Interference Avoidance Algorithms for Passive RFID Systems Using Contention-Based Transmit Abortion

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SUMMARY The performance of a passive RFID system in a dense multi-reader environment is limited by both reader-to-reader interference and reader-to-tag interference. In this paper, we formulate a practical RFID system model which takes into account the non-linear demodulation of the tags and the transmission spectrum of the readers. Using this model, we derive a novel linear programming formulation to obtain the optimum communication probability of the readers for a given reader deployment scenario. We then propose two novel distributed interference avoidance algorithms based on the detect-and-abort principle for multi-channel readers which can effectively mitigate the reader-to-tag interference as well as the reader-to-reader interference. Computer simulations show that the proposed algorithms can improve the successful communication probability and fairness among readers in dense reader environments, compared with the conventional listen-before-talk algorithm.

key words: RFID, reader collision, collision avoidance

1. Introduction

The radio frequency identification (RFID) technology has received much attention for applications in various industries. Passive RFID systems using UHF-band of 860–960 MHz enable identification from distances up to several meters which is longer than that of RFID systems using other frequencies such as 13.56 MHz, and therefore, have been gathering much interest in recent years. Major technical standardizations of the UHF-band passive RFID systems have been completed and local radio regulations have been developed in many countries. A passive tag does not have an on-label power source (i.e., a battery). Instead, it uses the power emitted from the reader to energize itself and transmit its stored data to the reader. Therefore, the output power of the readers is high enough to activate the passive tags which will be several watts in equivalent isotropic radiation power (EIRP). However, such high power transmission of readers will cause interference problem in the area where multiple readers are deployed.

In the dense reader environments, there are two interference problems which degrade the performance of RFID systems. The first is the mutual interference among readers which we call reader-to-reader (R-R) interference. This may sometimes be referred as reader collision. The tag back-scattered signal level received at the reader will become very low, for example, it will be about 90 dB below the reader transmission power when the distance between the reader and the tag is 4 m. Thus, the required signal to interference and noise ratio (SINR) could not be attained due to the R-R interference from nearby readers using same frequency channel which results in performance degradation. This problem can be mitigated by frequency division multiple access (FDMA) techniques such as the listen-before-talk (LBT) via carrier sensing on multiple frequency channels [1], [2], frequency hopping [3] and tag back-scattering using subcarrier modulation [4]. In the LBT scheme, each reader can transmit only when the interference level measured before the transmission is below the predetermined threshold level which guarantees the required SINR for receiving tag responses with a sufficient error probability. In some radio regulations mandating the use of LBT [1], [2], maximum continuous transmission time is also specified to improve fairness in the channel contents among readers. The frequency hopping technique is effective only when the available number of channels is large enough for reducing the probability of collision where multiple readers select the same channel simultaneously for their transmissions. In most of the current radio regulations except for in USA, enough bandwidth suitable for the frequency hopping is not available in UHF-band for RFID systems. In the system using the subcarrier modulation at tags, tag back-scatters its responses at shifted frequency bands from the reader transmission carrier frequency. By properly choosing the subcarrier frequency to have enough separation from the reader transmission spectrum, the R-R interference can effectively be mitigated even if a limited number of frequency channels is available. Time division multiple access (TDMA) techniques can also be used to avoid the R-R interference problem. The LBT readers will work in such a time division manner in a single channel system or in a multi-channel system without enough channels for concurrent reader operations. Centralized time scheduling schemes such as round-robin scheduling have been used in some applications with small reader networks [5]. However, such predetermined time scheduling will become more difficult in a large reader network than using FDMA-based control schemes.

The second is the interference from multiple readers to tags which we call reader-to-tag (R-T) interference. In contrast to the R-R interference problem, transmitted signals from nearby readers at any frequency channels can interfere with the tags because of its poor frequency selectivity. This means that the FDMA-based techniques are less effective
for controlling the R-T interference. Therefore, the TDMA-based approaches should be used for the problem.

Main objective of this paper is to find efficient distributed interference avoidance algorithms for multi-channel readers which maximize the successful communication probability and improve its fairness among readers in dense reader environments. Such an interference problem has been extensively studied for wireless LANs and wireless multi-hop networks. The difficulty of applying such technologies in RFID systems comes from the following reasons. The interference avoidance algorithms have to be implemented only in readers due to the limited functionalities of low cost tags. The tags have little frequency selectivity and also can not measure the R-T interference level by itself. These mean a carrier-sensing approach and an associated frequency channel selection used in wireless LAN can not work well. Large imbalance between the transmission power of reader and the back-scattered power of tag causes asymmetric interferences. Lastly, reader has to simultaneously transmit its carrier signal while it is receiving the tag responses using the same carrier frequency. So, the passive RFID system can not be treated as a pure time-division duplexing (TDD) system.

Requirements for the interference avoidance algorithms for RFID readers are summarized as follows. Since the interference problem might occur between reader networks deployed by different operators, distributed local algorithms without any data exchange among readers are preferred for easy implementations. Even if a central controller is used to realize all or part of the algorithm, a strict timing synchronization among readers or a critical timing control of each reader should be avoided. Fair allocation of communication opportunities among readers will be important in some applications. On the other hand, readers with different access priority requirements will need to operate concurrently in some scenarios. Therefore, flexibility in allocating the fairness and the priority should be considered in the design of the reader control algorithms.

There have been a lot of algorithms developed for RFID readers to solve the interference problem. Some of these algorithms use a centralized control for resource assignment of readers [6]–[8], while others operate on a distributed fashion [6], [9]–[11].

Engels proposes an optimal resource allocation problem formulation by graph coloring problem and its on-line implementations by both of centralized algorithms and distributed algorithms [6]. The centralized algorithm uses a central controller which allocates resources (frequency over time) to the readers upon their requests for transmission in order. In the distributed algorithm, each reader aborts the transmission when it detects the collision and attempts to transmit again at the next slot or after a random period. Another centralized algorithm is proposed in [7] where hierarchical control nodes learn the collision patterns of the readers and assign frequencies over time to the synchronized readers. This scheme can control the R-T interference as well as the R-R interference. In [8], a synchronized listen-talk sequence method is proposed. All the readers send their commands at the same time and then listen the responses from the tag at the same time in centralized fashion to avoid the R-R interference. The R-T interference is not addressed here. In all of these centralized algorithms, time slot synchronization is required among the deployed readers.

A distributed algorithm based on the framed ALOHA is proposed in [9]. This algorithm is combined with tag collision resolution algorithm [5]. In this algorithm, a reader sends a query command to tags at a randomly selected time slot to reduce the reader collision probability. However, the collision probability will increase when the number of the interferer readers is larger than that of the available time slots. Another distributed algorithm is proposed in [10] which uses a periodical busy packets exchange on a dedicated control channel from the reader communicating with tags. This scheme requires reader with an additional transceiver for the control channel. Also, this can not effectively control the R-T interference since the range of the R-T interference will be much different from that of the R-R interference. Colorwave [11] is a distributed algorithm based on TDMA with time slot reservation. Each reader chooses a random time slot to transmit. If it collides, it selects a new time slot and sends a reservation message to all its neighbors. This algorithm requires time synchronization among readers. The R-T interference may not be effectively controlled since the range of the R-T interference will be much different from the range within which the reservation messages are reached. We note that all of these distributed algorithms only consider single channel systems.

In this paper, we first formulate a multi-channel RFID system model which takes into account the non-linear demodulation of the tags and the transmission spectrum of the readers. Previous works did not take such factors into account for their performance analysis of RFID systems. This model can be used to estimate the reading performance, e.g. successful communication probability of actual multi-channel RFID systems in a dense reader deployment scenario. Then, using this model, we derive a novel linear programming formulation to obtain the optimum communication probability of the multi-channel readers. The optimum feasible solution of this model gives the maximum number of readers which can simultaneously communicate with tags in a given network. This also gives an upper bound of the successful communication probability of the on-line heuristic interference avoidance algorithms. As for such heuristic algorithms, we propose two novel distributed algorithms for multi-channel readers based on a detect-and-abort principle with a priority control capability which can effectively mitigate the R-T interference as well as the R-R interference. These algorithms can work in asynchronous fashion. This means that it does not require synchronization between readers which can greatly simplify the network design and reduce the cost. The first algorithm is a fully distributed algorithm and does not require any information exchange between readers. A reader communicating with tags aborts its transmission on the detection of interference for a
predetermined period and resumes the carrier sense after a sleep period. For the interference detection, we propose a novel contention-based R-T interference detection scheme. The priority of getting communication opportunity of each reader is dynamically updated according to the number of successive activations to improve the fairness. The second algorithm can effectively avoid the asymmetrical interferences, its definition is described in Sect. 2, by adding a simple centralized control of each reader’s the transmit duty. This algorithm can further improve the fairness. The simulation results reveal that the proposed algorithms can achieve improved communication probability and its fairness in dense reader environments.

In Sect. 2, we derive the passive RFID system model. The binary linear programming formulation of the model is proposed in Sect. 3. We propose two heuristic algorithms in Sect. 4. In Sect. 5, we demonstrate the performance of our proposed algorithms by simulations. Finally, we give conclusions in Sect. 6.

2. Passive RFID System Model

In this section, we formulate the system model of the multichannel passive RFID systems. The maximum distance for communication between reader and tag is determined as the minimum value of the following three distances, $D_p$: maximum distance at which tags can capture sufficient power for its activation, $D_f$: maximum forward-link distance where tag can correctly receive the interrogation commands from the reader, $D_b$: maximum backward-link distance where reader can correctly receive the responses from the target tags.

Tag can be activated when the received power is larger than its minimum required received power $P_{req}$. The required condition which determines $D_p$ is described as follows.

$$G_{ik} P_{ik} \geq P_{req} \quad \forall k \in V.$$  

(1)

$V$ is a set of the readers considered in the model. As node notations, we define $i_k$ as the $k$-th reader and $j_k$ as the tag interrogated by the reader $i_k$. $P_{ik}$ is the transmission power of the reader $i_k$. In free space propagation, the propagation gain $G_{ik}$ for transmission from the reader $i_k$ to the tag $j_k$ is expressed as [12],

$$G_{ik} = g_{ik} g_{jik} \left( \frac{\lambda}{4 \pi d_0} \right)^2 \left( \frac{d_0}{d} \right)^{\gamma} ,$$  

(2)

where $\lambda$ is the wave length of the center frequency of the RF signal, $d$ is the distance between the reader and the tag, $\gamma$ is the path loss exponent, and $d_0$ is the reference distance (usually 1m). And $g_{ik}$ and $g_{jik}$ are the directional antenna gains of the reader $i_k$ communicating with tag $j_k$ and of the tag $j_k$ communicating with reader $i_k$, respectively. Reader antenna usually has a directional beam pattern for efficient tag interrogation. Also, antenna beam pattern of each tag can be directional. Due to that, it should be noted that $g_{ik}$ and $g_{jik}$ are functions of its relative orientation. In this paper, we assume that channel is symmetrical, i.e. $G_{ik}$ is equal to $G_{ki}$.

For successful interrogation of tag, the SINR at the receivers should not be less than the threshold, $\gamma_{tag}$ for tags and $\gamma_{rw}$ for readers as follows,

$$\sum_{r \in V \cap \tau_k} G_{ik} P_{ik} \geq \gamma_{tag} ,$$  

(3)

$$\sum_{r \in V \cap \tau_k} F_{fr} G_{ik} P_{ik} + \eta_k \geq \gamma_{rw} .$$  

(4)

in which $F_{fr}$ is the R-T interference rejection gain of the tag at time slot $t$. This is a negative gain for the interference using frequency channel $f_r$, while the tag is also receiving the interrogation signal from the intended reader using frequency channel $f_k$. This rejection gain comes from the baseband filtering at the nonlinear demodulator of the tag, which is usually an Amplitude Shift Keying (ASK) signal envelope detector. $Q_{fr}$ is the back-scattered transmit power of the tag $j_k$. Typical values of $Q_{fr}$ are about 5 to 15 dB below the received signal power at the tag. $\eta_{fr}$ and $\eta_{fr}$ denote the power of noise at the receiver of the tag $j_k$ and of the reader $i_k$ respectively. $F_{fr}$ in (4) is the out-of-band leakage ratio of transmit signal at the channel apart from the carrier frequency with $[f_r-f_k]$ at time slot $t$. We note that (3) and (4) determine the distances $D_f$ and $D_b$, respectively.

We will now take a close look at the causes for the interference rejection gain $H_{fr}$. The bandwidth of tag RF receiver including the antenna is wide enough for receiving the wide range of RFID frequencies regulated in various countries, it is typically 860–960 MHz for UHF-band. Thus, all of the signals with frequencies in this range can be received at the tags. However, the baseband filter of the tag detector can suppress lower beat frequencies caused by undesired interference signals [13], [14]. For explanation purpose, we assume a simple rectifier detector for the tag detector. When the detector input signal $x(t)$ is sum of the $N$ different modulated carrier signals with the different carrier frequencies $\omega_i$ and the amplitudes $A_i(t)$ ($1 \leq i \leq N$), the baseband terms of the squared output signal can be expressed as follows,

$$x^2(t) = \sum_{i=1}^{N} \frac{A_i(t)^2}{2} + \sum_{i=1}^{N} \sum_{j=1, j \neq i}^{N} A_i(t) A_j(t) \cos(\omega_i - \omega_j)t + \text{higher order terms} .$$  

(5)

The first term of the right-hand side of (5) is the sum of the squared modulating signals. If all the interference signals are unmodulated carriers, these are constant and do not degrade the receiver performance. The second term of the right-hand side of (5) is the sum of the squared intermodulation (i.e. beat interference) components. When the desired signal is $A_i(t) \cos \omega_i t$ and $A_j(t) > A_i(t)$ ($2 \leq i \leq N$),
of the reader antennas. Figure 2(b) shows a typical scenario when the asymmetric R-R interference will occur. When each LBT reader operates asynchronously, Reader 1 is difficult to get the transmission opportunities because available channels will be used by other readers in most of time.

3. Binary Integer Linear Programming Formulation

Linear programming has been used to derive optimal solution for link scheduling and power control of wireless ad hoc networks [15],[16]. Based on the passive RFID system model described in the previous section, we present binary integer linear programming (BILP) formulations to find the optimum resource allocation of the readers which realizes the maximum communication probability of the system within a time frame in the dense reader environments. The communication probability is defined as the ratio of total time where readers can successfully communicate with the tags and total interrogation time of readers. A frame is divided into T time slots with equal length within which each reader communicates with multiple tags in the interrogation range. We assume that frame synchronization is established among the readers in the formulation. This constraint can be removed in our heuristic algorithms proposed in the later section.

We define binary variable $X_{ikjkf}$ that is equal to 1 if link $(i_k,j_k)$ is active using channel $f_m$ for time slot $\tau \in [1,T]$. Otherwise, it is 0. Our BILP formulation for the RFID interference problem is presented as follows.

\[
\text{Maximize } \sum_{\tau=1}^{T} \sum_{k=1}^{N_k} \sum_{m=1}^{N_{ch}} X_{ikjkf}, \tag{7}
\]

s.t.

\[
cX_{ikjkf} \leq G_{ikjkf} - \rho_{tag} + c
\]

\[(k \in V, \tau \in [1,T]), \tag{8}\]

\[
c_{ikjkf} + \gamma_{tag} \sum_{n=1}^{N_N} \sum_{r \in \mathcal{V}, r \neq i_k} X_{irjkf} H_{frjk} G_{irjkf} P_{fr}
\]

\[\leq G_{ikjkf} - \gamma_{tag} \eta_{jk} + c
\]

\[(k \in V, \tau \in [1,T]), \tag{9}\]

\[
c_{ikjkf} + \gamma_{rw} \sum_{n=1}^{N_N} \sum_{r \in \mathcal{V}, r \neq i_k} X_{irjkf} F_{rjk} G_{irjkf} P_{fr}
\]

\[\leq G_{jkjkf} - \gamma_{rw} \eta_{jk} + c
\]

\[(k \in V, \tau \in [1,T]), \tag{10}\]

\[
\sum_{m=1}^{N_{ch}} X_{ikjkf} \leq 1
\]

\[(k \in V, \tau \in [1,T]), \tag{11}\]

\[
\sum_{\tau=1}^{T} \sum_{m=1}^{N_{ch}} X_{ikjkf} \geq N_{\text{min}}
\]

\[(k \in V). \tag{12}\]

The number of the readers and the available channels are denoted as $N_{\text{ra}}$ and $N_{\text{ch}}$, respectively. The objective function (7) maximizes the number of readers successfully communicating with tags within a time frame. The received
power requirements for tag $j_k$ in (8) can be satisfied when the tag is properly located within the interrogation range of the reader $i_k$. In constraints (8), (9) and (10), $c$ is a sufficiently large positive number. Constraints (9) and (10) state the required SINR conditions of the tag $j_k$ and the reader $i_k$, respectively. For systems using the LBT, the SINR constraint (10) for successful reading of tag responses at the reader is always satisfied because the interference level is guaranteed to be lower than the carrier sense threshold level. In this case, (10) can be replaced by the following constraint.

$$cX_{i_kj_k}^{(r)} + \sum_{a=1}^{N_i} \sum_{r \in \mathcal{R}, \tau \neq i_k} X_{i_kj_k}^{(r)} F_{i_kj_k}^{(r)} G_{i_kj_k}^{(r)} P_{i_k} \leq \rho_{ra} - \eta_{i_k} + c \quad (k \in \mathcal{V}, \tau \in [1, T]),$$

where $\rho_{ra}$ is a carrier sense threshold level. Each reader selects at most one of the $N_{ch}$ available channels after each carrier sensing, which is represented by constraint (11). Constraint (12) guarantees the minimum number of the transmission opportunities, $N_{min}$, of each reader within a frame, which incorporates fairness in our formulation. The optimum feasible solution of our BILP formulation gives the maximum number of readers which can simultaneously communicate with tags in a given network. Thus, this can be used as an upper bound of the successful communication probability of on-line heuristic algorithms used in the actual multi-channel RFID systems with LBT function.

4. Distributed Interference Avoidance Algorithm (DIA)

In a practical algorithm implementation, it will be difficult to find an optimal solution of resource allocation for a network with large number of readers using our BILP formulation in a reasonable time. In this section, we propose two efficient heuristic algorithms that provide acceptable solutions in terms of the communication efficiency and the fairness in a distributed manner. One is the fully distributed algorithm called Distributed Interference Avoidance algorithm 1 (DIA1). The second algorithm (DIA2) adds a simple centralized control to DIA1 which controls the transmit duty of the readers to further improve the fairness.

4.1 Algorithm 1 (DIA1)

To avoid the R-T interference, allocation of the transmission time and the frequency channels among the readers should be properly controlled. As described in Sect. 2, optimization of transmission time scheduling is especially important when the available system bandwidth is narrow. Many applications of RFID systems require to have constant or periodic time allocation for the interrogation. Thus, fairness between readers is also an important requirement in some applications. On-line interference avoidance algorithms should take these requirements into account.

Our first algorithm (DIA1) is based on a detect-and-abort principle with a priority control capability. Each reader communicating with the tags aborts the communication when it detects the R-T interference on the tags it interrogates and sleeps for enough time to avoid the interference on other tags and readers. The advantage of this algorithm is that it does not require any time synchronization and control data exchanges between readers. Also, the algorithm can adapt well to the change of the interference conditions caused by e.g. the topology change or the use of mobile readers. A similar detect-and-abort mechanism is used in the MAC layer of IEEE 802.11 wireless LAN [17]. Nodes which detect the data packet set their network allocation vector (NAV) to the remaining time of the transmission. For this duration, these nodes prohibit their transmission to protect the ongoing session. In passive RFID systems, since readers can not directly measure the R-T interference level at the target tags and also can not get the duration information from other active readers, we propose a novel contention-based R-T interference detection scheme. We use the LBT scheme in order to avoid the R-R interference in this paper. However, other techniques such as use of the subcarrier back-scattering for tag transmission can be utilized in combination with our proposed scheme.

The pseudocode of the DIA1 algorithm is described in Fig. 3. In the reader operation, some underlined additional functions of our second algorithm which is described in the next sub section are also shown. While the reader is communicating with tags, existence of the R-T interference on the tags can be detected as no reply from the tags. Although there is no reply when no tag exists in the interrogation zone, the following sleep operation will not affect the performance due to the absence of tags.

Before the interrogation, carrier sensing using random back-off algorithm is performed on one of the available channels. When the carrier sensing is clear, the reader starts the communication with tags on the channel for the time $T_{tx}$, less than the maximum continuous transmission time $T_{tx,max}$. The length of $T_{tx,max}$ may be determined in the radio regulation of each countries, e.g. 4 seconds in Japan [1] and Europe [2]. After starting the communication, the reader calculates the reply-error-rate (RER) for every $T_{to}$ period, this RER is referred as RER1. If the RER1 exceeds a predetermined threshold value $P_{err}$, the reader further calculates the RER (RER2) for the last $T_{check}$ period of the $T_{to}$ period. If the RER2 exceeds a predetermined threshold value $P_{err2}$, the reader aborts the transmission and re-initiates the carrier sensing after the period of $T_{sleep}$. If there is no abortion, this process is repeated for $T_{ct}$ as shown in Fig. 4. This figure shows a case where there is an abortion in the first $T_{to}$ period after starting the transmission and the next attempted communication following the interval of $T_{sleep}$ is completed without experiencing the abortion.

The adaptive control of the values of $T_{to}$, $T_{sleep}$ and $T_{ct}$ according to the number of the successfully experienced abotions $N_{to}$ of each reader is proposed as follows.

$$T_{to} = T_{to}^{min} + [\alpha N_{to}] \Delta T + T_{rand},$$

(14)
Reader operation (Underlined parts are only for DIA2)

1: $T_{i0} = T_{i0,\text{init}}, T_{\text{sleep}} = T_{\text{sleep,init}}, N_{i0} = 0$
2: while communication with tags required do
3: ChannelSearch:
4: if $N_{i0} \geq N_{i0,\text{max}}$ then
5: Do carrier sense on all the channels.
6: Inform the worst channel info. to the controller
7: end if
8: Do channel search by carrier sense operation
9: if carrier sense finds an available channel then
10: Inform the channel info. to the controller
11: Communicate with tags
12: while communication time $\leq T_{i0}$ do
13: while communication time $\leq T_{i0}$ do
14: Calculate $RER$ for $T_{i0}$
15: if $RER_1 > P_{i1}$ then
16: Calculate $RER_2$ for the last $T_{\text{check}}$ of $T_{i0}$
17: if $RER_2 > P_{i2}$ then
18: Abort and wait for $T_{\text{sleep}}$
19: $N_{i0} = N_{i0} + 1$
20: $T_{i0} = T_{i0,\text{init}} + (\alpha N_{i0}) \Delta T + T_{\text{rand}}$
21: $T_{\text{sleep}} = \frac{T_{i0,\text{init}}}{(\alpha N_{i0})+1} + T_{\text{sleep,init}}$
22: $T_{ct} = T_{\text{sleep}}$
23: Goto ChannelSearch
24: else
25: Shift the window of $T_{i0}$ to the next
26: end if
27: else
28: Shift the window of $T_{i0}$ to the next
29: end if
30: end while
31: end while
32: Abort and wait for $T_{\text{break}}$
33: $T_{i0} = T_{i0,\text{init}}, T_{\text{sleep}} = T_{ct} = T_{\text{sleep,init}}, N_{i0} = 0$
34: else
35: Repeat ChannelSearch
36: end if
37: end while

Controller operation for DIA2

1: repeat
2: if channel informations received
3: Update the channel usage table
4: end if
5: if request for interference resolution received
6: Find the interferer reader from the table
7: Send request to the reader to reduce the duty
8: end if
9: end repeat

Fig. 3 Pseudocode of DIA1 and DIA2.

$T_{\text{sleep}} = \frac{T_{\text{sleep,init}}}{\alpha N_{i0}} + 1.$

$T_{ct} = T_{\text{sleep}}.$

where $T_{i0,\text{init}}$ is the initial value of $T_{i0}$, $\Delta T$ is the step size, $T_{\text{rand}}$ is the uniform random value less than $T_{\text{rand,\text{max}}}$, $T_{\text{sleep,init}}$ is the initial value of $T_{\text{sleep}}$ and $\alpha$ is a constant which is a positive number less than 1. $[x]$ means the largest integer less than or equal to $x$.

The objectives of the adaptive control are as follows. Readers using large $T_{i0}$ will be able to survive the abortion contention with the readers using $T_{i0}$ smaller than that, because the reader using smaller $T_{i0}$ will abort before the reader using larger $T_{i0}$ will make a decision on its abortion. Thus, using the $T_{i0}$ extension of (14), reader experiencing successive abortions becomes easier to complete the next communication attempt for $T_{i0}$. This prevents particular readers from successively experiencing the abortions for a long time, and improves the fairness of the communication opportunities among readers. The objective of the addition of the random value $T_{\text{rand}}$ is to reduce the collision probability among readers having the same length of $T_{i0}$ (i.e. same priority). When the reader completes the continuous transmission without experiencing the abortion, $T_{i0}$ is reset to the initial value of $T_{i0,\text{init}}$.

The lengths of $T_{\text{sleep}}$ and $T_{ct}$ become smaller as the reader experiences more successive abortions. Reducing $T_{\text{sleep}}$ results in more frequent carrier sensing which increases the communication opportunity. $T_{ct}$ is introduced to ensure the completion of the transmission for $T_{i0,\text{max}}$ at most when the reader experiences no abortion for the first $T_{ct}$ period. These adaptations ensure the $N_{i0}$-based prioritization in our contention-based allocation of the communication opportunities.

The proposed transmission abortion algorithm will effectively prevent the interference to the neighboring readers communicating with the tags while improving the fairness of the transmission opportunities by explicitly controlling it. This is not the case in the random slot selection algorithms [6], [9] where the transmission opportunities are determined in a probabilistic manner.

4.2 Algorithm 2 (DIA2)

In cases where there are asymmetric interferences at tags and/or readers, the DIA1 is not sufficient to control such interferences in principle because the interferer readers could not be aware that their transmission cause interference to the other readers and/or tags. In such cases, it will be necessary to control the transmission of the interferer readers by another method.

In our second algorithm (DIA2), the control of transmission duty of the interfering readers is added to the DIA1. Figure 3 shows pseudocode of this additional procedure in the reader operation with underline and the controller operation. Each reader informs the channel index used for the current transmission to the controller whenever the reader successfully completes the carrier sensing. The controller manages the current status of the channel usages of all the readers. When a reader is still experiencing successive abortions regardless of the $T_{i0}$ extension as in the DIA1 algo-
rithm, the reader performs carrier sensing on all the channels and then asks the controller to resolve the situation with the time-stamp and the index of channel experiencing the largest interference as the worst channel. This process can be repeated until the situation is resolved.

On the request of the interference resolution, the controller tries to find the interferer as the geographically nearest reader using the channel reported as the worst channel by the victim reader, and then instructs the detected interferer reader to reduce their transmit duty. The controller has to have the location information of all the readers. The reader instructed to reduce the transmit duty by the controller should increase the minimum break interval between continuous transmission $T_{\text{break}}$. After the predetermined period has elapsed, $T_{\text{break}}$ will be decreased either by the reader itself or by instruction from the controller.

Although DIA2 makes use of the centralized control, it does not require any timing critical controls such as strict start/stop timing control of each transmission or time frame synchronization among readers. The occurrence of the R-T interference largely depends on the geographical locations of the readers and the tags, and thus, the transmit duty control can be slow enough to track the situation changes.

5. Simulation Results

5.1 Simulation Model

We evaluate the efficiency of our proposed algorithms in terms of the average communication probability and the fairness among readers deployed. In our simulations, we use two deployment models of the readers and the tags.

In the first experiment, static readers are circularly located with an equal spacing as shown in Fig. 5(a). The radius of the circle is noted as $R$. Each reader’s antenna is directed toward the center of the circle and each reader communicates with a tag located in the direction at which the reader’s antenna has its maximum gain. In this model, each reader and tag have same conditions in terms of the mutual interference.

In the second experiment, we place 25 readers on a 5×5 square grid as shown in Fig. 5(b). Each reader’s antenna direction is randomly selected with uniform distribution except for readers on the edge of the square. In our model, the antenna directions of readers on the edge of the square are enforced to directing toward inside of the square. Each reader communicates with a tag located in the direction at which the reader’s antenna has its maximum gain. The distance between each reader and the interrogated tag is same for all the readers.

We evaluate the average probability of the reader transmission ($P_c$), the average probability of successful reception of interrogation signal at the tag ($P_r$) and the average probability of successful (bidirectional) communication ($P_c$) between the reader and the tags. These are defined as the ratio of the total reader transmission time with the total simulation time ($T_{\text{sim}}$), the ratio of the total time of successful reception at the tag with the total reader transmission time and the ratio of the total time of successful reader communication with $T_{\text{sim}}$, respectively. It is noted that $P_c$ equals to $P_rP_t$ since the required SINR for receiving the replies from tags correctly at the reader will be guaranteed by the carrier sense operation when the tag is within the interrogation range of the reader. The interrogation range will actually change depending on various factors such as the dielectric of the object labeled by the tag, the tag orientation, the radio multi-path condition around the interrogation area, etc. Here, we assume that the tags are always located within the interrogation range of the reader and that the reader can correctly receive the tag replies whenever the tag replies.

We also evaluate the fairness of the communication probability $P_c$ by using the following fairness index ($F$) of [18],

$$F = \left( \frac{\sum_{i=1}^{N} P_c(i)}{N \sum_{i=1}^{N} P_c^2(i)} \right)^{2},$$

where $P_c(i)$ is the communication probability of reader $i$. The value of $F$, whose range is $0 \leq F \leq 1$, approaches 1 when the variance of the communication probabilities becomes small. It approaches 0 when the variance becomes large. In the extreme case of $F=1$, all the readers can have same amount of time for successful communication with the tags.

Table 1 and Table 2 summarize the simulation parameters. Parameters of the carrier frequency, the channel bandwidth, the maximum reader transmission power, the carrier sense threshold and the transmit duty are based on the Japanese radio regulation for UHF-band passive RFID systems [1]. The simulator is written in MATLAB.

5.2 Circular Reader Deployment

First, we evaluate the performance of the proposed algorithms (DIA1 and DIA2) and the conventional LBT-only algorithm for the circular reader deployment where $N_{\text{rw}}=5$ and $N_{\text{rw}}=9$. Figure 6(a) shows $P_r$ and $P_c$ as a function of $R$. $P_r$ and $F$ are shown in Fig. 6(b) and Fig. 6(c), respectively. The
 optimum values of $P_c$ calculated by our BILP formulation described in Sect. 3 and $P_c$ of the round-robin scheduling where each reader is periodically assigned a time slot for communication by a centralized fashion are also plotted in Fig. 6(b).

When $R$ is decreased, the R-T interference experienced at tags increases and it degrades the performance. In the evaluated scenario where $N_{ch} = 5$, each reader can avoid the R-R interference effectively by using one of the odd numbered channels (i.e. ch1, 3, 5, 7, 9) with low out-band emissions from other readers. Therefore, because carrier sensing can not sense the R-T interference correctly, the $P_c$ of LBT is about 99% at any values of $R$ as can be seen in Fig. 6(a). This means all the reader can transmit anytime they want. Figure 6(b) shows that this excessive transmission causes severe R-T interference to tags and results in the poor performance of $P_c$ as well as $P_r$ when $R$ is less than 9 m. On the other hand, our proposed algorithms (DIA1 and DIA2) can effectively mitigate the R-T interference and show better $P_c$ performance than that of the LBT. We can also see that the $P_c$ of the DIA1 algorithms is fairly close to the BILP solution. When $R$ is less than 6 m, the DIA1 and DIA2 operates like as a round-robin scheduling. The proposed algorithms can attain pretty good fairness at any values of $R$ as can be seen in Fig. 6(c). Fairness of the LBT rapidly degrades when $R$ is less than 12 m. In our algorithms, the priority of transmission, i.e. length of $T_{on}$, is deterministically controlled by the number of successive abortions and this results in the improved fairness. Since there is no asymmetric R-T interference in this scenario, the DIA2 has no additional gain in the fairness.

Figure 7 shows the $P_c$ performance for the different number of readers $N_{on}$, where $N_{ch}=9$. When $N_{on}$ is larger than $N_{ch}/2 + 1 = 5$, the R-R interference from the adjacent

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**Table 1** Simulation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path loss exponent</td>
<td>$\gamma = 2$</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>950–956 MHz</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>200 kHz</td>
</tr>
<tr>
<td>Reader deployment</td>
<td>Circular and square-grid (Fig. 5)</td>
</tr>
<tr>
<td>Tag location</td>
<td>3 m at the bore-sight of the reader antenna</td>
</tr>
<tr>
<td>Reader antenna</td>
<td>6 dB gain, Omni directional</td>
</tr>
<tr>
<td>Tag antenna</td>
<td>0 dB gain, Omni directional</td>
</tr>
<tr>
<td>Reader transmission</td>
<td>59 dBm EIRP</td>
</tr>
<tr>
<td>Tag transmission</td>
<td>10 dB below the received power</td>
</tr>
<tr>
<td>Channel leakage of reader transmission</td>
<td>$-29.5$ dBc/ch at adjacent channels, $-59$ dBc/ch at the other channels</td>
</tr>
<tr>
<td>Required SIR</td>
<td>$\gamma_{ro} = \gamma_{tag} = 12$ dB</td>
</tr>
<tr>
<td>Tag frequency selectivity</td>
<td>$\rho_{ro} = -74$ dBm/channel</td>
</tr>
<tr>
<td>Carrier sense threshold</td>
<td>$T_{on, pass} = 4$ sec, $T_{break} = 50$ ms</td>
</tr>
<tr>
<td>Transmit duty</td>
<td>$T_{on, pass} = 4$ sec, $T_{break} = 50$ ms, $\Delta T = 20$ ms, $T_{off, pass} = 10$ ms, $T_{off, back} = 10$ ms, $P_{on} = P_{off} = 0.5$, $\alpha = 0.25$</td>
</tr>
<tr>
<td>Number of trials</td>
<td>1 for the circular deployment, 10 for the square-grid deployment with different antenna bore-sight combinations, 240 seconds for each trial</td>
</tr>
</tbody>
</table>

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**Table 2** Parameters for algorithms.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LBT</td>
<td>Carrier sense time $= 5$ ms, Linear random back-off $\leq 5$ ms</td>
</tr>
<tr>
<td>DIA1</td>
<td>$T_{on, pass} = 4$ sec, $T_{on, break} = 20$ ms, $\Delta T = 20$ ms, $T_{off, pass} = 10$ ms, $T_{off, back} = 10$ ms, $P_{on} = P_{off} = 0.5$, $\alpha = 0.25$</td>
</tr>
<tr>
<td>DIA2</td>
<td>$T_{on}$ for the low duty mode is 8 sec.</td>
</tr>
<tr>
<td>BILP</td>
<td>Frame size $T = 1$, $N_{on} = 1$</td>
</tr>
</tbody>
</table>

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![Communication probability and fairness for circular deployment.](image)
channel leakage emissions of other readers degrades the performance. This can be seen in the performance curves for \( R = 16 \text{m} \) where the R-T interference in not severe. Due to the little R-T interference, there is no performance difference observed. On the other hand, the R-T interference dominates the performance for the case of \( R = 10 \text{m} \). In this case, the performances of the proposed algorithms are much better than that of LBT due to the R-T interference control capabilities.

5.3 Square-Grid Reader Deployment

For the square-grid deployment, we evaluate average performances over 10 trials with different antenna directivity combinations. Figure 8(a) and Fig. 8(b) show the performance of \( P_c \) and \( F \) for different number of channels \( N_{ch} \), respectively. \( D \) is set to \( 10 \text{m} \).

Figure 8(a) shows that the \( P_c \) performance of the DIA1 is better than those of the others. We can also see that as \( N_{ch} \) increases, the \( P_c \) of each algorithm becomes high. For \( N_{ch} \ll N_{ro} \), the performance will be limited by the R-R interference. Therefore, the gains of the DIA1 and DIA2 over the LBT becomes smaller for small \( N_{ch} \). For \( N_{ch} \geq 20 \), because each reader can select a frequency channel well separated from those of the interfering readers, the R-T interference can be mitigated as explained in Sect. 2. This is why the LBT performance is better than that of the DIA2 for \( N_{ch} \geq 20 \). However, the fairness of the LBT becomes lower for \( N_{ch} \geq 16 \) due to the increased asymmetric R-T interferences. For \( N_{ch} \leq 2 \), the R-R interferences caused by the adjacent channel leakage from other readers are reduced. Therefore, those \( P_c \) performances are slightly better than that of \( N_{ro} = 4 \). Figure 8(b) shows that the fairness of the DIA2 is much better than those of the other schemes. In
this reader deployment, asymmetric R-T interferences will degrade the fairness. Gain in the fairness of the DIA2 can be explained by its asymmetric interferences resolution capability.

We evaluate the performances for different values of the inter-reader distance (D) for \( N_{ch} = 9 \) where the R-T interference will not be large. Figure 9(a) and Fig. 9(b) show the \( P_c \) and the \( P_f \) performances, respectively. Figure 9(a) indicates that the \( P_c \) of the DIA1 is slightly better than that of the LBT for \( D \leq 15 \) m, where larger R-T interferences are expected. The fairness of the DIA2 is high at the price of the slightly worse \( P_c \) performance for \( D \leq 20 \) m. This can be explained by its asymmetric interferences resolution capability using the low transmit duty. We note that the DIA1 has also good fairness performance while that of the LBT rapidly degrades for \( D \leq 10 \) m.

In all the evaluations so far, the maximum continuous transmission time (\( T_{tx,\text{max}} \)) is fixed to 4 seconds which equals to the value defined in the radio regulations [1], [2]. In practical applications, various readers using different \( T_{tx,\text{max}} \) will be operated concurrently. Figure 10 shows the \( P_c \) performance of the DIA1 for different \( T_{tx,\text{max}} \), i.e. fixed values of 1, 2, 4 seconds and random value with the range of 1 \( \leq T_{tx,\text{max}} \leq 4 \) in seconds. This figure shows that our proposed algorithm is robust to the variation of \( T_{tx,\text{max}} \).

### 6. Conclusions

In this paper, interference avoidance algorithms for passive RFID systems using contention-based transmit abortion have been proposed. First, we formulate a practical RFID system model and derive a novel linear programming formulation to obtain the optimum communication probability of the readers for a given reader deployment scenario. Then, we also propose two novel distributed interference avoidance algorithms (DIA1 and DIA2) for multi-channel readers. These algorithms are based on a detect-and-abort principle with a priority control capability to effectively control the R-T interference as well as the R-R interference. We show that the proposed algorithms can achieve high communication probability and its fairness in dense reader environments. Tag immunity for the R-T interference largely depends on the modulation index of the reader transmission. When a lower modulation index is used, the proposed algorithms will be more effective to avoid the large R-T interference and to improve the system performance.

We note that since our proposed algorithms use TDMA-based control for interference avoidance, one of the important requirements of the on-demand communication capability may not be fully supported. However, this problem can be mitigated by using higher transmission rate and shorter maximum transmission time. For example, use of 160 kbps or higher transmission rate in forward-link and/or back-link and use of \( T_{tr} \) and \( T_{sleep} \) of less than 1 second will improve the on-demand access capability with tags even in dense reader environments.

### References


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