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Optimal scheduling in single channel dense reader RFID environments

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***Abstract*—In this paper we solve analytically the problem of distributing optimally a set of t slots between a group of n readers in RFID dense environments where a single frequency channel is available. In these environments, the readers within reader-to-reader interference range must transmit at different times, otherwise tags cannot identified. This resource allocation problem is addressed for both static and dynamic Frame Slotted Aloha, which are the most broadly extended mechanism used in UHF RFID systems. The goal is maximizing the expected number of tags successfully identified within the t slots. Results demonstrate that the optimal solution outperforms an assignment proportional to the number of tags in each reader. The results heavily depend on the underlying reading algorithm of the reader.**

***Keywords*-RFID, Dense Reader Environment, Scheduling, Mathematical program**

I. INTRODUCTION

Passive Radio Frequency Identification (RFID) is increasingly being used to identify and trace objects in supply chains, manufacturing process, and so forth. These environments are characterized by a large number of items with attached tags which flow on conveyor belts, inside pallets or boxes, and the like, entering and leaving facilities. In large realistic installations several readers are commonly deployed, these are the so-called *dense reader environments*, comprising multiple readers within 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) occur when two or more readers, irrespectively of the working frequency, transmit at the same time, overlapping their read ranges (reader-to-tag range) and powering the same tags. For instance, in Fig. 1, if readers 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. That is, one reader that powers a tag within its reader-to-tag range can receive stronger signals from other readers, ruining 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.

The reader coverage area depends on the reader output power. In Europe, this value reaches up to 2W and guarantees a reader-to-tag range up to 10 meters, while this may cause interferences with readers up to 1000 m typically. Therefore, the output power determines interference ranges:

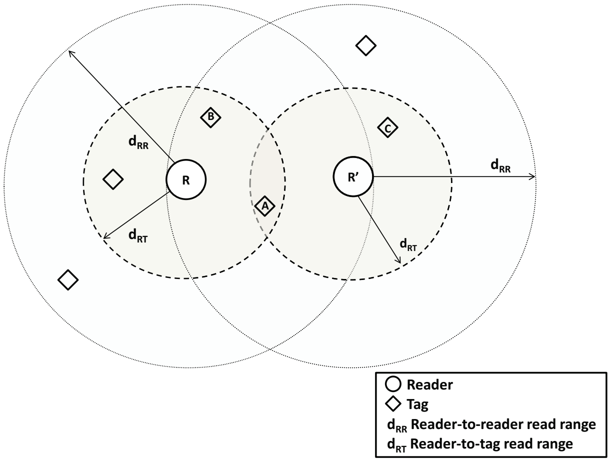

Figure 1. Interferences in dense reader environments

	$=$ **freq**	$\neq$ **freq**
$=$ **time**	$d > d_{RR}$	$d > d_{RT}$
$\neq$ **time**	$d > 0$	$d > 0$

Table I
READER OPERATION RESTRICTIONS VERSUS d

- If two or more readers are within two times the reader-to-tag range (e.g., d_{RT} = 20 m for 2 W output power), either part or the whole reading area overlaps, preventing tags operation. Hence, both RTI and RRI interferences are present. In this case, readers operation should be allocated at different working times.
- If the distance among readers is between d_{RT} and the maximum distance determined by the RRI (e.g., d_{RR} = 1000 m for 2 W output power) only RRI appears. Readers operation can be multiplexed either in frequency or in time.
- If distance among readers is larger than maximum RRI distance, they do not suffer interferences.

Table 1 summarizes the restrictions applying to readers operation for dense reader environments.

Therefore, in dense reader environments, the problem is

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how to distribute the reading resources available among the readers to perform optimally. The main parameters involved in this problem are the following:

- The number of readers, m.
- The number of available frequency channels, F.
- The number of time-slots available in each frequency, t.
- The topology of the readers.
- The implemented identification procedure in each reader.
- The characteristics of the traffic of tags.

Current standards (see Section II) propose some solutions to reduce collision issues, but exclusively focused on minimizing RRI. On the other hand, a number of papers (see also Section II) deal with minimization of the RTI, but without considering reader-to-reader interferences.

In a previous paper [2], a particular simplified problem with two tags $m = 2$ in reader-to-reader range and one channel $F = 1$ was addressed (*dual reader environment*). In this work we expand the results to the case of any arbitrary number of m considering also a single frequency channel, *i.e.* F=1, and for any particular network topology. Attending to the restrictions given above, in this case, the readers cannot transmits simultaneously if reader-to-reader interferences are present. That is, if the distance between them is less than d_{RR} (note that this case also comprises reader-to-tag interferences).

This resource allocation problem is addressed both for static and dynamic frame length identification procedures (which are described later in section III), considering that the number of tags in the identification area of each reader is known, and that the tags remain in coverage of their corresponding reader at least during the whole period of identification (t time-slots). The goal is maximizing the expected number of identified tags in the whole network.

The rest of the paper is organized as follows: In Section II the most relevant research proposals are shown. Section III describes the identification procedures commonly used in RFID readers. Section IV describes the optimization model. Section V shows the performance results achieved by the optimal algorithm. Section VI concludes and describes future works.

II. RELATED WORK

In this section, we review the most relevant research proposals for coordinating Dense Reader Environments, which are commonly classified into centralized and distributed [1].

A. Centralized algorithms

Centralized mechanisms are designed to be executed in a centralized device (server), connected to the readers through a wired or wireless network. In [3] the authors suggest the use of a centralized server. It coordinates the resources (one frequency channel) and manages the reader-to-tag communication requests through a multiplexing technique, where all reader requests are managed and shared into specific tags. The proposed technique requires that adjacent readers share tag information. Besides, the authors assume that reader-to-reader collisions are not present.

In [4], the authors propose a centralized server that distributes the available frequencies among the readers in the network using a FDMA scheme: readers close to each other are allocated in non-adjacent frequencies. Since no TDMA technique is included, reader-to-tag collisions are not eliminated. The authors assume that there are as many frequencies as readers, which is not realistic. They also suggest to reduce the reader output power to decrease the collisions. Naturally, this recommendation also reduces the size of the checking areas. In [5] a similar power control approach is proposed. It consists of controlling the reader output power optimally only to reduce reader-to-reader collisions.

In [6] readers share a unique frequency and a centralized server applies a TDMA technique to coordinate the readers, controlling, in real-time, the overlapping areas of the reader-to-tag read ranges and deciding if to disconnect the interfering readers to reduce reader-to-tag collisions. This scheme cannot be applied to those scenarios which do not admit to switch off readers. In [7], a central server manages in a TDMA scheme, the reader synchronization of mobile readers in a unique frequency, at 433 MHz, and only one frequency is used for reader transmissions at UHF band. In [8] a slight modification of NFRA is proposed to guarantee higher fairness. As in [7], authors only consider one frequency at 433 MHz is assumed.

B. Distributed algorithms

In these schemes the readers communicate directly with their neighboring readers or do not communicate with anyone to make the network resources allocation.

EPCglobal Class-1 Gen-2 standard [9] recommends the *Alternative-channel backscatter* method, where reader transmissions are located in a subset of channels and tag responses are located in a different subset of channels. Readers randomly alternate among the four channels recommended by ETSI-EN 302 208 [10] using the Frequency Hopping Spread Spectrum (FHSS) technique. This mechanism tries to mitigate reader-to-reader collisions.

In [11] the LEO protocol is suggested. Each reader detects the maximum number of neighboring redundant readers that can be safely turned off to minimize reader-to-tag collisions, preserving the original network coverage. This is done before running the RFID identification system process. In this approach, both tags and reader positions must be known in advance, making a real implementation difficult if mobile readers are considered. Pulse [12] is a protocol based on Listen Before Talk (LBT) strategy. It makes use of an auxiliary control channel and readers simultaneously listen 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] two distributed power control mechanisms are suggested: the reader transmission power is used by every reader as a system control variable to achieve a desired read range and read rates. The degree of interference measured at each reader is used as a local feedback parameter to dynamically adjust its transmission power. In [14] a similar mechanism is suggested, but only for minimizing reader-to-reader collisions, whereas [15] introduces another LBT aimed at reader-to-tag collision 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. DiCa [16] is another single channel distributed algorithm based on LBT, and focused on reader-to-tag collision reduction. It proposes to 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.

MCMAC [17] is a multi-channel LBT strategy combined with FDMA. 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 reader-to-reader collisions, it does not solve the reader-to-tag collisoins. Besides, if the number of readers (R) is higher than the number of frequencies (F), MCMAC delays the operation of $R-F-1$ readers.

Distributed Color Selection (DCS) protocol [18] is based on a TDMA scheme for mitigating RTC. The time is divided into fixed identification cycles, subdivided into slots (colors). Readers randomly select slots in every cycle to identify tags. When two or more readers select the same color, readers collide. Then, these readers select a new color to use in the next cycle. Neighboring readers that selected the same color as colliding readers have to change color. Probabilistic DCS (PDCS) is proposed in [19] for increasing the low performance of [18]. In PDCS readers, after a collision, select a new color with a probability P, reducing the number of readers changing color. The authors in [18] also proposed Colorwave [20] with the aim at improving the low performance of DCS. In Colorwave the identification cycles have a variable number of colors. When the reader-to-tag collisions rate is too high, the number of colors per cycle increases, reducing the probability of reader-to-tag collisions.

HiQ [21] is a hybrid mechanism (centralized and distributed) that provides a solution to minimize the RTC. 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.

III. TAG IDENTIFICATION PROCEDURE

The identification process involves communications between the reader and the tags and takes place in a shared wireless channel. Basically, the reader *interrogates* tags nearby by sending a *Query* packet (the exact format of this packet depends on the particular standard). Tags are energized by the reader's signal and respond to this request with their identification. When several tags answer simultaneously, a collision occurs, and the information cannot be retrieved. Therefore, an anti-collision mechanism is required when multiple tags are in range. Aloha-based protocols, also called probabilistic or random access protocols, are the most prevalent in the UHF band. They are designed for situations in which the reader does not know exactly how many tags will cross its checking area. The most common Aloha RFID protocol is Frame Slotted-Aloha (FSA), a variation of Slotted-Aloha. As in Slotted-Aloha, time is divided into time units called slots. However, in FSA, slots are subject to a super-structure called a "frame". Two options of FSA are commonly used in RFID technology:

1) **Static frame length FSA.** The reader starts the identification process with an identification frame by sending a *Query* packet with information about the frame length (k slots) to the tags. The frame length is kept unchanged during the whole identification process. At each frame, each unidentified tag selects a slot at random from among the k slots to send its identifier to the reader. FSA achieves reasonably good performance at the cost of requiring a central node (the reader) to manage slot and frame synchronization. FSA has been implemented in many commercial products and has been standardized in the ISO/IEC 18000-6C [22], ISO/IEC 18000-7 [23] and EPCGlobal Class-1 Gen-2 (EPC-C1G2) standards [9].
2) **Dynamic frame length FSA.** When tags outnumber available slots, identification time increases considerably due to frequent collisions. On the other hand, if the slots outnumber the tags, many slots will be empty in the frame, which also leads to long identification times. Dynamic FSA (DFSA) protocols were conceived to address this problem. They are similar

to FSA but the number of slots per frame is variable. In other words, parameter k may change from frame to frame in the *Query* packet to adjust the frame length. DFSA operation is optimal in terms of reading throughput (rate of identified tags per slot) when the frame length equals the number of contenders [24]. Therefore, to maximize throughput the reader should ideally know the actual number of competing tags and allocate that number of slots to the next frame. Different DFSA algorithms have been proposed to estimate the number of competing nodes based on the collected statistical information. The most relevant ones have been studied in depth in our previous papers [25], [26].

In the next section, both algorithms (static-FSA and dynamic-FSA) are considered in order to propose an optimal slot distribution for the single channel environment. In the case of Static-FSA, the frame length is k for both readers, and in the case of Dynamic-FSA we are assuming that each reader j actually knows the number of competing nodes at frame i (n_j^i), and that the reader is adjusting $k_j^i = n_j^i$ if the number of the remainder available slots is greater than n_j^i. The number of contenders n_j^i can be determined in real-time during the reading procedure by means of different tag estimation methods (see [25] and [26] for details).

IV. OPTIMAL TIME DISTRIBUTION

Recall from the introduction that it is assumed a dense-reader environment with the limitation of a single frequency channel F=1 in this study. Besides, let us consider m readers, and let us denote t as the number of slots available in the channel. In addition, for each reader i=1,. . .,m, let us denote:

- n_i, the tags unidentified in the range of the reader i
- t_i, the number of slots assigned to reader i

Topological dependencies among readers are defined by a $m \times m$ matrix $A = (a_{ij})$ whose elements are 1 if reader i and j cannot operate at the same time, and 0 otherwise.

Let $\varphi(n,t)$ denote the expected number of identified tags when n tags contend in t slots, and let us define Φ as the whole expected number of identified tags in the network, that is,

$$\Phi = \sum_{i=1}^{m} \varphi(n_i, t_i) \tag{1}$$

Then, the optimization problem can be stated as solving:

$$\max_{\delta_i, t_i} \Phi \tag{2}$$

Subject to

$$t_i \geq 0 \tag{3}$$

and

$$t_j + I_{t_j} \sum_{i=1, i\neq j}^{m} t_i A_{ij} \leq t, \text{ for all } j\text{=1,. . .,m} \tag{4}$$

Constraint (3) expresses a basic limiting condition on the values assigned to the number of assigned slots.

The key in our problem formulation is constraint (4) which establishes local conditions to regulate the spatial reuse of resources in our network. This condition states that the number of slots assigned to a reader j plus those assigned to its neighbours can not surpass the number of available slots. I_{t_j} is 1 if t_j is greater than 0, and 0 otherwise. It is included since if a reader has not slots assigned, it is equivalent to disconnect it, and no constraints have to be applied.

The former constraint guarantees that enough slots are available for each node in each neighbourhood (set of nodes bonded with topological constraints, *i.e.* a_{ij}=1) to obey with the limit of t slots among all neighbours. Note that it does not guarantee that these slots can be allocated consecutively. However, this is not an issue since tags do not proceed with the next slot until a *QueryRep* packet arrives from the reader. Therefore, even if slots are not consecutively allocated, tags perceive continuity and the identification can be performed seamlessly.

To solve the optimization problem the expected number of identifications $\varphi(n,t)$ must be computed. Next sections deal with its computation for both static FSA and dynamic FSA.

A. $\varphi(n,t)$ *computation for static FSA*

In this case, the reading process for each reader consists of several reading frames of length k, until all the t reading slots are eventually exhausted. It is assumed that t=ka, being a a positive integer. Given the last condition, $\varphi(n,t)$ can be described through the following recursive equation,

$$\varphi(n,t) = \varphi(n,k) + \sum_{i=0}^{n} \varphi(n-i, t-k) P(i|n,k) \tag{5}$$

That is, the total number of tags identified is the number of tags identified in the first frame plus those identified in the remainder process. The latter is computed by means of the conditional expectation sum in eq. (5) since the actual number of identifications in a frame is a random variable. In this sum, $P(i|n,t)$ denotes the probability that i tags are identified if n tags compete in a frame of t slots. Besides, note that $\varphi(n,0) = 0$ since $P(i|n,0)$ is null for all possible values of n and i.

From $P(i|n,t)$ probability it is also possible to compute the expectation on the number of identifications in a *single* frame of n tags and k slots, $\sum_{i=0}^{n} iP(i|n,k)$. Therefore,

$$\varphi(n,k) = \sum_{i=0}^{n} iP(i|n,k) \tag{6}$$

It can be demonstrated that the value of $P(i|n,t)$ is given by:

$$P(i|n,t) = \frac{n!}{t^n}\binom{t}{i}\sum_{c=0}^{n-i}(-1)^c\binom{t-i}{c}\frac{(t-i-c)^{n-i-c}}{(n-i-c)!} \tag{7}$$

Therefore equation (5) is finally expressed as,

$$\varphi(n,t) = \sum_{i=0}^{n}(i+\varphi(n-i,t-k))P(i|n,k) \tag{8}$$

B. $\varphi(n,t)$ *computation for dynamic FSA*

In this second case, the reading process for each reader also consists of several reading frames but of variable length $k_1, k_2, \ldots$, until all the t reading slots are exhausted. Besides, let us denote the number of contenders in each frame as $n_1, n_2, \ldots$. Since DFSA operation is used (see Section III), the reader seeks to maximize reading throughput and allocates the optimal number of slots in each frame. That is, as much slots as the number of contending tags (k_i=n_i). This is possible while $n_i < t - \sum_{j=1}^{i-1} k_j$, that is, if the remainder number of slots is greater that the number of contenders. Otherwise we assume that a last frame is allocated with all the remaining slots ($k_i = t - \sum_{j=1}^{i-1} k_j$).

Like in the previous case $\varphi(n,t)$ can be described through a recursive equation,

$$\varphi(n,t) = \begin{cases} \varphi(n,n) + \sum_{i=0}^{n}\varphi(n-i,t-n)P(i|n,n) \text{ if } n < t \\ \varphi(n,t) \text{ if } n \geq t \end{cases}$$

From eq. (6),

$$\varphi(n,n) = \sum_{i=0}^{n} iP(i|n,n)$$

and,

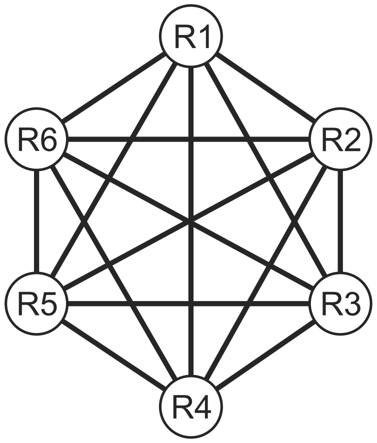
$$\varphi(n,t) = \sum_{i=0}^{n} iP(i|n,t), \quad \text{if } n \geq t$$

Hence,

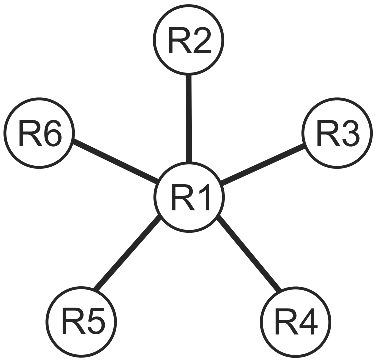
$$\varphi(n,t) = \begin{cases} \sum_{i=0}^{n}[i+\varphi(n-i,t-n)]P(i|n,n) \text{ if } n < t \\ \sum_{i=0}^{n} iP(i|n,t) \text{ if } n \geq t \end{cases} \tag{9}$$

V. RESULTS

The optimal assignment has been computed in static and dynamic FSA cases using the recursive formulas described in the previous section. Two representative scenarios (see Fig. 2) have been selected. Edges represent the existence of interference between two vertices (readers). On the first scenario, a full-mesh topology of m readers has been selected. It is a typical configuration in facilities, since the RRI distance is large (around 1 Km) as discussed in the introduction. On the other hand, the star topology of m readers selected for scenario 2 represents another practical case, where readers are confined to some areas (*e.g.* by screening the reading area), and interferences are restricted to some particular pairs, exclusively between R1 and the other readers in this example.



(a) Full-mesh topology



(b) Star topology

Figure 2. Example scenarios for m = 6

Besides, the following parameters have been considered:

- t = 512,
- n from 1 to 100 tags,
- m = 2, 4, 6, 8 and 10,
- and for static FSA k = 16 and 64.

Our optimization algorithm has been implemented using the *General Algebraic Modeling System* (GAMS), a high-level modeling system for mathematical programming and optimization, and AlphaECP, a MINLP (Mixed-Integer Non-Linear Programming) solver based on the extended cutting plane (ECP) method. It allowed us to define our optimization problem directly from the mathematical description provided in Section IV.

Tables II and III show examples of the optimal configurations (slots assigned to each reader) for the DFSA

n	Φ	R1	R2	R3	R4
10	40.000	128	128	128	128
20	80.000	126	115	155	116
30	119.999	128	128	128	128
40	159.427	128	128	128	128
50	186.355	128	128	128	128
60	189.195	94	140	139	139
70	189.113	110	70	166	166
80	188.949	80	162	190	80
90	188.992	0	212	89	211
100	188.905	157	157	99	99

Table II
Full-mesh scenario. Optimal assignment of slots for the DFSA protocol

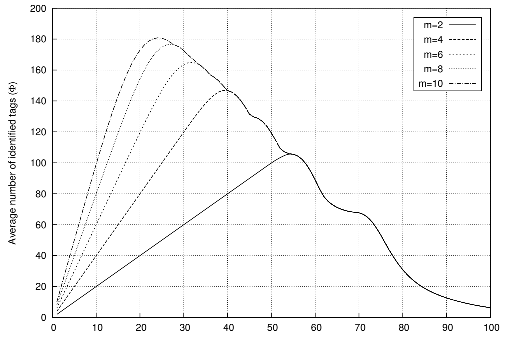
n	Φ	R1	R2	R3	R4
10	40.000	78	74	76	77
20	80.000	126	115	155	116
30	119.999	128	128	128	128
40	159.427	128	128	128	128
50	186.355	128	128	128	128
60	189.195	94	140	139	139
70	210.000	0	512	512	512
80	240.000	0	512	512	512
90	270.000	0	512	512	512
100	300.000	0	512	512	512

Table III
Star scenario. Optimal assignment of slots for the DFSA protocol

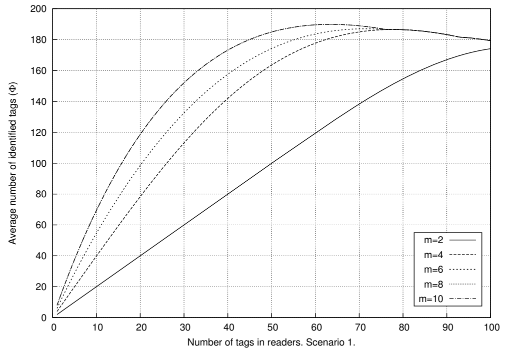
protocol in both scenarios with m = 4. Clearly, this solution is not unique: a circular permutation of the optimal solution, replacing the slots from Ri to R$(i+1)$ if $i < m$ and from Rm to R1 is also an optimal solution for the full-mesh scenario. The same applies to the star scenario if the slots in R1 are kept constant while any permutation is applied to the rest of the readers.

Let us remark that he optimal solutions are non-trivial, and the allocation changes depending on n and (although it is not shown in these tables) with the underlying reading protocol.

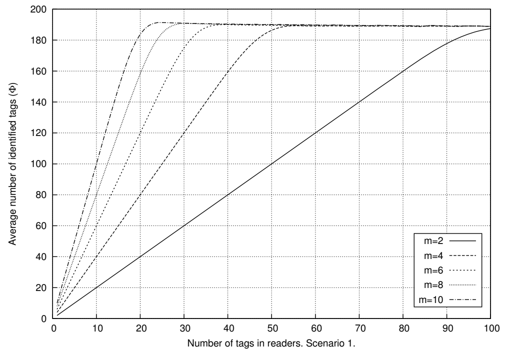
Besides, Figs. 3 and 4 show the expected number of tags identified (Φ) for all the possible values of m using the optimal assignments, for the full-mesh and the star scenario, respectively. Note that the resources available (t=512) are the same for all the configurations, however the performance clearly varies. This illustrates how the underlying reading protocol determines the final system performance. Dynamic FSA performs better than static assignment for both configurations of k (16, 64) as can be expected. This is reasonable since dynamic FSA achieves an optimal reading throughput frame-by-frame while the number of available slots is at least equal to the number of contenders.



(a) FSA16



(b) FSA64

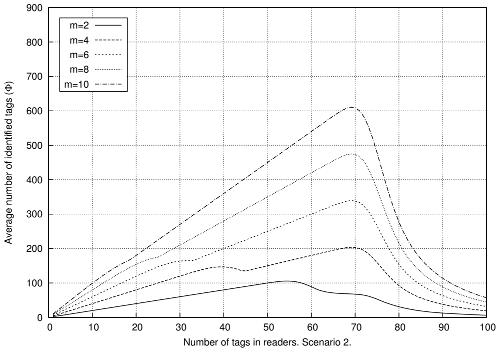


(c) DFSA

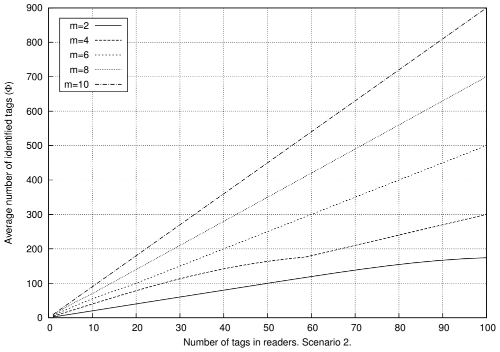
Figure 3. Expected number of identifications (Φ) versus n. Full-mesh scenario

In addition Fig. 5 shows, for m=4, the performance of the optimal allocation versus a non-optimal allocation scheme selected for comparison. Namely using $\frac{1}{m}$ of time allocated to each reader ("proportional" resource sharing), that is, t_1=...=t_4=128. This heuristic is a natural choice, since the number of tags in range of each reader is the same, therefore a good performance could be expected. In fact, the proportional scheme achieves in a range of n a performance close to the optimal one, as can intuitively be expected. However as the number of tags in reader 1 increases the allocation is clearly suboptimal.

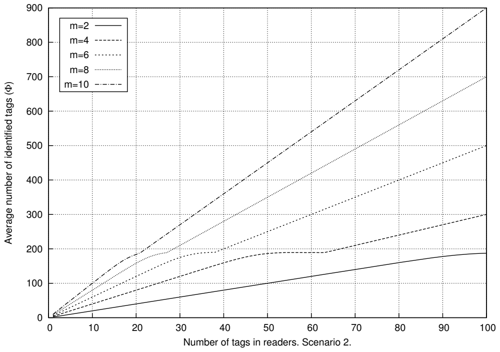
Noteworthy, in the star scenario, there is a point ($n \geq 70$) where the best option is directly to disconnect the central



(a) FSA16



(b) FSA64



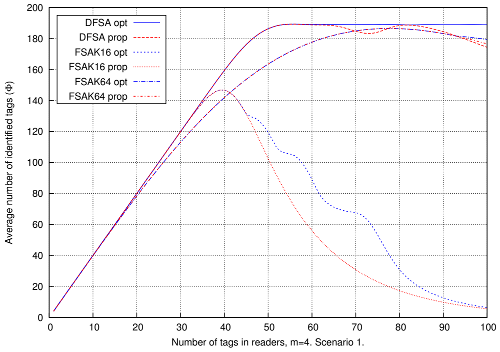
(c) DFSA

Figure 4. Expected number of identifications (Φ) versus n. Star scenario

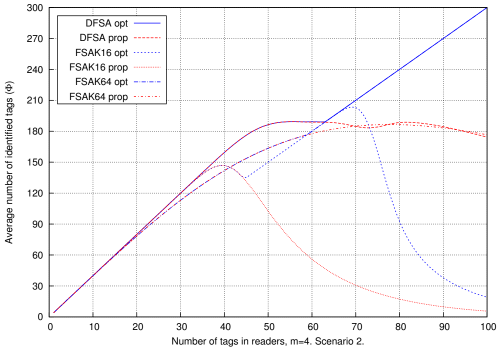
reader. In this case, without restrictions in the network, the remainder readers can be allocated each all the 512 slots.

VI. Conclusions

This work introduced a novel optimal scheduler for a particular dense reader environment composed by m readers which must share a single frequency channel. The scheduler proposed exceeds in performance to heuristic algorithms, improving the average number of tags identified in an RFID facility. Besides, the effect of the reading protocols has also been studied in depth, concluding that a dynamic FSA algorithm excels static frame length ones.



(a) Full-mesh topology



(b) Star topology

Figure 5. Optimal vs proportional allocation for m = 4

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