A Novel Anti-Collision Protocol with Collision-Based Dynamic Clustering in Multiple-Reader RFID Systems

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Abstract: The Reader Collision Problem (RCP) is a bottle-neck decreasing the reading efficiency in multiple-reader RFID systems. This paper proposed a novel anti-collision protocol – DRA (Distributed Reservation-based Anti-collision) protocol to solve the RCP in multiple-reader RFID systems. Temporal Cluster Headers (TCHs) are dynamically selected among the potentially interfered readers in DRA protocol. The selected TCHs coordinate the communication sequence of all the slave readers within their control range and enable a collision-free reading procedure among all the readers. Both analytical and simulation results show that DRA protocol dramatically outperforms the existing RCP protocols in both reading efficiency and power consumption. Moreover, DRA protocol can be easily extended and applied in general wireless sensor networks.

Key–Words: Radio Frequency Identification (RFID), Reader Collision Problem (RCP), Anti-collision, MAC

1 Introduction

RFID (Radio Frequency Identification) is a contactless identification technology using the wireless radio waves. The RFID system is typically composed of readers and tags, where the readers read the information stored in tags through wireless channels. The signal collision is the key problem decreasing the reading efficiency of the RFID system and can be classified into two categories. The first one is the "Tag Collision Problem", which happens when several tags respond to a single reader simultaneously [1, 2, 3]. The other is the "Reader Collision Problem", which occurs when the reading ranges of multiple readers overlap with each other and causes tags in the overlapped area unable to be identified [4, 7]. The paper focused on how to solve the latter reader collision problem.

The existing RCP solutions can be classified into two categories: scheduling based schemes and coverage based schemes. The main idea of the scheduling based approaches are establishing a networked architecture to collect collision information from readers and then allocating the system resources accordingly. Colorwave, HiQ-Learning, and PULSE protocols fall within this scheduling based approach [4, 5, 6]. However, the system resources required to establish and maintain such a networked architecture is extremely high. Moreover, even small variations of the structure will lead to a global-wide reallocation, thus increasing the protocol overhead significantly. Coverage based approaches generally introduce extra central controllers to detect the reader collisions. The central controllers can coordinate the power level of the readers to reduce the collision probability. HLLCR protocol is a typical example of this approach [7]. However, the control algorithm to adjust the power level is always inevitably complex. In addition, the introduction of the central controller will also increase the system cost.

This paper proposed a novel anti-collision protocol – DRA protocol to solve the reader collision problem in multiple-reader RFID system. Temporal cluster headers are dynamically selected from the interfered readers. Thus, the entire network is divided into multiple communication clusters in accordance with the current collision information. The reader collision can be completely avoided under the control of the selected TCHs. Compared with existing RCP protocols, DRA protocol improves both reading and energy efficiency dramatically.
2 System Structure

A typical RFID system is shown in Fig. 1, the circles and squares are representatives of readers and tags respectively. The reading range of readers are shown in solid lines. The interference range of readers figured out in dotted line is even larger. When multiple readers read tags simultaneously, some tags might be read by two readers simultaneously (i.e. Tag \( T_1 \)) while some other tags will be read by one reader and interfered by another (i.e. Tag \( T_2 \)). In both cases, readers are unable to read tags correctly. Some proposals have been introduced to solve the reader collision problem [4, 5, 6]. However, their performance is far from being perfect. PUSLE protocol is one of the most effective RCP protocols among existing RCP solutions. In PULSE protocol, multiple readers contend to access a beacon channel and the winner will inhibit adjacent readers from working by sending beacon signal on the beacon channel. The effective area of the beacon signal is required to be larger than the interference range shown in Fig. 1. However, the problem is that the beacon channel will demand extra frequency resources and increase the power consumption of the system.

3 DRA Protocol

The proposed DRA protocol divides the reading process in multiple-reader RFID system into three steps. First step, the temporal cluster heads are dynamically selected from readers based on a traditional contention scheme. Second step, the temporal cluster headers reserve and arrange the communication sequence of the readers within its cluster. Third step, slave readers are coordinated to work under the reserved reading sequence.

### 3.1 Temporal Cluster Header Selection

A temporal cluster header is only selected from adjacent readers interfered with each other. Then the RFID network can be divided into multiple communication groups centered by the temporal cluster headers. Each headers will coordinate the communication process of readers in its own clusters. The detailed selection procedure is given as:

1. Interfered readers in adjacent area contend to be the temporal cluster header based on a general contention scheme, such as CSMA (Carrier Sense Multiple Access). For instance, the reader firstly senses the channel, if the channel is free and there are no other readers working at this moment, the reader sends out the contention command to compete for the temporal cluster header.

2. The winning reader in the first step will broadcast at a proper power level within the cluster to claim as the header. Only those adjacent readers with potential interference possibilities are notified.

3. The informed readers that failed in the contention procedure work as slave readers and will be controlled by the cluster header in their communication clusters.

From the above description, multiple temporal cluster headers are selected based on the current interference topology and the RFID network is dynamically reorganized accordingly. It is necessary to point out that only the readers with communication demand involve in the competition. Those readers without transmission requirement will keep silence and never participate into the contention procedure. Moreover, the temporal cluster headers are dynamically selected according to transient reader collision information and only survive until the interference topology changes. In the following, we will focus on the working scheme within single interference cluster.
3.2 Reservation of Reading Sequence

The purpose of the second reservation step is to reserve the reading sequence under the control of temporal cluster headers. From the point of view of RFID, TDMA (Time Division Multiple Access) is a reasonable choice to solve RCP comparing to FDMA (Frequency Division Multiple Access) and CDMA (Code Division Multiple Access). Thus, there are two important problems to be considered about the resources allocation to all the readers. First, the reading sequence of all the readers should be determined. Second, since the number of tags for different readers to identify could be various, the time durations allocated to the readers should also be efficiently distributed based on their communication demands. The second time duration allocation problem can be solved through a ACK handshake scheme, and will be discussed later.

The DRA protocol provides a novel solution of the reading sequence reservation problem. As a result, the reservation process is divided into two serial steps. In the first step, readers send out reservation requests during the reservation process initiated by the temporal cluster header. The cluster header detects the reservation results and then reallocates the reading sequences to the slave readers in the second step to avoid the reader collisions. The whole reservation process is implemented as follows:

1. The temporal cluster header first broadcasts a start command to notify the slave readers to send out reservation requests, the range of the reservation sequence number is \([1 \sim N_r]\).

2. The controlled readers receive the command from the cluster header, select a number \(S_i \in [1 \sim N_r]\) as its sequence number and sends reservation request back to the cluster header at the \(S_i\)th reservation slot.

3. The temporal header checks the collision results of all the reservation slots and creates a reservation table for the slave readers.

Fig. 2 offers an example of the reservation process. From Fig. 2, we can see that there are three types of reservation slots: "blank slot" that no reader selects, i.e. No. 2, 5; "correct slot" that only one reader selects, i.e. No. 1, 4, 6; "collision slot" that more than one reader select, i.e. No. 3. Obviously, only the readers selecting the correct slots can be used in the following communication process. Based on the reservation table, the temporal cluster header form the collision free reading sequence as shown in Fig. 2, i.e. No. 1, 4, 6 could get the reading opportunities. Readers failed in the reservation competition will wait for the next round to contend for their sequence number again.

3.3 Collision-Free Reading Process

Based on the reservation sequence table, the temporal cluster header coordinates the slave readers to identify tags in their own reading range respectively. In the collision-free reading process, the temporal header sends out command to the slave readers to activate the reading process in the reserved order. After a informed slave reader finishes reading tags in its range, it sends back an ACK to the temporal cluster header to indicate its reading termination. Then the temporal cluster header notifies the next reader on the reservation sequence table to read tags.

After all the slave readers on the reservation sequence table finish their tag-reading procedure, the temporal cluster header repeats the above three steps until all the readers in the cluster accomplishes their tag-reading process.

Compared with current RCP protocols, the DRA protocol is characterized with several advantages. First, the temporal cluster headers are dynamically selected from adjacent interfered readers according to real-time interference topology. The introduced header competition scheme significantly saved the protocol overhead comparing to information flooding schemes in existing protocols such as Colorwave and HiQ-Learning [4, 5]. Second, the effective reservation-reallocation process contributes to reduce the contention overhead, thus the temporal cluster header is enabled to coordinate a collision-free reading procedure. Third, the ACK handshake scheme offer an efficient method to allocate exact time duration required by the slave readers. Moreover, DRA is a pure TDMA protocol and saves the introduction of extra control channel as PULSE [6].

3.4 Performance Analysis

Based on above description, the DRA protocol efficiency is discussed in this subsection. Suppose that there are \(N_s\) slave readers in a interference cluster and the number of reservation slots is \(N_r\), the probability that \(q\) readers selects one same slot obeys a binomial distribution:

\[
P_q = \binom{N_s}{q} \left(\frac{1}{N_r}\right)^q \left(1 - \frac{1}{N_r}\right)^{N_s-q},
\]

when \(q = 1\), \(P_1\) is the appearance probability of "correct slot". Therefore, the expected number of "correct slot" \(N_r\) is given as follows:

\[
N_r = N_r \times P_1 = N_r \cdot N_s \left(\frac{1}{N_r}\right) \left(1 - \frac{1}{N_r}\right)^{N_s-1}.
\]
Define the system efficiency $E$ as the efficient reading time divided by the total time including reservation time, we get:

$$ E = \frac{\text{Efficient Reading Time}}{\text{Total Time}} = \frac{E_r}{L_{av} \times N_r + L_r \times N_r}, \quad (3) $$

where $L_{av}$ is the average time duration allocated to slave readers and $L_r$ is the length of reservation slots. From equation (2) and equation (3), we can get:

$$ E = \frac{N_s \left( 1 - \frac{1}{N_r} \right)^{N_s-1}}{1 + \left( \frac{L_{av}}{L_r N_r} \right) N_s \left( 1 - \frac{1}{N_r} \right)^{N_s-1}}. \quad (4) $$

For simplicity, define

$$ \alpha = \left( \frac{L_{av}}{L_r N_r} \right) N_s \left( 1 - \frac{1}{N_r} \right)^{N_s-1}, \quad (5) $$

$$ \beta = \frac{L_{av}}{L_r}. \quad (6) $$

In order to maximize $E$ in Eq. (3), we have to maximize $\alpha$. It is obvious that bigger $\beta$ produces bigger $\alpha$. In another word, we should try to decrease the reservation slot length $L_r$.

The other challenge of maximizing $\alpha$ is to assign an optimal $N_r$ according to $N_s$. By differentiating $\alpha$, we get:

$$ \frac{\partial \alpha}{\partial N_s} = \beta \left( 1 - \frac{1}{N_r} \right)^{N_s-1} \left( 1 + N_s \ln \left( 1 - \frac{1}{N_r} \right) \right) = 0. \quad (7) $$

Solving Eq. (7), we can get the the optimal $N_r$ according to $N_s$:

$$ N_r(\text{opt}) = \frac{e^{1/N_r}}{e^{N_s} - 1}. \quad (8) $$

However, in practical systems, we can hardly to obtain the exact value of $N_s$ especially in a dynamically organized interference cluster. Thus, Eq. (8) can be hardly applied in practical system. On the other hand, it does not mean that we can not employ Eq. (8) at all. An estimation algorithm for $N_s$ has been proposed in [9] and could be employed to obtain an estimated version of $N_s$.

### 4 Simulation Results and Hardware Verification

This section compares the reading efficiency and power consumption between DRA and PULSE protocol. Moreover, DRA protocol is implemented and verified in RFID hardware prototype. The simulation scenario is setup as follows: multiple readers are deployed randomly in a 100m × 100m area, the reading radius of a reader is 5m, there are 30 tags in every reader’s reading range in average. The reading communication between readers and tags obeys EPC (Electronic Product Code) Global standard $Q$-Algorithm in [8]. Multiple communication clusters are dynamically organized according to the transient interference among readers. Different communication groups are assumed to be non-interference to each other and could work simultaneously. The same simulation parameters are employed in PULSE protocol and shown in Table 1.

Fig. 3 shows the reading efficiency comparison between DRA protocol and PULSE protocol. The abscissa is the number of readers, while the y-axis is the number of reading slots required for all readers to finish their reading tasks. As shown in Fig. 3, when the number of readers remains the same, the required reading slots of DRA protocol is much smaller than PULSE protocol. The difference becomes even larger when the reader number increases. In PULSE protocol, each reader competes for the beacon channel independently and the contention winner should send out beacon signal periodically to disable adjacent readers from activation. The overhead of contending and occupying beacon channel leads to high level of cost. In contrast, DRA protocol abandons the reader contention process and employ the reservation scheme described above. When the reader number approaches 100, DRA protocol saves nearly 500 reading slots compared with PULSE protocol. In other words, the reading efficiency is improved by about 50%.

Extra power consumption comparison results between DRA protocol and PULSE protocol is shown.
Table 1: Simulation Parameters

<table>
<thead>
<tr>
<th></th>
<th>PULSE Protocol</th>
<th>DRA Protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reader number</td>
<td>10 ∼ 100</td>
<td>10 ∼ 100</td>
</tr>
<tr>
<td>Average tag number for a reader</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Working frequency</td>
<td>915MHz</td>
<td>915MHz</td>
</tr>
<tr>
<td>Data rate</td>
<td>40Kbps</td>
<td>40Kbps</td>
</tr>
<tr>
<td>Contention slot</td>
<td>10ms</td>
<td>10ms</td>
</tr>
<tr>
<td>Average reservation time</td>
<td>No</td>
<td>5 ms</td>
</tr>
<tr>
<td>Reader power</td>
<td>0.2W</td>
<td>0.2W</td>
</tr>
<tr>
<td>Antenna polarity</td>
<td>Omni-directional</td>
<td>Omni-directional</td>
</tr>
</tbody>
</table>

Figure 4: Extra power consumption comparison

in Fig. 4. The abscissa is also the number of readers, while the y-axis is the extra power consumption for all the readers to complete reading tags. In PULSE protocol, it is the power spent in beacon channel contention and beacon broadcast. In DRA protocol, it means the power consumed in cluster header contention and communication sequence reservation. The simulation results indicate that the extra power consumption of DRA protocol is far less than PULSE protocol. When the reader number approaches 100, the extra power consumption of PULSE is 3W while DRA reduces the extra power consumption to only 0.2W. Moreover, the extra power consumption of PULSE protocol increases almost linearly with various reader number while DRA protocol consumes energy at almost the same level. The improvement should be attributed to the drop of beacon channel and introduction of efficient sequence reservation.

We have developed a RFID network verification platform in Peking University and implemented DRA protocol into the prototype for testing. The RFID platform is shown in Fig. 5. The testing platform is build based on CC1100 wireless radio module of InFortech Corporation. The testing results appear to be in highly accordance with the simulation results with a largest derivation of about 10%.

5 Conclusion

This paper proposed a novel RCP solution in multiple-reader RFID system – DRA protocol. The reader collision problem is solved by dynamically reorganizing the network into different communication clusters controlled by temporal cluster headers. In each communication cluster, the selected cluster header employs an effective reservation process to coordinate the reading sequence of slave readers. Thus, readers could read tags without interfering other readers under the control of cluster header. The drop of beacon channel in DRA helps to reduce the communication overhead significantly. Simulation results show that DRA protocol improves the reading efficiency over 50% and meanwhile reduces power consumption dramatically. Moreover, DRA is a fully distributed RCP protocol, promising the RFID system more extensive and ro-
bust. Additionally, DRA protocol can be easily implemented in current multiple-reader RFID systems.

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