Evaluation of the Additive Interference Model for RFID Reader Collision Problem

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***Abstract*—The reader collision problem is a critical issue in RFID systems, since it affects the reliability and the efficiency of the network. Although several solutions have been proposed to address the reader collision problem, they are usually based on models that consider only direct collisions among two readers. In real deployments, the additive interference model that captures the accumulation of n concurrent readers' interference is more accurate. Furthermore, even if an additive interference model is considered, it is important to decide how many concurrent readers' interferences have to be considered. The value of n determines a trade-off between the reliability and the efficiency of the RFID system. In this paper, the additive interference model with different values of n is evaluated. The proposed model provides an evaluation tool to select a suitable value of n according to the system requirements and the simulation results have shown the impact of n in a specific deployment.**

***Index Terms*—RFID, interference models, reader collision.**

I. Introduction

With the growing interest of end users in different applications, Radio Frequency Identification (RFID) technology is increasingly used in various areas such as identification, tracking, monitoring and electronic payment [1]–[3]. A basic RFID system is composed of several *tags*, one or more *readers* and a central *server*. The tag contains data which can be read by the readers located in the field. A unique Electronic Product Code (EPC) is stored in each tag. The range within which a reader can communicate with a tag is referred to as the *interrogation range* of the reader. The central server receives, processes and stores the data sent by the reader. According to [4], the entry of new players, the technological advancements and the growing government support will make the global RFID market grow at a compound annual growth rate of around 18% to a value of approximately $19.3 billion in the period of 2011-2014.

The readers in the RFID system operate in a specific frequency. The adopted frequency bands can be classified as low frequency (LF, 125-134 KHz), high frequency (HF, 13.56MHz), ultra high frequency (UHF, 866-868 MHz), microwave in EU (2.4-2.4835GHz) and microwave in USA (5.725-5.85GHz). Most of the RFID systems work at UHF [5] and many large installations deploy *dense reader environments* [6] where there are multiple readers in mutual range.

The tags in the RFID system are categorized into *passive*, *semi-passive* and *active*. Passive and semi-passive tags gather energy from the electromagnetic signal from the interrogating readers and backscattered the signal as a reply. Semi-passive tags also include a battery as a power source for the microchip on the tags. Active tags are supplied by a more powerful battery cell, so they can generate a radio frequency signal to reply to a reader interrogation and they can also initiate a communication. Among the three types of tags, passive RFID applications are by far the most adopted because of their best trade-off between the cost and the performance.

Since a wireless communication is used by the RFID reader when interrogating the tags, the interrogation activity is susceptible to suffer from the interferences from the simultaneous sensing activities of other RFID readers or tags. The RFID interferences can be classified into 3 types: tag-to-tag, reader-to-tag and reader-to-reader interferences [7] [8]. Tag-to-tag interference is the interference received by one tag when other tags are simultaneously energized and backscattering the replies, which can cause that the RFID reader is not able to differentiate individual tags. Reader-to-tag interference arises when a tag is located in the intersection of two or more readers' interrogation ranges. Tags suffering from reader-to-tag interference can behave and communicate in undesirable ways. Interferences on one RFID reader caused by the operation of other RFID readers is referred to as reader-to-reader interferences (or *reader collisions* [9]). Reader collisions can reduce the interrogation ranges of the colliding readers. Especially when passive or semi-passive tags reply with very weak signals to the interrogating reader, the interferences from other readers can fail the interrogation activity.

In order to deal with the reader collision problem, several models have been proposed, that can be classified into two types: *Single Interference Model* and *Additive Interference Model*. In the single interference model, it is assumed that each reader has a fixed collision range within which no other RFID reader with the same working frequency can operate. In the additive interference model, the interferences from other readers are assumed to be accumulative. The sum of the neighbors' interferences is considered to determine whether there will be collisions. When an additive model is used, it is important to decide how many concurrent reader's interferences have to be summed. In this paper, an evaluation framework is proposed to analyze the additive interference model, comparing scenarios with different values (called n) of considered readers. Based on the proposed evaluation method, an appropriate value of n can be set to reduce the impact of collision problems and

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allows to optimize the reader deployment.

The next section describes the single and the additive interference model. Section III illustrates the proposed simulator to evaluate the additive interference model with different n. Section IV analyzes the numerical results under different evaluation metrics, followed by the conclusions in Section V.

II. Models for reader-to-reader collisions

A. Single Interference Model

According to the single interference model [10] [11], each reader is characterized by its interrogation range, which depends on the output power used to query the tags. Within the interrogation range, the output power of the reader is enough to feed the circuitry of the tags and to receive a back scattered signal with adequate power. A reader can collect information from all the tags within its interrogation range, but it cannot query tags that are located outside. When a reader is receiving the backscattered signal from the passive tag, the signal may be interfered by other reader's output signal that are simultaneously querying tags in the same channel, consequently the query operation will fail. To avoid this interference, the threshold distance called *collision range* is introduced, within which the signal of one reader is strong enough to disturb the activity of other readers. As shown in Fig. 1, the readers within the collision range of a target reader are prevented from collecting any tag information when the target reader is interrogating tags. All the other readers that are located outside the collision range are not disturbed. The collision caused by one reader within the collision range is also called *direct collision*.

Under the hypothesis of the single interference model, two readers may collide if and only if they are located within a certain distance and they transmit simultaneously on the same channel. The collision happens if they transmit simultaneously on the same channel. The relationship of potential collision among a set of readers can be described by a graph, where where a node represents a reader and an edge exists between 2 nodes if the Euclidean distance between the nodes is below a fixed threshold. The graph obtained in this way is called *unit disk graph* [12]. If two nodes are connected by an edge in a unit disk graph, the corresponding readers may experience a collision.

B. Additive Interference Model

The additive interference models are based on the basic assumption that the total interference power from multiple interfering readers to the target reader is additive. It can be viewed as a generalized model of single interference model by considering multiple readers' collision instead of just considering direct collisions. The additive interference model can be further classified according to different criteria, such as sing-channel mode and dual-channel mode [9], noise considered [13] and noise negligible [9]. In this paper, we assume that the background noise is negligible and that the signal power at the receiver is only attenuated due to path loss. Besides, we also assume that the RFID medium access uses

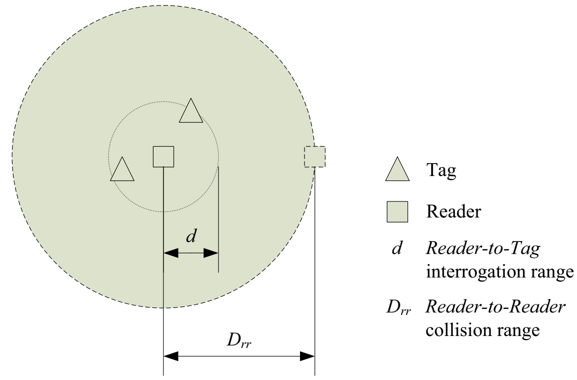

Fig. 1. The single interference model

a single-channel mode where the reader-to-tag query communication and tag-to-reader response communication share a bidirectional channel.

In a passive RFID system, as tags do not incorporate a battery and are powered by the carrier signal from readers, the backscattered signal will arrive at the readers very weakly. In order to be recognized, the backscattered signal needs to satisfy two conditions: on one hand, the strength of the signal must be above a lower bound, named *carrier receive level* (or receiver sensitivity), which guarantees that it can be correctly detected and decoded. On the other hand, the signal to interference ratio (SIR) must exceed a required threshold, which depends on the desired read rate and the bit error rate (BER). Let Θ and Γ respectively denote the carrier receive level and the required SIR, according to [9], the following condition must be satisfied:

$$(P_{t,r} \geq \Theta) \wedge (\frac{P_{t,r}}{I_r} \geq \Gamma) \qquad (1)$$

where $P_{t,r}$ represents the received signal power at the reader r from the tag t and I_r denotes the total interference that reader r receives.

Let d be the maximum interrogation range of reader r without any interference. In [9], the received signal power at tag t from reader r is expressed as

$$P_{r,t} = P_r \frac{G_r G_t}{K_0 d^{\alpha}} \qquad (2)$$

where P_r is the transmit power of the reader, G_r and G_t represent the antenna gain of the reader and the tag, respectively, and α is the path loss exponent. K_0 is a coefficient integrating the channel path loss and the fractional power ratio in the bandwidth. As the distance between the reader and the tag is short and the transmission path is a simple line-of-sight, fading effects can be ignored. K_0 can be derived by measuring the power P_t received by a tag at a reference distance d_0. Therefore K_0 can be set such that $P_r \frac{G_r G_t}{K_0} = P_t {d_0}^{\alpha}$. When $d_0 = 1\ m$, $K_0 = \frac{P_r}{P_t} G_t G_r$.

Let R_t be the effective power reflection coefficient of the tag antenna, i.e., the ratio of the power received by the tag that is reflected to the reader. Then, the power received by the reader from the tag is given by

$$P_{t,r} = R_t P_{r,t} \frac{G_t G_r}{K_0 d^\alpha}. \tag{3}$$

Based on equations (2) and (3), in order to satisfy the first condition in (1), the interrogation range d can be determined by the threshold Θ and the transmit power P_r of the reader. Θ and P_r are tuned according to the integrated circuit design and the environmental condition of the antenna. In order to satisfy the first condition in (1), P_r must be larger than the threshold power required for the tag operation.

The reader-to-reader collision occurs when the second condition in (1) is not satisfied, i.e., the backscattered signal from the tag to the reader is too weak with respect to the interfering signals of other readers. To prevent the reader-to-reader collision problem, the key point is to determine the potential interference range within which the reply signal from the tag is not interfered by signals from other readers.

Let D be the distance between two readers A and B. The interference power of reader B detected by reader A can be expressed as:

$$P_{r,r} = P_r \frac{G_r G_r}{K_0 D^\alpha}. \tag{4}$$

When considering n interfering readers, the total interference generated towards one target reader A can be evaluated by summing each individual contribution:

$$I_s = \sum_{i=1}^{n} P_r \frac{G_r G_r}{K_0 D_i^\alpha} \tag{5}$$

where D_i is the distance between reader A and reader i. According to the second condition in (1), the sum interference will generate a collision when I_s satisfies

$$I_s \geq \frac{P_{t,r}}{\Gamma}. \tag{6}$$

When the above equation is satisfied, the group of n readers is called the *collision set* of reader A. In this paper, *collision-set-n* is introduced to represent the collision set that considers the sum of n readers, in other words, n indicates the cardinality of the collision set. Conveniently, the value of $\frac{P_{t,r}}{\Gamma}$ is called the *threshold interference* that above which it can generate reader collisions. The number of interfering readers n is a tradeoff between efficiency and reliability of RFID systems. When a larger n is used, more reader collisions can be covered, which ensures a more reliable RFID system that does not suffer from reader collisions. However, a larger n also results in a more limited scheduler that fewer RFID readers can work at the same time. In order to evaluate n's impact, if the ratio between the number of readers affected by collision-set-n and the number of total readers is larger than 99%, collision-set-n is called *necessary*.

When only one interfering reader is considered, the additive interference model turns into a single interference model where collision-set-1 is considered. The total interference I_r received by reader A is actually $P_{r,r}$ in Equation (4). The reader-to-reader collision range (i.e., the minimum distance D_{rr} beyond which two concurrent readers do not generate a collision) is obtained by setting the SIR equal to the required threshold Γ according to the second condition in (1):

$$\frac{P_{t,r}}{P_{r,r}} = \Gamma. \tag{7}$$

After substituting Equation (2) and Equation (4), the reader-to-reader collision range in the single interference model can be set as

$$D_{rr} = d^2 \cdot \sqrt[\alpha]{\frac{K_0 \Gamma}{R_t {G_t}^2}}. \tag{8}$$

III. The Evaluation Simulator

The main difference between the single interference model and the additive interference model is the cardinality n of the considered collision set. Obviously, the value of n plays an important role in the evaluation of the reader collision models. In order to investigate the impact of n, we build a simulator based on the analysis in Section II.

Algorithm 1 Calculate the collision sets in the RFID reader set R with the cardinality less than $Card_{max}$

```
for all RFID reader i∈R do
  calculate the interference I_ij where j∈R and j≠i;
  sort {<j, I_ij>} in descending order of I_ij;
  call Subset({<j, I_ij>});
end for

Procedure Subset(set V)
for all Element <k, I_k> ∈V do
  if Stack.size < Card_max then
    push(<k, I_k>);
    sum the interferences in the stack to S_k;
    if S_k > P_t,r/Γ then
      collisionSets[i].add(Stack);
    else
      call Subset(V− <k, I_k>);
    end if
    pop(<k, I_k>);
  end if
end for
End Procedure
```

If one reader has one collision-set-n, it will be interfered by the sum of the interferences from the readers in the collision-set-n so that it cannot interrogate the tags normally when all the readers in collision-set-n are operating simultaneously. In order to avoid considering redundant collision sets, only *minimal collision set* is considered in this paper. A minimal collision set is defined as the collision set in which only the sum interference of all the member readers are larger than the threshold interference that can hamper the target reader's interrogation activity, but the sum interference of any subset will not influence on the target reader. In other words, a minimal collision set of one reader does not include any other

TABLE I
EVALUATION PARAMETERS

Parameters	Values
Path loss exponent (α)	2
SIR Threshold (Γ)	10
Reader antenna gain (G_r)	6 dBi
Tag antenna gain (G_t)	1 dBi
Tag's power reflection coefficient (R_t)	3/4
Reader's transmit power (P_r)	10 dBm
Constant coefficient (K_0)	G_r^2
Interrogation range (d)	5 m

collision sets. In order to collect the minimal collision sets of each reader, we check each subset of the reader set R (where the target reader is excluded) to judge whether it is a minimal collision set of the target reader.

Algorithm 1 describes the main algorithm of the simulator to evaluate the reader-to-reader collision model. Assume the total RFID set is R, the collision sets are calculated for each reader $i \in R$. When reader i is the target reader, the general idea is to check all the subsets of the RFID set $R - i$ which denotes the relative component of i in R. To check all the subsets, all the element $j \in R - i$ are first sorted by the descending order of the interference to i. Then a recursive procedure is called to check all the subsets of $R - i$ (i.e., the power set of $R - i$). In the recursive procedure, a stack is used to store the current subset of $R - i$ that is being evaluated to decide whether the sum interference of the readers in the stack can generate a collision to the target reader. When the set in the stack turns out to be a collision set, all the subsets that contain the stack will be ignored since only minimal collision sets are considered.

Since the complexity to consider the power set of a set *R* with a cardinality *r* is 2^r, a control parameter $Card_{max}$ is introduced to indicate that only the subset with the cardinality less than $Card_{max}$ are considered. As a result, the complexity after introducing $Card_{max}$ is reduced to $\sum_{i=1}^{Card_{max}} \binom{r}{i}$.

IV. EVALUATION RESULTS

In this section, the previously described simulator is used to find the necessary collision-set-n that should be considered in the reader collision problem. The effect of the number of interfering readers (i.e., the cardinality *n* of the collision-set-n) is evaluated according to the parameters listed in Table I. A free space model [14] is considered, assuming that no shadowing effect exists and the signal power at the receiver is attenuated with a path loss exponent equal to 2. The SIR threshold Γ is set to 10. The antenna gain of the reader and tag are set as 6 dBi and 1 dBi, respectively. The power reflection coefficient on a tag is 3/4. The transmit power of a reader, P_r is set to 10dBm. K_0 is set to be the lower bound, G_r^2, according to the received power P_0 measured at $d_0 = 1\ m$ [9]. The interrogation range d is set to 5 m.

In the simulation, 50 readers are randomly deployed in a $1000\ m \times 1000\ m$ field with uniform distribution. Since the collision range D_{rr} is 277.8 according to Equation (8), this is

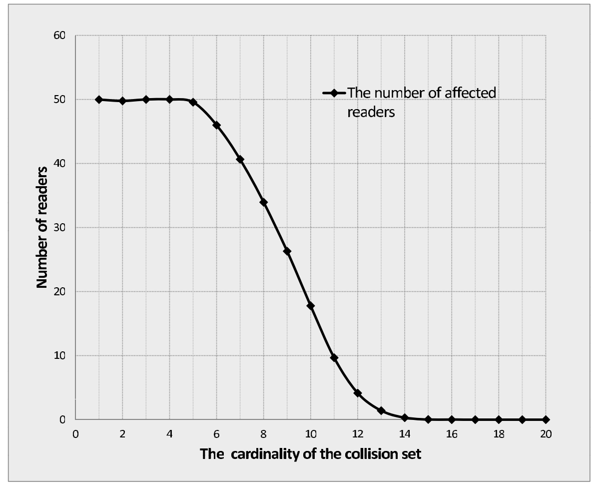

Fig. 2. The affected readers considering different collision-set-n

a dense deployment. The simulation is repeated 1000 times to reduce the effect of randomness.

A. The affected readers considering collision-set-n

If one reader has at least one collision-set-n, it is said to be affected by the reader collisions considering up to the sum of n interfering readers (collision-set-n). It is an important metric to investigate on how many readers can be affected by the sum of n readers' interferences. Fig. 2 shows the number of readers affected by collision-set-n. It can be observed that the number of readers affected by collision sets with the cardinality from 1 to 5 is around 50 out of 50 readers, which means that an additive interference model considering the sum of 5 readers' interferences is necessary since 99% of the total readers are affected. The number of readers affected by collision-set-2 until collision-set-5 are almost the same with the number of readers affected by direct collisions (collision-set-1), which reflects that the unit disk model that considers only direct collisions is not enough to cover all the collisions in a dense RFID deployment. Starting from collision-set-6, the number of affected readers starts to reduce in a great scale. The RFID reader can be affected until the sum of 14 readers' interference are considered. There is not any minimal collision set with more than 14 readers that can generate a total interference that can hamper the target reader, which means that it is not necessary to consider the additional interference of more than 14 readers. Based on the above observation, the additive reader interference model considering more than 5 readers is necessary to cover the reader collisions that can affect more than 99% readers.

B. The average number of collision-set-n

The average number of collision-set-n is the total number of collision-set-n divided by the number of RFID readers in the deployment. A larger value of the average collision-set-n number means that more collisions can be covered by the additive interference model taking into account the sum of *n* readers' interferences. Fig. 3 illustrates the average number of collision-set-n corresponding to different values of *n*, where it can be seen that the trend of the modification is a parabola. The average number of collision-set-n first climbs up when *n* grows from 0 to 9. After it reaches the peak when $n = 9$, it starts to fall down until 14. The average number of collision-set-15 until collision-set-20 stays at 0, which is in accordance with Fig. 2. That is because all the readers sets with the cardinality more than 14 have a subset (i.e., the minimal collision set) that can already generate a sum interference that can interfere the target reader. The average number when $n = 9$ represents a break point.

When $n < 9$, the reason why the average number climbs up is because of two reasons: first, the probability to generate collisions increases when more readers' interferences are summed; then, because the number of potential subsets that may generate collisions grows with the cardinality *n*. For example, the maximal number of subsets is $\binom{50}{1} = 50$ when the subset with the cardinality of 1 is considered, however, this maximal number grows to $\binom{50}{4} = 230300$ when cardinality 4 is considered. When $9 < n < 20$, although the maximal number of subsets continues to grow, the subsets that can generate collisions fall down since most of the minimal collision sets have been considered when the cardinality is less than 9. From Fig. 3, it may be concluded that $n = 9$ is a good choice since it corresponds to the largest number of collision sets.

To some extent, the average number of collision-set-n disposes the influence of different collision-set-n on the reader interference model. However, it is also important that how the data is spread out. If one reader has an extremely large number of collision-set-n while other readers have none, only the average number can not be used to evaluate the influence. Therefore, combining the numerical results in Fig. 2 and Fig. 3, we can conclude that considering the deployment parameters assumed in this paper, the additive interference model that considers up to 5 readers is necessary to model the reader collision problem.

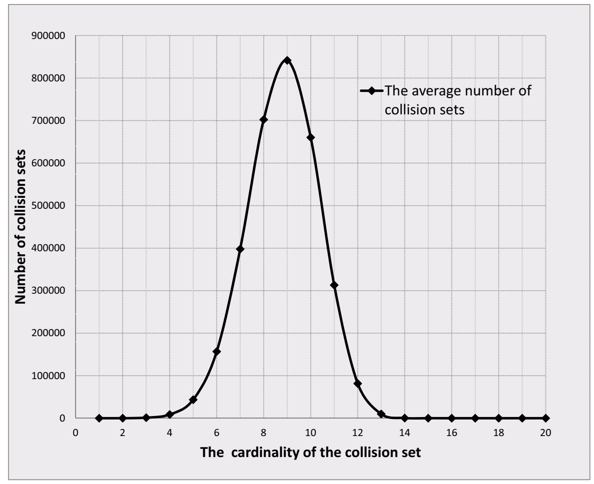

Fig. 3. The single interference model

V. Conclusion

In this paper, the reader-to-reader collision problem is evaluated considering the single and the additive interference models. The single interference model is viewed as a special case of the additive interference model that considers only on reader's interference. The number of interfering readers n is particularly analyzed. An evaluation simulator that collects all the minimal collision-set-n is proposed in order to evaluate the impact of n on the additive interference model. The numerical results are analyzed based on the affected readers, the average collision sets per reader and the distribution of the collision sets. As a result, it can be concluded that in order to make sure that the percentage of readers affected by the reader collision problem is less than 1%, according to the considered deployment, $n = 5$ is a necessary value to consider in the additive interference model. Generally, the proposed evaluation framework can be used to find the appropriate n whenever a deployment requirement is specified. In the future work, the impacts of deployment parameters such as the deployment density and network size can be evaluated.

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