Probabilistic DCS: an RFID Reader-to-Reader Anti-collision Protocol

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Abstract

The wide adoption of Radio Frequency Identification (RFID) for applications requiring a large number of tags and readers makes critical the reader-to-reader collision problem. Various anticollision protocols have been proposed, but the majority require considerable additional resources and costs. Distributed Color System (DCS) is a state-of-the-art protocol based on time division, without noteworthy additional requirements. This paper presents the Probabilistic DCS (PDCS) reader-to-reader anticollision protocol which employs probabilistic collision resolution. Differently from previous time division protocols, PDCS allows multichannel transmissions, according to international RFID regulations. A theoretical analysis is provided in order to clearly identify the behavior of the additional parameter representing the probability. The proposed protocol maintains the features of DCS, achieving more efficiency. Theoretical analysis demonstrates that the number of reader-to-reader collisions after a slot change is decreased by over 30%. The simulation analysis validates the theoretical results, and shows that PDCS reaches better performance than state-of-the-art reader-to-reader anticollision protocols.

Key words: RFID, reader-to-reader collision

1. Introduction

Radio Frequency Identification (RFID) is a well-known identification technology which is applied to several sectors, such as Supply Chain Management (SCM) [1], traceability [2], and emergency management [3]. The majority of RFID systems are composed of some RFID readers and many passive transponders, called *tags*. Passive tags get their power supply from the electromagnetic field of the reader. A reader can read and write the tag memories in its *interrogation range*, which is limited by the power requirements of the tag. However, the low power messages of the tags are affected by the stronger transmissions at the same frequency of the close readers. A reader affects the communications of other readers in its *interference range*. If two readers, within the reciprocal interference range, simultaneously try to communicate with different tags, the two transmissions may collide (*reader-to-reader collision*).

Usually, RFID systems for auto-identification employ ultra high frequency (UHF). In free space, the interrogation range of a reader transmitting at 33 dBm with tags requiring 14 dB is approximately 7 meters. According to the European regulation for UHF RFID, ETSI EN 302 208-1 V1.2.1 [4], the threshold level over that signals may degrade RFID transmissions shall be −35 dBm or less, depending on the RFID application. The ratio between interrogation range and interference range is 10 times, as stated in [5]. The high number of readers in the interference range can produce several collisions, impairing the network performance.

Waldrop et al. presented DCS and Colorwave [6][7], based on time division. The transmissions are composed of rounds divided in timeslots called *colors*. In DCS, after every collision, a reader randomly changes timeslot. DCS provides good performance without noteworthy additional requirements. Colorwave does not need a specific configuration, but it requires to manage an additional transmission among RFID readers. These protocols present an acceptable time efficiency and provide a high probability that readers do not collide twice consecutively. Other protocols (Pulse [5, 8], HiQ [9], and NFRA [10]) try to reach better performance using an additional control channel. However, these protocols require additional resources.

Since the change after a collision from the previous timeslots to a random timeslot can produce new collisions, in order to decrease the resulting next collisions, Gandino et al. [11] proposed to introduce in collision resolution of time division protocols an additional parameter p, representing the probability to change timeslot after a collision. This paper presents the Probabilistic DCS (PDCS) reader-to-reader anticollision protocol which exploits the probability p. Moreover, PDCS is a multichannel protocol, in accordance with the majority of the international RFID regulations (e.g. [4]). The present evaluation criteria are analyzed and an improved evaluation method is presented, in order to find a more accurate fairness of the protocols.

The paper presents a theoretical analysis on the proposed protocol and studies the effects of p. The behavior of PDCS has been simulated and compared to state-of-the-art approaches in order to compare their time performance and to validate the

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results of the theoretical analysis. Experimental results show that the number of reader-to-reader collisions after a slot change decreases by over 30%, and demonstrate that PDCS presents limited additional constraints and better time performance than state-of-the-art protocols with equivalent requirements. The analysis shows that PDCS is suitable also for RFID reader networks with mobile nodes.

The rest of the paper is organized as follows: in Section 2 the concept of efficiency is explained and the performance evaluation approach is introduced. In Section 3 the main previously proposed reader to reader anti-collision protocols are described, and in Section 4 the features of the proposed protocol are described. The theoretical and the simulation analysis are presented in Section 5 and in Section 6, respectively. Lastly, in Section 7 some conclusions are drawn.

2. Performance Evaluation Criteria

In state-of-the-art approaches, there is no existing accordance on the most effective criteria for performance evaluation of a general RFID reader-to-reader anticollision protocol. In this section the main evaluation approaches are described, and a novel proposal is presented.

The parameters used to evaluate RFID reader-to-reader anticollision protocols are:

- Waiting Time (WT), which corresponds to the time span between the request and the transmission. It involves:
  - Average Reader Waiting Time (ARWT), which corresponds to the average WT for all the transmissions of a specific reader;
  - Total Average Waiting Time (TAWT), which corresponds to the average WT for all the transmissions in the RFID network;
  - Overall Average Reader Waiting Time (OARWT), which corresponds to the average ARWT of all the readers in the RFID network;
  - Variance of Average Waiting Time (VAWT), which corresponds to the variance of ARWT of all the readers in the RFID network;
  - Reader Waiting Time Variance (RWTV), which corresponds to the variance of WT for all the transmissions of a specific reader;
  - Total Waiting Time Variance (TWTV), which corresponds to the variance of WT for all the transmissions in the RFID network;
  - Average Waiting Time Variance (AWTV), which corresponds to the average RWTV of all the readers in the RFID network;
  - Maximum Waiting Time (MWT), which corresponds to the longest WT among all the transmissions in the RFID network;
- Attempted Transmissions (AT), which corresponds to the total number of attempted transmissions in the RFID network;
- Number of Transmissions (NT), which corresponds to the total number of successfully performed transmissions in the RFID network.

2.1. Adopted Metrics

In [12], Engels and Sarma state that the goals of reader-to-reader anti-collision protocols are to minimize the time span required to allow all readers communicate at least once (*MWT*), and to schedule all readers to communicate as often as possible (*NT*).

In [7], the authors consider the requirements of real-time applications as inventory detection, so they suggest the goal of scheduling readers to communicate as often as possible (*NT*). The total successful transmissions performed by a set of readers according to different configurations is used to evaluate Colorwave and to compare Colorwave and DCS. In [6], the successful transmission percentage ($\frac{NT}{AT}$) is used to evaluate different configurations of DCS.

Birari and Iyer [5][8] use two parameters for the evaluation of anti-collision protocols: the throughput, which corresponds to the total number of successful transmissions performed by all the readers per unit of time ($\frac{NT}{time}$); and the efficiency, which corresponds to the percentage of successful transmissions ($\frac{NT}{AT}$).

In [9] the goal of anti-collision protocols is to maximize the number of readers simultaneously communicating ($\frac{NT}{time}$).

Gandino et al. [11] state that the goal of reader-to-reader protocols is to provide short (*TAWT*) and steady (*TWTV*) waiting times.

2.2. Proposed Evaluation Criteria

Methods based only on $\frac{NT}{AT}$ evaluate positively protocols where AT is close to NT, also if NT is low. Therefore, this kind of evaluation does not seem effective, since it does not consider the throughput.

The throughput is represented by NT, but this metric does not consider the time distribution of the transmissions and the different contribution of each reader to NT. Therefore, NT is not suitable for applications that require constant quality of service for the whole network.

$TAWT$ and $TWTV$ are effective indexes of the throughput and of the performance stability. However, these parameters do not consider the differences among the performance of the single readers. Moreover, a reader with optimal performance can strongly increase $TAWT$, hiding several readers with very low performance, because each transmission has the same weight. Therefore, we state that these problems can be solved analyzing $OARWT$ and $VAWT$, which give the same weight to each reader, instead of to each transmission. In detail, a protocol should mainly minimize:

- OARWT, in order to schedule readers to communicate as soon as possible,

- VAWT, in order to minimize the quantity of readers with minor efficiency,
- TWTV, in order to provide steady performance,
- MWT, in order to avoid large gaps between two transmissions of the same reader.

3. Related Work

This section describes the main relevant anti-collision protocols and their requirements.

3.1. Media Access Control Protocols

Several approaches try to address the reader-to-reader collision problem [13, 14]. The first reader-to-reader anti-collision protocols are strongly inspired by common Media Access Control (MAC) protocols used in radio wireless networks. However, they try to overcome common MAC protocols carefully considering the characteristics of RFID. This evolution process is common to other fields of research, e.g., [15] considers the inactive state of nodes. In wireless sensor networks, a common MAC family is based on Time Division Multiple Access (TDMA). DCS, Colorwave, and AC_MRFID [16] are RFID protocols inspired by this family. The RFID protocol Listen Before Talk is based on the family Carrier Sense Multiple Access (CSMA). Another MAC protocol is ALOHA [17], which has been tested and compared to DCS and Colorwave in [7], showing that ALOHA provides better performance only in RFID networks where the number of transmissions is low.

3.2. Distributed Color System (DCS)

In DCS [6][7] each communication round is composed of time slots. Each RFID reader can communicate only during its time slot. When a transmission collides, each involved reader stops the communication and randomly chooses a new timeslot that it has reserved, sending a specific signal named *kick*. When the reserved slot is used by some neighbors, they randomly choose a new slot and try using it without reservation.

The communications are divided in rounds. Each round is composed of μ timeslots. Each timeslot is composed of a kick phase and a transmission phase. The identification of a timeslot is called *color*. A color is assigned to a reader, and it works only during the corresponding time slot.

During the kick phase, each working reader that had collided at the previous transmission sends a kick. Each working reader that receives a kick changes color.

During the transmission phase, each working reader that has to read tags executes a transmission. If the transmission collides then the involved readers stop it and randomly choose a new color. At the subsequent round the colliding readers will send a kick, in order to reserve a timeslot.

In the described protocol when more than one reader transmits a kick during the same slot, all the transmitting readers also receive the kick, and they choose a new color.

The kick does not transport any additional information, but is used only to communicate to the neighbors that the channel is busy, so the readers do not need additional hardware. The only additional requirement is represented by the global synchronization, since each reader must initiate a new timeslot simultaneously to its neighbors.

3.3. Colorwave

Colorwave [6][7] is a protocol based on DCS. This protocol introduces a variable quantity of timeslots that compose a round (μ), differently from DCS where the number of timeslots is fixed. The value is dynamically changed in order to increase the efficiency of the RFID network. When the number of collisions is high, the number of used colors for round rises, while when it is small the number of colors decreases. This protocol requires a special kick transmission, which states the change to a new μ. The kick phase is divided in two subphases, where normal kicks are sent during the first one, and color kicks during the second one.

In order to manage changes of μ, Colorwave introduces two couples of thresholds: one is used to manage the increase of μ, and the other for the decrease. Each couple is composed of a hard threshold, which sets a change, and a soft threshold, which sets a transition state, where the reader changes μ only if a neighbor is already changing. Therefore, each reader counts its percentage of successful transmissions. When the percentage exceeds a hard threshold the reader changes μ and communicates the change to its neighbors during the second kick subphase. If a reader has exceeded a soft threshold and it receives color quantity kick compliant with the exceeded threshold, then it changes μ and communicates the change to its neighbors.

The variable μ allows Colorwave to autonomously find a good configuration. However, in addition to the requirements of DCS, this protocol also requires to manage the special color kicks.

The presence of neighbor readers with different μ can generate additional collisions, as at each round different couples of slots overlap. However, this problem is in part overcome by the improved efficiency introduced by the adaptable μ.

3.4. AC_MRFID

AC_MRFID [16] is a protocol based on DCS. Similarly to Colorwave, each reader dynamically changes its μ.

After a collision, the colliding reader communicates with its neighbors in order to count the number of readers in its interrogation range. Then, it estimates the number of readers (ρ) in its interference range, according to the ratio between the interrogation area and the interference area, and it sets $\mu = \rho + 1$. This protocol is especially suitable for networks with a regular deployment, since the calculation is close to the real value. However, this protocol is not fair, since it provides the readers with few neighbors in their interrogation range, with more resources. Furthermore, it introduces additional communication overhead, in order to count the neighbors.

3.5. Protocols with High Requirements

Various protocols characterized by larger requirements have been proposed. Typically these protocols require an advanced communication system. Therefore, they cannot be implemented with readers presently produced, and require additional costs.

The main protocol in this group is HiQ [9], which is based on reinforcement learning, and which involves a hierarchical structure composed of three levels. The RFID readers, which represent the lowest level, require channel resources to the higher level (e.g., a computer in charge of multiple readers). The elements of the second level require resources to the highest level (e.g., a central server), and distribute them to the readers. This system requires a communication system for the resources management.

A recent protocol which overcomes HiQ performance is NFRA [10]. This protocol requires a central server, which communicates with the RFID readers through an additional channel at 433 MHz. This communication system requires that each reader owns an additional radio reception device for that frequency.

3.6. Protocols based on Power Control

An alternative system to avoid collisions is the Power Control [18][19]. The power can be decreased in order to reduce the interference range. These protocols try to optimize the ratio between the interference and the interrogation range. However, the reduction of the interrogation range affects the performance of the RFID network. According to ETSI EN 302 208-1 V1.2.1 [4], the threshold level of the noise for transmitting without interferences shall be -35 dBm e.r.p. or less. If a tag needs -14 dBm in order to be in the interrogation range of the reader, the ratio between the interference and the interrogation range is close to 20 times. Therefore, in order to avoid reader-to-reader collisions reducing the power, the interrogation area cannot be accurately covered.

4. Probabilistic DCS (PDCS) Protocol

In DCS, after sensing a collision, all the involved readers choose a new color and reserve it. However, as soon as a large number of the timeslots are used, a change of color probably generates a second change without timeslot reservation, so a probable collision between two readers will occur. Furthermore, the kicked reader will not transmit during the reserved round, and during the subsequent collision round, so it would have to wait two rounds before transmitting. After a collision between two readers, all the involved nodes will change their color, so both readers will reserve a new color. When the majority of the colors are used up, both new timeslots could be engaged, so two readers would change their color. Therefore, this double color change could generate two consecutive collisions.

In [11], the authors state that the introduction of a parameter p, which represents the probability of readers to changing color after a collision, can increase the performance, decreasing the number of collisions generated by the change of color due to a previous collision. This section describes a new protocol named Probabilistic DCS (PDCS). Differently from [11], PDCS is a multichannel protocol, which can manage an arbitrary number of channels, according to the various regulations regarding RFID. Therefore, after a collision in PDCS, readers choose both a new color and a new channel.

The variables of the protocol are the following:

- $color_i$, the index of the time slot that $reader_i$ can use for transmissions;
- $channel_i$, the index of the frequency channel that $reader_i$ can use for transmissions;
- $prev\_channel_i$, the index of the previous channel that $reader_i$ used for transmissions;
- μ, the number of time slots in a round;
- μc, the number of channels in a round;
- $kickflag_i$, the boolean flag that is true when $reader_i$ requires a kick;
- $transflag_i$, the boolean flag that is true when $reader_i$ requires a transmission.

As in DCS, in PDCS the transmissions are organized in rounds divided in timeslots. The total number of slots available at each round is equal to $\mu \cdot \mu c$. Each slot is composed of the following phases and subroutines:

- *Timeslot initialization*, the readers update the value of their variables;
  - **New timeslot**:
    $\forall i : color_i = (color_i + 1) \bmod \mu$;
    `if (reader`$_i$` has to read tags)`
    `then` $transflag_i$ `= true;`
- *Kick phase*, the readers send the kicks in order to manage the slot reservation, and choose a new color if they receive a kick.
  - **Kick sending**:
    `if (`$kickflag_i$ `= true AND` $color_i = 0$`)`
    `then reader`$_i$` sends the kick;`
    $kickflag_i$ `= false;`
  - **Kick resolution**:
    `if (reader`$_i$` receives a kick`
    `on` $channel_i$ `AND` $color_i = 0$`)`
    `then` $prev\_channel_i = channel_i$;
    `while (`$color_i = 0$
    `AND` $channel_i = prev\_channel_i$`)`
    $color_i = random(\mu)$;
    $channel_i = random(\mu c)$;
- *Transmission phase*, the readers try to communicate with the tags, and eventually choose a new color if they collide.
  - **Transmission**:
    `if (`$transflag_i$ `= true AND` $color_i = 0$`)`

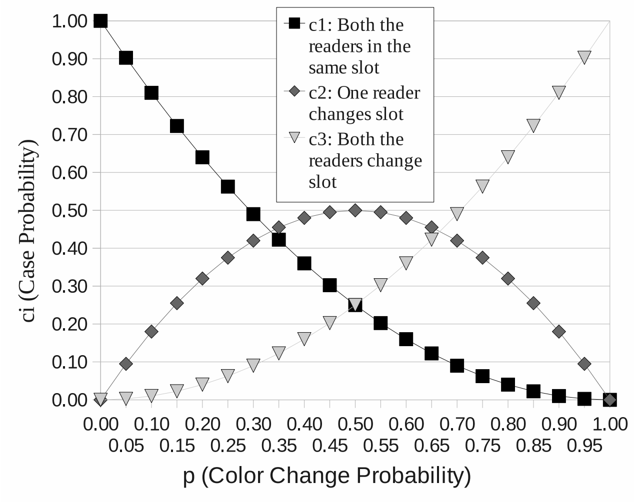

Figure 1: Color Change after a Collision between 2 Readers

then $\texttt{reader}_i$ transmits
$transflag_i$ = false;

– **Collision resolution**:

if ($\texttt{reader}_i$ collides AND $random(1.0) < p$)
then $color_i = random(\mu)$;
$channel_i = random(\mu c)$;
$kickflag_i$ = true;
$transflag_i$ = true;

5. Theoretical analysis

PDCS is characterized by the probability p. If $p = 1$, the behavior of PDCS corresponds to DCS.

The most relevant parameter for time evaluation of an anti-collision protocol is WT. The difference between PDCS and DCS is the collision resolution, so its effects on WT must be carefully analyzed.

The first step of this theoretical analysis is focused on the behavior of PDCS after a collision between two readers. A reader involved in a collision changes its color with probability p, so after a collision between two readers three cases are possible:

1. No reader changes its color, so at the subsequent round the involved readers will receive a kick and they will change color without reservation;
2. One reader changes its color, so at the subsequent round one reader will transmit with the previous color, and the second reader will reserve a new color, maybe requiring another reader to change;
3. Both readers change color, this case corresponds to the DCS collision resolution.

Case 1 is worse than DCS, since the involved readers will lose a second round. Case 2 is better than DCS, since one reader probably will not produce second generation collisions. Case 3 corresponds to DCS. Figure 1 shows the probability of each case (c_i), according to p. Roughly analyzing the effects of p on the performance of the RFID reader network, it is possible to consider that Case 1 is negative, Case 2 is positive, and that Case 3 is intermediate. Starting from $p = 1$, a short decrease of p corresponds to:

- a rise of Case 1 (*negative case*);
- a increase of Case 2 (*positive case*);
- a fall of Case 3 (*intermediate case*).

Therefore, since Case 2 improves the performance of the protocol, and Case 1 decreases it, the values of $0.5 < p < 1$ should bring positive results, as shown in Figure 1.

Although WT is the best metric for RFID network evaluation, the effects of the different cases on the time performance of the protocol can be more clearly analyzed observing the number of **second generation collisions** (γ), which represents the average number of readers involved in collisions produced by the **first generation collisions** (ϕ), which represents the number of colliding readers in a round.

5.1. *Second Generation Collisions*

The collisions affect the time performance of RFID networks, since the involved readers have to wait before transmitting. In DCS/PDCS, each collision generates possible new collisions. This behavior can produce a relevant number of collisions at each round, so it must be analyzed. This section carefully analyzes the effects of a collision between two readers. γ can be partitioned in three γ_i related to each case described in the previous section, so we have:

$$\gamma = c_1 * \gamma_1 + c_2 * \gamma_2 + c_3 * \gamma_3 \,. \tag{1}$$

Where c_i represents the probability of Case i, as reported in Fig. 1, and γ_i represents the average number of readers involved in second generation collision due to Case i. The formulas to calculate each γ_i are presented in the following, where γ_i is function of μ and of the number of engaged colors (ϵ).

5.1.1. *Case 1*

The probability of Case 1 is:

$$c_1 = (1 - p)^2. \tag{2}$$

This case involves a couple of concurrent kicks. After the kick each reader changes color without reservation, so the number of second generation collisions is related to the state of the new colors. If:

- both colors are free, then no second generation collision is produced and the contribution to γ_1 is null;
- one color is free and one color is engaged, then one second generation collision between two readers is produced; the contribution to γ_1 is $\gamma_{1a} \cdot c_{1a}$:

$$\gamma_{1a} = 2; \; c_{1a} = 2 \cdot \frac{\epsilon}{\mu - 1} \cdot \left(1 - \frac{\epsilon}{\mu - 1}\right); \tag{3}$$

- both colors are engaged, then two second generation collisions between two couples of readers are produced; the contribution to γ_1 is $\gamma_{1b} \cdot c_{1b}$:

$$\gamma_{1b} = 4; \; c_{1b} = \frac{\epsilon}{\mu - 1} \cdot \frac{\epsilon - 1}{\mu - 1}; \tag{4}$$

- the same free color is selected, then one second generation collision between two readers is produced; the contribution to γ_1 is $\gamma_{1c} \cdot c_{1c}$:

$$\gamma_{1c} = 2; \; c_{1c} = \left(1 - \frac{\epsilon}{\mu - 1}\right) \cdot \frac{1}{\mu - 1}; \tag{5}$$

- the same engaged color is selected, then one second generation collision between three readers is produced; the contribution to γ_1 is $\gamma_{1d} \cdot c_{1d}$:

$$\gamma_{1d} = 3; \; c_{1d} = \frac{\epsilon}{\mu - 1} \cdot \frac{1}{\mu - 1}; \tag{6}$$

Therefore, we have that:

$$\gamma_1 = \gamma_{1a} \cdot c_{1a} + \gamma_{1b} \cdot c_{1b} + \gamma_{1c} \cdot c_{1c} + \gamma_{1d} \cdot c_{1d}. \tag{7}$$

5.1.2. Case 2

The probability of Case 2 is:

$$c_2 = 2 \cdot p \cdot (1 - p). \tag{8}$$

In this case the reader that has not changed color will not produce second generation collisions, but it can collide with the second reader, since it could choose the same color again. The second reader changes color, so the number of second generation collisions is related to the state of the new color. If:

- the color is free, then no second generation collision is produced; the contribution to γ_2 is null;
- the color is engaged, then one reader changes color without reservation, so a collision between 2 readers has probability equal to the percentage of engaged colors; the contribution to γ_2 is $\gamma_{2a} \cdot c_{2a}$:

$$\gamma_{2a} = 2; \; c_{2a} = \frac{\epsilon}{\mu} \cdot \frac{\epsilon}{\mu - 1}; \tag{9}$$

- the color is the same as the previous collision, then there is a couple of concurrent kicks between the two readers of the first collision; the contribution to γ_2 is $\gamma_{2b} \cdot c_{2b}$:

$$\begin{aligned} \gamma_{2b} \;\; = \;\; & 2 \cdot \tfrac{\epsilon}{\mu-1} \cdot \left(1 - \tfrac{\epsilon}{\mu-1}\right) \cdot 2 + \tfrac{\epsilon}{\mu-1} \cdot \tfrac{\epsilon-1}{\mu-1} \cdot 4 + \\ & \left(1 - \tfrac{\epsilon}{\mu-1}\right) \cdot \tfrac{1}{\mu-1} \cdot 2 + \tfrac{\epsilon}{\mu-1} \cdot \tfrac{1}{\mu-1} \cdot 3. \end{aligned} \tag{10}$$

$$c_{2b} = \frac{1}{\mu}; \tag{11}$$

Therefore, we have that:

$$\gamma_2 = \gamma_{2a} \cdot c_{2a} + \gamma_{2b} \cdot c_{2b}. \tag{12}$$

5.1.3. Case 3

The probability of Case 3 is:

$$c_3 = p^2. \tag{13}$$

In this case both readers change color. The number of second generation collisions is related to the state of the new colors. If:

- both colors are free, then no second generation collision is produced; the contribution to γ_3 is null;
- one color is free and one color is engaged, then one reader changes color without reservation, so a collision between 2 readers has probability equal to the percentage of engaged colors; the contribution to γ_3 is $\gamma_{3a} \cdot c_{3a}$:

$$\gamma_{3a} = 2; \; c_{3a} = 2 \cdot \frac{\epsilon}{\mu} \cdot \frac{1 - \epsilon}{\mu} \cdot \frac{\epsilon}{\mu - 1}; \tag{14}$$

- both colors are engaged, then two readers change color without reservation, so they could produce:
  - one collision between two readers,

$$\gamma_{3b1} = 2, \tag{15}$$

$$\begin{aligned} c_{3b1} \;\; = \;\; & 2 \cdot \tfrac{\epsilon-1}{\mu-1} \cdot \left(1 - \tfrac{\epsilon-1}{\mu-1}\right) + \\ & \left(1 - \tfrac{\epsilon-1}{\mu-1}\right) \cdot \tfrac{1}{\mu-1}, \end{aligned} \tag{16}$$

  - two collisions between two couples of readers,

$$\gamma_{3b2} = 4, \tag{17}$$

$$c_{3b2} = \frac{\epsilon - 2}{\mu - 1} \cdot \frac{\epsilon - 2}{\mu - 1} + \frac{1}{\mu - 1} \cdot \frac{\epsilon - 1}{\mu - 1}, \tag{18}$$

  - one collision between three readers,

$$\gamma_{3b3} = 3, \; c_{3b3} = \frac{\epsilon - 2}{\mu - 1} \cdot \frac{1}{\mu - 1}, \tag{19}$$

  - or no collision;

  the contribution to γ_3 is $\gamma_{3b} \cdot c_{3b}$:

$$\gamma_{3b} = (\gamma_{3b1} \cdot c_{3b1} + \gamma_{3b2} \cdot c_{3b2} + \gamma_{3b3} \cdot c_{3b3}); \tag{20}$$

$$c_{3b} = \frac{\epsilon}{\mu} \cdot \frac{\epsilon - 1}{\mu}; \tag{21}$$

- the same free color is selected, then there is a couple of concurrent kicks between the two readers of the first collision; the contribution to γ_3 is $\gamma_{3c} \cdot c_{3c}$:

$$\begin{aligned} \gamma_{3c} \;\; = \;\; & 2 \cdot \tfrac{\epsilon}{\mu-1} \cdot \left(1 - \tfrac{\epsilon}{\mu-1}\right) \cdot 2 + \\ & \tfrac{\epsilon}{\mu-1} \cdot \tfrac{\epsilon-1}{\mu-1} \cdot 4 + \\ & \left(1 - \tfrac{\epsilon}{\mu-1}\right) \cdot \tfrac{1}{\mu-1} \cdot 2 + \\ & \tfrac{\epsilon}{\mu-1} \cdot \tfrac{1}{\mu-1} \cdot 3; \end{aligned} \tag{22}$$

$$c_{3c} = \left(1 - \frac{\epsilon}{\mu}\right) \cdot \frac{1}{\mu}. \tag{23}$$

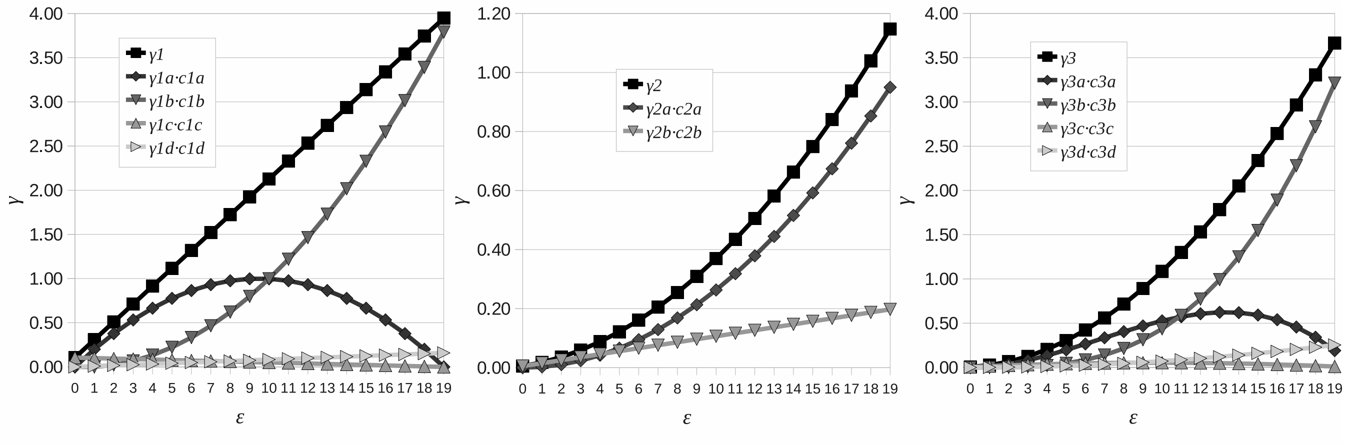

Figure 2: (a) γ_1 (b) γ_2 (c) γ_3 with $\mu = 20$

- the same engaged color is selected, then three readers change color without reservation, so they could produce:
  - one collision between two readers,

$$\gamma_{3d1} = 2, \quad (24)$$

$$c_{3d1} = 3 \cdot \frac{\epsilon-1}{\mu-1} \cdot \left(1 - \frac{\epsilon-1}{\mu-1}\right)\left(1 - \frac{\epsilon}{\mu-1}\right) + \left(1 - \frac{\epsilon-1}{\mu-1}\right)\left(1 - \frac{\epsilon}{\mu-1}\right) \cdot \frac{2}{\mu-1}, \quad (25)$$

  - two collisions between two couples of readers,

$$\gamma_{3d2} = 4, \quad (26)$$

$$c_{3d2} = 3 \cdot \frac{\epsilon-1}{\mu-1} \cdot \frac{\epsilon-2}{\mu-1} \cdot \left(1 - \frac{\epsilon-1}{\mu-1}\right) + 3 \cdot \frac{\epsilon-1}{\mu-1} \cdot \left(1 - \frac{\epsilon-1}{\mu-1}\right) \cdot \frac{1}{\mu-1}, \quad (27)$$

  - three collisions between three couples of readers,

$$\gamma_{3d3} = 6, \quad (28)$$

$$c_{3d3} = \frac{\epsilon-1}{\mu-1} \cdot \frac{\epsilon-2}{\mu-1} \cdot \frac{\epsilon-3}{\mu-1}, \quad (29)$$

  - one collision between three readers,

$$\gamma_{3d4} = 3, \quad (30)$$

$$c_{3d4} = \left(1 - \frac{\epsilon-1}{\mu-1}\right) \cdot \left(\frac{1}{\mu-1}\right)^2 + 3 \cdot \frac{\epsilon-1}{\mu-1} \cdot \left(1 - \frac{\epsilon-1}{\mu-1}\right) \cdot \frac{1}{\mu-1}, \quad (31)$$

  - one collision between three readers and one collision between two readers,

$$\gamma_{3d5} = 5, \quad (32)$$

$$c_{3d5} = \frac{\epsilon-1}{\mu-1} \cdot \frac{\epsilon-2}{\mu-1} \cdot \frac{2}{\mu-1}, \quad (33)$$

  - one collision between four readers,

$$\gamma_{3d6} = 4, \quad (34)$$

$$c_{3d6} = \frac{\epsilon-1}{\mu-1} \cdot \left(\frac{1}{\mu-1}\right)^2, \quad (35)$$

  - or no collision.

the contribution to γ_3 is $\gamma_{3d} \cdot c_{3d}$:

$$\gamma_{3d} = \sum_{i=1}^{6} \gamma_{3di} \; ; \;\; c_{3d} = \frac{\epsilon}{\mu} \cdot \frac{1}{\mu}. \quad (36)$$

According to previous formulas, we have that:

$$\gamma_3 = \gamma_{3a} \cdot c_{3a} + \gamma_{3b} \cdot c_{3b} + \gamma_{3c} \cdot c_{3c} + \gamma_{3d} \cdot c_{3d}. \quad (37)$$

5.1.4. Results

Figure 2 shows the values of γ_1, γ_2, and γ_3, and of their components, with $\mu = 20$. The component that mainly affects the value of γ_1 is $\gamma_{1b} \cdot c_{1b}$, which represents the number of second generation collisions due to the choice of two engaged new colors. γ_1 rises constantly, according to the increase of ϵ. The component that mainly affects the value of γ_2 is $\gamma_{2a} \cdot c_{2a}$, which represents the number of second generation collisions due to a kick on an engaged color, and to the subsequent change to a new engaged color. The component that mainly affects the value of γ_3 is $\gamma_{3b} \cdot c_{3b}$, which represents the number of second generation collisions due to two kicks on an engaged color, and to the subsequent change to two new colors.

Figure 3 compares the γ_i values according to $\mu = 20$, and shows that γ_1 represents the largest number of second generation collisions, and γ_2 the smallest.

Figure 4 shows γ according to various values of p, with $\mu = 20$. The graph roughly highlights the effects of p on γ, with $p = 0$ and $p = 1$, $\gamma = \gamma_1$ and $\gamma = \gamma_3$, respectively. Since γ_1 is always larger than γ_3, the value of γ reached by $p' < 0.50$ is larger than γ reached by $p'' = 1 - p'$, so the minimization of γ requires $p >= 0.50$. When $0 \leq \epsilon \leq 3$, the smallest γ is reached by $p = 1$, when $4 \leq \epsilon \leq 12$, the smallest γ is reached by $p = 0.75$, and when $15 \leq \epsilon \leq 19$, the smallest γ is reached by $p = 0.50$. Therefore, in order to minimize γ, at the rise of ϵ there should be a corresponding decrease of p from 1 to 0.50.

When a collision among readers produces new collisions among a larger number of readers, the number of collisions

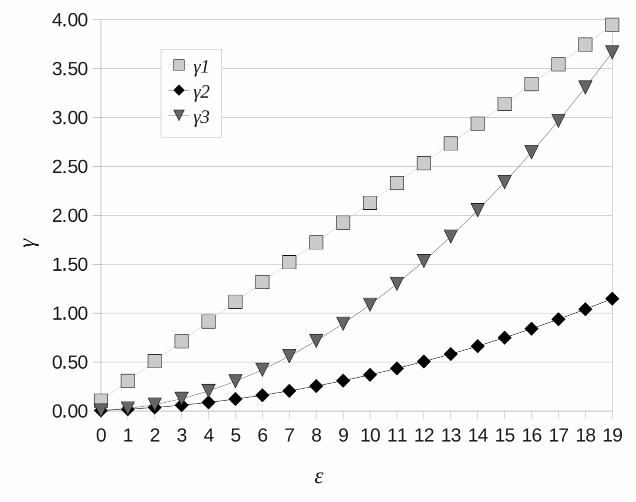

Figure 3: γ_i with $\mu = 20$

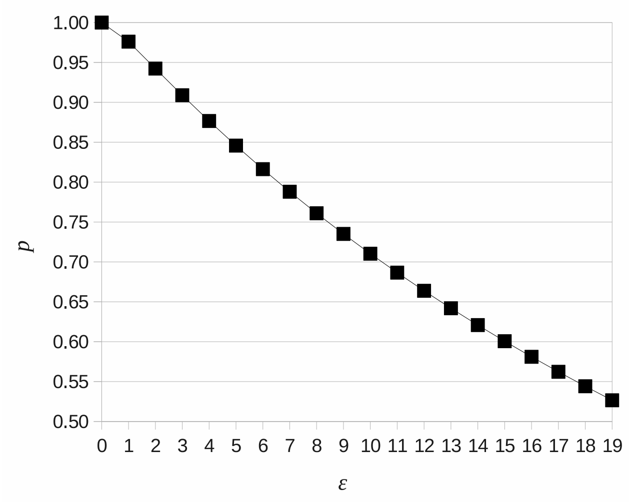

Figure 5: Values of p that minimize γ with $\mu = 20$.

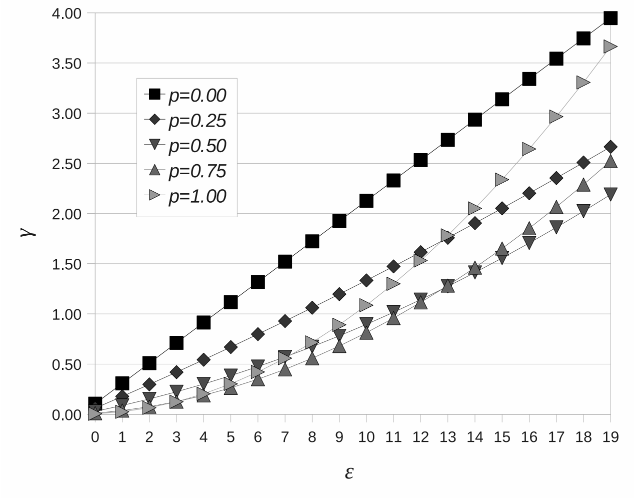

Figure 4: γ with $\mu = 20$, according to p.

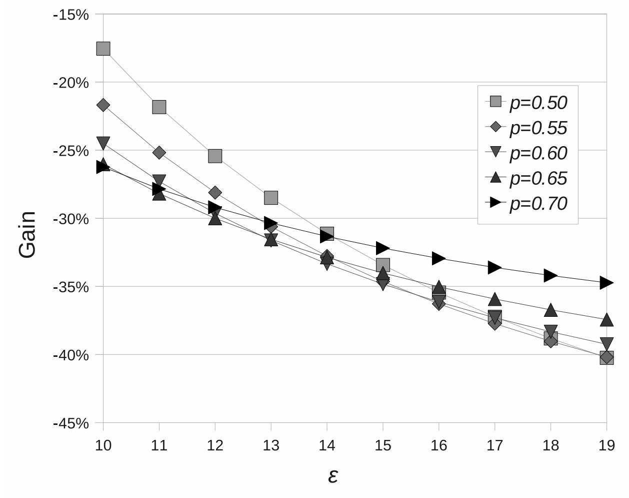

Figure 6: Gain of γ between PDCS with various p and DCS.

increases, but the engaged colors decrease. The decrease of engaged colors produces a decline in γ, until the number of colliding readers is stable. Since γ is the average number of second generation collisions produced by the collision of two readers, if $\gamma > 2$, the number of collision rises, while $\gamma < 2$, the number of collision decreases.

In order to find the optimal values of p that minimizes γ, we set to 0 the first derivative of (1) and solve it for p. So we have:

$$\gamma(p) = (1-p)^2 \cdot \gamma_1 + 2 \cdot p \cdot (1-p) \cdot \gamma_2 + p^2 \cdot \gamma_3 \; ; \qquad (38)$$

$$\frac{d\gamma}{dp} = (2p-2) \cdot \gamma_1 + 2 \cdot (1-2p) \cdot \gamma_2 + 2p \cdot \gamma_3 = 0 \; ; \quad (39)$$

$$p = \frac{2\gamma_1 - 2\gamma_2}{2\gamma_1 - 4\gamma_2 + 2\gamma_3}. \qquad (40)$$

Figure 5 shows the values on p that minimize γ with $\mu = 20$. Figure 6 shows the comparison among the γ values reached by PDCS and DCS. The comparison is performed for values of ϵ between $\frac{\mu}{2}$ and $\mu - 1$, since an efficient protocol should work with a value of ϵ close to μ. Setting p to a value consistent with the value of ϵ, PDCS reaches over 30% of reduction of γ, with respect to DCS.

5.1.5. Collisions with More Readers

The effects of a collision are different when more than 2 readers collide in the same timeslot. Figure 7 shows the color change probability after a collision among 3 readers:

1. no reader changes its color, so at the subsequent round the involved readers will receive a kick and they will change color without reservation;
2. one reader changes its color, so at the subsequent round two reader will receive a kick and they will change color without reservation, and the second reader will reserve a new color, maybe requiring another reader to change;
3. two reader changes its color, so at the subsequent round one reader will transmit with the previous color, and the

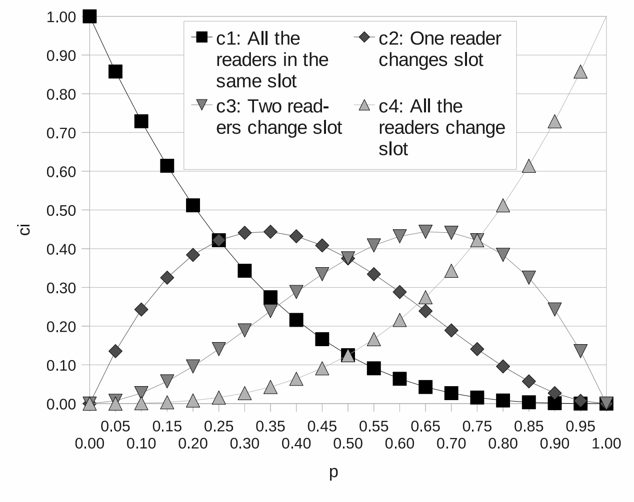

Figure 7: Color Change after a Collision between 3 Readers

other readers will reserve a new color, maybe requiring to other readers to change;

4. all the readers change color, this case corresponds to the DCS collision resolution.

Case 3 is the best, since one reader does not change color, with high probability to transmit. However, Case 1 and Case 2 are worse than Case 4, which corresponds to DCS, since they involve a larger number of kicks.

The highest value of c_3 is reached for $p = 0.66$, so the lowest γ can be reached when $0.66 < p \leq 1$, while after a collisions between 2 readers, the lowest γ can be reached when $0.50 < p \leq 1$. Also for collision among more readers, the best case requires always that only one reader doesn't change color. When the number of colliding readers is N, the probability of the best case is maximized by $p = \frac{N-1}{N}$. Therefore, collisions among a large quantity of readers require a larger value a p.

5.2. DCS-Like Protocol Behavior

An analysis of the behavior of DCS is required in order to compare PDCS to DCS. At this purpose we can evaluate ϕ and γ. When

- $\frac{\gamma}{\phi} > 1$, ϵ decreases according to the larger number of colliding slots, so $\frac{\gamma}{\phi}$ also decreases;
- $\frac{\gamma}{\phi} = 1$, the network is steady;
- $\frac{\gamma}{\phi} < 1$, ϵ increases, so $\frac{\gamma}{\phi}$ also increases;

Therefore the network should aim at a steady condition, where $\frac{\gamma}{\phi} \cong 1$. Moreover, the behavior of the protocols changes according to three classes of configuration:

1. $\mu \ll number\ of\ neighbors$, in this class the number of colors is too low, so the network is characterized by several collisions, the network tends towards high γ and ϕ, and their values are greater when μ is lower. Thus, the resulting WT could be poor, as the readers often have often to wait for many rounds;
2. $\mu \gg number\ of\ neighbors$, this class is characterized by some starting random collisions, and $\frac{\gamma}{\phi} \gg 1$, so the network tends towards a steady condition, without collisions; however, WT converges to $\mu - 1$, because each reader must wait for $\mu - 1$ slots between two transmissions;
3. $\mu \cong number\ of\ neighbors$, the best configurations can be found in this class, since it contains the configuration with the lowest μ so that the network tends towards a steady condition without collision. Apparently the best configuration should be $\mu = number\ of\ neighbors + 1$, but according to the previous analysis, if $\frac{\gamma}{\phi} > 1$ then ϕ increases, so the effects of the starting random collisions and the collisions due to a change of slot generated by a neighbor with a different neighborhood together with the high ϵ can cause a steady condition with collisions; therefore the best configuration shall require a larger μ.

The main effect of a proper $p < 1$ is the reduction of γ. This configuration also decreases the value of $\frac{\gamma}{\phi}$, so when $\mu \cong number\ of\ neighbors$, it shall tend towards a steady condition if there are also no collision with a lower μ.

6. Experimental Simulations

Simulations of DCS, Colorwave, AC_MRFID, and PDCS were performed on several kinds of RFID networks, with 250 readers, randomly and regularly deployed, considering a variable number of neighbors described by the average number of neighbors (AN) and its variance (NV).

Each protocol configuration was simulated 50 times for $2 \cdot 10^5$ timeslots. The simulator was written in Java language, and the simulations were run on a DELL Workstation Precision T7500, under Linux Operating System.

6.1. Colorwave Configuration

Here, PDCS is compared to DCS according to different values of μ.

Colorwave has been simulated with different configurations changing the values of the 4 thresholds with a step of 5%, in order to find the best configuration. The configuration which provides the best OARWT has been selected and used for the comparison. The selected thresholds are 85% (hard up), 75% (soft up), 55% (soft down), 25% (hard down). The provided performance are OARWT 7.54 s; TAWT 7.17 s; MWT 88.49 s; TWTV 64.80 s^2; VAWT 3.46 s^2; throughput 32.70 NT/s.

In Colorwave μ is dynamic, so in the following graphs that compare the performance of the described protocols according to μ, Colorwave is represented by a horizontal line.

6.2. PDCS Behavior According to μ

The value of μ must be carefully selected, in order to reach good performance. When μ is too low, the percentage of colliding transmissions is high, so WT is high and it is not steady. When μ is too high, WT is close to $\mu - 1$ timeslots. According to the theoretical analysis, the best value of μ is the lowest one that

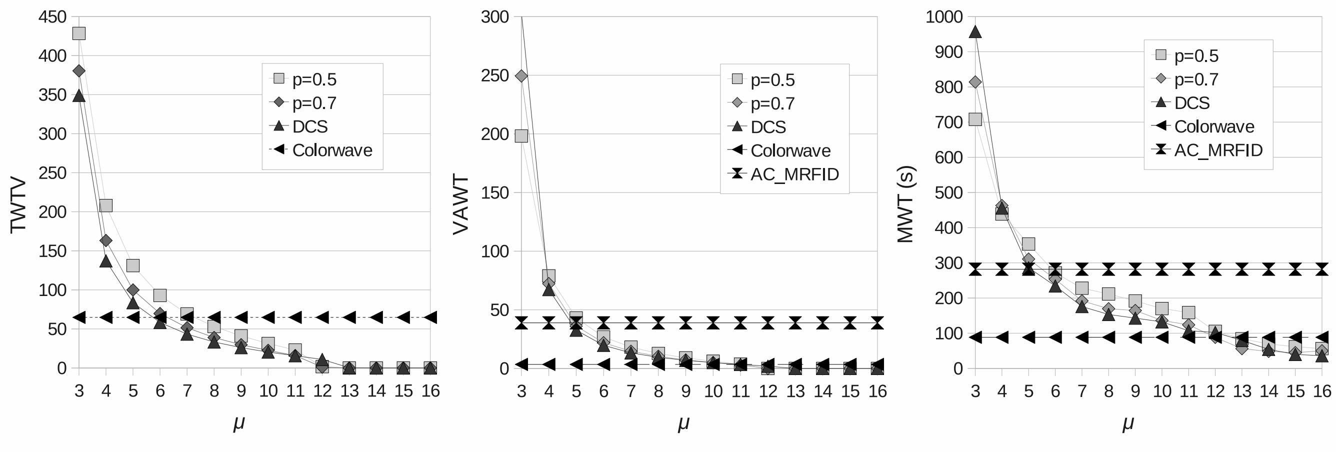

Figure 9: TVWT (a), VAWT (b), and MWT provided by DCS, PDCS, Colorwave, and AC_MRFID with AN = 9.94, NV = 9.41, and random deployment

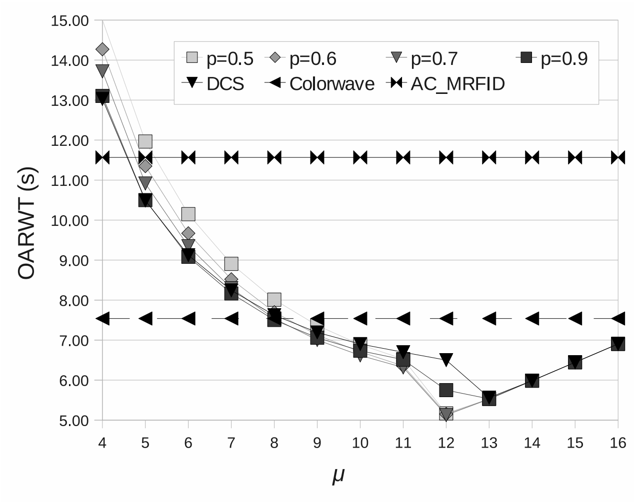

Figure 8: OARWT provided by DCS, PDCS, Colorwave, and AC_MRFID with AN = 9.94, NV = 9.41, and random deployment

Table 1: Performance of DCS and PDCS with μ = 12, AN = 9.94, NV = 9.41, and random deployment

	PDCS				DCS
p	0.5	0.6	0.7	0.9	1.0
NT/s	44.31	44.46	44.85	41.11	37.13
MWT	105.41	99.42	88.29	85.52	102.28
TAWT	5.09	5.10	5.10	5.16	6.28
TWTV	1.68	0.78	1.15	6.72	10.92
VAWT	0.03	0.03	0.00	0.79	1.93
OARWT	2.37	2.36	2.36	2.65	2.99

Table 2: Time reduction provided by PDCS with respect to standard DCS, with μ = 12, AN = 9.94, NV = 9.41, and random deployment

	$p = 0.5$	$p = 0.6$	$p = 0.7$	$p = 0.9$
NT/s	+19.34%	+19.75%	+20.79%	+10.73%
MWT	+3.06%	-2.79%	-13.68%	-16.38%
TAWT	-18.98%	-18.75%	-18.82%	-17.82%
TWTV	+243.27%	-66.33%	+135.67%	+371.97%
VAWT	-98.35%	-98.70%	-99.85%	-59.27%
OARWT	-20.78%	-20.97%	-20.99%	-11.44%

allows a steady WT. Furthermore, the theoretical analysis states that the introduction of $p < 1$ decreases the best μ improving WT.

Fig. 8 shows the OARWT provided by DCS and PDCS according to several μ and p, on a network with $AN = 9.94$, $NV = 9.41$, and random deployment. This graph is a good indicator of the time performance of the network. Fig. 9 shows the TWTV, VAWT, MWT, in the same conditions. The graphs support the results of the theoretical analysis presented in Section 5.2:

1. $\mu \ll number\ of\ neighbors$ ($\mu \ll 10$), the provided WT is not good, since the readers collide many times; DCS provides better performance, and PDCS provides the best OARWT with p as close as possible to 1;
2. $\mu \gg number\ of\ neighbors$ ($\mu \gg 10$), the network is steady, since there are no collisions; however, WT converges to $\mu - 1$ timeslots, because each reader must wait $\mu - 1$ slots between two transmissions; DCS and PDCS provide the same performance, independently from p;
3. $\mu \cong number\ of\ neighbors$ ($\mu \cong 10$), the best configurations are in this class, where the network tends towards a steady condition without collisions at the lowest μ; the best configurations require $\mu > 10$. In DCS and PDCS with a high probability ($p \geq 0.9$), the best OARWT is provided with $\mu = 13$. In PDCS with a probability $p < 0.9$, the

best OARWT is provided with $\mu = 12$. The best OARWT is provided by PDCS with $p = 0.72$ and $\mu = 12$, where OARWT= 5.08 s, 21.87% better than DCS with the same μ, and 8.69% better than the best configuration provided by DCS. The provided TWTV rapidly falls, according to the lower number of colliding transmissions. Tab. 1 shows the performance provided by PDCS and DCS with $\mu = 12$, and Tab. 2 shows the difference between PDCS and DCS in percentage. All the indicators show that a low p provides good performance.

Furthermore, Fig. 8 and Fig. 9 compare PDCS and DCS with Colorwave and AC_MRFID. Fig. 8 shows the OARWT provided by Colorwave and by AC_MRFID. AC_MRFID does not provide a good OARWT, since this algorithm gives more resources to the readers with less neighbors, decreasing the fairness among readers and OARWT. Colorwave provides a good OARWT, but it can not reach the one provided by the best configurations of DCS and PDCS.

Observing Fig. 8, Fig. 9, Table 1, and Table 2, we can state that:

- with a low p and $\mu \cong number\ of\ neighbors$, PDCS provides shorter OARWT;
- with a very low μ, a minor p in PDCS provides worse performance;
- with a very high μ, all the protocols provide the same efficiency;
- with a high μ, when all the configurations reach a steady network, all the protocols provide the same fairness, since VAWT is 0;
- when $\mu \cong number\ of\ neighbors$, PDCS with low p is the fairest, since more readers are reaching a steady behavior;
- with a very low μ, DCS is the fairest;
- the introduction of p reduces γ, decreasing WT, but it increases the possibility of a single reader to collide several consecutive times, according to Case 1 described in Section 5. The best MWT is normally provided by PDCS with a high p, since it decreases WT, with a low occurrence of Case 1.

6.3. PDCS Behavior According to AN

In order to analyze the behavior of PDCS according to networks with different size, PDCS and DCS have been simulated with networks with $3 \leq \mu \leq 12$.

Fig. 10 shows the difference between the OARWT provided by DCS and PDCS with various p. With a sparse network (AN$\leq$ 4) low values of p (0.5 and 0.6) provide results worse than DCS, instead with denser networks PDCS is always better than DCS. The best p is 0.7, which provides an optimal OARWT. Fig. 11 shows the OARWT provided by PDCS with $p = 0.7$ compared to DCS.

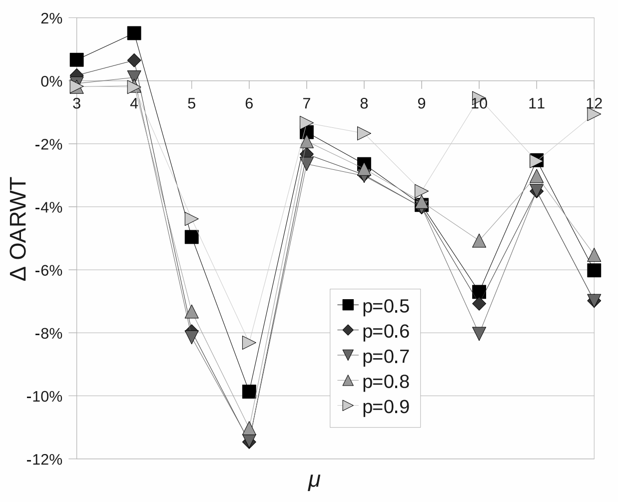

Figure 10: difference between the OARWT provided by DCS and PDCS with various p, with $AN = 9.94$, $NV = 9.41$, and random deployment

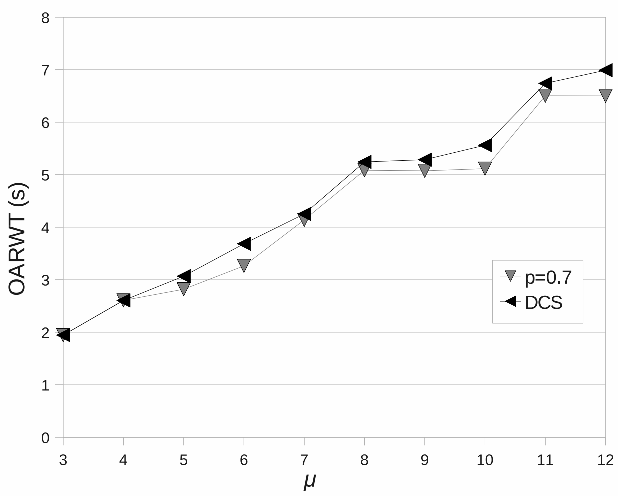

Figure 11: OARWT provided by DCS and PDCS ($p = 0.7$) with $AN = 9.94$, $NV = 9.41$, and random deployment

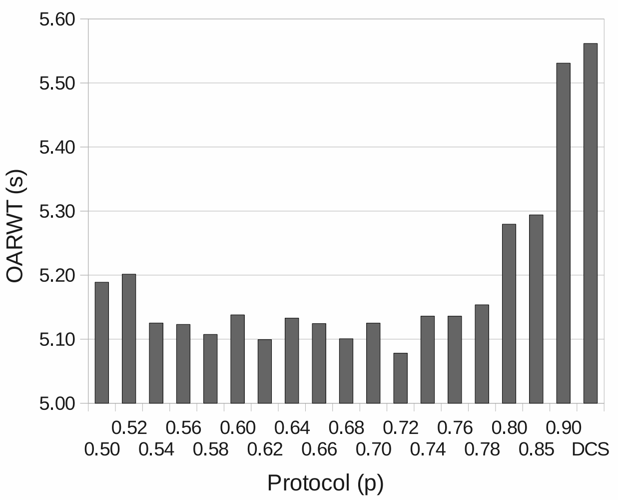

Figure 12: OARWT provided by DCS and PDCS with $AN = 9.94$, $NV = 9.41$, and random deployment

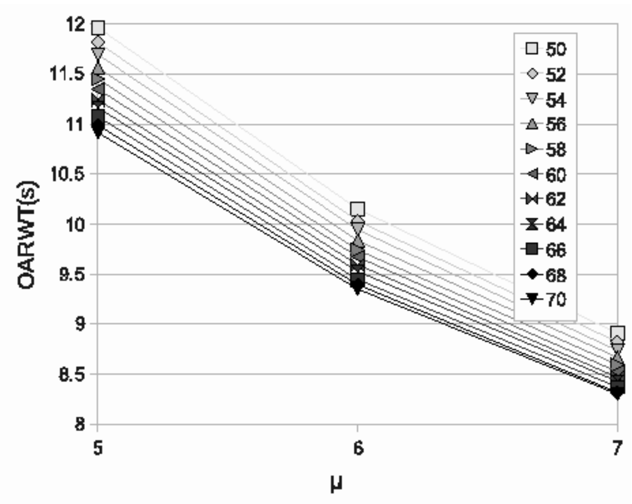

Figure 13: OARWT provided by PDCS, with $AN = 9.94$, $NV = 9.41$, and random deployment

6.4. Best PDCS Configurations

In order to find the best PDCS configuration, it is possible to observe which value of p provides the best OARWT. Fig. 12 shows the performance provided by DCS and PDCS in a network with $AN = 9.94$, $NV = 9.41$, and a random deployment. The best results are provided from $p = 0.5$ to $p = 0.78$. In this range OARWT fluctuates between 5.08 and 5.19.

Since several values of p provide good results with a proper μ, also their performance with a worse μ must be analyzed. When μ is too high, p does not affect the performance, and always PDCS provides the same result. However, when μ is too low p strongly affects the performance. Fig. 13 shows PDCS with $0.5 \leq p \leq 0.7$, $5 \leq \mu \leq 7$. Although the values of p are similar, OARWT does not fluctuate, and the higher p always provides a lower OARWT.

Therefore, $p = 0.7$ is an optimal configuration, since it provides good OARWT with a proper μ, and an OARWT better than the one provided with a lower p and a low μ.

6.5. Matrix Vs Random Deployment

In order to reach a selected number of neighbors, several random deployments have been considered, with the same number of readers but on areas with different sizes. However, in order to check how different deployments with similar AN affect performance, we have simulated also a network with matrix deployment, where the locations of the readers create a regular shape representing a matrix. The performance of PDCS and DCS on a network with random deployment, $AN = 9.94$, and $NV = 9.41$, and on a network with matrix deployment, $AN = 9.94$, and $NV = 3.90$ have been analyzed. Fig. 14 shows the provided OARWT. All the protocols provide better performance on the matrix deployment. The best OARWT is provided by PDCS with $p = 0.5$ and $\mu = 11$, where OARWT= 4.68 s, 22.92% better than OARWT provided with the same μ, and 8.17% better than the best DCS configuration.

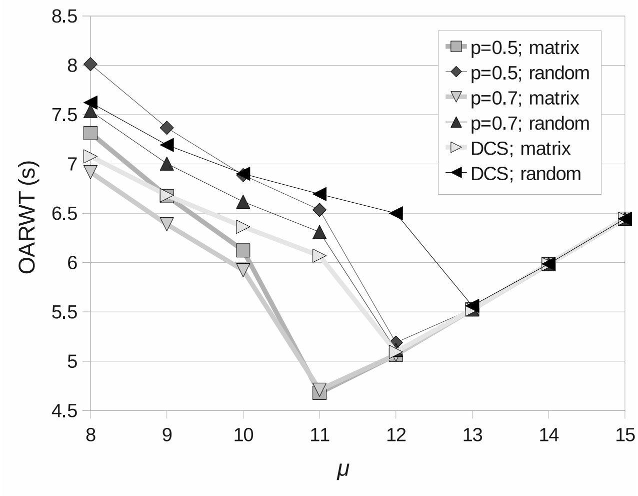

Figure 14: OARWT provided by DCS and PDCS with $AN = 9.94$, $NV = 9.41$, random deployment and $AN = 9.94$, $NV = 3.90$, and matrix deployment

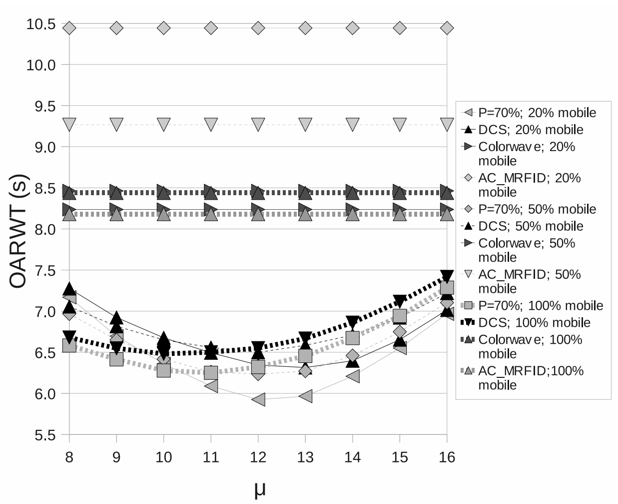

Figure 15: OARWT provided by DCS, PDCS, Colorwave, and AC_MRFID with starting $AN = 9.94$, $NV = 9.41$, random deployment, and 20%, 50%, and 100% of mobile readers

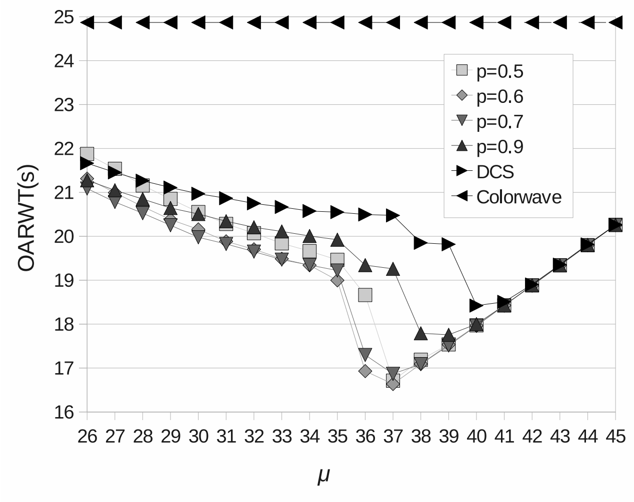

Figure 16: Effects of p on OARWT with $AN = 29.92$, $NV = 70.19$, and random deployment

6.6. Mobile RFID Networks

Real RFID applications can require networks composed of mobile readers mixed to static readers. The presence of mobile readers affects the performance of anticollision protocols, because when a reader changes location it finds new neighbors with new colors.

Fig. 15 shows the OARWT provided by PDCS, DCS, Colorwave and AC_MRFID in a network with $AN = 9.94$, $NV = 9.41$, random deployment, and 20%, 50%, and 100% of mobile readers. Similarly to static networks, the best results, at $\mu = 12$, are provided by PDCS with $p = 0.7$. However, the curves of DCS and PDCS change more slowly than in previous graphs, and they are shifted up, since mobile readers can not reach a steady color, and shifted left, since the quantity of neighbors is more regular. The OARWT provided by Colorwave is only slightly worse with several mobile readers, since the negative effects due to the impossibility to reach a steady color configuration are reduced by the adaptable parameter μ. Differently from other protocols, the OARWT provided by AC_MRFID improves with mobile readers, since this protocol adjusts rapidly its configuration to the new position of readers, and the adopted method is suitable to regular quantity of neighbors per reader.

6.7. Dense RFID Networks

The results of the simulation of PDCS with dense RFID networks are similar to the results for networks with less neighbors, but the gap between PDCS and DCS time performance is wider. The simulations have been performed considering $0.5 \leq p \leq 1$, with a step of 0.1.

Figure 16 shows the OARWT provided by PDCS and DCS for a network with $AN = 29.92$, $NV = 70.19$, and random deployment. The best OARWT, with $p = 0.6$ and $\mu = 37$ reaches 18.75% time reduction with respect to the OARWT of DCS with the same μ, and 9.69% with respect to the best OARWT provided by DCS with $\mu = 40$.

7. Conclusion

The paper proposes PDCS, a new reader-to-reader anticollision protocol. The proposed protocol is multichannel, according to the international regulation for UHF RFID. Thanks to the parameter p, representing the probability to change color after a collision, the number of collisions is lower, and PDCS reaches a steady state with a lower μ. A theoretical analysis demonstrates that the correct configuration of p can provide over 30% reduction of second generation collisions (γ).

Several evaluation methods have been analyzed, and an evaluation approach based on Waiting Time (WT) has been adopted. The Overall Average Reader Waiting Time (OARWT) has been chosen as the main parameter representing the efficiency of the network. The time performance provided by PDCS is better than state-of-the-art approaches. A theoretical analysis justifies the improvement. Experimental simulations validate the theoretical analysis, showing that PDCS can reach a time reduction about 10%, compared to the best DCS configuration. PDCS results also fairer than DCS, since all the readers have more possibility to transmit. According the analysis, the best configuration of PDCS requires $p \cong 0.7$. For all the analyzed networks, values close to 0.7 provide optimal performances.

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