Enhanced Collision Arbitration Protocol Utilizing Multiple Antennas in RFID Systems

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Abstract—In this paper, we present an enhanced collision arbitration protocol that operates over multiple antennas in RFID systems. An RFID system consists of a reader and tags, and all tags have to be quickly recognized by a reader. Due to a contention based tag transmission, collision arbitration is a very important issue in tag identification. However, collision always happens in the existing single antenna based collision arbitration scheme when more than one tag simultaneously transmit message. In order to reduce the number of collisions, we propose to use multiple antennas at the reader such that the reader can recognize multiple tags simultaneously by utilizing multi-user receiver at the reader and multiple orthogonal preambles used by each tag. In this scheme, only the tags that are not identified retransmit in the next time slot while the identified tags keep silent. Then the identification delay significantly decreases because the number of retransmissions decreases in comparison with the single antenna scheme. We analyze the performance of this proposed scheme and conduct simulations to confirm the validity of the mathematical modeling. According to the analytical and simulation results, the proposed scheme outperforms the existing single antenna scheme.

I. INTRODUCTION

Radio frequency identification (RFID) systems consist of a reader and multiple tags. Each tag stores a unique ID and information of the attached object. The reader should know the IDs of all tags within its radio field in order to obtain the information about the objects. Thus, all tags send their IDs to the reader and the reader must identify them as quickly as possible. However, when multiple tags send their IDs simultaneously, collision occurs and so they should retransmit their IDs. It results in waste of energy and increases identification delay. Therefore, a collision arbitration protocol which decreases the number of retransmissions and reduces the identification delay is required.

Collision arbitration protocols are grouped into two different types [1]–[3]: ALOHA based protocols and tree based protocols. ALOHA based protocols are characterized by the fact that the reader determines the frame size and each tag sends its ID in the time slot chosen by itself until the tag is successfully recognized during the frame size. Tree based protocols split the set of colliding tags into two subsets. The tags in the first subset transmit their IDs in the next slot. The tags in the other subset wait until the first subset of tags are successfully identified. This process is done recursively until all tags have been recognized. Tree based protocols can be classified into query tree (QT) protocols and binary tree (BT) protocols. QT splits tags according to the prefix of tags’ IDs, while BT uses the random binary number to decide the split of tags. Thus, the identification delay of QT is affected by the distribution of tags’ IDs but QT needs not to have additional memory to store the counters of tags. In general, BT outperforms QT at the cost of higher complexity.

There have been reported several researches considering multiple antennas at the reader. In [4]–[6], the authors introduced MIMO configuration and discussed spatial multiplexing gain for tags by using MIMO techniques. In [7]–[8], the authors presented and analyzed the advanced collision arbitration protocols exploiting multi-packet reception capability. Especially, they focused on improving the performance of ALOHA based protocols and QT. However, to the best of our knowledge, no work exists in the literature that addresses the BT protocol utilizing multiple antennas at the reader.

In this paper, we present and analyze an enhanced BT based collision arbitration protocol that is designed to identify multiple tags simultaneously by exploiting multiple antennas at the reader. The key idea is to use multiple orthogonal preambles instead of a common preamble and the multi-user receiver at the reader. If multiple tags simultaneously transmit their IDs along with different preambles, the reader can recover all or part of them by applying multi-user receiver. In the conventional single antenna based scheme, although the reader has multiple antennas, it cannot recognize multiple tags simultaneously because of a common preamble. Note that the orthogonality of preambles enables the reader to estimate and discriminate the channel information from the transmitting tags. If the reader successfully decodes part of them, it separates out the identified tags, and then the tags that are not identified retransmit their IDs in the next slot. This process curtails the identification delay significantly. We analyze the proposed protocol by a recursive form and evaluate the performance.

The rest part of the paper is organized as follows. Section II presents the enhanced collision arbitration protocol. Then Section III analyzes the proposed protocol and, finally, Section IV examines the performance of the proposed scheme in comparison with the existing scheme.

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II. ENHANCED COLLISION ARBITRATION PROTOCOL

Fig. 1 shows the RFID system model in consideration. We consider the system that is composed of a reader with $M$ antennas and multiple tags with a single antenna. The reader sends all tags the message including preamble, command, ID_SET, and cyclic redundancy check (CRC). In response to the message of the reader, the corresponding tags transmit their own IDs with a randomly selected preamble out of multiple orthogonal preambles and CRC. Note that in the conventional protocol each tag uses a common preamble. We denote the message of the reader as $\mathcal{M}(\text{Command, ID}_\text{SET})$. The ‘Command’ field is filled with one of $\text{Start}$, $\text{Success}$, $\text{Fail}$ and $\text{Partial success}$. The ‘ID_SET’ field is used only when the command is $\text{Partial success}$.

The reader broadcasts $\mathcal{M}(\text{Start})$ when the collision arbitration begins. After receiving several IDs from tags, if the reader recovers all received IDs or nothing, it sends $\mathcal{M}(\text{Success})$ or $\mathcal{M}(\text{Fail})$, respectively. On the other hand, if the reader successfully decodes part of the received IDs, it has to inform the transmitting tags which tags are identified since the unidentified tags have to retransmit their IDs. In order to distinguish recognized tags with others, the reader sends $\mathcal{M}(\text{Partial success, ID}_\text{SET})$. The ‘ID_SET’ represents the set of successfully decoded IDs. Note that the command $\text{Partial success}$ is not necessary in the conventional protocol since the reader sends $\mathcal{M}(\text{Success, ID}_\text{SET})$ if the single tag transmits its ID or sends $\mathcal{M}(\text{Fail})$ otherwise.

Fig. 2 shows the pseudo code of the proposed protocol. Like the conventional protocol, a tag stores an 8-bit counter COUNT and a random number generator with two possible values, 0 or 1. The tag uses COUNT to determine how many more slots to wait before transmitting its ID. Thus, each tag transmits its ID when COUNT=0. In the beginning, all COUNTs are initialized to zero and the reader sends $\mathcal{M}(\text{Start})$ to all tags. After receiving $\mathcal{M}(\text{Start})$, every tag transmits a randomly selected preamble along with its ID because COUNT=0. The reader then detects several preambles, decodes the messages by using multi-user receiver, and sends a message with an appropriate command. All tags adjust their COUNTs according to the newly-received command.

Consider a case that more than one tag transmit their IDs simultaneously. If they choose the same preamble, the reader cannot recover the received signals at all as in the conventional protocol. On the other hand, if they select different preambles, the reader obtains the each tag-to-reader channel information while detecting received orthogonal preambles. The multi-user receiver at the reader decodes their IDs by using the estimated channel information. Although the reader is aware of the perfect channel information from transmitting tags, it can happen...
that the multi-user receiver at the reader does not recover their IDs when their channels are hard to cancel out each other. Thus, the multi-user receiver cannot always recover all the received IDs while it detects all the received preambles regardless of the channel information due to their orthogonality. Therefore, whether the reader successfully decodes all or part of transmitting tag IDs is determined by comparing the number of the detected preambles with that of the successfully decoded IDs. If the reader succeeds in identifying all the transmitting tags, the number of the detected preambles is larger than that of the successfully decoded IDs. Thus, in the case that the tags, the number of the detected preambles is larger than that of the successfully recovered IDs or no IDs are recovered, the number of the detected preambles is the same as the number of the successfully decoded IDs. Therefore, if the reader fails to decode all of the transmitting tag IDs, the number of consumed slots is just one. If they choose different preambles and the reader decodes their IDs successfully, the number of consumed slots is just one. If they choose different preambles but the reader decodes only one of them, an additional slot is needed to recognize the remaining tag. Otherwise, i.e., if the reader fails to decode all of them, they are separated into two subsets. If the number of tags in the first subset is \( n \), the number of tags in the other subset is \( 2 - n \). It takes additional \( (D(i) + D(2 - i)) \) slots to identify all tags in each subset. Thus, \( D(2) \) takes the expression

\[
D(2) = S(2, 2) + S(2, 1) (1 + D(1)) + S(2, 0) 2^{-2} \sum_{i=0}^{2} \binom{2}{i} \{1 + D(i) + D(2 - i)\},
\]

where \( D(0) = 1, D(1) = 1 \). The result from (1) can be easily generalized to the case of \( n \geq 2 \) as follows:

\[
D(n) = S(n, n) + S(n, n - 1) (1 + D(1)) + \sum_{k=0}^{n-2} S(n, k) G(n - k),
\]

III. Mathematical Analysis

We analyze identification delay of the proposed protocol in terms of time slots required for recognizing all tags. We denote by \( D(n) \) the average number of consumed slots for the entire identification process when the number of tags is \( n \). We denote by \( S(i, j) \) the probability that \( j \leq i \) tags are successfully recognized when \( i \) tags transmit their IDs in the same slot.

We first consider the case that only two tags exist in the RFID system. In the beginning, the reader sends \( M(\text{Start}) \) and tags transmit their IDs simultaneously. If they choose different preambles and the reader decodes their IDs successfully, the number of consumed slots is just one. If they choose different preambles but the reader decodes only one of them, an additional slot is needed to recognize the remaining tag. Otherwise, i.e., if the reader fails to decode all of them, they are separated into two subsets. If the number of tags in the first subset is \( n \), the number of tags in the other subset is \( 2 - n \). The reader transmits \( M(\text{Partial success, ID}_1) \) or \( M(\text{Fail}) \), respectively. Otherwise, the reader transmits \( M(\text{Partial success, ID}_2) \).

After receiving this message, each tag checks which command the reader sends. If the command is \( \text{Success} \), all tags decrease their COUNTs by one. If the command is \( \text{Fail} \), the tags involved in this slot, (i.e., tags with COUNT\(=0\)) add a random binary number (0 or 1), and the tags with COUNT\(\neq 0\) just increase their COUNTs by one. If the command equals to \( \text{Partial success} \), each tag with COUNT\(=0\) checks whether its ID is included in \( \text{ID}_1 \). If it is included, it means that the tag has been identified in this slot and so it decreases its COUNT by one. If not, the tag holds its COUNT to try again the identification process in the next slot. Also, tags with COUNT\(\neq 0\) hold their COUNTs.

Fig. 3 illustrates the operation of the proposed protocol for the case of four tags: \( T_1, T_2, T_3, T_4 \) and two antennas at the reader. First, the reader sends \( M(\text{Start}) \) to begin the identification process. At the second slot, the reader identifies \( T_3 \) because they select different preambles and the multi-user receiver at the reader successfully decodes only one of two IDs. Thus, the reader sends \( M(\text{Partial success, ID}_3) \). After receiving this message, \( T_3 \) perceives that it has been recognized and keeps silent while \( T_4 \) holds their COUNT and transmits its ID in the third slot. Both \( T_1 \) and \( T_2 \) also hold their COUNTs. At the fourth slot, both \( T_1 \) and \( T_2 \) are identified because they use different preambles and the reader successfully recovers both IDs by utilizing the multi-user receiver.
where
\[
G(n) = 2^{-n} \sum_{i=0}^{n} \binom{n}{i} \{1 + D(i) + D(n - i)\}
\]
\[
= 1 + 2(1-n) \sum_{i=0}^{n} \binom{n}{i} D(i).
\]

Thus, a closed form expression of \(D(n)\) is given by
\[
D(n) = \left\{ S(n, n - 1) (1 + D(1)) + \sum_{k=1}^{n-2} S(n, k) G(n - k) + S(n, n) + S(n, 0) \left\{ 1 + 2^{(1-n)} \sum_{i=0}^{n-1} \binom{n}{i} D(i) \right\} \right\} / \left\{ 1 - S(n, 0) \frac{2}{2(n-1)} \right\}. \tag{3}
\]

We assume that each tag randomly selects a preamble out of \(K\) orthogonal preambles. \(S(i, j)\) depends both on \(M\) and \(K\). As an example, consider \(M = 2\). When only one tag sends its ID, it always succeeds to be recognized. Thus, \(S(1, 0) = 0\) and \(S(1, 1) = 1\). In case two tags send their IDs simultaneously, if they select different preambles, the reader can decode their IDs successfully. The probability that two tags select different preambles out of \(K\) preambles is \(K(K-1)/K^2\). Thus, \(S(2,1) = (K-1)/K P_{\text{succ}}(2) (1 - P_{\text{succ}}(2))\), \(S(2,2) = (K-1)/K (P_{\text{succ}}(2))^2\) and \(S(2,0) = 1 - S(2,1) - S(2,2)\), where \(P_{\text{succ}}(n)\) is the successful decoding probability of a tag given that \(n\) tags send their IDs simultaneously.

For the simplicity of the analysis, we assume that a zero-forcing receiver is used as the multi-user receiver. Also, we assume an i.i.d. Rayleigh fading channel with an average SNR, \(\rho\), fixed for all tags. It has been shown in [13] that the received SNR on the output data streams after zero forcing reception is distributed by
\[
f(x) = \frac{H \cdot e^{-\frac{Hx}{\rho}}}{\rho M ![M-H]!} \left( \frac{H}{\rho} \right)^{M-H} \cdot u(x) \quad (H \leq M), \tag{5}
\]
where \(H\) is the number of transmitting tags. Since we assume the success criteria that the received SNR after the zero forcing reception is greater than \(\rho_{th}\), the success probability of a tag given that each of \(H\) tags transmits its ID simultaneously is
\[
P_{\text{succ}}(H) = \left\{ \int_{\rho_{th}}^{\infty} \frac{H \cdot e^{-\frac{Hx}{\rho}}}{\rho [M-H]!} \left( \frac{H}{\rho} \right)^{M-H} dx \quad \text{if } H \leq M, \right\}
\]
case otherwise.

Consider \(T(\geq 2)\) tags transmit their IDs at the same slot. If the number of detected preambles is larger than \(2\), the reader cannot identify any IDs, since \(M = 2\). If the number of detected preambles is equal to one, the reader also cannot identify IDs at all as in the conventional protocol. Thus, for the reader to be able to decode a tag out of \(T\) tags, each of \(T\) tags must select a preamble out of only two preambles.

In detail, if a tag selects preamble \(k\), the remaining \((T - 1)\) tags must select the same preamble except the preamble \(k\). Thus, \(S(T,1) = T \frac{(K-1)}{K} P_{\text{succ}}(2)\), \(S(T,0) = 1 - S(T,0)\), \(S(T,j) = 0\) for \(j > 1\). For the case of \(M > 2\), \(S(i,j)\) can be easily calculated in a similar manner. Note that if \(S(i,0) = 1\) and \(S(i,j) = 0\) for \(i > 1\) and \(j > 0\), \(D(n)\) equals to the identification delay of the conventional protocol.

IV. PERFORMANCE EVALUATION

We evaluate the performance of the conventional and proposed protocols by computer simulations, and then, confirm the mathematical analysis by comparing the simulation results with the analytical results. The conventional protocol is the collision arbitration algorithm in ISO-18000 Part 6B [1]. For the computer simulations, we set the average SNR \(\rho = 12 \text{ (dB)}\) and the success criteria \(\rho_{th} = 10 \text{ (dB)}\).

Fig. 4 depicts the resulting identification delay (measured in the number of slots) with respect to different number of tags for different numbers of antennas, \(M\), and preambles, \(K\).
We observe that the analysis results closely match the simulation results. It demonstrates the validity of the mathematical analysis developed in Section III. We also observe that the proposed protocol outperforms the conventional protocol, and the performance gap obviously increases as the number of antennas and preambles increases.

Table I shows the partial success probability that the reader decodes successfully one or more tags when more than one tag transmit their IDs simultaneously. We observe that the partial success probability increases as the number of antennas, \( M \), and that of preambles, \( K \), increase. It means that more tags can be identified simultaneously as \( M \) and \( K \) increase. For this reason, the proposed protocol outperforms the conventional protocol.

V. CONCLUSION

In this paper, we have presented an improved collision arbitration protocol that takes advantage of the multiple antennas at the reader in RFID systems. It is designed to transmit the ID of a tag with a randomly chosen preamble, not with the common preamble, so that multiple tags succeed to be identified simultaneously. If the reader decodes part of tags that simultaneously transmit their IDs, it sends the message that contains the command Partial success such that the identified tags can be distinguished from others. Such a partial success contributes to decreasing the identification delay as compared with the conventional protocol. Analytical and simulation results demonstrate about 29% performance gain of the proposed protocol when \( M = 2 \) and \( K = 2 \). Therefore, the proposed protocol is confirmed to reduce the identification delay significantly at the expense of the relatively minor modification.

REFERENCES


