Received: 22 June 2022 | Revised: 10 October 2022 | Accepted: 21 October 2022

DOI: 10.1049/rsn2.12346

IET Radar, Sonar & Navigation

The Institution of Engineering and Technology WILEY

ORIGINAL RESEARCH

A radio frequency identification reader collision avoidance protocol for dense reader environments in the context of Industry 4.0

Hadiseh Rezaie[1] | **Mehdi Golsorkhtabaramiri**[2] | **Nima Jafari Navimipour**[3]

[1]Collage of Rouzbahan, Sari, Iran

[2]Department of Computer Engineering, Babol Branch, Islamic Azad University, Babol, Iran

[3]Department of Computer Engineering, Faculty of Engineering and Natural Sciences, Kadir Has University, Istanbul, Turkey

Correspondence

Mehdi Golsorkhtabaramiri, Department of Computer Engineering, Babol Branch, Islamic Azad University, On the 3rd kilometer of Qaemshahr Rd, Babol, Mazandaran 44471-37381, Iran.
Email: golesorkh@ieee.org

Abstract

In the new industrial revolution known as Industry 4.0, radio frequency identification (RFID) systems are a key component of automatic detection. These systems have two main elements, namely Reader and Tag. In many Internet of Things (IoT) applications, the RFID system is used with lots of readers working together in a dense environment to read tags. The simultaneous operation of readers with a common sensory range increases the likelihood of reader-to-tag collision and reader-to-reader collision and reduces the number of successful reading and as a result, reduces network performance and average waiting time for each reader increased. Collisions happen when readers are in the interference range and start reading tags simultaneously, so it is necessary to use the right solution to control channel access in these systems. So far, various solutions have been proposed to control readers' access to the communication channel. Some of them have not considered the existing standards for this type of system or have not been efficient enough to be used in the IoT. In this study, we propose a method that, by considering the distance between readers and the number of neighbourhoods, and the possibility of information sharing, allows readers to successfully read more tags with fewer collisions in a certain time frame. The results of the performance study in a real-world environment showed that the suggested method outperformed similar methods in terms of network performance and has much better throughput, making it a superior choice for usage in IoT-based RFID systems.

KEYWORDS

average waiting time, Industry 4.0, reader-to-reader collision, reader-to-tag collision, RFID, throughput

1 | INTRODUCTION

The main performance of radio frequency identification (RFID) technology is automatic detection, interception, and detection without a physical connection. RFID systems are widely used in current industries to reduce size and cost and raise efficiency and reliability. The new industrial revolution, known as Industry 4.0, is based on developments and revolutions that have taken place despite important technologies, such as the Internet of Things (IoT), big data, cloud computing, and artificial intelligence. In Industry 4.0, RFID systems are widely used alongside wireless sensor networks to classify objects, track goods and supply chains, and also contribute to many other IoT-related applications [1].

Real-time location system and RFID are one of the technologies supported in Industry 4.0. A RFID system usually consists of one or more readers, several tags, and a central server [2].

Tags are usually tiny electrical labels embedded in or attached to objects or animals for identification. Tags hold the information of the objects to which they are attached and are divided into three types [3, 4]: Active Tags, Semi-active Tags, and Passive Tags. Passive tags do not have a power source; they get their energy from the transmitted waves of the readers and respond to them. Semi-active tags rely on the power source for internal processing and the energy delivered by readers for response. Active tags have a power supply and use that power supply to do all the work [5]. In RFID systems, passive tags are mostly used because they are cost-effective and have a short interrogation spectrum [6].

Readers are electrical components that detect the tags in their surroundings by transmitting radio waves. Each reader has two ranges: interference range and reading range [7]. The maximum physical distance that the propagated waves from one reader affect the transmitted waves from other readers is called the interference range, while the maximum physical distance in which a reader can read the tags around it is called the reading range. Readers that are in this range are known as neighbouring readers. The greatest distance between these two ranges is determined by the reader's transmission power [8].

As shown in Figure 1, a reader recognises the surrounding tags and reads the tag information through the reader-to-tag recognition protocols, stores and collects them, and sends them to the central server through wireless or wired connection [3, 9, 10].

In some industrial environments or the process of supply and cataloguing of goods and equipment, a single reader is not sufficient to optimally cover the environment, so multiple readers are used in the environment that works together and simultaneously. In such a case, the readers are in an interference range called a dense reading environment [11]. Due to wireless communication in RFID systems in dense environments, data transmission usually encounters collision problems [12]. The problem is caused by readers and tags sending signals at the same time. Placing readers in interference ranges is one of the major challenges of RFID systems that affect the performance of these systems [13]. The collision of readers makes them unable to read tag information correctly. In this case, the need for multiple connections and repeated attempts to communicate with the tags reduces the throughput and efficiency of the entire system and wastes time and energy. Therefore, preventing readers from colliding is an important issue in such systems [14].

In RFID systems, reader interference can be divided into two categories: reader-to-tag and reader-to-reader collision.

(a) In a reader-to-tag collision, as shown in Figure 2a, two readers want to identify a tag that is within their common reading range at the same time [15]. In many common industrial applications that use RFID technology to identify objects on the IoT, the use of RFID is intended to identify and track products and passive tags that are attached to objects and products. These types of tags have simple hardware that will not be able to perform many complex processes due to the lack of support for their internal power supply as well as the cost of production and physical size; therefore, a passive tag is not able to operate at several frequencies simultaneously by tuning between different frequencies; it also cannot support advanced collision avoidance protocols such as channel coding. Due to the inherent limitations of passive tags, readers should begin identifying tags at unequal intervals in order to avoid collisions caused by more than one reader interacting with a tag at the same time [16, 17].

(b) A reader-to-reader collision happens when two or more readers close to each other simultaneously begin to communicate with tags on a single frequency. In this case, if one reader is operating within the range of receiving interference signals of another reader, it will have trouble interfering when reading the surrounding tags due to the simultaneous reception of neighbouring reader signals. This is because it is not able to distinguish the radio waves reflected from the tags from the reading waves received from neighbouring readers [18]. A Reader-to-tag collision occurs in a reader's reading range, while a reader-to-reader collision occurs when two readers are within the range of receiving interfering signals. The transmission radius of the interfering signals of a reader is much larger than that of the reading range of a reader [17].

The present paper presents a combined method of time division and simultaneous use of several frequencies in which readers can work in several time intervals according to the TDMA protocol (time division multiple access) and in several available channels according to the FDMA protocol (frequency

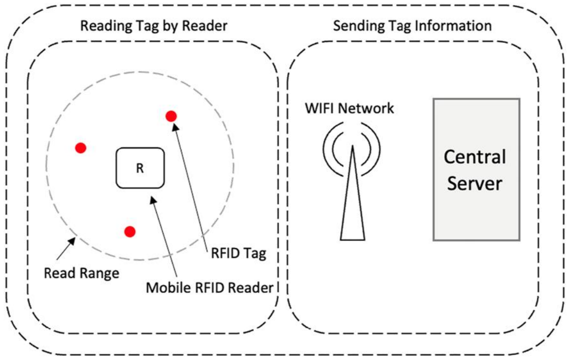

FIGURE 1 The RFID network structure. RFID, radio frequency identification

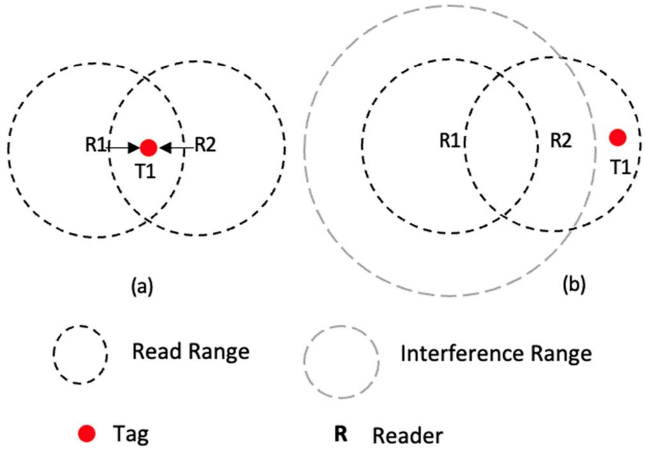

FIGURE 2 (a) Reader to tag collision (b) Reader to reader collision

division multiple access) simultaneously. The central server makes the necessary adjustments by sending an arrangement command (AC) control packet. As stated in ref. [19], each round is split into several slots or time intervals; each slot is divided into 16 sub-slots. Before the start of the competition, the readers get the number of their neighbours in 16 sub-slots. Readers randomly select an interval based on the sift distribution function to avoid collisions. Initially, each reader sends a message at a specific time interval. In case of no collision, the readers will start communicating with the tags in the next period of time, and the tag information will be shared in the information sharing phase. As a result, the operational capacity of the network increases compared to previous protocols while preventing collisions and saving energy.

The rest of this paper is arranged as follows. Section 2 describes related studies. Section 3 contains the characteristics of the proposed method. In Section 4, the evaluation and simulation results of the proposed solution are presented. Finally, we present the results of our proposed method and the orientation for future work in Section 5.

2 | RELATED WORK

In the process of industrialisation, and when using emerging technologies, it is possible to provide grounds for interaction between industrial devices and information exchange with the environment where the devices can work well together with a common goal, and without being of the same type. Many applications of RFID technology in Industry 4.0 require the use of a large number of readers together. Readers can use a variety of methods to prevent collisions in RFID systems to record the channel through which they want to communicate with the tag. These methods can be classified into: TDMA, FDMA, and carrier sense multiple access (CSMA) [2].

Many solutions have been proposed so far to prevent collisions. These solutions can be classified into two mechanisms, distributed and centralised [5]. In the distributed mechanism, the readers are not related to the central server to obtain resources and operate apart. In the centralised technique, the central server communicates with the readers through a wired or wireless network. The central server is responsible for coordinating readers and sharing resources on the network. This section presents the most important protocols based on these two methods [20].

2.1 | Fully distributed protocols

The distributed colour selection protocol (DCS) is based on the TDMA and distributed methods. In this protocol, time is divided into separate periods, each of which is in turn split into equal time slots. The reader chooses one of the time periods randomly. In the event of a collision, readers must select another slot at random. Readers should notify neighbours about the new time via a kick message. If the selected time interval of the reader is the same as the selected time interval of one of the neighbouring readers, that neighbouring reader must select another time slot. Readers who succeed in reading tag information do not change their time in the next period [21, 22].

In the DCS protocol, readers choose a new time interval after the collision. Selecting a new time period may lead to another collision. To reduce subsequent collisions, the possible distributed colour selection protocol (PDCS) allows readers to change their time interval based on the probability p. This is done in such a way that the reader decides based on the probability p to choose a new time period subsequently. The optimal value collision for this probability is estimated at 70%. The PDCS protocol, like DCS, is based on the distributed protocol and TDMA. In this protocol, all the readers also use multiple channels to communicate with tags [23].

The Colorwave protocol is a DCS-based protocol. In this protocol, each period consists of many variable time intervals. By two pairs of thresholds, each reader alone determines the number of time intervals for each period. Readers announce the change in the number of time intervals by sending a kick message. Upon receiving this message, neighbouring readers estimate their percentage of successful readings and, depending on the value of their threshold pairs, change the number of their time intervals as needed [21]. In this method, the readers need to be synchronised. Finding the minimum colour creates a large number of connections. This protocol has more overhead than the DCS protocol and requires an additional signal to change the colour. The efficiency of this protocol is lower in the first stages of transmission. Because the number of time intervals in this method is variable, this method has a good configuration, and in addition to DCS's requirements, it requires impact message management. Here, readers with different numbers of time intervals can cause collisions [24].

The GENTLE protocol provides a solution to prevent reader-to-reader collisions. This protocol assumes that there are no hidden terminal problems in the real world since an adjacent reader can interfere with a tag up to a distance of 9 m. This protocol works distributed method based on the TDMA technique that uses the multi-channel method with a beacon message. This way, readers can share their tag information in the control channel with adjacent readers via a beacon message [25].

The anti-collision protocol for RFID (APR) protocol is a distributed method based on the CSMA technique. In APR, readers use multiple channels to communicate with tags, and they use data and control channels to prevent reader-to-reader collisions. Control and data channels are used for the reader-to-reader and the reader-to-tag communication. To prevent a reader-to-tag collision, the reader who reads the tag Identification (ID) sends a beacon message to the control channel. The beacon message contains the tag ID. Readers who have received a bacon message estimate their distance from the reader who has occupied the channel by measuring the signal transmission power. If the reader is too close, they will be deactivated by the end of the current period [14].

2.2 | Protocols from the NFRA family

The neighbourhood friendly reader anti-collision protocol (NFRA) is based on the centralised mechanism and the TDMA protocol. This protocol is useable for dense reader environments in large spaces. In this protocol, readers are connected to a central server. The central server divides the time into periods and announces the beginning of each period by sending a sequenced packet (AC) to all readers. The amount of time slots is contained in the AC packet. After receiving the AC packet, readers randomly select a time slot. The beginning of each time period is announced by the central server's sending of a command (ordering command [OC]) to all readers [26]. The OC packet includes the current time slot number. Readers compare their selected time slot number with the number in the OC packet. If the two numbers match, it means that the reader can work on the channel during this time. The reader sends a light message to neighbouring readers. If there is no collision, the reader sends a frame packet (overriding frame [OF]) to the neighbouring reader, which starts reading the tags. Neighbour readers are disabled on the current slot after receiving the OF packet. This method can therefore prevent reader-to-reader collision [24].

In the NFRA contention (NFRA-C) protocol, each reader keeps a history of successful tag communication in the form of a counter. For each successful connection, the counter increases by one unit. Counters are exchanged by beacon messages. Whenever a collision is detected from the beacons, the counter of the two readers that collided is compared, and any reader with a lower counter value can use it remotely. This algorithm provides higher throughput and fairness in dense environments of RFID networks. The performance of the NFRA algorithm depends on the number of neighbours and the probability of a collision, but NFRA-C guarantees higher power and fairness by introducing a priority mechanism. This method is 15% more efficient than NFRA [3].

In the fairness reader collision avoidance 1 (FRCA1) method, as in the NFRA method, coordination is made between the server and the readers. Combining FDMA and TDMA mechanisms has improved throughput and reduced the average network waiting time, thus providing better fairness. In this method, because the readers work simultaneously at various frequencies, they do not receive a signal from each other, which decreases the number of reader-to-reader collisions, resulting in more successful readings and improved throughput. In other words, the fairness reader collision avoidance 2 (FRCA2) method has solved the reader-to-tag collision problem of the FRCA1 method to some extent, but due to the fact that a number of readers have been prevented from reading to reduce the collision of the reader with the tag, it is expected that FRCA2 has lower throughput than FRCA1 [12].

In ref. [27], a method has been presented called NFRA ++. Because the NFRA method delays the readers' reading of the tag, in NFRA ++, to solve this problem at the beginning of each round, a method is provided in which the readers prioritise a number according to their waiting time. This means that a reader's priority equals the number of times the reader has nothing to do with the tag. After receiving the AC, each reader guesses its priority. The reader participating in the last rounds will have the lowest priority.

The distance reader collision avoidance (DRCA) protocol [13] is a centralised mechanism-based anti-collision protocol. This protocol is a suitable solution for dense fixed/mobile reader environments. The purpose of this protocol is to enable more readers to work simultaneously without colliding with each other. The proposed method is based on TDMA, and the readers randomly select the interval based on the sift distribution. In this multi-channel protocol, when the reader sees the channel busy, it measures its distance from the active reader. Suppose the reader is not within the range of an active reader. In that case, it adds a unit to its selected interval number before leaving the channel, and another channel is randomly selected. The reader sends a beacon message to its neighbours if the new channel is free. If there is no collision, it starts working. But if the reader is located in the active reader interference range, to avoid the reader colliding with the tag, it just leaves the channel and does not work until the end of the current period. This minimises reader collisions in DRCA and increases the throughput of RFID networks.

The NFRA-adaptive interrogation capacity protocol has been proposed as a new protocol following the core NFRA framework. The main idea is that readers can determine their interrogation time according to the number of tags in their interrogation area. By inserting sub-rounds, the reader who completes the interrogation tags can exit the interrogation conditions and notify adjacent readers. Other surrounding readers might choose whether or not to rejoin the competition based on the status of their neighbours. By allocating a period between the AC signal and the first OC signal, the reader who has not completed the tag interrogation can continue interrogating the tags without facing extra competition [28].

The geometric distribution reader anti-collision (GDRA) is a TDMA-based protocol with a centralised mechanism. This protocol uses the geometric probability distribution function to minimise the reader collision problem. The main central server manages resources (time slots and frequencies) and minimises interferences by controlling network resources [29]. The readers are equipped with two biostatic antennas. They comply with the global standard of electronic product code (EPC) global Class 1-Gen 2 and operate on the UHF band in Europe at 865–868 MHz [30]. The reader randomly selects one of the four suggested channels in this protocol and starts working. The central server notifies all readers at the beginning of each course by transmitting an AC packet. The AC packet includes the number of channels and time slots. Readers select a time slot based on the geometric probability distribution function [29]. This function minimises the likelihood of a collision between readers and maximises the likelihood of a reader choosing a shorter time period. The winner of the contest enters the reader's connection to the tag and sends the tag information alternately to the central server via the low-level reader protocol (LLRP) [31].

Consider the grid shown in Figure 3, where the readers start reading the tags using the GDRA algorithm. As shown in Figure 4, in the AC packet, time slot [1,4] and frequency [1,4] have been introduced, where in time slot 1, reader R2 sends the beacon message and finds channel number 2 empty; no collision occurs, and the tag is read successfully. Reader R1 also listens to channel 2 in time slot 1, finds the channel busy, and so waits until the start of the next round and a new AC playback. On the other hand, readers R3, R4, R5, and R6 listen to channel 2 in time slot 2, whereas reader R3 finds channel 3 empty; it then starts reading tags in time slot 3. Readers R4, R5, and R6 listen to the channel and find channel number 3 empty in time slot 2, and thus send a beacon packet in time slot 3 and have a collision; all readers leave the channel and wait until the start of the next round and a new AC playback. Using the GDRA algorithm for the network shown in Figure 3, only 2 readers (R2 and R3) out of 6 can read the tag.

3 | THE PROPOSED ALGORITHM

The protocol proposed in this paper presents a method that has been approved according to industrial standards without requiring them to change. It maintains the necessary efficiency in reducing reader-to-reader collision and reader-to-tag collision, and with regard to its saving of system resources by increasing operational capacity, it is a good option for use in Industry 4.0. This protocol is a new approach based on a centralised mechanism and TDMA and FDMA methods and is implemented in dense RFID systems without needing additional hardware. The name of the proposed method is industrial reader anti-collision protocol (IRAP).

This protocol complies with EPC-European Telecommunications Standard Institute (EPC-ETSI) regulations. Readers are connected to the central server wirelessly or through wires. They are also equipped with a Bistatic antenna. This hardware allows readers to detect the status of the channel's occupancy. The readers comply with the global standard EPC global Class 1-Gen 2 and operate in the UHF band in Europe at a frequency of 865–868 MHz and send tag information to the central server via the LLRP protocol. The proposed protocol's procedure is divided into 4 phases. The first phase is called the preparation phase. The second phase is each reader's counting of its neighbours; the third phase is the competition phase for reading the tag. Finally, the fourth phase is the information sharing phase, in which the reader who succeeds in reading the tags shares the read information. This method uses TDMA and FDMA protocols to prevent reader collision.

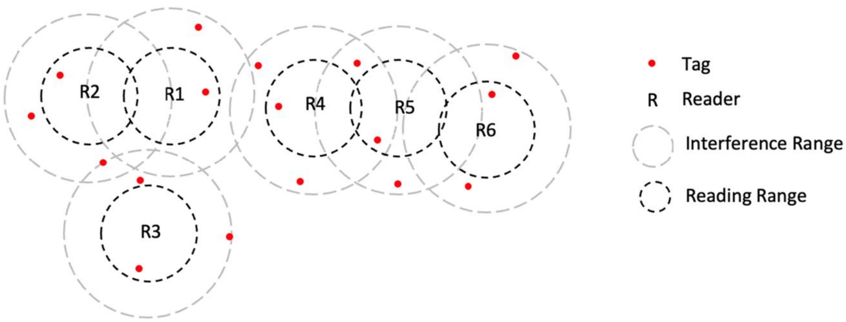

FIGURE 3 The example of the supposed network

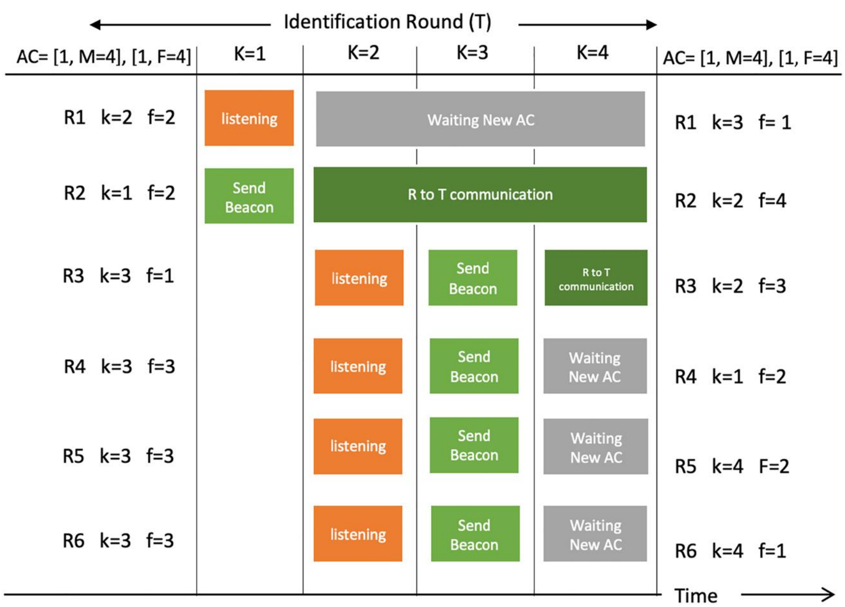

FIGURE 4 Geometric distribution reader anti-collision protocol function

Phase 1 (Preparation): In the initial phase of the start of each time period, the activity of the readers begins with the distribution of the AC packet from the server. The AC packet contains values such as the number of time slots [1, M] and the number of available channels [1, F] for the competition phase and contains values such as the number of time slots [0,15] for the neighbours' counting phase.

Phase 2 (counting neighbours of each reader): The second phase is a single slot divided into 16 sub-slots. In this phase, the readers first select a random number C using the sieve distribution function and send a neighbour counter (NC) message to the channel below their own time slot. The following three conditions occur:

- If the reader receives an NC, it means that the reader has a neighbour and sets N to one.
- If the reader receives a collision of NCs, it means that it has at least two neighbours and sets the value of N to two.
- If the reader senses a collision when sending NC in its time slot, it means that the reader has at least one neighbour and sets the value of N to one.

Finally, each reader keeps its own N value to compete with other readers.

Phase 3 (reader competition to read tags): In this phase, each reader selects a time slot between [1, M] based on the sift distribution function and a channel between [1, F] based on the uniform distribution function. In the example, the number four is examined for M and F. To conserve energy, after picking time slot k, the reader waits as long as time slot $k-2$ and does not listen to the channel. The reader awakens at the $k-1$ time slot and listens to the selected channel. The following two conditions occur:

- If the channel is busy in the $k-1$ time slot due to the sending of a beacon, the reader calculates its distance from the active reader. If the distance is <2 times the interference range, the readers are in each other's neighbourhood. Then the reader enters the standby mode and listens to the channel so that after successful reading it can receive information from its neighbour reader in the information sharing phase. Otherwise, it leaves the competition and waits for a new AC packet.
- If the channel is available in the $k-1$ time slot, the reader transmits a beacon message during the k time slot. In this manner, the reader indicates his need to connect with the tags via the channel. The reader listens to the channel, and after sending the message b, one of the following two situations occurs:
  1. If there is no other reader to send the beacon message in the neighbourhood, no collision will occur, and the reader will win the contest and start reading the tag information.
  2. But if another reader sends the beacon message at the same time, a collision occurs. The readers choose a backoff-time for themselves and wait as long as the selected time. Because readers know the number of their neighbours, the reader with the most neighbours chooses the backoff-time for itself through Equation (1), and takes over the channel faster than the other reader. It then shares the read information in the information sharing phase. The looser readers wait until the information sharing phase.

In Formula number (1), the backoff-time is calculated for each reader. The number selected for each reader based on the number of neighbours should be such that the reader with a larger number of neighbours chooses his own backoff-time from a smaller number range. CW is the maximum contention window size, and N is the number of neighbours per reader. A backoff-time number is a random number obtained from the rough formula.

$$\text{Backoff}-\text{time}=\text{Rand}\left(0,\ \frac{CW}{N}\right) \tag{1}$$

Phase 4 (information sharing phase): Each reader who succeeds in reading the tag in each period must share the information read in this phase so that close neighbours who have a close neighbourhood with the winning reader will receive the tag information.

Neighbouring readers are assumed to be twice as small as the distance between the reader's reading range; that is, their reading range overlaps. Readers calculate their distance from each other through Equation (2).

The proposed method ensures that each reader does not compete in the same time period with readers whose read range and interference range overlap so that reader collision is reduced and the number of successful readings increases and as a result, the efficiency of the system increases which this result is shown in the simulation part.

3.1 | Performance of the proposed method

In the following, we show the performance of the suggested method on the network shown in Figure 3. As shown in Figure 5, the readers first select a time slot, a channel, and a number between 0 and 15 for their sub-slot to determine the number of their neighbours. In the neighbour counting phase, the readers calculate the number of their neighbours according to the sub-slot they chose and keep it in N. In time slot 1, reader R2 sends a beacon message on channel number 2 and starts reading because no accident occurs. Then reader R1 in time slot 1 starts listening to channel number 2, and the channel is busy. For this reason, it calculates its own distance from the reader while reading and finds that the reader is its neighbour (their distance from each other is less than two times their reading range) and is in the expected state and receives read information from the R2 reader in the information sharing phase. In time slot 2, the four readers, R3, R5, R4, and R6, listen to the channel. Reader R3 listens to channel 1 and sees that the channel is empty. In time slot 3, it sends a

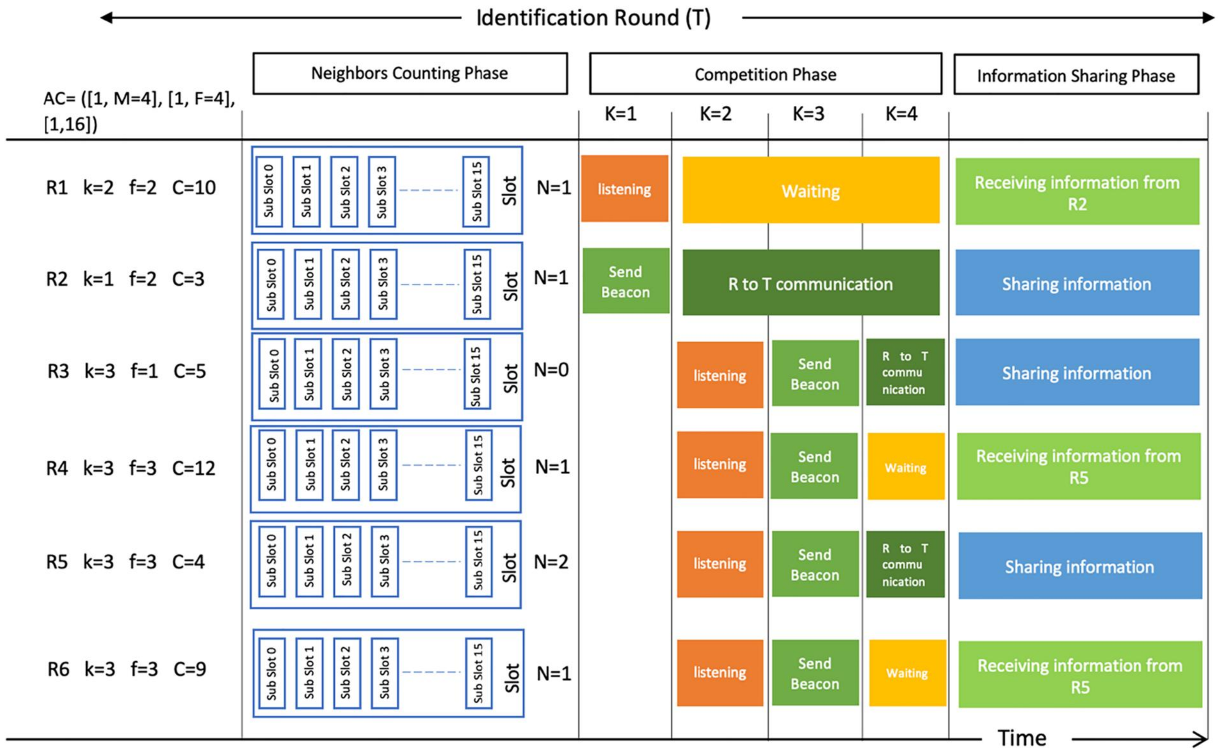

FIGURE 5 Proposed protocol function

beacon message, and no collision occurs. It starts reading tags and shares the read information in the information sharing phase. The three readers, R5, R4, and R6 listen to channel number 3 and find channel number 3 empty; all three send a beacon message in time slot 3, and because all readers are in the reading and the interference ranges, a collision occurs. In this case, because the readers know the number of their neighbours in that round, they choose a backoff-time based on it and wait until then. The reader with more neighbours chooses a shorter backoff-time to speed up the channel. In this example, because it has more neighbours, the R5 reader selects a shorter backoff-time and selects channel number 3 in the time slot faster than the R4 and R6 readers. Readers R4 and R6 find the channel busy in their backoff-time and calculate its distance from the reading reader. They realise that the reader is their neighbour. Thus, they are in the waiting state and receive the read information in the information sharing phase from reader R5.

Using the proposed method in this round, all readers with the least energy consumption have received information about the surrounding tags. In similar situations before this, however, only two readers were able to read the tag using the GDRA protocol.

In Algorithm (1), the pseudocode of the proposed method is observed. In line 2, the reader selects a random number for its time slot employing the sift distribution function. In line 3, the reader selects a frequency for its own channel using the uniform distribution function. In line 4, the reader selects a number between 0 and 15 by using the sift distribution function for the sub-slot number to determine the number of its neighbours. On lines 5–12, the reader determines the number of its neighbours and sets it to the variable N. In lines 13–20, if the channel is busy in the $k-1$ time slot, the distance between the readers is calculated. If the readers were neighbours, the reader waits to receive its tag information from the winning reader in the information sharing phase. Lines 21 to 34 show that if the channel in the K-time slot is empty, in the event of a collision, the reader waits as long as the backoff-time and listens to the channel again. If the channel is empty, it takes over the channel. Otherwise, it waits until the information sharing phase. In case of no collision, the reader manages to read the tag and shares the read information in the information sharing phase.

Algorithm 1 Proposed method pseudo code

```
Pseudo code:
1: if a reader receives AC from the Server:
2:       k = Generates a number by sift
         function among [1, M]
3:       f = Generates the frequency by
         random among [1, F]
4:       C = Generates a number by sift
         function among [0,15]
5:       the reader counts the number of its
         neighbours in the neighbours
         counting phase
6:       if the reader receives a NC message:
7:             the reader sets N = 1
8:       else the reader listens NC message
```

```
        collision:
                the reader sets N = 2
        else the reader' NC message
        collides with another reader'
        NC message
                the reader sets N = 1
        end
        the reader waits k - 2 and then
        listens to channel in k - 1
        if channel is busy:
                the reader calculates
                D (= distance between
                itself and the rival
                reader)
                if D < (2 × Read Range):
                        the reader waits
                        to information
                        sharing phase for
                        receives
                        information
                if:
                        the reader leaves the
                        channel and waits to
                        new AC
                end
        else if the channel is free:
                the reader sends a beacon
                message
                if collision is detected:
                        the reader waits as
                        long as it's backoff-
                        time and listens to
                        the channel.
                        if channel is empty:
                                the reader
                                reads tag
                                information
                                in channel
                                and shares
                                tag
                                information
                                in the
                                information
                                sharing
                                phase.
                        else:
                                the reader
                                waits to
                                information
                                sharing phase
                                for receives
                                information
                        end
                else if collision isn't
                detected:
                        the reader reads tag
                        information and
                        shares information
                        in the information
                        sharing phase
                end
        end
end
```

3.2 | Distance between readers

In relation (2), D is the distance between the two readings R1 and R2, which is shown in Figure 6. $\propto$ is the path loss exponent; P_R is the reader transmission power; G_R is the reader antenna gain, and K_0 is the coefficient of channel path loss and power ratio in the bandwidth, while I_R denotes the whole interference that the reader receives [32].

$$D^{\propto} = \frac{P_R G_{R_1} G_{R_2}}{K_0 I_R} \tag{2}$$

3.3 | Sift distribution function

Readers randomly select one of the time slots in the NFRA protocol using the uniform distribution function. According to this function, the likelihood of a collision in each time slot for competing readers is identical. Rival readers are those that operate on the same channel and share the same reading range and interference range [29].

In the carrier sense multiple access/P^* (CSMA/P^*) protocol [33], network nodes use the non-uniform P^* probability distribution according to Formula (3) to select competing slots. This function minimises collisions between competing readers and maximises the probability of selecting a time slot by just one reader. R indicates the number of contending readers and also K indicates the number of time slots.

$$P_k^* = \left(\frac{1 - f_{K-k}(R)}{R - f_{K-k}(R)}\right)\left(1 - P_1^* - P_2^* - \ldots - P_{k-1}^*\right) \tag{3}$$

Given Formula (4), $f_{K-k}(R)$ is a recursive function for $1 \le k \le K$:

$$f_{K-k}(R) = \left(\frac{R-1}{R - f_{K-k-1}(R)}\right)^{R-1} \tag{4}$$

For $2 \le k \le K$, $R \ge 2$ and $f_1(R) = 0$.

In order for the CSMA/P^* protocol to be used in a dense environment of the RFID system, each reader must be able to estimate the number of neighbours. But if the reader does not know the number of its neighbours, the sift distribution probability (P_k) function is used to select competitive intervals according to Formula (5) [34].

$$P_k = \frac{(1-\propto)\propto^K}{1-\propto^K} \propto^{-k} \quad (5)$$

Formula (5) holds for $1 \le k \le K$, $0 < \propto < 1$ and $\propto = M^{-1/K-1}$; where M is the maximum number of competing readings [34]. When $\propto = 1$ and $M = 1$, the Formula (6) corresponds to a uniform probability distribution function:

$$\lim_{\propto \to 1} P_k = 1/K \quad (6)$$

The probability of selecting higher time slots will grow in the sift probability distribution function. With this perspective, the likelihood of a single reader selecting lower time slots increases [34]. This competitor swiftly wins the contest. In the sift probability distribution function, the likelihood of a reader winning a competition in the presence of R neighbours $(P_c(R))$ is calculated by Formula (7) [35]:

$$P_c(R) = R \sum_{k=1}^{K-1} P_k \left(1 - \sum_{z=1}^{k} P_z\right)^{R-1} \quad (7)$$

4 | SIMULATION AND EVALUATION

The simulation and evaluation results of the suggested method are described in this section. The R2RIS software has been used to simulate the proposed process [36]. This simulator measures the efficiency and effects of reader-to-reader collisions in RFID systems. An RFID system consists of a set of readers equipped with a Bistatic antenna, randomly distributed in a square environment with an area of 1000 square metres and the direction of movement of the readers is random and depends on their speed, which is considered a random number for the speed of the readers in the simulation. The output power of the reader is 2.3 W effective isotropic radiated power. With this output power, readers can read the tags up to 10 m, and the interference range is 1000 m [7]. The simulation parameters for the existing protocols and the proposed method have been given in Table 1. Other required parameters are equal to the parameters in ref. [26].

The parameters used to compare the protocols are each reader's throughput and average waiting time. The throughput is the number of tags read per unit of time, whereas the average waiting time is the average read time passed by all readers to read the tag [8].

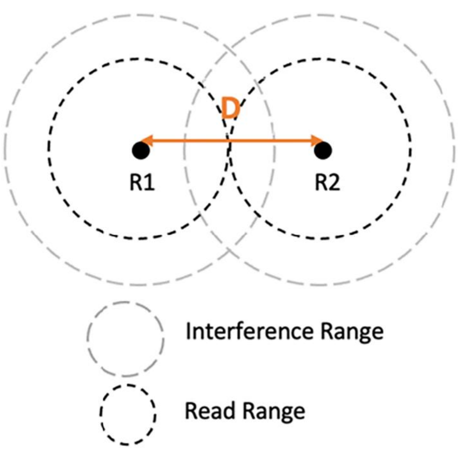

FIGURE 6 Two readers with distance D from each other

TABLE 1 Evaluation parameters

Parameter	Value
Mechanism = IRAP	
Reader-to-tag communication	0.46 s
Beacon packet	0.3 ms
AC packet	2.83 ms
Period time	5 ms
Duration of sending read data on the channel	100 ms
Number of the time period	128
Mechanism = GDRA	
AC packet	2.83 ms
OC packet	1 ms
Beacon packet	0.3 ms
T_{slot}	5 ms
Reader-to-tag communication	0.46 ms
Mechanism = PDCS	
Reader-to-tag communication	0.46 ms
Reader exchange signal	1 ms
MinTimeInColor	100 slots
Probability of changing colour	0.70
Mechanism = NFRA	
AC packet	2.83 ms
OC packet	1 ms
OF packet	0.3 ms
Beacon packet	0.3 ms
Reader-to-tag communication	0.46 ms
Mechanism = FRCA 1 and FRCA 2	
SO packet	2.83 ms
EO packet	1 ms
Beacon packet	0.3 ms
Reader-to-tag communication	0.46 ms

Note: Several situations were evaluated to demonstrate the performance of the suggested protocol, and the findings were compared to those of the NFRA, FRCA1, FRCA2, GDRA, and PDCS protocols.

Abbreviations: AC, arrangement command; EO, elect order; FRCA1, fairness reader collision avoidance 1; FRCA2, fairness reader collision avoidance 2; GDRA, geometric distribution reader anti-collision; IRAP, industrial reader anti-collision protocol; NFRA, neighbourhood friendly reader anti-collision; OC, ordering command; OF, overriding frame; PDCS, possible distributed colour selection; SO, start order.

4.1 | The first scenario

In the first scenario, the proposed method is compared with four protocols, namely FRCA1, FRCA2, GDRA, and PDCS in a 4-channel mode and with NFRA protocol in a single-channel mode. 100, 150, 200, 250, 300, 350, and 400 fixed readers were randomly distributed in the space of 1000 square metres. The number of competitive slots was 128, and the collision rate in this environment was approximately 100%. As shown in Figure 7, the performance of the proposed method has been compared with that of the NFRA, FRCA1, FRCA2, GDRA, and PDCS protocols, where the performance of the proposed method was shown to be better than those of the other protocols at all points of evaluation. The reason for this better performance is that a reader shares the read tag information on the channel so that close neighbour readers can read the tag information simultaneously. Thus, in the proposed method, more readers can read the tag information over a period of time compared to the NFRA, FRCA1, FRCA2, GDRA, and PDCS protocols, thus increasing RFID throughput. To put it differently, the percentage of throughput improvement of the IRAP compared to FRCA1, NFRA, FRCA2, PDCS, and GDRA is approximately 36%, 360%, 32%, 153%, and 90% respectively.

4.2 | The second scenario

The second scenario compares the proposed method in single-channel mode to the FRCA1, FRCA2, and GDRA protocols. In this scenario, 100, 150, 200, 300, and 400 fixed readers were randomly distributed in the space of 1000 square metres. The number of competitive slots was 128. As illustrated in Figure 8, the method's performance has been compared to the FRCA1, FRCA2, and GDRA protocols, where the proposed method, even in single-channel mode, has much better results than the FRCA1, FRCA2, and GDRA protocols. In single-channel scenarios, the readers have more neighbours, and as a result, the readers are more likely to be close to each other. The proposed method consequently works much better in this situation. To put it differently, the percentage of throughput improvement of the IRAP compared to FRCA1, FRCA2, and GDRA is approximately 512%, 350%, and 1200% respectively.

4.3 | The third scenario

The third scenario compares the proposed method to 5 protocols, namely FRCA1, FRCA2, GDRA, and PDCS in 4-channel mode and with NFRA in single-channel mode (as shown in Figure 9). In this scenario, 100, 150, 200, 300, and 400 fixed and mobile readers are randomly distributed over 1000 square metres. 20% of readers are mobile, while the rest are fixed. Also, the number of time slots is 128. Due to the presence of mobile readers, the average number of readers that are very close to each other in each period is different, under these conditions, and according to Figure 8, the proposed method's performance was better than those of other multi-channel protocols in all evaluation points. To put it differently, the percentage of throughput improvement of the IRAP compared to FRCA1, NFRA, FRCA2, PDCS, and GDRA is approximately 33%, 275%, 26%, 152%, and 73% respectively.

4.4 | The fourth scenario

The fourth scenario compares the proposed method to GDRA, PDCS, FRCA1, and FRCA2 protocols in 4-channel mode and NFRA in single-channel mode. In this scenario, 100, 150, 200, 300, and 400 readers were randomly distributed over 1000 square metres. The number of competitive slots was 128. The results, provided in Figure 10, show that the average waiting time of each reader in the proposed method was less

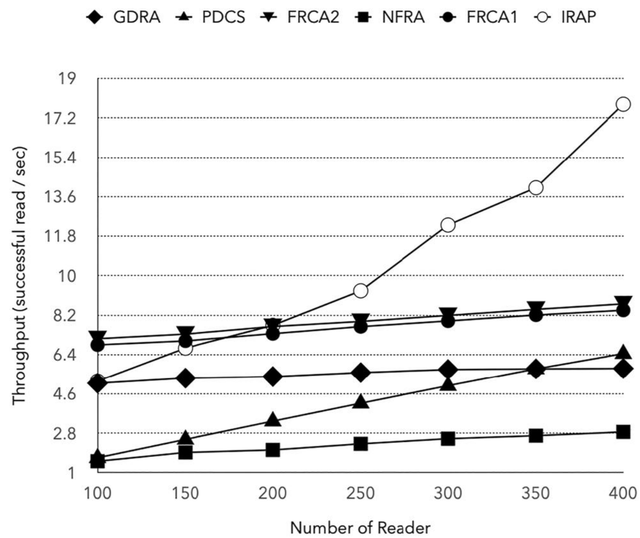

FIGURE 7 Throughput of the appraise situation in scenario 1

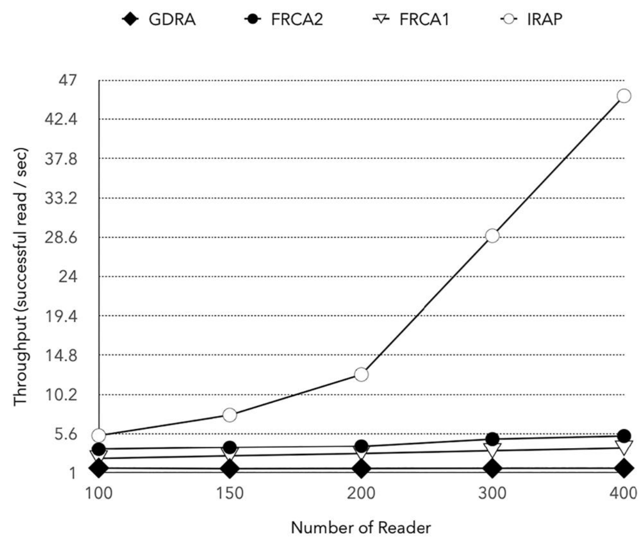

FIGURE 8 Throughput of the appraise situation in scenario 2

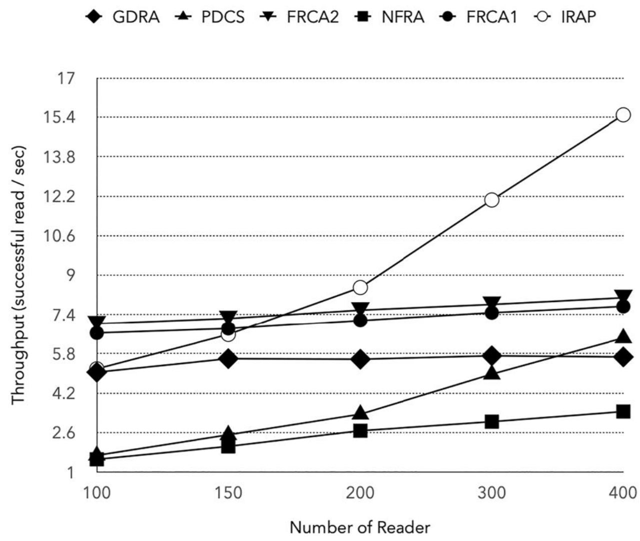

FIGURE 9 Throughput of the appraise situation in scenario 3

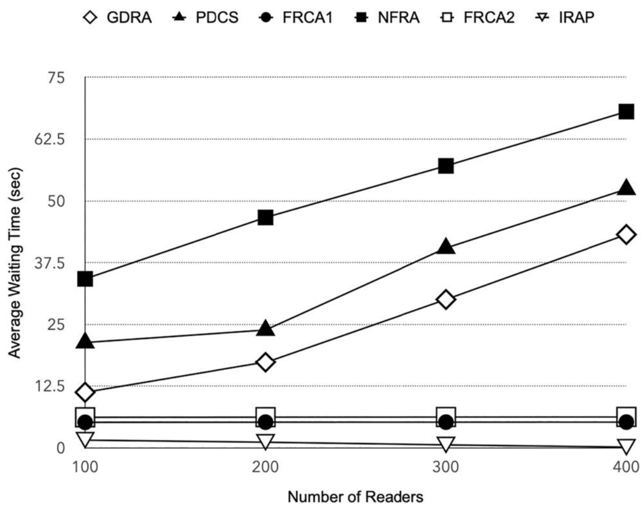

FIGURE 10 Average waiting time of the appraise situation in scenario 4

than that of other methods. Because, in this method, each reader obtains the tag information that all their neighbours have read in each round and so, spends less the average waiting time to read the tags. To put it differently, the percentage of average waiting time improvement of the IRAP compared to FRCA2, NFRA, FRCA1, PDCS, and GDRA is approximately 86%, 98%, 83%, 97%, and 96% respectively.

As can be seen from the simulation results, the proposed method has been able to reduce the amount of reader collisions and increase the number of successful readings by sharing information between readers and calculating the number of neighbours by each reader. As a result, the system efficiency and throughput are improved compared to the other methods.

In Industry 4, many readers and tags that work intensively and simultaneously in the same environment will potentially cause collision problems. Therefore, employing an appropriate solution to reduce collisions by considering very efficient performance is critical in this situation. The protocols presented so far to avoid collisions do not have the necessary efficiency for such environments, so the new method is proposed with a focus on being used in industrial environments with a high density of RFID readers [12, 24, 26, 29].

5 | CONCLUSION

One of the most critical ways to automate in Industry 4.0 as defined by IoT and the use of new technologies is to use RFID systems. If multiple readers use the channel simultaneously, a collision occurs due to the lack of optimal channel access control management. This is a bottleneck affecting the throughput and efficiency. In this paper, after analysing previous methods to reduce reader collision in high-density environments, the advantages and disadvantages of those methods were first identified, after which attempts were made to resolve their disadvantages while allowing their strengths to remain. One of the most vital goals of RFID systems is to increase throughput while avoiding reader collision. The IRAP method reduces the collision problem by applying the TDMA and FDMA techniques and observing current RFID standards. Also, in this method, to increase productivity and resource savings, the readers obtain information about their surrounding readers by sharing information, which increases the throughput when the number of readers rises in the environment; this is impressive. The efficiency of the proposed method has been compared and evaluated by simulations and comparisons with previously presented methods, the results of which were significant in terms of throughput.

For future studies, since nothing has been done to allocate the frequencies and it uses the random function. We intend to allocate frequency channels and time slots to each reader, employing machine learning techniques more efficiently and reducing the number of possible unemployed time slots. We also can use successful readings of readers to prioritise them in their potential competition for time slots.

AUTHOR CONTRIBUTIONS

Hadiseh Rezaie: Conceptualisation, Data curation, Formal analysis, Funding acquisition, Investigation, Software, Writing – original draft. **Mehdi Golsorkhtabaramiri**: Project administration, Software, Supervision, Validation, Visualisation, Writing – original draft, Writing – review & editing. **Nima Jafari Navimipour**: Investigation, Methodology, Resources, Validation, Writing – review & editing.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

ORCID

Mehdi Golsorkhtabaramiri https://orcid.org/0000-0002-9932-2477

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How to cite this article: Rezaie, H., Golsorkhtabaramiri, M., Jafari Navimipour, N.: A radio frequency identification reader collision avoidance protocol for dense reader environments in the context of Industry 4.0. IET Radar Sonar Navig. 17(3), 362–373 (2023). https://doi.org/10.1049/rsn2.12346