11], the authors propose a centralized algorithm that manages fixed and mobile readers. It decides which readers operate at each time to minimize both RRI and RTI. Since mobile readers are specifically considered, a wireless link must be present to interact with them. Besides, only one channel is considered.

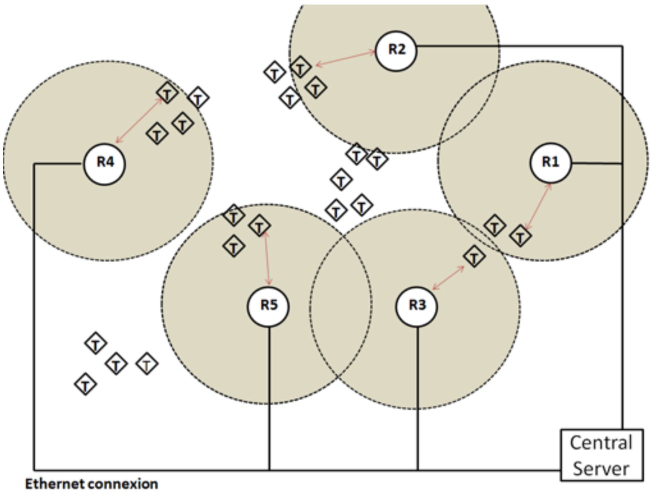


Figure. 2. Centralized scenario[1]

B. Distributed mechanisms

In this case, the readers communicate directly with their neighbors –usually, wireless links are assumed- to allocate the resources and control/maintain the synchronization.

In [5], the authors propose *Leo*, a decentralized mechanism where each reader, before running the RFID identification process, detects the maximum number of neighboring redundant readers that can be safely turned off to minimize RTI, preserving the original network coverage. In this approach, both the tags and the reader positions must be known, hence making a real implementation difficult. Besides, mobile readers are not contemplated.

Pulse [12] is a LBT protocol that makes use of an auxiliary control channel. 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 neighbor 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 [13] a similar mechanism is suggested, but only for minimizing RRI, whereas [6] introduces another LBT aimed at RTI minimization. In the latter, a wireless sensor network is selected for reader-to-reader communications, but this network is not use for sensing any particular parameter, thus resulting in higher costs. In addition, [6, 12-13] only consider a single reading channel, instead of five or ten, as in the European regulations and standards [1-2].

DiCa [14] is another single channel distributed algorithm based on LBT, and focused on RTI reduction. It proposes to use a control channel with doubles the range of the reading channel. In case that collision with another reader is detected, *DiCa* decreases both channels range proportionally. Authors claim that this is an energy saving system, but this issue is of minor interest in passive RFID.

MCMAC [15] is a multi-channel LBT strategy combined with FDMA. If there are *N* readers, the mechanism uses *N-1* non-overlapping channels for reading and one control channel. 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 RRI, it does not solve the RTI. Besides, if the number of readers (*R*) is higher than the number of channels (current European standards are limited to 10 data channels), MCMAC operates as well, but delaying operation of *R-N-1* readers.

Colorwave [7] is based on a *Time Division Multiplexing Access* (TDMA) scheme for RTI. Time-slots are randomly selected by the readers, performing the reading process in the right slot. Colliding readers repeat again the process, since RTI makes tag identification impossible.

HiQ [8] is a hybrid mechanism (centralized and distributed) that provides a solution to minimize the RTI. It is 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 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 with this approach is that each reader has to manage a high quantity of information, and results depend on the quality of the neural network training.

V. PERFORMANCE EVALUATION

The previously discussed proposals offer comparative results using different metrics: detection of redundant readers, number of successful *Query* packets transmitted (packets sent by the reader to identify tags), throughput (defined as the ratio of successful *Query* packets *vs.* total *Query* packets), reader-to-reader and reader-to-tag collision probability (denoted as RRP and RTP respectively), *etc*. These metrics are aimed at measuring the mitigation of RRI and RTI. However, we consider the schedulers have to, not only mitigate RRI and RTI, but also to share to the readers the resources available in the network to maximize the number of tags identified per reader. Therefore, in this section we compare the performance of the schedulers discussed in terms of a fair metric that measure the efficiency of the network resources management, that is, once the resources are shared (using the mechanisms introduced in the previous section) between the readers, we measure the ratio of resources free of RTI and RRI to the total resources demanded by the readers. On the other hand we measure the usability of the network resources, extracting the ratio of resources allocated free of RTI and RRI to the total resources of the network, that is, the total of resources available, independently the scheduler (frequencies and slots).

[1] Note that only reader-to-tag range is shown.

Mechanism / Criterion	CC[3]	Harr[10]	Array[4]	Leo[5]	Pulse[12]	Kim[6]	Dica[14]	MCMAC[15]	Color[7]	HiQ[8]	NFRA[11]	Kind[13]
Reader-to-tag	✓		✓	✓	✓	✓	✓		✓	✓	✓	
Reader-to-Reader		✓			✓		✓	✓			✓	✓
Centralized	✓	✓	✓							✓	✓	
Distributed				✓	✓	✓	✓	✓	✓	✓		✓
One Data channel	✓		✓	✓	✓		✓		✓		✓	✓
Control Channel					✓	✓	✓	✓		✓	✓	✓
FDMA		✓						✓		✓		
TDMA									✓	✓	✓	✓
Fixed Readers	✓	✓		✓	✓	✓		✓		✓	✓	✓
Mobile Readers		✓			✓	✓	✓	✓			✓	
Extra Hardware	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓
Compatibility current standards			✓					✓				

Table 1. Comparison of Reader Collision Solutions

A. Scenario Description and Considerations

We consider a dense reader environment with $R=5$ fixed readers (as depicted in figure 3). The relative distances among readers are given in matrix D. Each row in the matrix represents the distance between one reader to the others, measured in meters (*e.g.* $d_{2,4}$ is the distance from reader 2 to reader 4).

Every reader transmits with the same output power P_{out}= 2 W (maximum power in Europe). This value establishes the reader coverage area, and hence, the overlapping distances caused by RRI and RTI, denoted as d_{RRI} and d_{RTI}, respectively.

The resources available for allocation in the scenario are the number of reading sub-channels, F, and the number of time-slots in each sub-channel reading frame: S time-slots (see note[2]). If all the readers in the system are placed within the d_{RRI} distance, the total number of time-slots to allocate is:

$$\alpha = S \cdot F \tag{1}$$

Otherwise, they can share the same frequency and slots, then,

$$\alpha = S \cdot (F + C(d_{RRI}) - 1) \tag{2}$$

Where $C(d_{RRI})$ denotes the number of clusters of readers as a function of distance d_{RRI}, that is, the number of sets separated more than d_{RRI}. Notice that neighbor cluster may share some readers. Indeed, if there is a single cluster, $C(d_{RRI})$ = 1, and equations (1) and (2) match.

Other assumptions for the evaluation are:

- The RFID system is reconfigured periodically, every frame time L, *e.g.* according to [1], L = 4 s.
- Every L, a uniform population of tags is placed in the checking areas.
- Once a reader i detects the population of tags in its coverage range, it determines (following an internal procedure [16]) the resources it needs to identify the population (in number of slots). The number of slots required by every reader i is randomly and uniformly distributed, $r_i = rnd(0, \alpha/R)$.
- The resources without interferences allocated by the scheduler to every reader i is denoted as β_i, being $\beta_i \le r_i$.

Let us introduce the *scheduler efficiency (γ)* of the system to measure the ratio of the actually assigned resources free of RTI and RRI, to the total resources demanded by the readers:

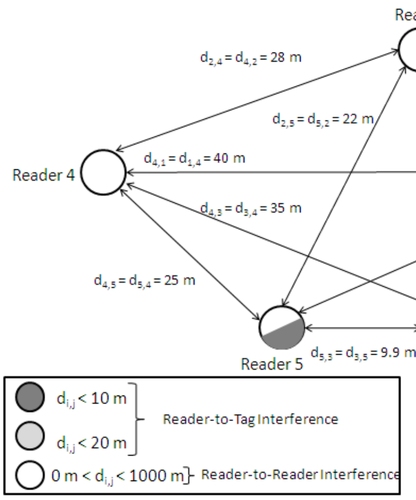
$$\gamma = \frac{\sum_{i=1}^{R} \beta_i}{\sum_{i=1}^{R} r_i} \tag{3}$$

On the other hand we define the *network usability (μ)* of the scheduler as the ratio of the actually assigned resources free of RTI and RRI to the total network resources available:

$$\mu = \frac{\sum_{i=1}^{R} \beta_i}{\alpha} \tag{4}$$

Note that taking into consideration an optimal scheduler and assuming that every reader i requests α/R, then $\gamma=\mu$.

[2] Note that S value depends the particular duration of the frame (L). In this work S = 1600 time-slots assuming typical parameters of the standard [2].



$$D_{RxR} \begin{pmatrix} 0 & 15 & 15 & 40 & 22 \\ 15 & 0 & 24 & 28 & 22 \\ 15 & 24 & 0 & 35 & 9.9 \\ 40 & 28 & 35 & 0 & 25 \\ 22 & 22 & 9.9 & 25 & 0 \end{pmatrix}$$

Figure. 3. Dense reader scenario

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B. *Simulation results*

The scenario in consideration has been simulated using the simulator developed with OMNeT++ tool [17]. This simulator is an extended version of a previous simulator developed by the authors [16]. We have considered all proposals with a feasible implementation and compatible with the current standards. They have been grouped as follows:

- Switch-off interfering readers: [5]
- Based on TDMA: [4][7][13]
- Based on FDMA: [15]
- Regulations: [1]
- Standards: [2]

These proposals have been implemented and simulated in the scenario depicted in Fig. 3, taking the parameters of Table 2. Note that the initial scenario (Fig. 3) consists of a single cluster with two separated sets at distance d_{RTI} :{R_4} and {R_1, R_2, R_3, R_5}. In the evaluations, the number of readers increases up to R = 50, with each new at a distance between d_{RTI} and d_{RRI} of all the previous readers. The number of resources available is extracted from eq. (2), and β_i and r_i is measured using the simulator. A time-slot is considered interference-less if it is exclusively used by only one reader.

Figure 4 shows the resulting *scheduler efficiency*. Note that [1] and [2] work at 10 and 5 frequencies respectively. The rest of the schedulers have been set to F=5 (number of frequencies defined by the standard [2]). The best scheduler efficiency is achieved by [1], only surpassed by FDMA [15] and switch-off [5] when R is lower than 8 and 7, respectively. Note that, although [15] shows better response than [2], its implementation in a real reader is not feasible because it uses an available frequency as control channel, not compatible with current standards. The worst efficiency is shown by the proposals based on TDMA. This is because in we have studied the worst case, when a reader i requires slots during r_i slots, it is allocated in a frequency and any other reader can use it. In other cases the TDMA proposals will have a better response.

Figure 5 shows the resulting *network usability* per scheduler. In this case, the worst usability is shown by TDMA, independently the number of readers because only one of five available frequencies is occupied. [1] shows a low usability when R<10 because the resources required is lower than the frequencies available ([1] set F=10). When $R>10$, this scheduler shows the best network usability. [2] has a good usability but lower than [1] because one of the available frequencies is used as control channel.

From the results obtained we conclude that, when the number of readers is high, the number of frequencies available is mandatory to obtain, not only a good efficiency, but also a good usability. However, the possibility of sharing frequencies can supply the lack of frequencies. Therefore, we suggest the use of schedulers based on combination of FDMA and TDMA techniques.

VI. CONCLUSIONS

In this paper we have reviewed the Redundant Reader Problems and the solutions proposed by the current standards, regulations, as well as numerous proposals. We have checked that, most of them are focused on minimizing only one type of collision. Besides, most of the proposals require extra hardware, or are incompatible with current standards. We have evaluated the proposals compatible with the standards and the results demonstrate that most of them show a low efficiency in scenarios with a high number of readers. The network usability of schedulers is also low, motivated by the exclusive use of FDMA or TDMA, but not the combination of both techniques. From the results we extract that combining TDMA and TDMA could be a good strategy to improve the scheduler efficiency and the network usability. This suggestion involves the scheduler must solve an optimization problem, where a set of readers must be allocated in a set of frequencies and slots to minimize the Reader Collision Problems, with several constraints.

Parameter	Value
P_{out}	2 W
RTId	20 m
RRId	1000 m
F	5
T	4 s
S	1600
R	[5, …, 50]

Table 2. Simulation parameters

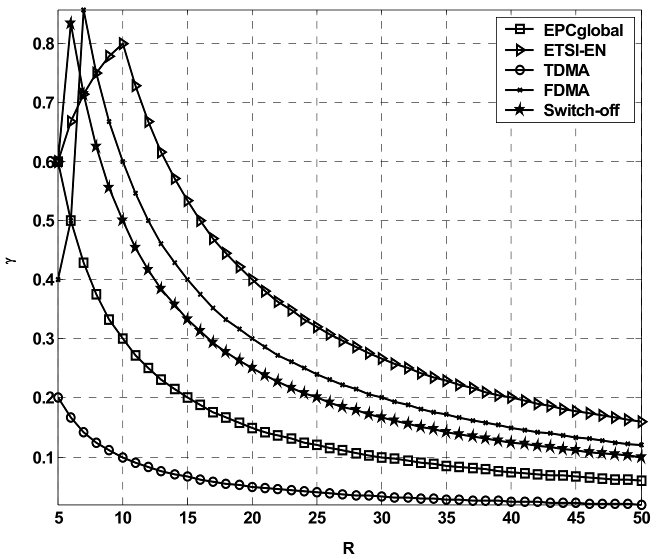

Figure 4. Efficiency *vs.* number of readers, *F*=5

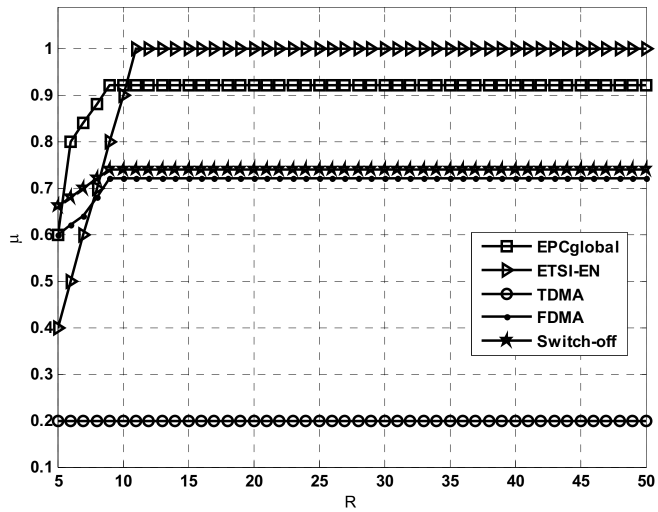

Figure 5. Network usability *vs.* number of readers, *F*=5

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