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A maximum likelihood-based distributed protocol for passive RFID dense reader environments

M.V. Bueno-Delgado · P. Pavón-Mariño

Abstract In passive RFID Dense Reader Environments, a large number of passive RFID readers coexist in a single facility. Dense environments are particularly susceptible to reader-to-tag and reader-to-reader collisions. Both may degrade the system performance, decreasing the number of identified tags per time unit. Some proposals have been suggested to avoid or handle these collisions, but requiring extra hardware or making a non-efficient use of the network resources. This paper proposes MALICO, a distributed mechanism-based protocol that exploits a maximum-likelihood estimator to improve the performance of the well-known Colorwave protocol. Using the derivation of the joint occupancy distribution of urns and balls via a bivariate inclusion and exclusion formula, MALICO permits every reader to estimate the number of neighboring readers (potential colliding readers). This information helps readers to schedule the identification time with the aim at decreasing collision probability among neighboring readers. MALICO provides higher throughput than the distributed state-of-the-art proposals for dense reader environments and can be implemented in real RFID systems without extra hardware.

Keywords RFID · Reader collision problems · Maximum likelihood estimate · DCS · Colorwave

1 Introduction

Radio Frequency Identification (RFID) is a technology that allows the automatic identification of objects, animals or people by means of a wireless communication

M.V. Bueno-Delgado (✉) · P. Pavón-Mariño
Communications and Information Technologies Department, Telecommunications Faculty, Universidad Politécnica de Cartagena, Plaza del Hospital 1, 30202 Cartagena, Spain
e-mail: mvictoria.bueno@upct.es

P. Pavón-Mariño
e-mail: pablo.pavon@upct.es

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link [1]. The communication takes place between a large number of *tags* and one or more *readers*. Tags are small devices attached to the items to identify. They store in a memory relevant information about the items (price, expiration date, etc.). Readers are more complex devices which collect and manage information about the identified items.

RFID systems are classified according to the tags power supply, distinguishing between active and passive tags. The former contain a battery to feed their circuitries. They are used in sophisticated applications which typically require to sense the environment (e.g. Wireless Sensor Networks [2]). Passive tags do not incorporate battery and feed their circuitries by the incident energy emitted by the readers. The lack of battery makes passive tags to be low-cost devices of easy implementation and durability. They are the preferred in those scenarios where a large number of tags are required, e.g. supply chains, product traceability, manufacturing process, etc.

In passive RFID systems, readers transmit electromagnetic waves, creating identification areas where tags enter and leave. When a tag is in the reader read range, it is energized, allowing it to send its identifier back to the reader. The size of an identification area depends on the reader transmission power. In Europe, the maximum reader transmission power at Ultra High Frequency (UHF) band is 3.2 Watts Effective Isotropic Radiated Power (EIRP) [3]. This value limits the reader-to-tag read range to a maximum of 10 meters in indoor scenarios [4]. This short range provokes that, in some installations, the final application may require the existence of multiple checking areas because a single reader is not sufficient to cover a specific area. These scenarios are forced to use RFID systems with several readers; 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 [5]:

– *Reader-to-Reader Collisions* (RRC) happen when the signal generated by one reader interferes with the reception system of other readers (e.g. in Fig. 1, reader-to-reader interference range of R1 and R2, or R2 and R3 interfere each other). RRC hinders the tags identification process: a reader can receive strong signals from neighboring readers, interfering with the weak response signal of tags in coverage. To avoid RRC effects, two readers located in RRC range should operate at

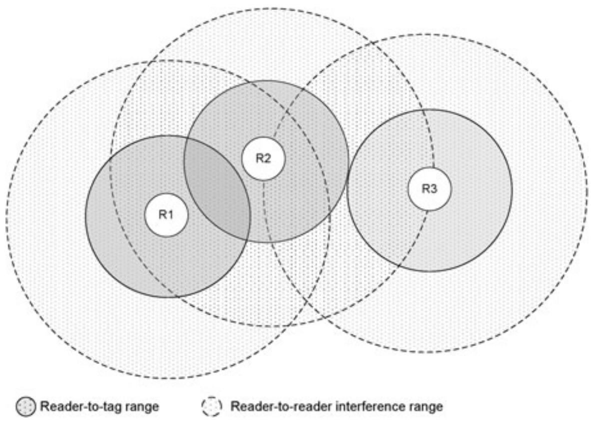


Fig. 1 Example of a RFID Dense Reader Environment

different frequencies and/or at different times. According to [4], at maximum output power in Europe the reader-to-reader interference range is about 1000 meters in indoor scenarios.
– *Reader-to-Tag Collisions* (RTC) occur when two or more readers overlap their reader-to-tag read ranges and try to read the same tag simultaneously (e.g. in Fig. 1, reader-to-tag ranges of R1 and R2 interfere). To avoid RTC, those readers should operate non-simultaneously. According to [4], RTC occurs when readers are placed at less than 20 meters each other in indoor scenarios.

Both collisions degrade the RFID system performance. In the last years, a significant amount of research effort in the community has been made to devise mechanisms mitigating these harmful effects [6–20]. Two of the most extended proposals are the distributed-based protocols DCS and Colorwave [18, 20]. The distributed nature of the approach means that readers take decisions on how to minimize collisions based on local information, and no centralized elements in the system are required to assist the process. DCS and Colorwave are based on Time Division Multiplexing Access (TDMA). The time is divided into identification rounds, subdivided into slots called *colors*. Those readers in RRC range each other are considered neighboring readers, and compete in the same identification rounds. These readers randomly select one color in every round to communicate with tags. In DCS the number of colors per round does not change, it is fixed, and it is the same value for all identification rounds. This lack of flexibility involves a low throughput in those scenarios where the number of contenders (neighboring readers) in an identification round is high and the number of colors is low, because several collisions occur. Otherwise, in those scenarios with a low number of contenderes and a high number of slots, many empty slots occur, which also decreases the throughput. Thus, Colorwave was suggested to improve DCS, implementing a mechanism to change the number of colors per round. In Colorwave, the decision to change color depends on five input parameters: UpSafe, UpTrigger, DownTrigger, DownSafe, MinTimeInColor. It is obvious that the values of these parameters strongly affect the network performance. For example, MinTimeInColor indicates the time (number of rounds) the readers have to wait before to change again the number of colors. If MinTimeInColor is too high, the identification rounds will suffer from a slow variation, even if many collisions are happening. Besides, Colorwave also experiences a slow colors variation because every change of color is restricted to one unit variation, that is, every time that the readers change the number of colors, they increase or decrease the current value in only one color.

In this paper we present MALICO (Maximum Likelihood COlorwave), a new distributed algorithm that eliminates the need of manually set input parameters to decide the number of slots per round in Colorwave. With MALICO, every reader varies the number of colors in every round, without unit variation restrictions. The value of the color is computed by using a maximum-likelihood estimator, and the theoretical value that maximizes the throughput in every round is obtained. The estimate is addressed as follows: every reader decides to increase, decrease or not to modify the number of colors in a new round according to the observation (number of empty, collision and slots successfully occupied) in the last round. The statistical information collected by the reader is used by the estimator to compute the number of neighboring readers at the beginning of every new identification round. Once the number of neighboring readers is estimated, the number of colors is adjusted accordingly to maximize the throughput in the next identification round. MALICO minimizes RRC and RTC partially, yielding higher throughput than other distributed state-of-the-art proposals for DRE. The increase of throughput is provided, not only by the use of a maximum-likelihood estimator, but also by the use of more than one frequency in reader-to-tag communication, like European standards and regulations suggest [3, 12]. Although the use of a single frequency reduces RTC, the use of four frequencies increases the probability to transmit without collisions (reducing RRC) because the number of neighboring readers per reader is reduced (reader transmissions are distributed into four frequencies).

The rest of the paper is organized as follows: Section 2 introduces the related work. Section 3 addresses the Colorwave mechanism and Sect. 4 the new proposal. Section 5 provides the scenario description and simulation results and Sect. 6 concludes our article.

2 Background

In this section we review the most relevant proposals for coordinating readers in passive DRE. They are classified into centralized and distributed mechanisms, like in [21].

2.1 Centralized algorithms

Centralized mechanisms are designed to be executed in a coordinator device (e.g. server) connected to the readers through a wired or wireless network. In [6] the authors propose the use of a centralized server which manages the reader-to-tag communication through a technique that multiplexes the reader requests to specific tags. Readers have to share tags information among neighbors, although the authors do not specify if they use a dedicated channel or a specific hardware for this purpose. In [7] the authors propose a centralized server that distributes available frequencies among readers in a pure Frequency Division Multiplexing Access (FDMA) scheme, so readers which are closer to each other are allocated in non-adjacent frequencies. Since no TDMA technique is included, RTC is not eliminated. The authors assume that there are as many frequencies as readers, without considering the frequency restrictions by country regulations [3]. They also suggest reducing the reader output power to decrease RRC. Naturally, while this recommendation reduces the size of the checking areas and thus the associated interferences, it is not possible in many real systems, where the identification region is strictly defined. In [8] the authors propose a similar approach, consisting of controlling readers output power in order to reduce RTC but not considering RRC. In [9] readers share a unique frequency and the centralized server uses a TDMA technique to coordinate them. The mechanism controls, in real time, the overlapping areas of the reader-to-tag read ranges and decides to disconnect the interfering readers to reduce RTC. In [10] the Neighbor Friendly Reader Anti-collision (NFRA) protocol is proposed. A central server manages reader synchronization in a unique frequency (433 MHz) and only one frequency at UHF band is used for reader transmissions. In [11] a slight modification of NFRA is proposed to improve the system fairness. As in [10], authors only consider one frequency at 433 MHz. This frequency is used in active RFID systems, rather than passive ones.

2.2 Distributed mechanisms

In distributed mechanisms, readers work independently of each others, or communicate with their neighbors—usually by means of wireless links—and do not rely on a centralized device that allocates the network resources. EPCglobal [12], under the European regulation ETSI EN 302 208 [3], proposes a distributed algorithm in DRE mode denoted in this work as EPC-ETSI. In EPC-ETSI every reader in the DRE randomly selects one of the four available frequencies for reader-to-tag communication. Readers listen to the selected channel for, at least, 5 ms following the Listen Before Talk (LBT) strategy. If the channel is free, readers start the tag identification procedure in that frequency. During the identification procedure, the reader releases the channel if no tags are detected in 100 ms. Then, the reader randomly selects a new frequency. The maximum duration of the identification procedure (called reader-to-tag communication phase) is four seconds. After that, the reader is forced to release the channel, to wait 100 ms and randomly to select a frequency for the next identification procedure.

Other work has been proposed to improve the performance of EPC-ETSI in DRE mode: in *Leo* [13] readers detect their number of neighboring redundant readers and turn them off to minimize RTC, while RRC is not considered. The main drawback is that the physical location of tags and readers must be known in advance, making a real implementation difficult. Besides, mobile readers are not considered. Other proposals [14–17] are based on the use of two channels: one as an auxiliary control channel and the other one as a data channel for reader-to-tag communication. However, these mechanisms require extra hardware in readers to listen both channels simultaneously; e.g. in [17] a wireless sensor network is required for reader-to-reader communication. This network is not used for sensing any particular parameter, thus resulting in extra costs.

Distributed Color Selection (DCS) [18], Probabilistic DCS (PDCS) [19] and Colorwave [20] are other well-known distributed strategies based on TDMA. PDCS and Colorwave were proposed for increasing the low performance of DCS. But, compared with the state-of-the-art distributed mechanisms, only Colorwave reports the best results in terms of throughput. For that reason, Colorwave has been used as the starting point for our proposal. It is discussed in detail in Sect. 3.

3 Colorwave

Colorwave procedure is an improved version of DCS. Therefore, we start introducing DCS. In DCS [18] the time is divided into identification rounds. Every identification round is composed by K time slots (*colors*). The number of colors is an input to the DCS algorithm, and does not change throughout the functioning of the algorithm. Every slot is divided into a short kick phase and a long reader-to-tag communication

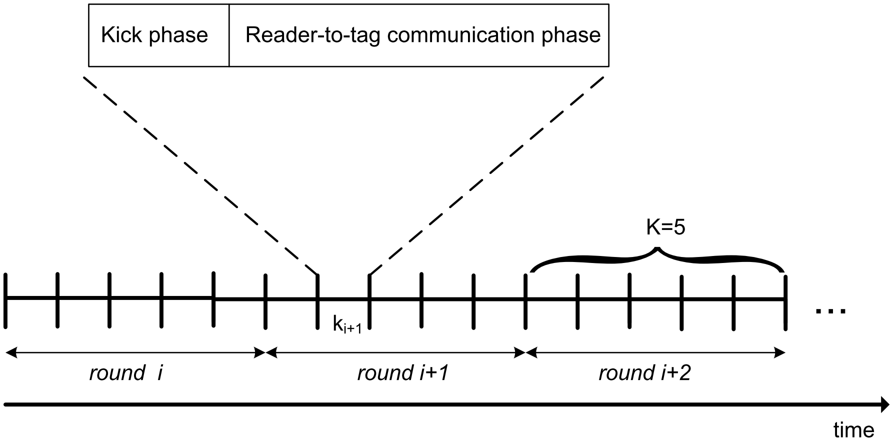


Fig. 2 Managing the identification time in DCS protocol

phase (see Fig. 2). The former is used by readers that collided in a previous round in order to reserve the slot, announcing to their neighbors that they will use that slot. The latter is used by readers to identify tags.

At the beginning of every identification round i, the readers in the network randomly select one color k_i, where $k_i \in 1, 2, \ldots, K$. Readers use the uniform distribution function for selecting colors. After selecting k_i, readers keep waiting for $k_i - 1$ colors. The beginning of every color in the contention round is controlled by the readers, using an onboard clock or by means of an external synchronization entity [18]. When k_i starts, two actions can occur:

– If two or more readers select the same color k_i, they collide. Those readers involved in the collision leave the contention and randomly select a new color for the next contention round, k_{i+1}. At the beginning of the corresponding slot k_{i+1}, a colliding reader in the previous round will announce to its neighbors that it requires the slot for reader-to-tag communication by means of a *kick* signal sent in the kick phase. Those neighboring readers that receive a *kick* signal check if their color is equal to the announced one. If the colors match, these readers leave the contention and select a new color (k_{i+2}) for the next contention round.
– If a single reader selects k_i, it can communicate with those tags in its coverage area during the reader-to-tag communication phase. After that, the reader selects a new color for the next contention round k_{i+1}, but it will not announce the new color to its neighbors, that is, the kick phase in k_{i+1} will not be occupied by this reader.

Note that if two or more readers send a *kick* signal simultaneously in an arbitrary k_i, they detect the *kick* collision, and have to select a new color for the subsequent round k_{i+i}, announcing again to their neighbors the new reservation in the kick phase of k_{i+i}.

A major limitation of DCS scheme is the fixed number of colors. This entails a low throughput in those scenarios where the number of neighboring readers is far from the

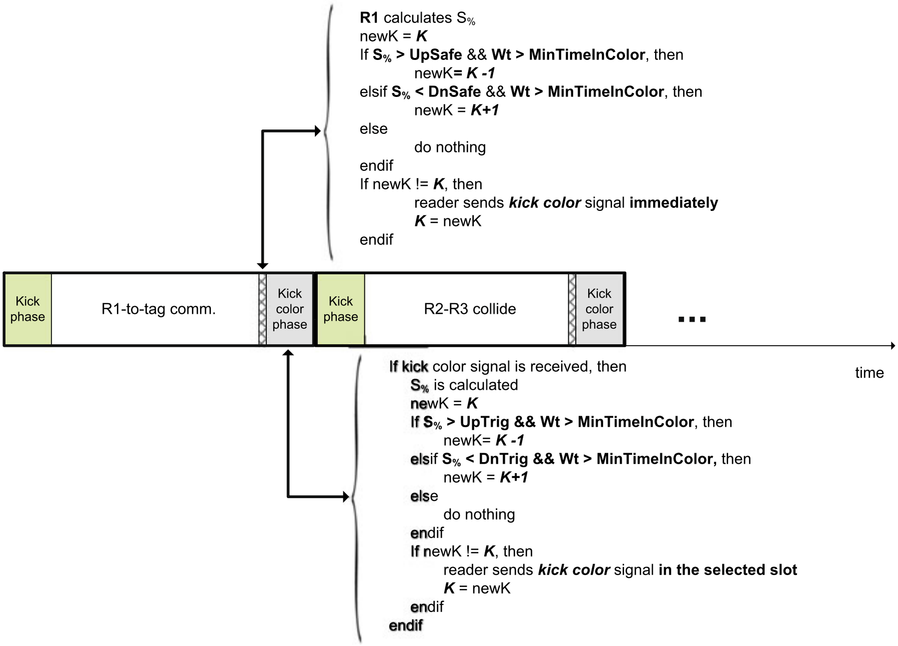


Fig. 3 Managing the identification time in Colorwave protocol

number of colors per round, giving many empty slots if the number of neighboring readers is lower than the number of colors, or giving many collisions per round if the number of neighboring readers is much higher than the number of colors.

In [19] Probabilistic DCS (PDCS) is proposed for increasing the performance of [18] under two configurations. First, the use of a multi-channel strategy. Second, adding a mechanism where readers, after a collision, select a new color with a probability P, in order to reduce the number of colliding readers. However, the limitation of the number of colors of DCS still exists. Colorwave [20] solves this issue allowing readers to change the number of colors per round K. Every reader manages independent identification rounds. When a reader detects a high percentage of collisions, it increases the value of K per round, independently of the K value managed by the rest of the readers in the network.

The mechanism to vary K works as follows (see Fig. 3): in an arbitrary round i, when the reader-to-tag communication phase of the color selected by a reader finishes, this reader computes the percentage of successful transmissions ($S_{\%}$) as

$$S_{\%} = \sum_{z=1}^{i} \sum_{y=1}^{j} \frac{s_z - s_y}{t_z - t_y} \quad (1)$$

j being the last round where the reader changed the value of K, s_z and s_y the number of collision-free transmissions experienced by the reader in z and y rounds, respectively, and t_z and t_y the number of transmissions (collision and collision-free) experienced by the reader in z and y rounds, respectively. Note that a collision-free transmission is a reader-to-tag communication phase where no reader collisions (RTC or RRC) were experienced.

If $S_{\%}$ is higher than a threshold (denoted as UpSafe), it means that the reader experienced few collisions and maybe, many empty slots occurred. Hence, with the aim of reducing the number of empty slots, the reader changes the number of colors in the subsequent rounds to $K-1$. Otherwise, if $S_{\%}$ is lower than a threshold (denoted as DnSafe) it means that the reader experienced many collisions. Consequently, the reader changes the number of colors in the subsequent rounds to $K+1$. After varying K, the reader immediately informs its neighbors about the new value. To do this, the reader sends a new signal, not present in DCS, called *kick color* signal. The use of this signal involves the need of a third phase in the slots' structure, the kick color phase (see Fig. 3). Those neighboring readers that receive a *kick color* signal estimate their percentage of successful transmissions ($S_{\%}$) and compare it with two other thresholds (UpTrig and DnTrig) in order to evaluate the suitability of the induced variation, increasing K if $S_{\%} >$ UpTrig and decreasing K if $S_{\%} <$ DnTrig. Note that, after changing K, readers must wait a stabilization period before to address a new variation of K, independently of the $S_{\%}$ value. This time is denoted as MinTimeInColor. In Fig. 3 is shown how the time elapsed up to MinTimeInColor is controlled by Wt parameter.

As can be seen, the thresholds strongly affect the behavior of the network. Since they are input parameters of the algorithm, they can be modulated to find the optimal configuration. But the optimal configuration depends on the network characteristics: topology, neighborhood, traffic load, etc. In [18], the authors propose an optimal configuration for a specific scenario, suggesting UpSafe and UpTrig close to 1, and DnTrig and DnSafe close to 0, so the readers only vary K when their throughput is very low. Still, any specific values set in the input parameters of Colorwave, which may work in some circumstances, but they could degrade the system performance if the scenario changes, e.g. if the pattern of tag arrival changes, or mobile readers appear changing the network topology.

4 MALICO: Maximum Likelihood Colorwave

In this section we present the MALICO (Maximum Likelihood COlorwave) approach. MALICO is intended to improve the throughput of Colorwave in two aspects. First, MALICO permits Colorwave to adapt to changeable identification scenarios, by adapting the number of colors K in every round, eliminating the unit variation restriction imposed by Colorwave. Besides MALICO eliminates the need to engineer the input parameters of Colorwave, since the protocol converges to working values optimizing the system throughput. Finally MALICO eliminates the Colorwave limitation of operating in a single frequency. In this sense, the MALICO protocol is designed to operate in the four frequencies recommended by the EPC-ETSI [3, 12].

We assume a dense RFID system composed of a set of R fixed and/or mobile readers connected to higher entity by means of a wired (e.g. Ethernet infrastructure) or wireless connection (e.g. Wi-Fi). Readers are provided by two bi-static antennas

[22]: one for transmitting and the other one for being continuously receiving. This hardware allows readers to detect if other readers are using the channel while they are transmitting. Readers are working under the EPCglobal Class-1 Gen-2 standard [12], in particular at UHF Europe band, allocated at 868 MHz. They collect information from tags identified in their target region and send it back to the higher entity periodically, following the Low Level Reader Protocol (LLRP) defined by EPCglobal Network [23].

To avoid both RTC and RRC effects, we base our approach on coordinating the readers in a combined FDMA and TDMA scheme. The FDMA scheme is suited on readers compliant with ETSI-EN 302 208. The readers randomly select one out of four available frequencies to communicate. The TDMA scheme is addressed like in Colorwave, where a higher entity synchronizes slots, whereas every reader divides the time into independent identification rounds of variable length K. The identification rounds are formed by only one phase: the long reader-to-tag communication phase. The other phases are eliminated due to the readers will adapt their identification rounds with their own collected info and they will not need to announce any info to their neighbors. This permits MALICO, under the same slot length as Colorwave, to have a larger reader-to-tag communication phase.

4.1 Algorithm procedure

When a mobile or fixed reader enters to participate in the DRE, it selects one of the four available frequencies at UHF band (line 1 in Algorithm 1). After that, the reader is synchronized by a higher entity, guaranteeing that the reader frame is time-aligned with the rest of the readers in the network (line 2). Once the reader is properly configured, the reader starts a first identification round ($i = 1$), with a random number of colors (K_i). The reader selects one color k_i in K_i, $k_i \in 1, 2, \dots, K_i$ (line 6), and keeps listening the channel, collecting the information about the state of the colors in round i: number of empty (e_i), successful (s_i) and colors with collision (c_i). When the selected k_i color starts, reader tries to communicate with tags (lines 9–10). If its neighboring readers try to communicate simultaneously, a collision occurs (line 13). The reader detects the collision and leaves the contention, collects the state of the color where it participated and continues listening to the channel and collecting data until the end of the round (lines 14–19). When the round finishes, the reader uses the collected info in that round to estimate the number of neighboring readers ($\hat{R}$) in its working frequency (lines 22–33). To do this, the reader uses the maximum-likelihood estimator introduced in Sect. 4.2. Once $\hat{R}$ is estimated, the length of the next identification round is adjusted to a new K_{i+1} value (line 34), and a new identification round starts, executing the algorithm again.

In contrast to Colorwave, the mechanism in MALICO quickly reacts to the real-time topology changes provoked by mobile readers, permitting to adjust the length of the identification rounds to the desired value.

4.2 Neighboring reader estimation

In this section the computation of $\hat{R}$ is addressed by the maximum-likelihood estimate of the number of neighboring readers that competed in an arbitrary identification round.

Algorithm 1 MALICO procedure

```
set frequency f_i = (int)random(1, 4)
set clock synchronization
set K_i = (int)random(1, MAXCOLORS)
set e_i = s_i = c_i = 0
loop
   set k_i = (int)random(1, K_i)
   r_i listens f_i
   for z = 1 to K_i do
      if z == k_i then
         r_i starts reader-to-tag communication in f_i
      end if
      if channel busy then
         if collision detected then
            c_i = c_i + 1
         else
            s_i = s_i + 1
         end if
      else
         e_i = e_i + 1
      end if
   end for
   set prob[1000] = 0
   for r_i = s_i + 2c_i to 100 · (s_i + 2c_i) do
      set prob[r_i − (s_i + 2c_i) + 1] = computeP(r_i, K_i, e_i, s_i, c_i)
      if (r_i == s_i + 2c_i) or (prob[r_i − (s_i + 2c_i) + 1] >= prob[r_i − (s_i + 2c_i)]) then
         do nothing
      else
         /*prob[r_i − (s_i + 2c_i) + 1] < prob[r_i − (s_i + 2c_i)]*/
         set R̂ = r_i
         set e_i = s_i = c_i = 0
         break
      end if
   end for
   set K_{i+1} = R̂
end loop
```

Let us denote $P(r_i, K_i, e_i, s_i, c_i)$ as the probability of obtaining, at the end of a round i, a sample of e_i colors with no neighboring reader responses, s_i colors filled with exactly one reply and c_i colors with a collision of two or more readers if r_i neighboring readers compete for identifying tags in K_i colors. To compute this probability we apply the technique proposed in [24], where the author addresses the derivation of a joint occupancy distribution of urns (in this study colors) and balls (in this study readers) via a bivariate inclusion and exclusion formula. Let us review this formulation [24].

Let r_i reader signals randomly distributed into K_i distinguishable colors in the contention round i, and X_j the number of reader signals distributed in the j-th color, $j = 1, 2, \dots, K_i$, and $S_{K_i} = \sum_{j=1}^{K_i} X_j$. Assume that the random variables

$X_1, X_2, \dots, X_{K_i}$ are independently and identically distributed, with common probability function $P(X = x) = q_x$, $x = 0, 1, \dots$. Then,

$$q_{r_i}(K_i) \equiv P\big(S_{K_i}(r_i)\big) = \sum q_{x_1} q_{x_2} \cdots q_{x_{K_i}} \tag{2}$$

for $r_i = 0, 1, 2, \dots$ and $x_1 + x_2 + \cdots + x_{K_i} = r_i$. Further, the conditional joint probability function of the random variables $X_1, X_2, \dots, X_{K_i}$ given $S_{K_i} = r_i$, is given by

$$q\big(x_1, x_2, \dots, x_{K_i} \mid r_i\big) = \frac{q_{x_1} q_{x_2} \cdots q_{x_{r_i}}}{q_{r_i}(K_i)} \tag{3}$$

with $x_j = 0, 1, \dots, r_i$. Under this random occupancy model, let W_z be the number of colors occupied by z reader signals each and W_v the number of colors occupied by v reader signals each, $z = 0, 1, \dots, r_i$, $v = 0, 1, \dots, r_i$, and $z \neq v$. The joint probability function is denoted as

$$p_{\alpha,\beta}(r_i, K_i, z, v) = P\big(W_z = \alpha, W_v = \beta \mid S_{K_i} = r_i\big) \tag{4}$$

for $\alpha = 0, 1, \dots, K_i - \beta$, $\beta = 0, 1, \dots, K_i$ and $z \neq v$. The binomial moment is

$$b_{(\alpha,\beta)}(r_i, K_i, z, v) = E\left[\binom{W_z}{\alpha}\binom{W_v}{\beta} \mid S_{K_i} = r_i\right] \tag{5}$$

for $\alpha = 0, 1, \dots, K_i - \beta$, $\beta = 0, 1, \dots, K_i$, $z \neq v$, and $b_{0,0}(r_i, K_i, z, v) = 1$.

Then, under the random occupancy model with $q_z > 0$ and $q_v > 0$, the conditional probability, $p_{\alpha,\beta}(r_i, K_i, z, v)$, that α colors are selected by z readers and β colors are selected by v readers, given that r_i readers are distributed into K_i colors, is given by

$$p_{\alpha,\beta}(r_i, K_i, z, v) = \binom{K_i}{\alpha, \beta} \cdot \big[\Delta_m^{K_i-\alpha-\beta} \Delta_n^m p_{\alpha+m-n, K_i-\alpha-m}\big]_{m=0,n=0} \tag{6}$$

where

$$p_{\alpha+m-n, K_i-\alpha-m} = \frac{q_z^{\alpha+m-n} q_v^{K_i-\alpha-m} q_{r_i - z(\alpha+m-n) - v(K_i-\alpha-m)}(n)}{q_{r_i}(K_i)} \tag{7}$$

and

$$\begin{aligned} &\big[\Delta_m^{K_i-\alpha-\beta} \Delta_n^m p_{\alpha+m-n, K_i-\alpha-m}\big]_{m=0,n=0} \\ &\quad = \sum_{l=0}^{K_i-\alpha-\beta} (-1)^{K_i-\alpha-\beta-l} \binom{K_i-\alpha-\beta}{l} \big[\Delta_n^l p_{\alpha+l-n, K_i-\alpha-l}\big]_{n=0} \end{aligned} \tag{8}$$

$$\big[\Delta_n^l p_{\alpha+l-n, K_i-\alpha-l}\big]_{n=0} = \sum_{t=0}^{l} (-1)^{(l-t)} \binom{l}{t} p_{\alpha+l-t, K_i-\alpha-l} \tag{9}$$

Since the number of readers selecting a specific color obeys a binomial distribution, then $q_x = P(X = x) = \binom{a}{x} p^x q^{a-x}$, where a is a positive integer, $x = 0, 1, \dots, a$,

$q = 1 - p$ and $0 < p < 1$. Its n-fold convolution is also a binomial distribution with $q_{r_i}(K_i) \equiv P(S_{K_i}(r_i)) = \binom{a\cdot K_i}{r_i} p^{r_i} q^{(a\cdot K_i - r_i)}$, where $r_i = 0, 1, 2, \ldots, a \cdot K_i$.

Hence, considering α colors with $z = 0$ reader responses (empty colors) and β colors with $v = 1$ reader responses (successful colors), Eq. (7) is denoted as follows:

$$p_{\alpha,\beta}(r_i, K_i; z = 0, v = 1) = P\big(W_0 = \alpha, W_1 = \beta \mid S_{K_i} = r_i\big) \\ = \frac{\binom{K_i}{\alpha,\beta}\binom{r_i - K_i + \alpha - 1}{r_i - 2K_i + 2\alpha + \beta}}{\binom{K_i + r_i - 1}{r_i}} \tag{10}$$

Note that the total number of ways of distributing r_i reader signals into K_i colors is $\binom{K_i + r_i - 1}{r_i}$. Further, the K_i distinguishable colors $1, 2, \ldots, K_i$ are divided into three disjoint subsets $\{u_1, u_2, \ldots, u_\alpha\}$, $\{u_{\alpha+1}, u_{\alpha+2}, \ldots, u_{\alpha+\beta}\}$ and $\{u_{\alpha+\beta+1}, u_{\alpha+\beta+2}, \ldots, u_{K_i}\}$ in $\binom{K_i}{\alpha,\beta}$ different ways. There are zero reader signals into each α color $\{u_1, u_2, \ldots, u_\alpha\}$, one reader signal in the β colors $\{u_{\alpha+1}, u_{\alpha+2}, \ldots, u_{\alpha+\beta}\}$, two reader signals into the $K_i - \alpha - \beta$ colors $\{u_{\alpha+\beta+1}, u_{\alpha+\beta+2}, \ldots, u_{K_i}\}$, and the remainder $r_i - \beta - 2(K_i - \alpha - \beta) = r_i - 2K_i + 2\alpha + \beta$ reader signals are distributed into the $K_i - \alpha - \beta$ colors.

Following the notation introduced at the beginning of this section, Eq. (10) can denoted as

$$\begin{aligned} p_{\alpha,\beta}(r_i, K_i; z = 0, v = 1) &= P(r_i, K_i, \alpha = e_i, \beta = s_i) \\ &= P(r_i, K_i, \alpha = e_i, \beta = s_i, K_i - e_i - s_i) \\ &= P(r_i, K_i, e_i, s_i, c_i) \end{aligned} \tag{11}$$

Equation (11) is computed for $r_i \geq s_i + 2c_i$, since r_i is, at least, the sum of the single reader responses plus those colliding reader signals (at least two per collision). Finally, the best guess number of neighboring readers is computed as

$$\hat{R} = \underset{\{r_i \geq s_i + 2c_i\}}{\arg\max} \big\{P(r_i, K_i, e_i, s_i, c_i)\big\} \tag{12}$$

In Fig. 4 an example of $\hat{R}$ computation is shown. At the end of a round with $K_i = 16$ slots, the reader has collected the following info: $e_i = 2$, $s_i = 6$ and $c_i = 8$. This info permits to calculate the minimum number of neighboring readers competing, $r_i \geq s_i + 2 \cdot c_i$, in the example $r_i \geq 22$. The computation starts in that value and calculates, for every $r_i \geq 22$, the probability function $P(r_i, K_i, e_i, s_i, c_i)$. When the probability function reaches its maximum value, the computation stops, and the estimator takes the r_i value that maximizes the probability. In Fig. 4, when the estimator takes $r_i = 41$, the probability function reaches its maximum value. For higher values of r_i, the probability function decreases.

4.3 Computation of a new color

The computation of K for every new identification round must be addressed with the aim of maximizing throughput (τ). In Frame Slotted Aloha (FSA) mechanism the

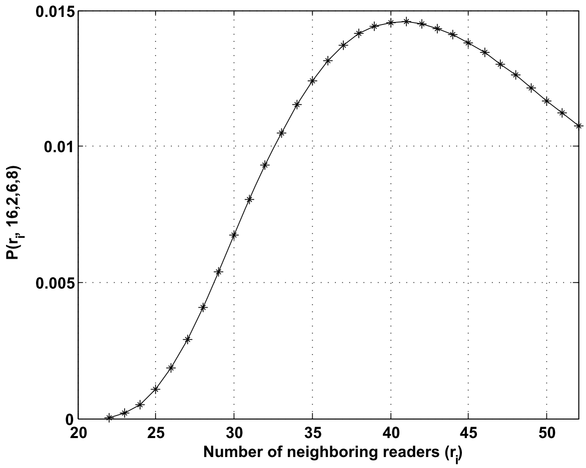


Fig. 4 Computation of maximum-likelihood estimator when $K_i = 16$, $e_i = 2$, $s_i = 6$, $c_i = 8$

maximum throughput is achieved when the number of competing nodes in a system matches the number available slots, getting $\tau = e^{-1} \approx 0.36$ [25]. Since our mechanism is based on FSA procedure, we look for maximizing the throughput in our system following the FSA formulation, that is, the theoretical maximum throughput will be achieved when $K_{i+1} = \hat{R}$. The formulation is reviewed below.

Once $\hat{R}$ is estimated after an identification round i, the expected throughput in next identification round is calculated as

$$\tau_{i+1} = \frac{E(z=1)}{K_{i+1}} \tag{13}$$

where $E(z)$ is the expected number of colors filled with exactly z readers, $E(z) = K_{i+1} \cdot \Pr(z)$. $\Pr(z)$ is the fill level of z readers in a color, which is given by the binomial distribution function,

$$\Pr(z) = \binom{\hat{R}}{z} \left(\frac{1}{K_{i+1}}\right)^{z} \left(1 - \frac{1}{K_{i+1}}\right)^{(\hat{R}-z)} \tag{14}$$

Hence, the expected throughput in the next identification round is computed as follows:

$$\tau_{i+1} = \binom{\hat{R}}{1} \frac{1}{K_{i+1}} \left(1 - \frac{1}{K_{i+1}}\right)^{\hat{R}-1} \tag{15}$$

4.4 Computation cost

The computation cost of an algorithm can be determined by the number of floating point operations per second (FLOPS) that are required for its execution, or by the order of magnitude of the algorithm $O(d)$, as a function of a parameter d which is related to the problem dimension. The latter is the most common factor taken into account for evaluating the feasibility of an algorithm for a further practical use. In this subsection we study the feasibility of MALICO under this metric.

As we stated before, the computation of $\hat{R}$ at the end of every round requires to calculate (10)–(12) for every $r_i \geq s_i + 2 \cdot c_i$, that is, at most $(R_{\max} - s_i - 2 \cdot c_i + 1)$ computations. Note that $R_{\max}$ is the upper limit that denotes the maximum number of readers that could work in a DRE. Equation (12) can be simplified as follows:

$$P(r_i, K_i, e_i, s_i, c_i) = \left(\frac{K_i!}{e_i! s_i! c_i!}\right) \cdot \left(\prod_{j=0}^{c_i-2} \frac{(r_i - K_i + e_i - 1 - j)}{j+1}\right) \times \left(\prod_{z=0}^{r_i-1} \frac{(K_i - 1 + r_i - z)}{z+1}\right) \tag{16}$$

where $c_i = K_i - s_i - e_i$. Note that maximizing the above probability is equivalent to maximize its logarithm, as we pointed out in [26]. Hence, the previous equation can be denoted as

$$\begin{aligned} P(r_i, K_i, e_i, s_i, c_i) &= \log(K_i!) - \log(e_i!) - \log(s_i!) - \log(c_i!) \\ &\quad + \log\left(\prod_{j=0}^{c_i-2} (r_i - K_i + e_i - 1 - j)\right) - \log\left(\prod_{j=0}^{c_i-2} (j+1)\right) \\ &\quad + \log\left(\prod_{z=0}^{r_i-1} (K_i - 1 + r_i - z)\right) - \log\left(\prod_{z=0}^{r_i-1} (z+1)\right) \end{aligned} \tag{17}$$

Simplifying,

$$\begin{aligned} P(r_i, K_i, e_i, s_i, c_i) &= \log\bigl(\Gamma(K_i + 1)\bigr) - \log\bigl(\Gamma(e_i + 1)\bigr) - \log\bigl(\Gamma(s_i + 1)\bigr) \\ &\quad - \log\bigl(\Gamma(c_i + 1)\bigr) + \sum_{j=0}^{c_i-2} \log(r_i - K_i + e_i - 1 - j) \\ &\quad - \sum_{j=0}^{c_i-2} \log(j+1) + \sum_{z=0}^{r_i-1} \log(K_i - 1 + r_i - z) \\ &\quad - \sum_{z=0}^{r_i-1} \log(z+1) \end{aligned} \tag{18}$$

To speed computations up we can assume every reader keeps an array with predefined computations of $\log(\Gamma(x))$, and $\sum_{x=0}^{\max\{r_i, K_{\max}\}} \log(x)$, where $x = 1, 2, \ldots, \max\{r_i, K_{\max}\}$, and $K_{\max}$ the maximum value that K can take. Then, the computation of Eq. (18) requires at most $4 + 4 \cdot \max\{r_i, K_{\max}\}$ sums. Since $\hat{R}$ is obtained after computing Eq. (18) at most $(R_{\max} - s_i - 2 \cdot c_i + 1)$ times, the total number of operations required for computing $\hat{R}$ at the end of every round will be, at most $d = (R_{\max} - s_i - 2 \cdot c_i + 1) \cdot (4 + 4 \cdot \max\{r_i, K_{\max}\})$ sums. As can be seen, the algorithm has a linear complexity because requires $O(d)$ operations.

Since we have assumed that some predefined computations are stored, we are forcing MALICO algorithm to access the computer memory to extract these predefined computations (*input* and *output* phases) for every estimate. It entails that MALICO will spend some CPU time, which must be also considered. In [27], the CPU time (in seconds) required to access to all data of a vector with m elements on a PC at 433 MHz was calculated, and results showed that the time required for reading all data of a vector with $m = 600$ positions was about 0.025 seconds. Since a current CPU in a commercial UHF RFID reader has about 1.6 GHz, we can conclude that the time required to access to a vector of similar size will be much more lower. Therefore, we can claim that the entire process of MALICO execution is not computationally demanding and it is feasible to be executed in commercial RFID readers.

5 Performance evaluation

This section presents the results of the simulations conducted to evaluate the performance of MALICO. In order to provide a fair comparison, two different experiments are conducted. In the first one, we compare a single channel version of MALICO with Colorwave and DCS due to these distributed mechanisms being the base of the new approach. We also compare with NFRA [10], one of the most extended centralized mechanisms for DRE based on TDMA technique in a single data channel. In a second group of experiments we compare MALICO working under four frequencies and PDCS, the multi-channel extension of DCS, also set to four frequencies.

Since a good DRE mechanism must guarantee a high number of successful reader transmissions, regardless of the collisions, we have considered the throughput, defined as the mean number of successful reader transmissions per second, as an appropriate parameter for measuring the performance. The performance evaluation has been carried out by means of an in-house simulator developed in Matlab.

We study a RFID system working at UHF band (868 MHz) composed by a set of bi-static RFID readers randomly placed in a square area of different sizes. Readers output power is set at the maximum value permitted in Europe, $P_{tx} = 3.2$ Watts EIRP [3]. As we discussed in Sect. 1, this value limits the reader read distance (reader-to-tag read range) and the reader interference range to a maximum of 10 and 1000 m in indoor scenarios, respectively [4]. Note that at $P_{tx} = 3.2$ Watts EIRP, RTC occurs when readers are placed at less than 20 m each other and RRC at less than 1000 m each other [4].

The parameters of the evaluated approaches are summarized in Table 1. Note that the reader-to-tag communication phase is set to 0.46 s for all the protocols. The reason comes from the assumption that the readers in the network identify tags and handle/avoid collisions using the Frame Slotted Aloha (FSA) procedure suggested by EPCglobal Class-1 Gen2 [12]. This mechanism was studied by the authors in [28], where it was analyzed that, taking the standard configuration parameters enumerated in [28], during 0.46 s, on the average 100 tags were queried.

Three different scenarios have been sampled to show the performance of MALICO and to compare it with the other strategies in different environments. Scenario 1 is an usual situation with a moderate quantity of fixed readers R, $R \in [25, 50, 75, 100]$,

Table 1 Parameters of the mechanisms simulated

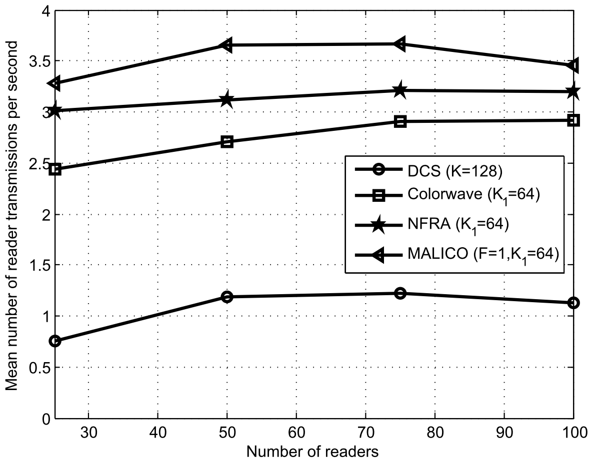
Mechanism	Parameters
DCS [18]	Kick phase length = 1 ms
	Reader-to-tag communication phase length = 0.46 s
PDCS [19]	Kick phase length = 1 ms
	Reader-to-tag communication phase length = 0.46 s
	Probability of changing color $P = 0.70$
Colorwave [20]	Kick phase length = 1 ms
	Kick color phase length = 1 ms
	UpSafe = 93 %
	DnSafe = 90 %
	UpTrig = 2 %
	DnTrig = 1 %
	MinTimeInColor = 100 slots
	Reader-to-tag communication phase length = 0.46 s
NFRA [10]	*AC* packet = 2.83 ms
	OC packet = 1 ms
	OF packet = 0.3 ms
	B packet = 0.3 ms
	Reader-to-tag communication phase length = 0.46 s
MALICO	Reader-to-tag communication phase length = 0.46 s

in an area of 2000 × 2000 m. In this scenario, the percentage of interfering readers is ∼95 %. In the second scenario the size of the area and the quantity of readers is the same, but a 50 % of the readers in the network are mobile readers. Readers location randomly changes over time. We assume readers move up to 1 m/s in any direction. Hence, every new location (x_t, y_t) can be computed $x_t = x_{t-1} \pm \mathrm{rnd}(0, 0.5)$ and $y_t = y_{t-1} \pm \mathrm{rnd}(0, 0.5)$. The third scenario evaluates the effect of the size of the neighborhood in a network with 100 % of fixed readers. R=50 readers are placed in different areas to obtain a size of neighborhood from 5 to 45 in steps of 5, that is, the percentage of neighboring readers varies from 10 % to 90 %. In this scenario only a fixed network is evaluated because the network has to maintain a percentage of neighboring readers over time, which entails a limited readers' mobility, not significantly affecting the final performance.

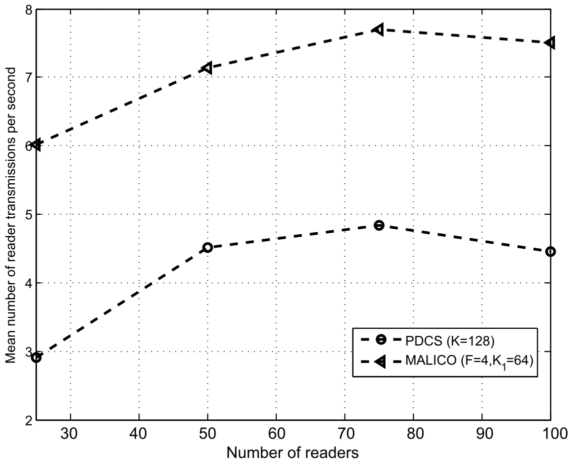
In every scenario, the approaches have been simulated for different identification round lengths (number of colors) in DCS and PDCS and for initial number of colors in Colorwave, NFRA and MALICO. From these simulations we have extracted the configurations that show the best performance for every protocol. DCS and PDCS show the best response in scenario 1 and 2 when the number of colors per round is 128, and 32 in scenario 3. Colorwave, NFRA and MALICO shows the same best performance for the same initial number of colors: 64 in scenario 1 and 2 and 16 in scenario 3.

MALICO has been evaluated under two different frequency configurations: with four ($F = 4$) and one ($F = 1$) frequencies. The former is the proposed configuration

Fig. 5 Performance evaluation of DRE strategies in a scenario with fixed readers and ∼95 % of interfering reader



(a) Single frequency strategies



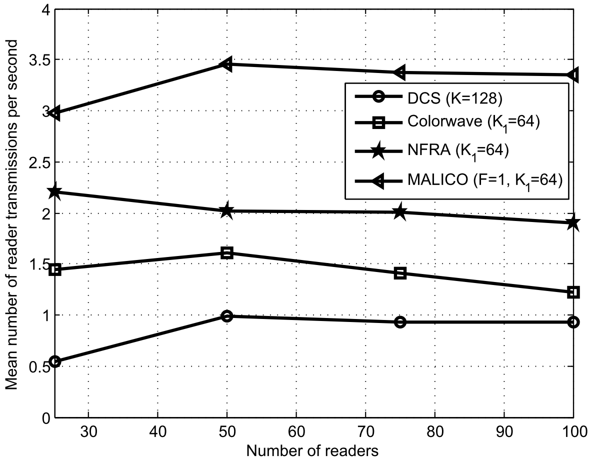
(b) Multi frequency strategies

that fulfills the European regulation [3]. The latter configuration is plotted to obtain a fair comparison with the state-of-the-art protocols adopting a single frequency.

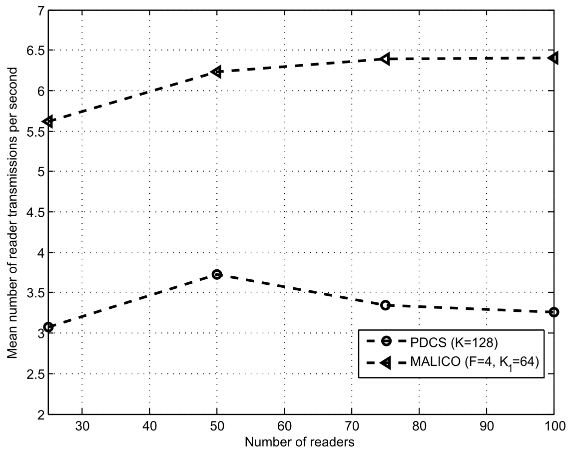
In Fig. 5 we compare the performance of the best configurations in scenario 1, with Fig. 5(a), where only the single frequency strategies are plotted and Fig. 5(b), where multi-frequency strategies are plotted. As can be seen, MALICO with $F = 4$ improves all the other strategies, increasing PDCS throughput in, at least, 200 % in the worst case. The throughput of MALICO with $F = 1$ is quite lower than the previous one but still better than the single-frequency strategies studied.

The performance of the best configurations in scenario 2 is plotted in Fig. 6(a) and (b), following the same criteria as in the previous figure. The former shows that DCS has a similar (and low) throughput to the previous scenario, while Colorwave and NFRA are strongly affected by the network mobility, decreasing their throughput ∼40 % in all the cases. In Colorwave, these results come from the slow variation of

Fig. 6 Performance evaluation of DRE strategies in a scenario with 50 % of mobile readers



(a) Single frequency strategies

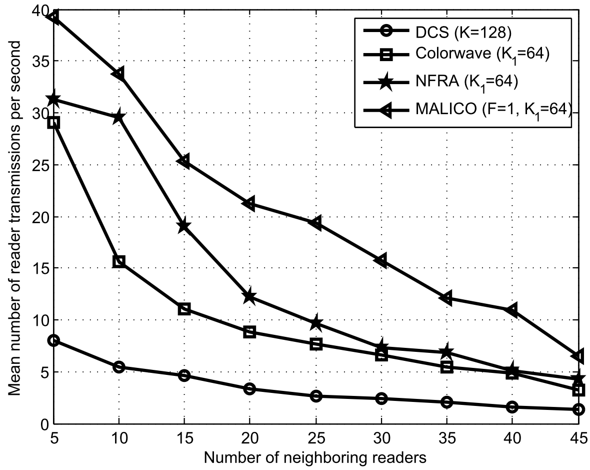


(b) Multi frequency strategies

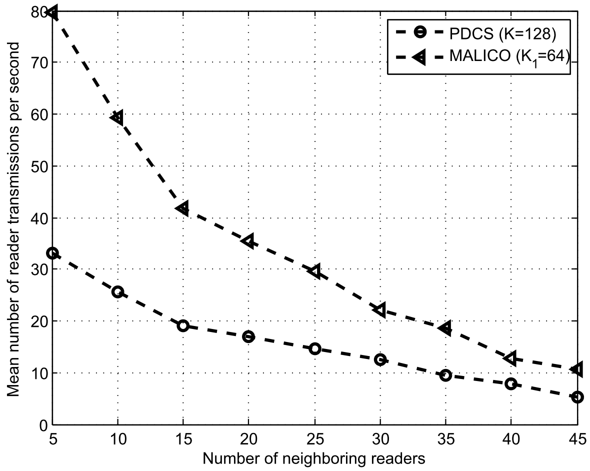
the identification round length, as we discussed in Sect. 3. In NFRA, its centralized nature penalized it when mobile readers are working in the DRE. MALICO shows in both strategies (one and four frequencies) the best performance but lower than the previous results due to the existence of mobile readers. The velocity of mobile readers strongly affects the well performance of MALICO in dynamic networks. If readers move too fast, the (best) color computed for a new identification round may be not the best strategy due to the number of neighboring readers may change, not reaching the maximum throughput per round. However, MALICO with $F = 4$ is still better than PDCS, since it adapts the identification round length much more faster.

Finally, the best performance of the approaches in scenario 3 is shown in Fig. 7. As can be seen, MALICO in both strategies shows the best throughput. In Fig. 7(b) MALICO shows ∼300 % better throughput than PDCS when the number of neigh-

Fig. 7 Performance evaluation in a fixed DRE with $R = 50$ and variable % of interfering readers



(a) Single frequency strategies



(b) Multi frequency strategies

boring readers varies from 5 to 20. If the number of neighboring readers increases, the performance rapidly decreases in both strategies, but MALICO still shows the best throughput. This behavior is also presented in the comparison plotted in Fig. 7(a). MALICO with a single frequency shows a ∼33 % better performance than NFRA in almost all the evaluations and the difference is higher if we compare it with DCS and Colorwave. Note that, when the number of neighboring readers is 45 (90 % of interfering readers), the results are close to those presented in Fig. 5(a) for R=50, where the percentage of interfering readers reaches 95 %. From these results we can conclude that MALICO strategy, not only outperforms the other approaches in those scenarios with a high number of fixed and mobile neighboring readers (like in scenario 1 and 2), but also in low density environments.

6 Conclusions

In this paper, the Maximum Likelihood Colorwave (MALICO) protocol is proposed as a new mechanism based on Colorwave that minimizes collision problems in Dense Reader Environments, providing higher throughput than most of the distributed mechanisms for DRE. MALICO implements a maximum-likelihood estimator as a mechanism to estimate the number of neighboring readers. MALICO uses the statistical information collected by the readers (number of empty, successful and collision slots) to accurate the estimate. Once the number of neighboring readers is estimated, the number of colors is adjusted accordingly to maximize the throughput in the next identification round. A maximum-likelihood estimate provides a good accurate estimator, minimizing collision probability between contending readers while maximizing the probability that a single reader takes a slot, increasing the throughput. Different scenarios have been evaluated. The results show that MALICO outperforms DCS and Colorwave as well as other strategies like PDCS, the multi-channel version of DCS and NFRA, one of the most extended centralized proposals for DRE. MALICO is better than the other strategies not only in scenario with fixed readers, but also with mobile ones, and also when MALICO works in a single frequency. This holds even for those harsh environments where the percentage of neighboring readers is close to 100 %.

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