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Low Access Delay Anti-Collision Algorithm for Readers in Passive RFID Systems

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Abstract Even though radio frequency identification (RFID) systems are spreading more and more as a medium for identification, location and tracking purposes, some reliability issues of these systems still need to be solved. In fact, RFID readers and tags experience collisions when sharing the wireless transmission channel over the same area. In this work, we propose a centralized scheduling-based algorithm as possible candidate solution for the reader collision problem in passive RFID systems. This algorithm has been designed taking into account the circuitry limitations of the tags, which do not allow the usage of frequency or code division multiple access schemes in passive RFID systems. The solution herewith proposed, which is suitable for those scenarios involving static or low mobility readers, aims at preventing reader collisions and provides at the same time low channel access delay to the readers. The performance of this algorithm has been tested via computer simulations. The results show that the proposed solution strongly reduces collision occurrences and, especially in static scenarios, provides low access delay to the readers during the channel contention phase.

Keywords RFID · Anti-collision algorithm · Reader · Scheduling · Channel access delay · Collision avoidance

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1 Introduction

Though not being a brand new technology, Radio Frequency Identification (RFID) is expected to play a key role in several economic sectors as a medium of asset identification, location and tracking through the whole productive chain in the near future [1].

The identification process by means of RFID systems is carried out as follows: a mobile RFID tag, after being queried by an apposite RFID reader via wireless connection, replies to the reader sending its own ID code [2]. However, as wireless devices sharing the same transmission channel, RFID readers and tags experience interference and collisions among themselves when placed in the same area, thus requiring the use of a medium access technique or of an anti-collision algorithm [3].

Basically, two different kinds of collisions can be experienced. The first one occurs when a reader communicates with two or more tags simultaneously [4] (referred to as tag-to-tag collision or tag collision problem), while the second occurs when two or more readers are communicating at the same time with one or more tags [5] (reader collision problem).

In this paper, one presents an algorithmic solution to the reader collision problem, while the tag collisions are not taken into account. Only passive tags, which harvest energy from the signal received by the reader instead of using a battery [2], are here considered.

The purpose of the proposed algorithm is two-fold. First, the aim is to avoid the collisions among the readers rather than to mitigate their mutual interference. Second, the reduction of the access delay of the readers to the channel is also targeted in this work. In fact, for some specific applications (i.e. check points placed in gates or portals), the access delay is as important as the collision avoidance. Thus, the access delay is of primary importance for evaluating the performance of the anti-collision for those scenarios in which a high reactivity is absolutely required for the RFID readers.

Some proposals to cope with the reader collision problem have already been issued [6–9]. Nevertheless, most of these solutions are not suitable to be implemented in the RFID systems due to the hardware limitations imposed by the low cost passive tags which, mainly due to the cost limitations, do not have high computational or filtering capabilities [7,9]. Furthermore, most of the reviewed works do not consider the performance of the proposed algorithm in terms of access delay of the RFID readers.

The reader anti-collision algorithm presented in this paper consists of a centralized scheduler which dynamically assigns the readers a time slot, depending on the channel occupancy. The proposed solution, designed based on the previously mentioned hardware limitations imposed by the passive tags and aiming to keep the access delay to the channel as low as possible, is specially suitable for scenarios employing static readers. However, though with lower performance in terms of access delay, the algorithm is still effective against collisions even with low mobility (pedestrian) of RFID readers. This paper is an extended version of [10].

The remainder of this paper is organized as follows. In Sect. 2 the architecture of the RFID systems is presented, while in Sect. 3 an overview of the state-of-the-art concerning reader anti-collision algorithms is given. In Sect. 4, one presents the proposed algorithm, while the simulation results are reported in Sect. 5. In Sect. 6, conclusions are drawn.

2 RFID Systems and Reader Collision Problem

2.1 RFID Systems Architecture

The purpose of the RFID systems in companies or warehouses is to collect the data from the tags, read by the readers, which are connected to a central unit responsible for collecting the

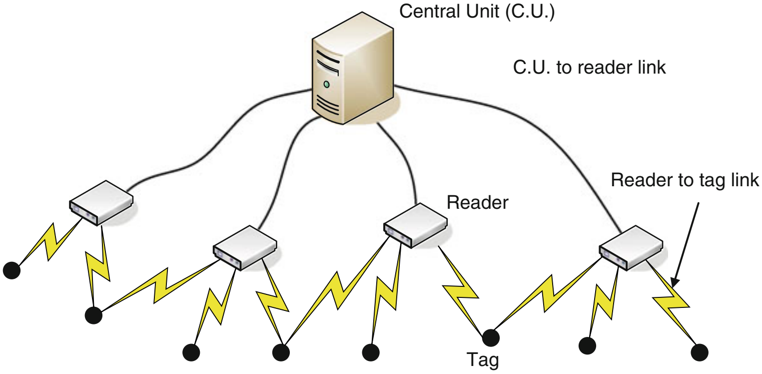

Fig. 1 RFID system architecture

data [1]. Thus, the RFID systems have implicitly a centralized networking architecture, where all the readers have a communication link (wired or wireless) to the central unit (see Fig. 1).

The readers can be either fixed or mobile. The wireless links between readers and tags can change frequently, due to the mobility of the tags and potentially of the readers. Thus, the number of tags which can communicate with the same reader is a priori unknown. This implies that the time required by a reader to read all the tags in its read range is also a priori unknown. For this reason, it is not possible to estimate the time that reader will need in order to read all the tags in its read range.

In order to solve the tag-collision problem, the reader-tag communication is carried out by a tag anti-collision algorithm [11], whose usage is also required by the standard EPC Class 1 Generation 2 (EPC C1G2) [12]. For this reason, we assume that our network is tag collision-free. Furthermore, as outlined in Sect. 1, the tags are supposed to be passive, without any filtering capability. Moreover, due to the limitation in the computational power of the tags and in order to avoid undesired increases in their circuitry complexity and cost, one considers to exclude them from the algorithm implementation as a constraint to the solution to be designed.

2.2 Reader Collision Problem

A reader can be thought as a device able to read all the tags within a certain distance r_r (read range) from its antenna (which is here supposed to be omni-directional). Anyway, the signal emitted by the reader can still interfere with readers or tags within a given distance r_i (interference range) from its antenna (see Fig. 2), with $r_i \geq r_r$ [6,7]. Moreover, two readers out of their mutual read ranges can still interfere with an intermediate tag (see Fig. 2), leading to the well known hidden terminal problem [6,7].

3 Related Work

Due to the hardware limitation of the passive tags outlined in Sect. 1, the standard multiple access techniques are not directly applicable to the considered RFID network.

As far as it concerns Frequency Division Multiple Access (FDMA), the use of different sub-bands in order to allocate several interfering readers would require the tags to be able to

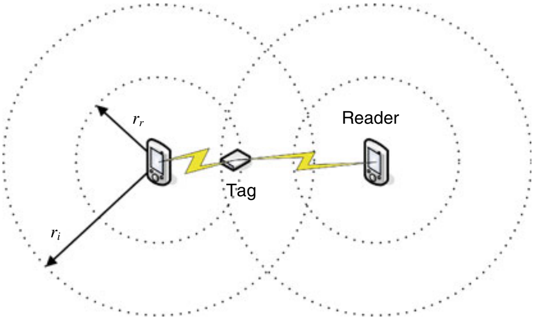

Fig. 2 Read and interference ranges

separate their band of interest from the unwanted ones. Since passive tags do not have this filtering capability, the necessary addition of circuitry would lead to an undesired increase in tag complexity and cost [7]. Indeed, the standard EPC C1G2 [12] provides a way to spectrally separate the transmission of the readers from that of the tag, but this turns out to be effective only to limit the interference experienced by the readers and not that experienced by the tags. Thus, collisions may still occur. Also Code Division Multiple Access (CDMA) turns out to be not suitable for RFID systems, as the encoding and decoding processes require extra computational capabilities in the tags [7].

The usage of carrier sense multiple access-collision avoidance (CSMA-CA) algorithm (initially proposed for the standard IEEE 802.11) for anti-collision purposes has been regarded as non effective against the hidden terminal problem that affects the readers in passive RFID system [7].

From the implementation complexity point of view, Time Division Multiple Access (TDMA) seems to be more suitable than the above-mentioned access techniques for RFID systems. However, as the time required for the readers to read the tags is a priori unknown, it is not possible to allocate the readers to tag communication in a predetermined number of time slots.

One of the first proposals to solve the reader anti-collision problem was a TDMA-based distributed algorithm, i.e. Colorwave [8]. In this algorithm, the time is divided in frames and, in turn, each frame is divided in slots, which are referred to as "colors". In order to share and reuse these colors in such a way that no collision occurs, each reader is supposed to choose a different color within the frame with respect to its colliding neighbors. When using Colorwave, the readers attempt to transmit over a given slot and, in case that any collision is detected, they choose a different time slot. After changing color, the reader must inform its neighbors that a redistribution of colors among neighbor readers is necessary. However, this method requires the readers to be able to detect collisions, which is not easily implementable, unless the tags collaborate in this process [7]. Unfortunately, this does not match with the requirements reported above in Sect. 2.1.

Pulse protocol [7] has been proposed to solve the hidden terminal problem. Basically, two non-interfering channels are used by this algorithm. The first one, i.e. the control channel, is reserved for reader-to-reader communication while the second, i.e. the data channel, is employed for reader-to-tag communication. While transmitting, each reader broadcasts a beacon message over the control channel, so that the potentially colliding readers are aware of this transmission and they delay their access to the channel. By properly adjusting the transmission power over the control channel, the algorithm ensures that the beacon message can be received by all the readers which could experience collisions with the transmitting one. However, being basically a contention based method, the access delay performance of

Pulse can be low, especially when the density of readers contending the channel increases. Hence, one believes that a centralized coordination of the readers for the anti-collision protocol could provide a gain in terms of access delay performance with respect to a distributed contention based approach.

Slotted-Listen Before Talking (Slotted-LBT) is a medium access technique for RFID readers which was proposed in [9]. This scheme reduces the interference among the readers, while working in a readers-dense environment. Based on the carrier sensing or Listen Before Talk (LBT), this algorithm makes use of several channels, which is not practical if the tags have no filtering capabilities. Furthermore, even though this algorithm is beneficial to reduce the interference among readers [9], the carrier sensing is not always effective to avoid collisions, for example due to the hidden terminal problem [7] (two readers far from each other but interfering with respect to a tag—see Fig. 2—cannot detect their mutual transmissions, as the carrier sensing is carried out in the readers and not in the tag).

In [13], the authors proposed a solution that dynamically assigns different frequencies to the neighbor readers, with both the aims of minimizing the collision occurrences and reducing the number of required bands to allocate the RFID readers. This algorithm, also called Hierarchical Q-Learning (HiQ), is based on reinforced Q-learning which first learns the collisions pattern and then assigns the bands to the readers so that to minimize their collisions. However, also HiQ relies on the collision detection which, as previously observed, is not easily implementable without involving the tags in this process. Furthermore, as the passive tags have no filtering capabilities, the usage of different bands for allocating the neighbor readers does not reduce the interference caused by the readers to the tags and thus it does not prevent the collisions in an effective manner.

4 Proposed Algorithm

The proposed solution is a centralized algorithm, which schedules in different time intervals the potentially colliding readers willing to transmit.

The RFID network is represented as a non-oriented graph, with the potentially colliding vertices (readers) connected by an edge. In order to build the graph, each reader broadcasts periodically a beacon message carrying its own identification number (ID). All the receiving readers forward this information about their colliding neighbors to the central unit, which can then build the collision graph. As suggested in [7], the beacon messages are sent over a control channel, in order to avoid interference with the reader to tag communication. Furthermore, in order to avoid collisions among beacons, the readers should send the message in different time periods. The broadcasting periodicity T_{beacon} should be set in accordance to the mobility of readers.[1] In order to make the algorithm effective against the hidden terminal problem, the beacon should be received at a distance r_b (beacon range) from the transmitting reader,[2] with $r_b \geq r_i + r_r$ [7] (see Fig. 3).

Once the collision graph is built and kept updated, the algorithm can schedule the adjacent (colliding) readers to transmit in different time periods. The scheduling is proposed in different versions, which are explained hereafter.

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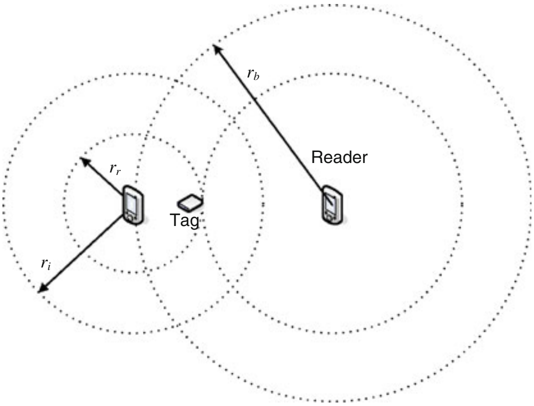
[1] The topology is likely to change fast if the readers move with high speed, thus requiring to update the graph at a higher rate, i.e. to broadcast the beacon message more often.

[2] A tag located at the edge of the reading zone (at a distance r_r from the transmitting reader) can be interfered by a reader located at distance r_i from the tag. Thus, to make it sure that this does not occur, r_b should be not less than $r_i + r_r$.

Fig. 3 Beacon range



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Variables:
Collision graph $G$: (Reader set $V$, edge set $E$)
Set $T$ of transmitting readers and set $Q$ of readers waiting for transmission.

CASE: $T_{beacon}$ expired.
1. Update the collision graph $G$.

CASE: A reader $R$ requires to have access to channel.
1a. Check from $G$ if the reader $R$ collides with any transmitting reader in $T$.
2a. If so, postpone the transmission of $R$ (add the reader $R$ to $Q$).
3a. Otherwise, let the reader $R$ transmit (add $R$ to $T$).

CASE: A reader $R$ terminates its transmission.
1b. Remove $R$ from $T$.
2b. Check if there are some readers waiting for transmission (in $Q$) which do not collide
with any of the transmitting readers in $T$.
3b. If so, from 2b. find any of the sets with the maximum number of readers that can
transmit simultaneously without collision and let them transmit.
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Fig. 4 Algorithm version 1

In the first one, referred to as "Version 1", each time a new reader requires to have access to the channel, the algorithm checks first if some of its neighbors are transmitting. In case the channel is free (no transmitting neighbors), the reader can have access to it. Otherwise, the access will be postponed till the neighbors have finished their transmissions. The algorithm tries to schedule the maximum number of non-colliding readers to transmit at the same time. The pseudo-code for the algorithm "Version 1" is shown in Fig. 4.

Let us notice that only the readers that required accessing the channel are scheduled by the algorithm which, in order to reduce the average access delay, tries to allocate the maximum number of non-colliding readers at the same time.

The second version of the algorithm ("Version 2"), though similar to the previous one, follows a different approach. In this case, the reduction of the readers' access delay is carried out by giving priority to the reader which first requested accessing the channel. Basically, when storing the reader's ID in the waiting set Q, also the reader's storage time is memorized. This allows to give a priority to those readers which spend a waiting time longer than a certain time T_{th} (queue threshold time), which is one of the "Version 2" algorithm parameters. Whenever a reader R_p stays in the queue Q for a time longer than T_{th}, all the new incoming readers willing to transmit and potentially colliding with R_p are put in the queue, even if the

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Variables:
Collision graph $G$: (Reader set $V$, edge set $E$).
Set $T$ of transmitting readers, set $Q$ of readers waiting for transmission and set $Q_p$ of reader with priority.

CASE: $T_{beacon}$ expired.
1. Update the collision graph $G$.

CASE: A reader $R$ requires to have access to channel.
1a. Find the priority readers (those standing in the queue longer than $T_{th}$ and add them to $Q_p$).
2a. Check from $G$ if $R$ collides with any reader in $T$ or in $Q_p$.
3a. If so, postpone the transmission of $R$ (add the reader $R$ to $Q$).
4a. Otherwise, let the reader $R$ transmit (add $R$ to $T$).

CASE: A reader $R$ terminates its transmission.
1b. Remove $R$ from $T$.
2b. Find the priority readers (those standing in the queue longer than $T_{th}$) and add them to $Q_p$.
3b. Find the highest priority reader (that standing for longest in $Q_p$) and let it transmit if it does not collide with any reader in $T$.
4b. Check if there are some readers in $Q$ which do not collide with any reader in $T$ or in $Q_p$.
5b. If so, find from 4b. the maximum number of readers that can transmit simultaneously without collision and let them transmit.
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Fig. 5 Algorithm version 2

channel is free. Then, as soon as the R_p transmitting neighbors finish their transmission, R_p can have access to the channel. The purpose of giving priority to the reader R_p is to avoid that it stays in the queue (with an increase of its access time) for a long time. The pseudo-code of the "Version 2" of the algorithm is presented in Fig. 5.

One could point out that the operation of finding the maximum number of non-colliding readers performed in the algorithms presented above becomes a high computational complexity problem (i.e. coloring problem in graphs [5]) when the number of graph's nodes is large. Nevertheless, in the algorithm implementation, this operation is not performed over the whole set of readers but only over the subset of readers waiting for the transmission and not potentially colliding with the transmitting readers.

Indeed, it has been verified by simulation that the cardinality of this subset is small enough to guarantee that the time to find the maximum number of non colliding readers does not impact the algorithm delay performance.

5 Simulation Results

In this section, one presents a comparison between the algorithms proposed in Sect. 4 and "Pulse algorithm" [7] which, among all the solutions taken into account, is the only one aiming to avoid collisions and not just to limit the mutual interference among readers. Furthermore, [7] does not involve the tags in the algorithm implementation as no collision detection is required. Since these characteristics belong also to the algorithm proposed in this paper, the comparison of these two solutions is fair (Table 1).

As the aim of this present study is the performance evaluation of our solutions in terms of the access delay of the readers to the channel and the collision avoidance, three different metrics are considered, that is, average access delay D_{av}, maximum access delay D_{max} and collision avoidance efficiency η_{ca}. As proposed in [7], the η_{ca} is defined as follows:

$$\eta_{ca} = \frac{\text{Successful tag reads carried out by all the readers}}{\text{Total tag reads attempted by all the readers}}. \qquad (1)$$

Table 1 Qualitative comparison of anti-collision algorithms

Algorithm	Pros	Cons
EPC C1G2 FDMA-based Scheme [12]	Reduces the interference among readers	Reduces only the interference rather than preventing collisions
Colorwave [8]	Reduces the collisions among readers	Relies on collision detection, which is not feasible unless the tags are involved in this process
Pulse [7]	Effective against collisions. Solves the hidden terminal problem	Being a contention-based method, readers may suffer from high access delay when working in readers-dense environments Designed for mobile scenarios
Slotted-LBT [9]	Reduces the interference among readers. Low access delay	Not so effective to reduce the interference caused by the readers to the tags
HiQ [13]	Reduces the interference among readers	Not so effective to reduce the interference caused by the readers to the tags, as it is based on the use of different transmission bands for the readers Relies on collision detection, which is not feasible unless the tags are involved in this process

Table 2 Simulation parameters

Area	Squared room 10 m × 10 m
Number of readers N_r	10, 15, 20, 25, 30
Number of tags N_t	400
Read query model	Exponentially distributed, average arrival time 50 ms

5.1 Simulation Scenario and Parameters

The parameters used in the simulation are reported in Table 2.

The simulation has been carried out under the assumptions that the signal transmitted by the omni-directional antenna of the reader propagates according to the free-space path loss model and that no interference is experienced between the control channel and the channel used for reader-to-tag communication. Several values of N_r allow to test the algorithms for different readers' densities, while N_t is high enough to ensure that there is at least one tag in each reader's read range.[3]

Readers can have read range r_r varying from some centimeters up to some meters [2,4]. Furthermore, it is sometimes possible to adjust r_r by setting the transmission power [7]. In this case, r_r has been set to 0.96 m, which is proportioned to the dimensions of the considered environment. The interference range r_i can be obtained by considering the following approximated model for the interference phenomenon. Given the minimum signal power

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[3] When a tag is inside both a reader's read zone and a different reader's interference zone, a collision occurs (Fig. 2). The detection of this kind of collision in the simulator requires at least one tag in the read range of each reader.

Table 3 Simulation parameters for static readers scenario

Beacon range r_b	4 m
Tag read time	T_{tx} uniformly distributed over $[T_{min}, T_{max}]$
T_{min}	10 ms
T_{max}	160, 320 ms
Queuing threshold time	$T_{th} = N_r \cdot 0.1$ s

P_{dec} necessary to perform a correct decoding of the received signal, any other signal transmitted by interfering readers can interfere with tags or readers when its power P_{int} at receiver verifies $P_{int} \geq P_{dec} - 10$ dB [7]. Thus, if $r_r = 0.96$ m, considering an attenuation of 10 dB, r_i becomes 3.04 m.

The read query average arrival time of 50 ms, clearly too high for a realistic case, has been set in order to test how the algorithm behaves in the worst case scenario, i.e. when all the readers attempt to access the channel.

5.2 Static Scenario

In this subsection, all the readers are considered to be fixed in order to test the access delay performance provided by the anti-collision algorithms for static scenarios. The additional parameters set for this scenario are reported in Table 3.

With reference to Table 3, the beacon range has been set to 4 m. With r_i and r_r set as reported in Sect. 5.1, 4 m is the minimum value of the beacon range for which it is possible to prevent the hidden terminal problem (see Sect. 4).

In the simulator, we suppose that the time T_{tx} taken by a given reader to read all the tags in its read zone is uniformly distributed over T_{min} and T_{max}, where $T_{min} = 10$ ms is approximately the time required to read only one tag [11]. In order to test how the access delay varies depending on the average value of T_{tx},[4] 160 and 320 ms have been chosen for T_{max}. With $T_{min} = 10$, 160 and 320 ms are the time values necessary to read 16 and 32 tags, respectively (i.e a reasonable number of tags on a shelf).

Regarding the parameter T_{th} of the "Version 2" of the scheduling algorithm (i.e. the waiting time after that a reader gets priority in the scheduling), this has been set to $N_r \cdot 0.1$ sec. Considering the simulated scenario, this value guarantees that T_{th} is not less than the average waiting time D_{av} of a reader in the queue, which is shown to increase when N_r increases.

The performance metrics here taken into account are average and maximum access delays, while the collision avoidance efficiency is not considered. In fact, due to the used signal propagation model (e.g. free-space path loss, with no obstacles and no signal reflections), all the algorithms are fully able to avoid collisions once $r_b \geq r_i + r_r$ (see Sect. 4). Indeed, the simulations showed that the efficiency is 1 for all the static cases which have been tested.

In Fig. 6, the results concerning the average access delay of the three algorithms are presented. As it is possible to see from the plot in Fig. 6, the average delay D_{av} increases as the number of readers increases. It turns out that the pulse algorithm exhibits higher values of D_{av} with respect to both the scheduling algorithms here proposed. As far as it concerns D_{av},

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[4] A reader in the queue must wait for the transmitting readers to finish their own transmission before accessing the channel. Hence, the reader access delay depends also on the time T_{tx} taken by readers to read all the tags in their read zone.

Fig. 6 Average access delay

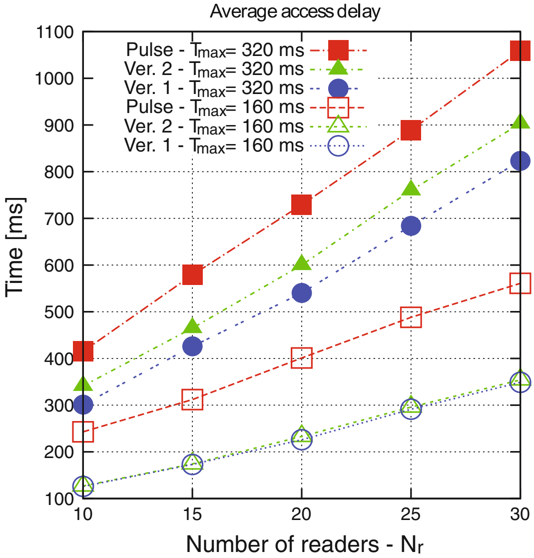
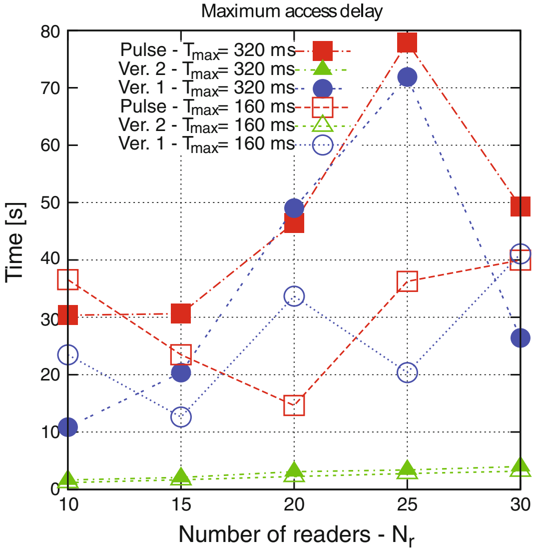


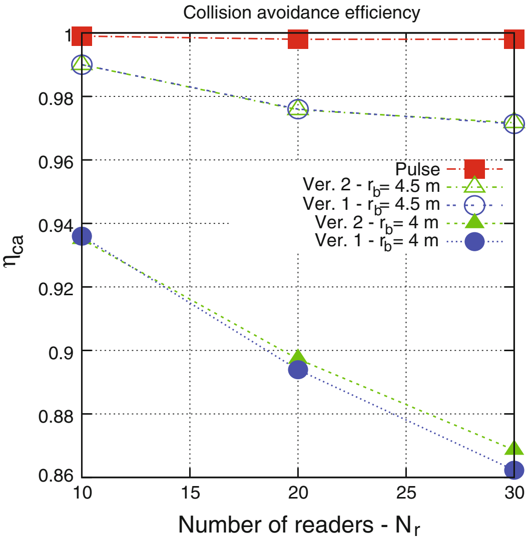
Fig. 7 Maximum access delay



"Version 1" and "Version 2" of the scheduling algorithm have similar performance when $T_{max} = 160$ ms, while "Version 1" shows a lower D_{av} as T_{max} increases.

Nevertheless, "Version 1" still suffers from high maximum access delay, which can be sometimes even higher than the value shown by Pulse (Fig. 7). Let us notice that, since D_{max} depends more on the position of readers randomly placed in the area rather than on N_r, D_{max} is not necessarily an increasing function of N_r. However, the problem of the high maximum access delay is well solved by the "Version 2", which in fact explicitly aims to limit the maximum value of D_{max} by prioritizing the readers which are in the waiting state for longer than a certain threshold T_{th}. Indeed, as it can be seen from Fig. 7, the values of D_{max} for the "Version 2" algorithm are much lower compared to the other algorithms.

Fig. 8 Collision avoidance efficiency in mobile scenario



This means that limiting the average access delay does not contribute necessarily to limit the maximum access delay. In fact, in order to reduce D_{max}, the anti-collision algorithm should make use of an explicit control of the maximum delay, e.g. a priority queue as proposed in this paper.

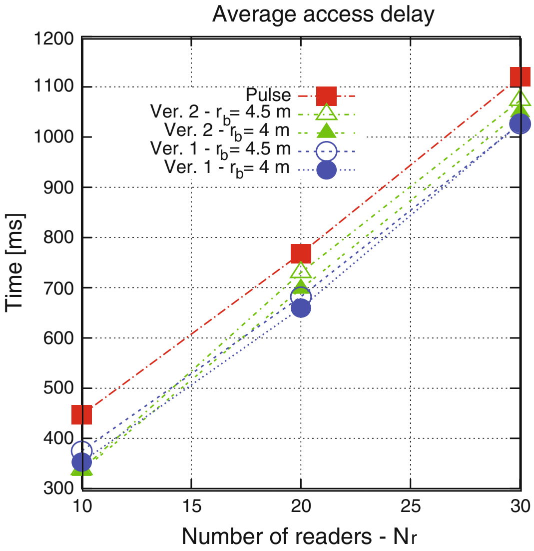
5.3 Mobile Scenario

In this subsection, the effect of the readers' mobility on the algorithms' performance is taken into account. In order to have results closer to a realistic case, in the simulation the readers do not move continuously, but each of them alternates a period of motion T_{mot} and a period of immobility T_{stat}. Both T_{mot} and T_{stat} are set to 10 s. During the period T_{mot}, the readers move independently with a constant speed of 1 m/s (pedestrian mobility). The parameter T_{max} is set to 320 ms, while T_{beacon} is set to 1 s. This value is low enough in order to guarantee the proper update of the collision graph for the adopted model of mobility.

Concerning the value of the beacon range, 4 and 4.5 m have been chosen for r_b. As observed in Sect. 5.2, 4 m is the minimum value of the beacon range for which it is possible to prevent the hidden terminal problem in static scenarios. However, in mobile environments where the readers can change their position over time, increasing r_b helps to prevent collisions. Unfortunately, this is paid in term of access delay, which increases as r_b increases. As it will be shown later in this subsection, the value 4.5 m for r_b will provide a good trade-off between the collision avoidance and the access delay performance.

Due to the mobility, readers communicating with tags can interfere with each other while moving and thus the collision avoidance efficiency η_{av} is used to evaluate the anti-collision algorithm performance in this scenario. The plot in Fig. 8 shows the results concerning η_{av} versus the number of readers. From this plot we can notice that Pulse outperforms the scheduling algorithms in terms of η_{ca}. However, after increasing r_b from 4 to 4.5 m, the values of η_{ca} improve and the difference between the Pulse algorithm and the proposed scheduling algorithms becomes smaller. In fact, with $r_b = 4.5$ m, η_{ca} is close to the unitary value for all the tested N_r. Let us notice that the value 4.5 m is not considered for Pulse algorithm,

Fig. 9 Average access delay in mobile scenario



as its η_{ca} values are already very close to 1 with $r_b = 4$ m and there is then basically no need of increasing its performance. Hence, even though the performance in terms of collision avoidance is lower for the scheduling solutions than for the Pulse algorithm, the results show that the proposed algorithms successfully avoid collisions among readers.

The performance of the algorithms in terms of average access delay is shown in Fig. 9. From the plot in Fig. 9 we can see that, even in mobile scenarios, the scheduling algorithms have better performance compared to the Pulse algorithm as far as the access delay is concerned. Even when we increase r_b from 4 to 4.5 m, the average access delay of the proposed algorithms is still lower than the one of the Pulse algorithm, though this reduction of access delay given by the proposed solutions is lower with respect to the case of static readers.

Thus, altogether, the proposed algorithms represent an effective solution to the reader collision in the mobility case, since they avoid up to 97–99% of the collision occurrences, while providing a low channel access delay to the readers.

6 Conclusions

In this work, we have proposed a solution for the reader collision problem in passive RFID systems and we compared it with the Pulse algorithm in terms of collision avoidance and channel access delay. The simulation results show that the proposed algorithm effectively avoids the collisions in static readers scenarios and reaches collision avoidance efficiency values between 0.97 and 0.99 in mobile readers scenarios. In static readers scenarios, our solution considerably reduces the average access delay that the readers experience during the channel contention phase. Furthermore, one of the two versions of the algorithm is shown to be effective in limiting the maximum access delay of the readers, which is instead not possible by using contention-based methods such as Pulse.

The future work on this topic will aim at enhancing the access delay performance in mobile readers scenarios.

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Neeli Prasad IEEE Senior Member, Head of research at the Center for TeleInfrastruktur (CTIF) at Aalborg University and Director of CTIF-USA, Princeton, USA. She has over 14 years of management and research experience both in industry and academia. She has gained a large and strong experience into the project coordination of EU-funded and Industrial research projects. She joined Libertel (now Vodafone NL), The Netherlands in 1997 as radio engineer and team leader. Till May 2001, she worked as systems architect and corporate member of architecture team at Wireless LANs in Wireless Communications and Networking Division of Lucent Technologies, The Netherlands. From June 2001 to July 2003, she was with T-Mobile Netherlands, The Netherlands as Senior Core Network architect. Subsequently, from July 2003 to April 2004, at PCOM:I3, Aalborg, Denmark. She has been involved in a number of EU-funded R&D projects, including FP7 CIP-PSP LIFE 2.0, FP7 CIP-PSP ISISEMD, FP7 IP ASPIRE, FP7 IP FUTON, FP6 IP eSENSE, FP6 NoE CRUISE, FP6 IP MAGNET and FP6 IP Magnet Beyond as the latest ones. She is currently the project coordinator of the FP7 IST IP ASPIRE, FP7 CIP-PSP LIFE 2.0 and was project coordinator of FP6 NoE CRUISE. She was also the leader of EC Cluster for Mesh and Sensor Networks and is Counsellor of IEEE Student Branch, Aalborg. Her current research interests are in the area of QoL, SON, IoT, Identity Management, mobility, network management and monitoring; practical radio resource management; cognitive learning capabilities and modelling; Security, Privacy and Trust. Experience in other fields includes physical layer techniques, policy based management, short range communications. Her publications range from top journals, international conferences and chapters in books. She has also co-edited and co-authored two books and has over 50 peer reviewed papers in international journals and conferences. She is also very active in several conferences as chair and as program committee member.

Ramjee Prasad has been holding the Professorial Chair of Wireless Information and Multimedia Communications at Aalborg University, Denmark (AAU) since June 1999. Since 2004 he is the Founding Director of the Center for TeleInfrastruktur (CTIF), established as large multi-area research center at the premises of Aalborg University. Ramjee Prasad is a Fellow of IEEE, the IET and IETE is a worldwide established scientist, which has given fundamental contributions towards development of wireless communications. He achieved fundamental results towards the development of CDMA and OFDM, taking the leading role by being the first in the world to publish books in the subjects of CDMA (1996) and OFDM (1999). He is the recipient of many international academic, industrial and governmental awards and distinctions of which the most recently is the cross of the order of chivalry (Ridderkorset af Dannebrogordenen) from the Danish Queen due internationalization of top-class telecommunication research and education. He has published a huge number of books (more than 25), journals and conferences publications (together more than 750), more than 15 patents, a sizeable amount of graduated Ph.D. students (over 60) and an even larger amount of graduated M.Sc. students (over 200). Several of his students are today worldwide telecommunication leaders themselves. He is the founding chairman of the Global ICT Standardization Forum for India (GISFI) and was the founding chairman of the European Center of Excellence in Telecommunications known as HERMES of which he is now the honorary chairman. Recently, under his initiative, international M.Sc. and Ph.D. programmes have been started with the Sinhgad Technical Education Society in India, the Bandung Institute of Technology in Indonesia and with the Athens Information Technology (AIT) in Greece. Ramjee Prasad has a long path of achievements until to date and a rich experience in the academic, managerial, research, and business spheres of the mobile and wireless communication area. Namely, he played an important role in the success that the Future Radio Wideband Multiple Access Systems (FRAMES) achieved. He was the leader of successful EU projects like the MAGNET and MAGNET Beyond, among others, as well as the driver of fruitful cooperation with companies in projects, like Samsung, Huawei, Nokia, Telenor, among others. He is advisor to several multinational companies. He started as a Senior Research Fellow (1970–1972) and continued as an Assistant Professor (1972–1980) at the Birla Institute of Technology (BIT), Mesra, Ranchi, India. He was appointed as an Associate Professor in 1980–1983 and head of the Microwave Laboratory there. From 1983–1988 Ramjee Prasad worked at the University of Dar es Salaam (UDSM), Tanzania, where he became Full Professor of Telecommunications in the Department of Electrical Engineering in 1986. From February 1988 till May 1999 Ramjee Prasad worked at the Delft University of Technology (DUT), The Netherlands at the Telecommunications and Traffic Control Systems Group. He was the founding head and program director of the Centre for Wireless and Personal Communications (CWPC) of the International Research Centre for Telecommunications-Transmission and Radar (IRCTR) at DUT, The Netherlands. Prior to founding CTIF, Ramjee Prasad was the Co-Director of the Center for PersonKommunikation until December 2002. He became the research director of the department of Communication and Technology in 2003. Prof. Prasad has authored or co-authored more than 700 high cited scientific articles published in peer-reviewed conference proceedings and international journals. Since 1999, he has published 8 monographs, 22 books, 18 book chapters and more than 70 and 190 articles in journals and conference proceedings. Furthermore he has 15 patents within his research areas.