Optimal scheduling in dual 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 two readers in RFID dense environments. In these environments only one reader can transmit simultaneously, otherwise they would interfere each other, and tag identification would not be possible. This problem is addressed considering both static and dynamic frame length readers. The goal was to maximize the expectation on the number of tags successfully identified. Results demonstrate how the optimal time distribution outperforms trivial assignments, and how the results depend on the underlying reading algorithm of the reader.**

***Index Terms*—RFID, Dense-environments, DFSA**

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 commonly 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 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) 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, cancelling 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:

- If two or more readers are within two times the reader-to-tag range (e.g., d_{RT} = 10 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 will not suffer interferences.

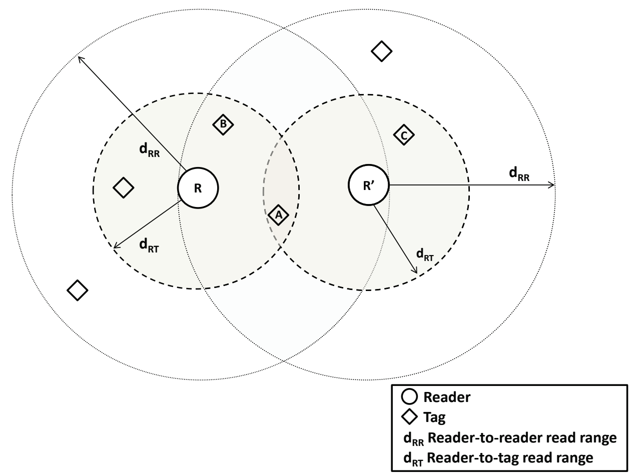

Fig. 1. Interferences in dense reader environments

	= freq	≠ freq
= time	$d > 2d_{RR}$	$d > 2d_{RT}$
≠ time	$d > 0$	$d > 0$

TABLE I
READER OPERATION RESTRICTIONS VERSUS d

Table 1 summarizes the restrictions set to reader operation in dense readers environments.

Therefore, in dense-reader environments, the problem is 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 this work, a particular problem with two tags $m = 2$ in reader-to-reader range and one channel $F = 1$ is addressed (*dual reader environment*) both for static and dynamic frame length identification procedures (see section III), considering that the number of tags per 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 selected was to maximize the expectation on the number of identified tags.

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 [2] 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 [3], 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 [4] a similar power control approach is proposed. It consists of controlling the reader output power optimally only to reduce reader-to-reader collisions.

In [5] 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 [6], 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 [7] a slight modification of NFRA is proposed to guarantee higher fairness. As in [6], 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 [8] 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 [9] using the Frequency Hopping Spread Spectrum (FHSS) technique. This mechanism tries to mitigate reader-to-reader collisions.

In [10] 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 [11] 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 [12] 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 [13] a similar mechanism is suggested, but only for minimizing reader-to-reader collisions, whereas [14] 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 [15] 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 [16] 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 [17] 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 [18] for increasing the low performance of [17]. In PDCS readers, after a collision, select a new color with a probability P, reducing the number of readers changing color. The authors in [17] also proposed Colorwave [19] with the aim of 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. In [20] 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 [20] authors assume every reader can calculate the number of neighbors using a binary tree protocol in a short length slot [21].

HiQ [22] 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, 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.

Summarizing, all previous proposals seek to improve performance of RFID dense-environments by coordinating readers using some heuristic methodologies. In our work a mathematical programming methodology is used for this purpose, in a restricted environment with two readers. To our knowledge, this is the first work addressing RFID readers scheduling based on this approach.

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 [23], ISO/IEC 18000-7 [24] and EPCGlobal Class-1 Gen-2 (EPC-C1G2) standards [8].
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 [25]. 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 a previous study by our group [26].

In the next section, both algorithms (static-FSA and dynamic-FSA) are considered in order to propose an optimal slot distribution for the dual reader 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^i_j), and that the reader is adjusting $k^i_j = n^i_j$ if the number of the remainder available slots is greater than n^i_j. The number of contenders n^i_j can be determined in real-time during the reading procedure by means of different tag estimation methods (see [26] and [27] for details).

IV. Optimal time distribution for dual reader case

Recall from the introduction that it is assumed a particular case of the general dense-reader environment in this study. Namely, let us consider m=2, that is, two readers in range. Besides, let us denote t as the number of slots to be distributed between these two readers, and let us assume that n_1 are unidentified in the range of the first reader, while n_2 tags are in the range of the second one. Let $\varphi(n,t)$ denotes the expectation of the number of identified tags when n tags contend in t slots. For the dual reader case the optimization problem can be stated as finding the value t_1 that fulfills:

$$t_1 = \arg\max_{0 \le t_1 \le t} \{\varphi(n_1,t_1) + \varphi(n_2, t-t_1)\} \tag{1}$$

The optimal solution is to assign t_1 consecutive slots to the first reader and the remainder $t_2 = t - t_1$ consecutive slots to the second one.

A. $\varphi(n,t)$ computation in 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 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,

$$\varphi(n,t) = \varphi(n,k) + \sum_{i=0}^{n} \varphi(n-i, t-k) P(i|n,k) \tag{2}$$

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. (2) 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,

$$\varphi(n,k) = \sum_{i=0}^{n} iP(i|n,k) \tag{3}$$

The value of $P(i,n,t)$ is obtained in [28]:

$$P(i|n,t) = \frac{\binom{t}{i} \prod_{j=0}^{i-1}(n-j) G(t-i, n-i, 1)}{t^n} \tag{4}$$

where G is defined as,

$$G(a,l,v) = a^l + \sum_{j=1}^{\lfloor \frac{l}{v} \rfloor} \left\{ (-1)^j (a-j)^{l-jv} \frac{1}{j!} \prod_{y=0}^{j-1} \left\{ \binom{l-yv}{v} (a-y) \right\} \right\}$$

Therefore equation (2) is finally expressed as,

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

The following algorithm allows a fast computation of this recursive formula by storing the values already computed for the expectation and for the probability in tables f and p respectively:

Algorithm 1 $\varphi(n,t)$ computation - Static FSA case

```
# f, p are static matrices initiated to -1

if f(n,t) ≠ -1 then
  return f(n,t)
else
  sum ← 0
  for i = 0 to n do
    if p(i,n,k) ≠ -1 then
      sum ← sum + (i + φ(n-i, t-k)) p(i,n,k)
    else
      p(i,n,k) ← compute P(i,n,k)
      sum ← sum + (i + φ(n-i, t-k)) p(i,n,k)
    end if
  end for
  f(n,t) ← sum
  return f(n,t)
end if
```

This expression allow the computation of t_1 in equation (1) by exhaustively examining the space state of $t_1 = 0, \ldots, t$. That is, computing equation (1) for all possible values of t_1. In section V results are introduced for different configurations.

B. $\varphi(n,t)$ computation in 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. (3),

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

and,

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

Hence,

$$\varphi(n,t) = \begin{cases} \sum_{i=0}^{n} [i + \varphi(n-i, t-n)] P(i|n,n) \text{ if } n < t \\ \sum_{i=0}^{n} iP(i|n,t) \text{ if } n \geq t \end{cases} \tag{6}$$

As in the static FSA case an algorithm (see Algorithm 2) was developed to allow a fast computation of this recursive formula by storing the values already computed for the expectation and for the probability in tables f and p respectively.

In the next section, results are introduced for different configurations.

Algorithm 2 $\varphi(n, t)$ computation - Dynamic FSA case

```
# f, p are static matrices initiated to -1

if f(n,t) ≠ −1 then
  return f(n,t)
else
  if n < t then
    sum ← 0
    for i = 0 to n do
      if p(i,n,n) ≠ −1 then
        sum ← sum + (i + φ(n − i, t − n)) p(i,n,n)
      else
        p(i,n,n) ← compute P(i,n,n)
        sum ← sum + (i + φ(n − i, t − n)) p(i,n,n)
      end if
    end for
    f(n,t) ← sum
    return f(n,t)
  else
    sum ← 0
    for i = 1 to n do
      if p(i,n,t) ≠ −1 then
        sum ← sum + ip(i,n,t)
      else
        p(i,n,t) ← compute P(i,n,t)
        sum ← sum + ip(i,n,t)
      end if
    end for
  end if
  f(n,t) ← sum
  return f(n,t)
end if
```

V. Results

The optimal assignment has been computed in static and dynamic FSA cases using the algorithms described in the previous section. As a representative scenario, the following parameters have been considered:

- t = 128,
- n_1 from 1 to 50 tags,
- n_2 = 50,
- and for static FSA k = 16, 32.

Figure 2 shows the number of slots that must be assigned to the first reader to achieve maximum performance. Note that all the remaining slots are therefore assigned to the second reader. Clearly, the optimal assignment is non-trivial, and the optimal allocation differs in all the studied cases, that is, depending on the underlying reading mechanism implemented by the readers.

Besides, Figure 3 shows the average number of tags identified (in both readers) using the optimal assignment computed in Figure 2. Note that the resources available (t=128) 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, 32) 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. Moreover, Figure 3 depicts the average number of identification using two non-optimal allocation schemes selected for comparison, namely:

1) 50% of time allocated to each reader (labelled as "half"), that is, t_1=t_2=64, and
2) time allocation proportional to the number of tags (labelled as "proportional"), t_1=$128 \times \frac{n1}{n1+n2}$ and t_2=$128 \times \frac{n2}{n1+n2}$

Both schemes have been tested for dynamic FSA operation. The proportional scheme achieves in some range 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. Besides, the half allocation scheme performs poorly, and only achieves a reasonable operation for large values of n_1, but again, below the optimal

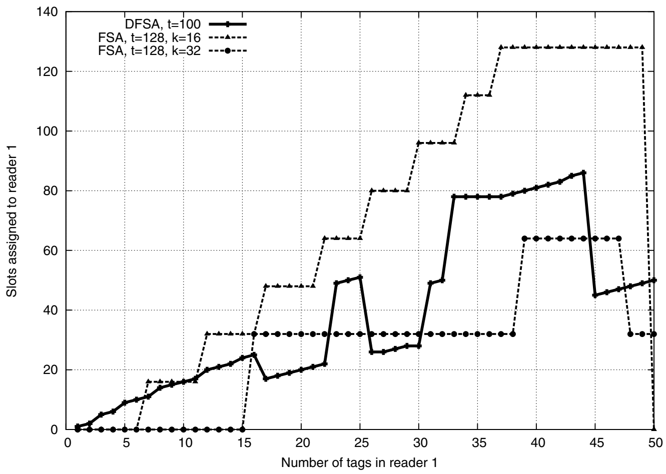

Fig. 2. Optimal t distribution for the scenario: $n_1 = 1, \ldots, 50$, $n_2 = 50$, $t = 128$

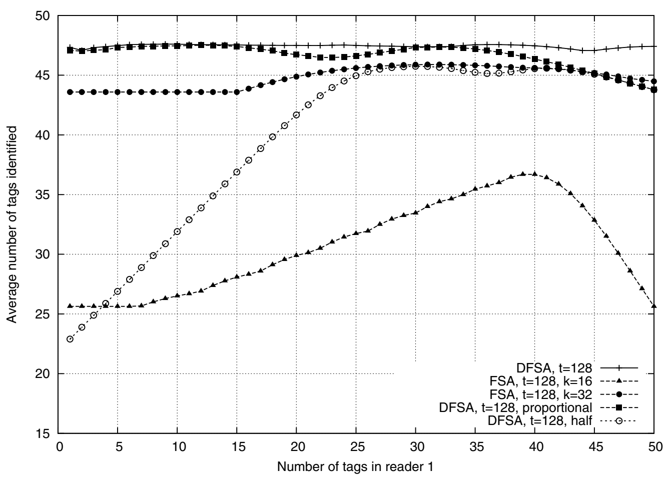

Fig. 3. Average number of identified tags using the optimal distribution of t for the scenario: $n_1 = 1, \ldots, 50$, $n_2 = 50$, $t = 128$

scheduler.

Related to the previous comments, Figure 4 shows another interesting insight in the system's performance. The expected number of identifications is compared in two cases, (i) when the DFSA algorithm is applied using the number of contenders as the frame length (except possibly in the last frame, where the number of available slots is less than the number of tags), and (ii) using a single frame of t slots. Oddly, the performance in this second case is greater than the optimal assignment for a range of tags (from 36 to 48 tags). The rationale behind this issue is that although dynamic FSA performs optimally if the available slots exceed the number of contending tags, it *does not* otherwise. That is, it performs suboptimal in the last frame, causing a degradation in the reading operation. To show this effect numerically, consider n=25 tags and t=30. If only one frame is used, the average number of identifications are 11.08, whereas using optimal dynamic FSA more than one reading frames are necessary, identifying 9.38 tags on average in the first one (note that the frame length is 25 slots

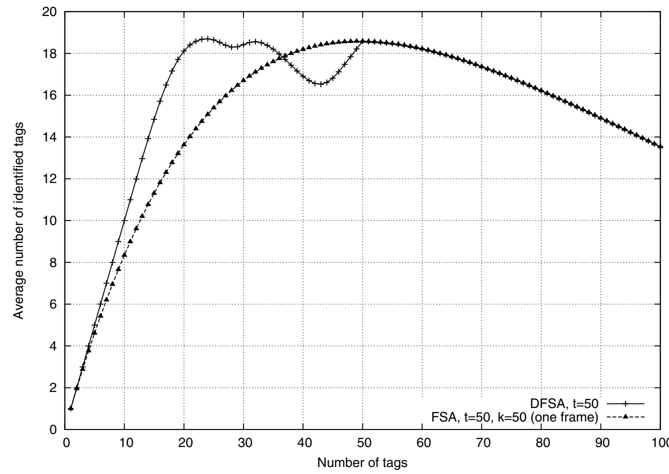

Fig. 4. Average number of identified tags for scenario: $n = 1, \ldots, 100$, $t = 50$

in the first frame), and totalling 10.02 tags in the whole reading process. This effect can be neglected as long as the number of available slots overwhelms the number of tags, however if both are comparable, a reduction in the performance may be noticeable.

VI. Conclusions

This work introduced a novel optimal scheduler for a particular dense reader environment composed by two readers. 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. As a future work we aim at developing optimal schedulers able to operate with an arbitrary number of readers.

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