Enhanced Pulse Protocol RFID Reader Anti-collision Algorithm using Slot Occupied Probability in Dense Reader Environment

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Abstract

The Radio Frequency IDentification (RFID) system is a contactless automatic identification system, which comprises readers and tags. In RFID systems, a reader collision occurs when there is interference in communication between one reader and the tags, due to the signals from other readers. The reader collision problem is considered as the fundamental problem affecting high density RFID reader installations. In this paper, we analyze the existing reader anti-collision algorithms. We also propose a pulse protocol-based reader anti-collision algorithm using slot occupied probability (SOP). The implementation of this improvement is simple, yet it effectively mitigates most reader collisions in dense reader mode, as shown in our simulation. That is, the proposed algorithm reduces the identification time, and increases the system throughput and system efficiency compared with the conventional reader anti-collision algorithms.

Keywords: RFID, reader anti-collision, pulse protocol, slot occupied probability

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1. Introduction

The Radio Frequency IDentification (RFID) system is a form of sensor network that is used to identify physical objects. RFID is increasingly used in many applications such as inventory management, object tracking, retail checkout etc. The RFID system consists of readers and tags. Readers use radio signals to communicate with tags, while tags may be passive (powered by the reader's signals) or active (battery powered). Readers communicate with tags using radio frequency signaling for obtaining the identifier and other data elements stored in the tags. All readers are centered in a finite area within which they can communicate with tags. This area is referred to as the reader's interrogation zone. Readers with overlapping interrogation zones can interfere with one another, often to the point where neither reader can communicate with any tags located within their respective interrogation zones. Readers may also interfere with the operations of other readers, even if their interrogation zones do not overlap. Such interference occurs because the same radio frequency is used for communication. Interference detected by one reader and caused by another reader is referred to as a reader collision [1]. In RFID systems, the reader collision problem is considered to be the bottleneck for the system throughput and reading efficiency. The primary works on reader collision problem have been done in [2]. In this paper, an improved pulse protocol-based reader anti-collision algorithm is proposed for reducing reader collisions via slot occupied probability. Simulation results show that the proposed algorithm improves the reading speed, throughput and system efficiency compared with the conventional anti-collision algorithms.

The remainder of this paper is organized as follows. Section 2 introduces and analyzes the reader collision problem. In section 3, we review the conventional anti-collision algorithms. Section 4 describes the details of our proposed pulse protocol-based reader anti-collision algorithm. In section 5 we present several simulation results illustrating the effectiveness of the proposed algorithm. Finally, in section 6 we present our conclusions.

2. Reader Collision Problem

Traditionally, most RFID systems have been designed for only a single reader scenario. However, with the increasing use of mobile RFID readers and the huge scope for deploying RFID readers, many scenarios require readers to operate in close proximity to each other. Thus, signals from one reader might interfere with signals from other readers. This interference is referred to as a reader collision. There are two kinds of reader collision problems in RFID systems: reader-to-reader interference and multiple reader-to-tag interference [1].

2.1 Reader-to-Reader Interference

Reader-to-reader interference occurs when a reader transmits a signal that interferes with the operation of another reader, thus preventing the second reader from communicating with tags in its interrogation zone. Interrogation zones need not overlap for reader-to-reader interference to occur.

For example, in **Fig. 1** [3] reader R_1 lies in the interference region of reader R_2. There is interference in communication between reader R_1 and tag T_1 due to signals transmitted from R_2. We use the spherical interrogation zone model to identify readers that may cause a collision. Let $D(R_1, R_2)$ be the distance between reader R_1 and reader R_2. Let d_{min} be the minimum distance at which reader R_1 and reader R_2 will not cause a reader collision, i.e., the reuse distance. Then, reader R_1 and reader R_2 may cause a reader-to-reader collision if

$$D(R_1,R_2) < d_{min} \tag{1}$$

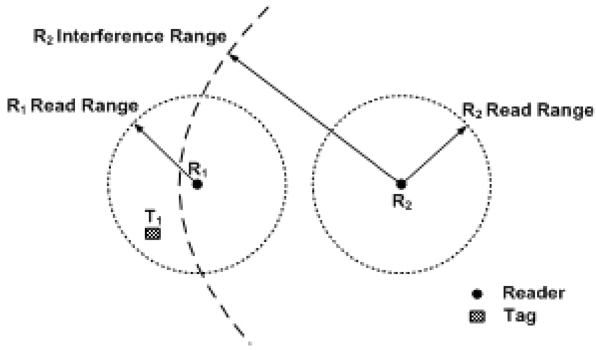

Fig. 1. Reader-to-reader interference

2.2 Multiple Reader-to-Tag Interference

Multiple reader-to-tag interference occurs when one tag is located in the interrogation zones of multiple readers. Every reader attempts to communicate with that tag simultaneously.

For example, in **Fig. 2** [3] the reading ranges of the two readers overlap. In this case, neither R_1 nor R_2 can communicate with T_1 correctly, because the signals from R_1 and R_2 interfere at tag T_1. On the other hand, R_1 can still read T_2 and T_3, because no reader collision occurs for T_2 or T_3.

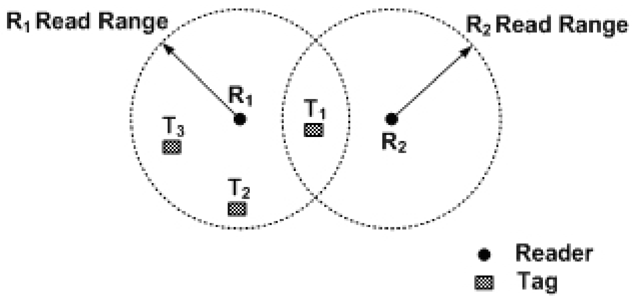

Fig. 2. Reader-to-tag interference

Let D_1 and D_2 represent the maximum interrogation zone distances of R_1 and R_2 respectively. Then, R_1 and R_2 may cause a reader-to-tag collision if

$$D(R_1,R_2) < D_1 + D_2 \tag{2}$$

3. Reader Anti-collision Algorithms

Current solutions to the reader collision problems can be classified into two categories: scheduling-based approach and coverage-based approach [4]. For the scheduling-based approach [3][4][5][6][7][8], the available system resources, such as the frequency and time, are suitably allocated among readers, to prevent readers from transmitting simultaneously. The coverage-based approach is introduced in [9], where the reading ranges of readers are adapted dynamically, to reduce the overlapped area between adjacent readers to a minimum. This kind of approach needs a central node for calculating the distance between any two readers, which increases the complexity of implementation, and the cost of the system. We focus on scheduling-based approaches.

3.1 Colorwave

Colorwave [5][6] was one of the first works to address the reader collision problem. Colorwave is essentially a distributed TDMA (Time Division Multiple Access) based anti-collision algorithm, where the time is divided into frames and a frame is divided into a number of slots. Each reader chooses a random time slot for transmission. If there is a collision, the reader selects a new time slot and sends a kick (small control packet) to all its neighbors, to indicate the selection of a new time slot. If any neighbor has the same color, i.e., same time slot, the reader chooses a new color and sends a kick, and this process is repeated. If the percentage of collisions exceeds a certain threshold, maxColors (frame size) is increased, and if the percentage of collisions falls below a certain threshold, maxColors is decreased. By changing the color, the Colorwave algorithm reduces the reader collision problem to the classic coloring problem in graph theory, thus, it efficiently reduces reader collisions.

3.2 Enhanced Colorwave

Colorwave adjusts the frame size depending on the interference. The frame size may change frequently, due to the fluctuating collision probability, which is defined as the percentage of collision slots in a frame. This problem is solved in the enhanced Colorwave reader anti-collision algorithm [7]. In enhanced Colorwave, if the frame size is decreased and the collision probability increases rapidly, the reader doubles minTime, which is defined as the minimum number of time slots before the reader changes the frame size. Thus, the stability of the frame size is maintained by the enhanced Colorwave algorithm, and the efficiency of the algorithm is improved.

3.3 Channel Monitoring Algorithm

Both Colorwave and enhanced Colorwave can reduce reader collisions by adjusting the frame size according to the collision probability. However, a reader randomly chooses the time slot in the next frame, which interrupts the tag reading of another reader choosing the same time slot, and a reader collision occurs. In the channel monitoring algorithm [8], each reader monitors the slots in the frame and chooses the slot with the minimum occupied probability, which is defined as the percentage of readers that choose a certain time slot among all readers. Thus, collisions caused by randomly choosing a time slot are reduced in the channel monitoring algorithm.

3.4 Pulse Protocol Algorithm

Pulse protocol [3] is another TDMA based anti-collision scheme. Pulse protocol assumes that there are two separate communication channels: data and control channel. A reader communicates with tags via the data channel, and uses the control channel to send a beacon signal, which notifies other readers to avoid collisions. If a reader receives a beacon, it waits for a certain time, and then rechecks the control channel, until no beacon is received from other readers. Afterwards, the reader waits for another random backoff time, to avoid collisions between readers. Otherwise, many readers may try to transmit beacons simultaneously. If the random backoff time has expired and no beacon is received by the reader, the reader assumes that other readers do not compete, and hence it sends a beacon via the control channel and starts communicating with the tags via the data channel.

Although the pulse protocol is simple, it effectively mitigates the reader collision problem. Besides, it requires much less overhead on the reader side, and absolutely no support on the tag side [3].

All the aforementioned three algorithms have an additional management overhead, and the complicated structures also render them un-suitable for general RFID applications. In section 4, we propose a new simple yet effective reader anti-collision algorithm based on the pulse protocol.

4. Proposed Improved Pulse Protocol-based Reader Anti-collision Algorithm

The proposed reader anti-collision algorithm is based on the existing pulse protocol algorithm. In the conventional pulse protocol algorithm, when a reader generates a new random backoff delay, there is a probability that the backoff delay time is the same as that of another reader. Thus, a reader collision occurs.

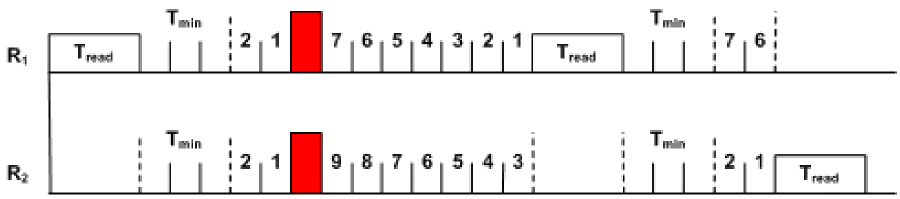

Fig. 3. Reader collision in the conventional pulse protocol

This problem is illustrated in **Fig. 3**, where there are two readers, R_1 and R_2. R_1 communicates with tags via the data channel and sends beacon signals to R_2 via the control channel during the *Tread* period. R_2 receives beacon signals from R_1 and waits until the control channel is *idle*. After *Tread*, both R_1 and R_2 remain in the *waiting* state for a minimum time T_{min}, to ensure that no beacons are received. Subsequently, R_2 resumes its previous residual backoff delay, which is two time slots in **Fig. 3**, and R_1 generates a new random backoff delay, which is also two time slots, in our example. Thus, a reader collision occurs during the shaded time interval in **Fig. 3**.

To mitigate this type of collision, we propose an improved pulse protocol-based reader anti-collision algorithm, which uses slot occupied probability to reduce reader collisions.

Definition 2.1 (Slot Occupied Probability) *Slot occupied probability (SOP) is defined as the percentage of readers that choose the same time slot all active readers, as given in equation (3)*

$$\text{SOP} = \frac{\text{Number of Readers choosing the Same Time Slot}}{\text{Total Number of Readers}} \tag{3}$$

In the conventional pulse protocol algorithm, it is assumed that power of the beacon signal is boost-up enough to be received by all of neighboring readers. By communicating with other readers via the control channel with beacon signal, which includes back-off time information, a reader can easily find the backoff delay time of other readers. Thus, whenever it generates a random backoff delay, the reader calculates the SOP for the backoff time slot and compares the value with zero. If SOP is larger than zero, this means other readers are supposed to communicate with tags during the same time slot. Thus, the reader generates another backoff delay for avoiding collisions with other readers during that time slot.

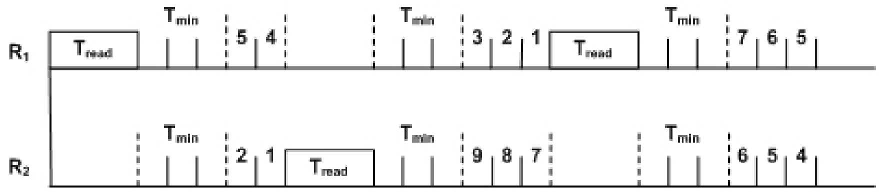

Fig. 4. Proposed algorithm for mitigating the reader collision problem

The proposed algorithm is illustrated in **Fig. 4**. If the random backoff delay generated by R_1 is two time slots, R_1 calculates SOP, to check the occupied probability. In this example, SOP is equal to 50%, because R_2 is supposed to communicate with tags during the same backoff time slot. Thus, in order to avoid collisions with R_2, R_1 generates another backoff delay, e.g., five in **Fig. 4**, and rechecks SOP. This time SOP is equal to zero, which means this slot is not occupied by any other reader. Hence, R_1 uses five as the actual backoff delay and avoids collisions with R_2.

Fig. 5 shows the detailed flowchart. **Fig. 6** shows the detailed algorithm for the proposed pulse protocol-based reader anti-collision algorithm. The anti-collision procedure for the proposed algorithm is explained below.

Before communicating with the tags, a reader remains in the *waiting* state for a minimum time T_{min}, to ensure no beacons are received during this time. The time T_{min} is analogous to the DIFS time in the 802.11 protocol [3]. If the reader receives a beacon while in this state, it resets its waiting time to T_{min}.

If no beacon signal is received by the reader during T_{min}, it considers that no other neighboring readers are communicating with tags. Thus, it enters the *contend* state. Subsequently, the reader chooses a random backoff time (contend_backoff), e.g., n time slots, between zero and the maximum backoff delay, and calculates the value of SOP for the nth time slot. If SOP is equal to zero, the reader does not need to change the random backoff time. If SOP is larger than zero, this means there are other readers that are supposed to communicate with tags during that time slot. Hence, the reader changes its backoff time to another random value, to avoid collisions with other readers, until SOP is equal to zero.

If a beacon signal is received by the reader during the backoff time, it returns to the *waiting* state until no beacon is received for at least T_{min} time. If the random backoff time has expired and no beacon is received by the reader, it sends a beacon via the control channel and starts communicating with the tags via the data channel. The beacon notifies the neighboring readers that they should delay communication with the tags and thus avoid possible collisions.

Whenever the reader wants to send a beacon, it first senses the control channel. When a reader transmits a beacon signal to neighboring readers through the control channel during the period *Tread*, it only includes 5 additional bits for the next back-off time information to avoid reader collision. If the control channel is busy, it waits until the control channel is *idle* and generates a random delay (delay_before_beaconing), which helps to prevent multiple readers from accessing the channel simultaneously. Similar to the case of contend_backoff, the reader checks SOP and decides whether to use the current delay_before_beaconing or another one, to avoid collisions with other readers.

The contend_backoff and delay_before_beaconing in the protocol are reduced, as long as the control channel is *idle*, stopped when a transmission is detected, and reactivated when the control channel is *idle* again. Whenever a reader receives a beacon signal, it stores its residue backoff timer and waits for the next opportunity, i.e., until no beacon is received for at least T_{min}. Then, the reader resumes the backoff time. This is for improving fairness among readers [3]. Complexities of the other three algorithms come from the constraint on the frame size and structure, whereas the proposed algorithm is constraint-free. Although the import of SOP is simple, the proposed algorithm effectively improves the performance of the RFID system, as shown in section 5

Fig. 5. Flowchart of the proposed algorithm

```
CASE: Receive packet from application to send on the network
if state = IDLE then
    state= WAITING
    Set waiting_time_expired timer to Tmin
end if
CASE: Control channel becomes busy
if state = CONTEND then
    Pause contend_backoff_expired timer
end if
if state = DELAY_BEFORE_BEACONING then
    Pause delay_before_beaconing_expired timer
end if
CASE: Control channel becomes IDLE
if state = CONTEND then
    Resume contend_backoff_expired timer
end if
if state = DELAY_BEFORE_BEACONING then
    Resume delay_before_beaconing_expired timer
end if
CASE: BEACON Received
if state = CONTEND OR state = WAITING then
    Cancel all timers
    state= WAITING
    Set waiting_time_expired timer to Tmin
end if
CASE: Timer Expired
if waiting_time_expired timer AND state = WAITING then
    state = CONTEND
    if contend_backoff_expired timer  = 0 then
        Set contend_backoff_expired timer to previous residual value
    else
        Select a new random contend backoff
        for SOP > 0
            Select a new random contend backoff
        end for
    end if
end if
if (beacon_interval_expired timer AND state = READING) OR (contend_backoff_expired timer AND state =
CONTEND) then
    if Control channel is IDLE then
        Transmit BEACON on control channel
        Set reading_time_expired timer to max communication time
        Set beacon_interval_expired timer
        state = READING
        Start communication with the tags
    else
        state = DELAY_BEFORE_BEACONING
        Set delay_before_beaconing_expired timer to a random delay
        for SOP > 0
            Set delay_before_beaconing_expired timer to new random delay
        end for
    end if
end if
if reading_time_expired timer AND (state = READING OR state = DELAY_BEFORE_BEACONING) then
    Cancel all timers
    state= WAITING
    Set waiting_time_expired_timer to Tmin
end if
```

Fig. 6. The proposed improved pulse protocol-based algorithm.

5. Simulation Results and Performance Verification

We performed simulations in MATLAB, to verify the improvement in the reading efficiency of the proposed improved pulse protocol-based algorithm over conventional reader anti-collision algorithms. The simulation parameters are shown in **Table 1**. 500 tags were used, and the number of readers was varied from 1 to 12, to evaluate the anti-collision performance of each algorithm. The parameters Tari, T_1, T_2, T_3, and T_4 are defined in [10].

We evaluated the anti-collision performance using the following performance indices: identification time, system throughput, and system efficiency.

Definition 5.1 (Identification Time) *Identification time is defined as the time required to identify all the tags (500 tags) in the interrogation zone.*

Table 1. Simulation Parameters

Parameter	Description	Value
Readers	Total number of readers in the same region	1-12
Tags	Total number of tags in the region to be identified	500
Slot Time	Time for one slot	20 ms
Query Size	Data transmission for one query	40 bytes
Tari	Reference time interval for a data-0 in reader-to-tag signaling	12.5 μs
T_1	Time from reader transmission to tag response	93.75 μs
T_2	Time from tag response to reader transmission	93.75 μs
T_3	Time a reader waits, after T_1, before it issues another command	0 μs
T_4	Minimum time between reader commands	75 μs

A good algorithm can reduce the probability of collision so that less time is required for identification of tags.

Definition 5.2 (System Throughput) *System throughput is defined as the total queries sent successfully by all readers during the total transmission time, as given in equation (4)*

$$\text{System Throughput} = \frac{\text{Total queries sent successfully by all readers}}{\text{Total time}} \quad (4)$$

A query is considered to have been sent successfully if it was sent by a reader and successfully received by all the tags in the interrogation zone. That is, it does not collide with any other query in the network [3].

Definition 5.3 (System Efficiency) *System efficiency is defined as the percentage of the total queries sent successfully by all readers to the total number of queries sent by all readers, as given in equation (5)*

$$\text{System Efficiency}(\%) = \frac{\text{Total queries sent successfully by all readers}}{\text{Total queries sent by all readers}} \times 100 \quad (5)$$

The total queries sent by all readers include both successful queries and collided queries. The comparison of the algorithms for each performance index is shown in **Fig. 7** to **Fig. 9**. **Fig. 7** shows the identification time of the proposed algorithm and other conventional reader anti-collision algorithms. We found that the proposed improved pulse protocol-based algorithm reduces the identification time compared with the conventional channel monitoring algorithm and pulse protocol, when the number of readers is larger than one. This verifies that the proposed algorithm reduces the probability of collisions. We also found that the improvement in the identification time by the proposed scheme is proportional to the number of readers compared with the conventional pulse protocol.

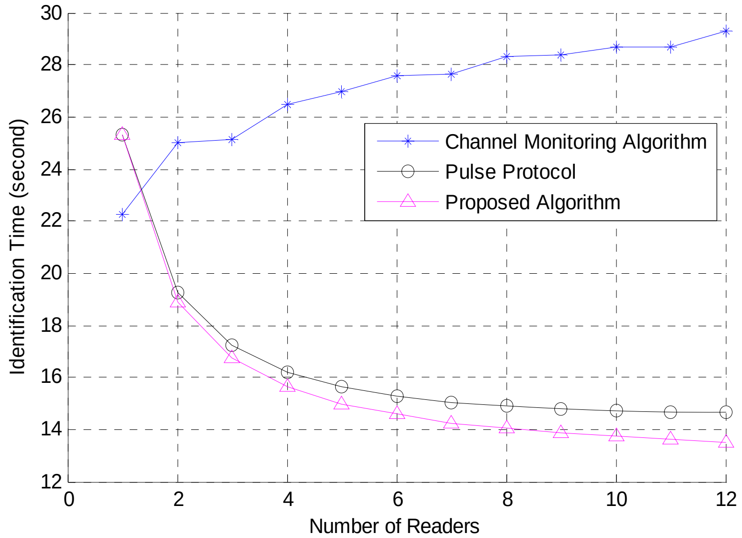

Fig. 7. Identification time of the proposed algorithm and conventional algorithms

The comparison of the system throughput is shown in **Fig. 8**. Again, the proposed algorithm improves the system throughput compared with other conventional algorithms. The improvement in the throughput shows an increase in the reading rate, thus increasing the efficiency of the reader anti-collision algorithm.

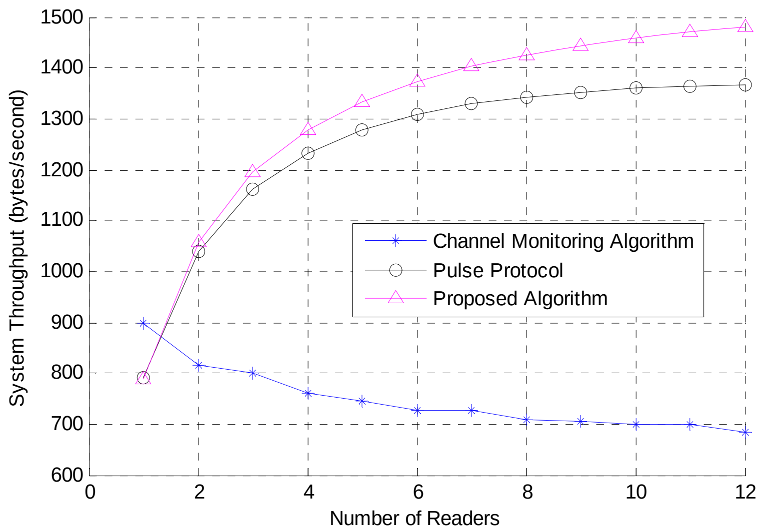

Fig. 8. System Throughput of the proposed algorithm and conventional algorithms

Fig. 9 shows the system efficiency for each reader anti-collision algorithm. We found that the proposed algorithm ensures that the system efficiency remains above 99%, even in highly dense reader mode, which indicates that the proposed pulse protocol eliminates most reader collisions compared with other conventional algorithms.

Based on this discussion, we conclude that the proposed improved pulse protocol-based algorithm is more effective than other conventional reader anti-collision algorithms. That is, the proposed algorithm reduces the identification time and increases the system throughput and system efficiency.

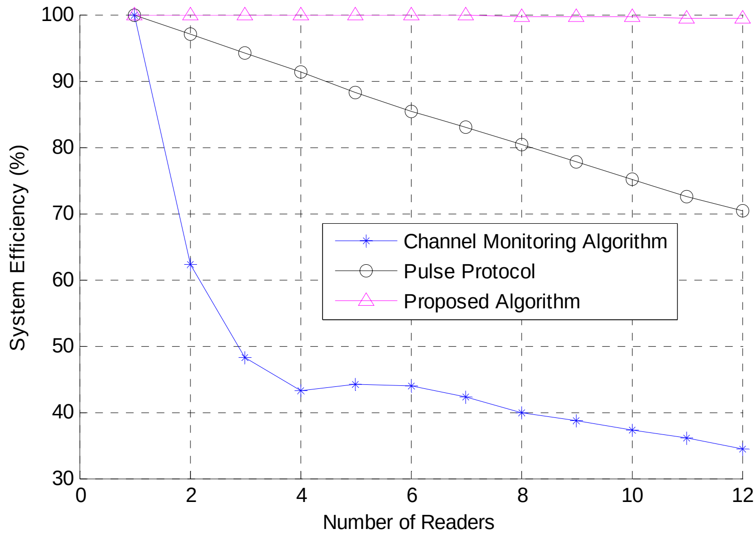

Fig. 9. System efficiency of the proposed algorithm and conventional algorithms

6. Conclusion

In this paper, we analyzed the reader collision problem, and described the existing anti-collision solutions to the problem of reader collisions. We also proposed a new pulse protocol-based reader anti-collision algorithm, which improves the conventional pulse protocol by introducing slot occupied probability. The implementation of this improvement is simple, yet it effectively mitigates most reader collisions in dense reader mode. The simulation results show that the proposed algorithm reduces the identification time, and increases the system throughput and system efficiency compared with the conventional reader anti-collision algorithms.

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