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INTERFERENCE ANALYSIS OF UHF RFID SYSTEMS

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Abstract—In this paper, RFID reader-to-reader interference is analyzed from the point of view of interrogation range. To evaluate RFID interference quantitatively, the new figure-of-merit, *interrogation range reduction ratio* (IRRR), is defined. In order to show the usefulness of IRRR, its value is calculated in various environments. Additionally, the calculated IRRR values are verified by measurements using two RFID readers and an RFID tag. IRRR can be referred to an important design parameter to analyze more complex interfering problems in instances of actual RFID system deployment.

1. INTRODUCTION

Recently, ultra-high frequency (UHF) band passive RFID systems have drawn a great deal of attention [1]. It is generally accepted that UHF RFID systems can revolutionize various commercial applications such as supply chain management [2, 3]. Several major supply chain companies such as Wal-Mart and Tesco plan to mandate the use of

UHF RFID system in their supply chains, which operates in the 860–960 MHz band [4]. In these deployments, however, tens or hundreds of readers will be in operation within close range to each other, which may cause serious interference problems.

There are three types of UHF RFID interference: tag interference, multiple reader-to-tag interference and reader-to-reader interference. Tag interference arises when multiple tags are simultaneously energized by the reader and reflect their respective signals back to the reader. Due to a mixture of scattered waves, the reader cannot differentiate individual IDs from the tags; therefore, anti-collision mechanisms such as those known as binary-tree and ALOHA are needed [5]. Multiple reader-to-tag interference happens when a tag is located at the intersection of two or more reader interrogation ranges and the readers attempt to communicate with the tag simultaneously. This can cause a tag to behave and communicate in undesirable ways.

The last type of interference, reader-to-reader interference, is induced when a signal from one reader reaches other readers [6]. This can happen even if there is no intersection among reader interrogation ranges. As signals transmitted from distant readers may be strong enough to impede accurate decoding of the signals back-scattered from adjacent tags, reader-to-reader interference can cause serious problems in a UHF RFID system deployment. Moreover, the interference is potentially magnified in a dense reader environment, which can involve hundreds of readers in one warehouse or manufacturing facility. Many attempts to mitigate reader-to-reader interference have been made [6–8]. They are normally based on standard multiple access mechanisms such as frequency-division multiple access (FDMA), time-division multiple access (TDMA), or carrier-sense multiple access (CSMA). For example, the electronic product code for global class 1 generation 2 (EPCglobal C1G2) includes spectrum management of a UHF RFID operation in a dense reader environment. According to EPC C1G2, reader transmission and tag backscattered signals are separated in a spectral domain; that is, all readers transmit their signals in either even-numbered or odd-numbered channels [7]. However, this does not eliminate reader-to-reader interference completely due to the incomplete spectral separation, which can affect the reader operation.

Recent works have explained that reader-to-reader interference only affects the interrogation range reduction using the signal-to-interference ratio (SIR) [9, 10]. In fact, much more RFID interference implies only that the interrogation range is significantly reduced, not that it is reduced to zero. In this paper, the *interrogation range reduction ratio* (IRRR) evaluates the efficiency of reader-to-reader interference mitigation for any protocol. Using this parameter, it is evaluated in a somewhat dense reader environment, and reader-to-reader interference problems are analyzed in detail. Finally, IRRR is verified via measurement results.

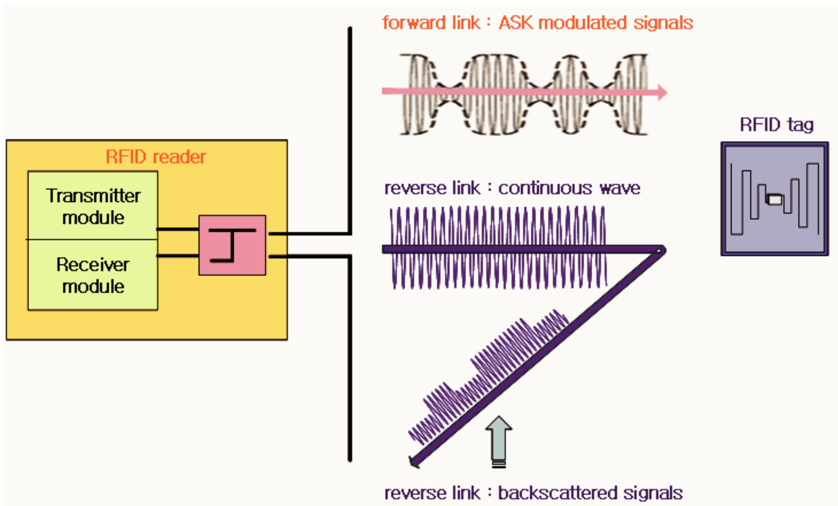


Figure 1. A forward link and a reverse link in a UHF RFID system.

2. RFID INTERFERENCE PROBLEM

In Fig. 1, the communication link of RFID is divided into a forward and a reverse link. In a forward link, a reader sends a modulated carrier to a tag. In a reverse link, a reader receives a backscattered signal from a tag which is powered by what is known as continuous wave (CW) from the reader. Unlike other wireless communication systems, RFID does not provide reciprocity between forward and reverse links in communication. This implies that the transmission range of a forward link is much greater than that of a reverse link. An inverse square law governs the available energy reaching a tag from a reader, whereas the backscatter energy radiated from a tag is inversely proportional to the fourth power of the distance between them. This link unbalance creates potential interference, even when other readers are distributed over a range of several kilometers. However, the power from backscatter signals rapidly vanishes at distances of a few meters. Consequently, a dense reader environment, which includes tens or even hundreds of readers within close proximity to each other, involves reader-to-reader interference problem, as follows:

2.1. Reader-to-Reader Interference

This interference occurs when a reader transmits a command signal that interferes with the tag reception procedure of another reader. For example, when a desired reader and the ith interfering reader exist as shown in Fig. 2, the backscattered signal reaching the desired reader from a tag can be distorted by signals from the interfering reader. Thus, reader-to-reader interference results in the SIR reduction at the desired reader, which reduces its interrogation range [11].

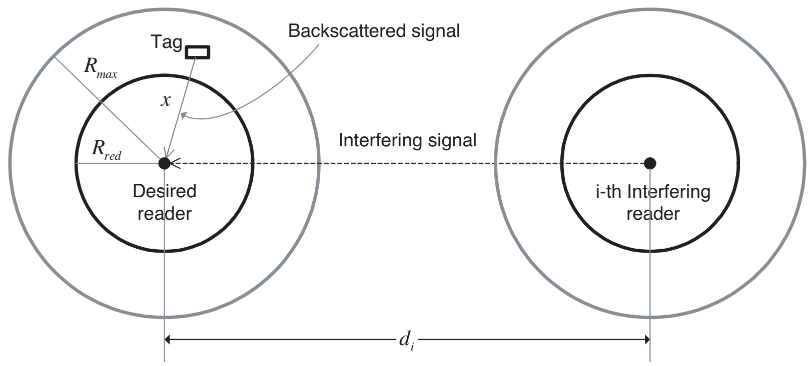


Figure 2. Reader-to-reader interference in UHF RFID systems.

The separation distance between a desired reader and the ith interfering reader is denoted by d_i. R_{max} represents the maximum interrogation range, or the maximum distance in which a desired reader can detect a tag without interference from another reader. If an omni-directional antenna is used, the interrogation range of a desired reader takes on a circular-shape. When interfering readers exist, the actual interrogation range of the desired reader decreases to a circular region with radius R_{red}.

This phenomenon can be modeled by a mathematical equation. For a desired reader, the received backscattered power, $P_S(x)$, is given as

$$P_S(x) = \alpha_{BW} E_{tag} P_{TX} G_T G_R \times 10^{2\times PL(x)/10}, \tag{1}$$

where P_{TX} denotes the total transmit power, α_{BW} is the spectrum power of a used channel normalized by the total power, $PL(x)$ is the path-loss for the distance of x m between a desired reader and a tag, and E_{tag} is the effective power reflection coefficient of a tag. As the received signal undergoes forward link and reverse link channel path losses all together and when the two path-loss values are identical, the total path-loss is the twice the value of $PL(x)$. Additionally, G_T and

G_R are the transmit antenna and receive antenna gains, respectively. In (1), fading effects are ignored, as the line-of-sight (LOS) pathway between a desired reader and a tag is a short.

The interference power from ith interfering reader is then given as

$$I(i) = h(i)P_{TX}(i)\alpha_{mask}(i)G_T(i)G_R \times 10^{PL(d_i)/10}, \tag{2}$$

where the interference power involves a fading coefficient, $h(i)$, in the channel between a desired reader and the ith interfering reader [12, 13]. In addition, this includes the path-loss $PL(d_i)$ for separation distance d_i, the limit level $(\alpha_{mask}(i))$ of the spectrum mask used in simulation.

Finally, the SIR at the receiver is calculated by

$$SIR(x) = \frac{P_S(x)}{N + \sum_i I(i)}, \tag{3}$$

where N is the thermal noise power.

2.2. IRRR (Interrogation Range Reduction Ratio)

Recently, a number of studies related to mitigating reader-to-reader interference have been introduced [5–10]. However there are few figures-of-merit for interference assessment. In order to analyze reader-to-reader interference, a new figure-of-merit, IRRR is proposed.

When interfering readers exist, the actual interrogation range of the desired reader decreases to a circular region with radius R_{red}, which can be represented by (4).

$$R_{red} = \arg \max_{0 \le x \le R_{max}} SIR(x) \ge V_{TH}, \tag{4}$$

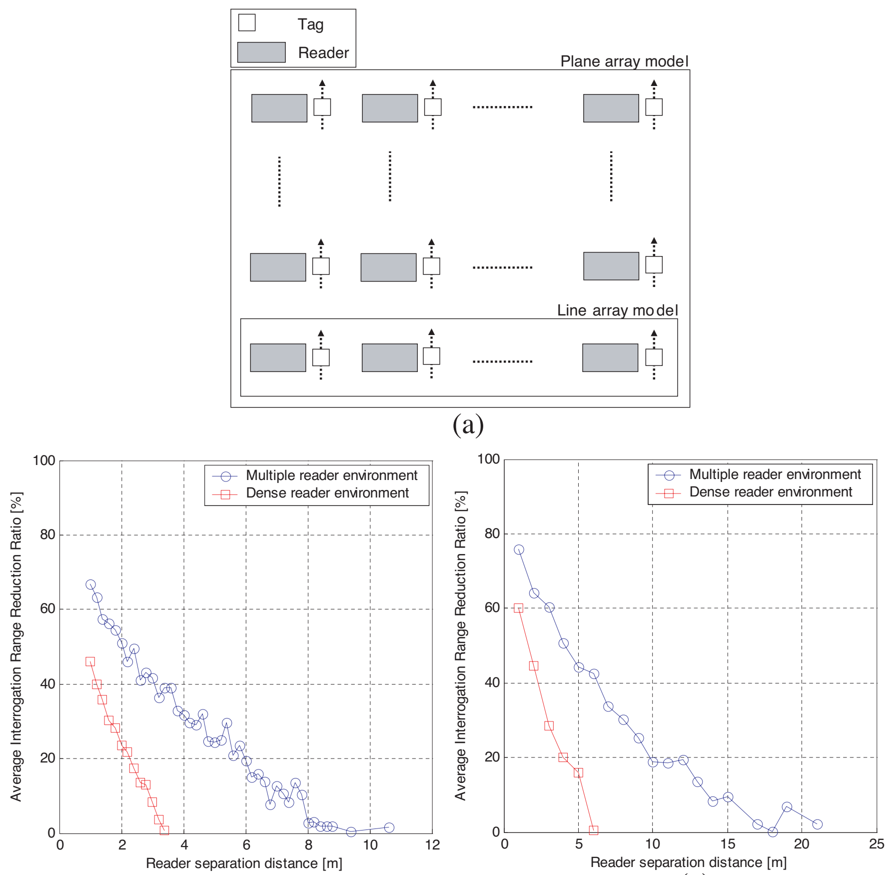
here V_{TH} represents the threshold value, which can be determined by a combination of the data encoding schemes of the tag and its target-bit error rate (BER) values. It is assumed that if the SIR is greater than V_{TH}, the received signal can be correctly recovered at the receiver. For a rigorous analysis of the influence from an interfering reader on the interrogation range for a desired reader, IRRR is formulated as the percentage of a ratio of $R_{max} - R_{red}$ to R_{max} for a desired reader. Thus, IRRR is given by

$$IRRR = \frac{R_{max} - R_{red}}{R_{max}} \times 100\ [\%]. \tag{5}$$

If IRRR is 0%, a desired reader can interrogate a tag in the region with the radius R_{max}. In other words, there is no interference between the two readers. On the other hand, an IRRR of 100% implies that a desired reader is unable to recognize any tag.

3. SIMULATION RESULTS

In the previous section, reader-to-reader interference was explained and the new figure-of-merit, IRRR, was defined. In order to show the usefulness of IRRR, its values are calculated in two RFID scenarios, line- and plane-array models, in an EPCglobal C1G2 multi-channel regulatory environment. In this environment, reader transmissions and tag responses are separated spectrally. To be precise, readers transmit their signals in even-numbered channel and tags response in odd-numbered channels.



(a) (b) (c)

Figure 3. Simulation models and results: (a) the line- and plane-array models (b) average IRRR results of the line-array model, (c) average IRRR results of the plane-array model.

Figure 3(a) shows a line-array model and a plane-array model consisting of M readers and a single tag per reader, in which readers are distributed over a line or a plane, respectively, for the two aforementioned models. It is assumed that each tag is a uniform random distance from the desired reader.

In the simulation, an omni-directional antenna is used for all readers, and the free space path-loss model is utilized. In order to calculate the interference power in the channel bandwidth, the transmit masks of multiple reader and dense reader environments in EPCglobal C1G2 [7] are considered. The total number of channels and the number of readers are assumed to 20, and the channel bandwidth is set to 200 kHz. Reader transmissions are unsynchronized in time, hopping among frequency channels. In this simulation, it is assumed that readers may transmit only either a CW or a modulated signal with equal probability, and that only modulated signal transmissions of a reader interfere with other RFID systems. Therefore, half of all readers statistically interfere with each other at any given time. The simulation parameters are summarized in Table 1.

Table 1. Simulation and measurement parameters.

Parameters	Values
Transmit Power of a reader (P_{TX})	30 dBm
Tag's power reflection coefficient (E_{tag})	0.1
Noise Figure	10 dB
Link Frequency	200 kHz
Data rate : FM0 Miller(M = 4)	50 kbps 50 kbps
Maximum interrogation range (R_{max})	4.25 m
Channel Bandwidth	200 kHz
The number of channels	20
The number of readers	20
Tag's Antenna Height	1.5 m
Reader's Antenna Height	1.5 m
Antenna Gain	6 dBi

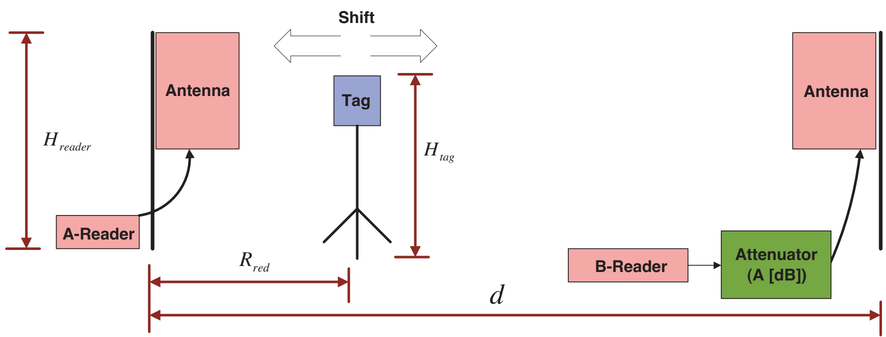
Figure 3(b) shows the average IRRR in a line-array model as a function of the reader separation distance, where the circle and square markers indicate multiple reader and dense reader environments, respectively. From the results, it is shown that reader separation distances achieving 0% IRRR, indicating no interference between them, are at least 10 m for the multiple-reader environment and 3.5 m for the dense-reader environment. Therefore, reader separation distance achieving no interference in a dense reader environment is one-third less than in the multiple reader environment. Fig. 3(c) shows the case of the plane-array model. The simulation results show that reader separation distances that achieve 0% IRRR are at least 18 m and 6 m for the multiple reader and dense reader environment, respectively. In a dense reader environment, the distance among readers is also shorter; they are approximately one third less than that of a multiple reader environment. From the above results, it is clear that the spectral planning for a dense reader environment proposed by EPCglobal C1G2 is a good efficiency method to mitigate the reader-to-reader interference. Additionally, comparisons of the IRRRs between a line-array and a plane-array models show that the former is a more effective positioning method than the latter for mitigation interferences, as there are more interfering readers with neighboring positions in a plane-array model, and it statistically generates a higher interference power.

4. MEASUREMENT RESULTS

In the previous sections, IRRR is defined and its value calculated in various environments in an effort to evaluate the influence of reader-to-reader interference. In order to verify the previous simulations, measurement results for two readers and a tag were compared with simulation results in this section. In particular, to analyze the effects of a frequency separation on reader-to-reader interference, the co-channel interference (CCI) and adjacent-channel interference (ACI) cases are considered. CCI and ACI occur when readers operate in identical and adjacent channels, respectively.

The measurements were taken in a radio frequency anechoic enclosure, as shown in Fig. 4(a). In order to determine the reference value for the interrogation range, the maximum interrogation range R_{max} of a desired reader was initially measured without an interfering reader. The reader used for the measurements supports a 50 kbps data rate using FM0 encoding and uses a 500 kHz channel bandwidth, which is the bandwidth specified by RFID regulations in the United States. After determining R_{max}, the measurements for a two-array model were taken for both the CCI and ACI cases. The measurement setup is shown in Fig. 4(b). The method used in these measurements followed the following steps:

(a)



(b)

Figure 4. (a) IRRR measurement scenario, (b) measurement setup in the anechoic enclosure.

- *Step 1*: Place the tag at the initial distance (1 m) from the desired reader.
- *Step 2*: Fix the interfering reader at a fixed point (10 m) and select the attenuation (A dB) value (as the anechoic enclosure had a limited area).
- *Step 3*: Turn on the interfering reader, and ensure that the desired reader can detect the tag.
- *Step 4*: Determine the maximum interrogation distance R_{red}. If the reader can read the tag, gradually move the tag away from the reader. However, if the reader cannot read the tag, gradually move the tag toward the reader.
- *Step 5*: Repeat this measurement while changing the A dB value of the attenuator.

In the measurements, R_{max} of the desired reader was 4.25 m

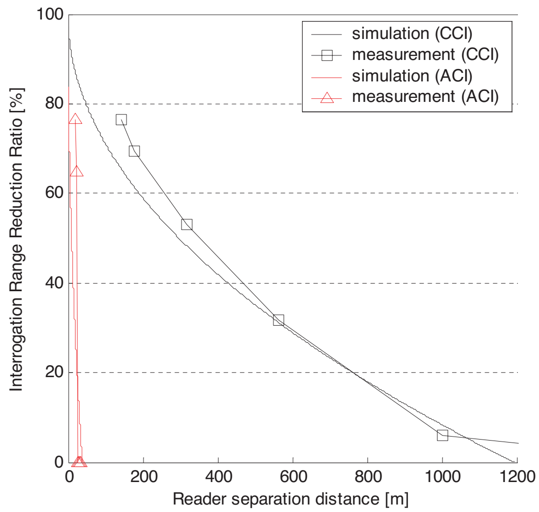


Figure 5. IRRR in the multiple reader environment.

without any interference. Thus, IRRR was calculated using both the above value of R_{max} and that of R_{red}. Fig. 5 compares IRRR values between interference cases (CCI and ACI) as a function of the reader separation distance d m. Here, the CCI and ACI cases are depicted with black lines and red lines, respectively. To distinguish the simulation and measurement results, markers are also used for the latter case. The simulation results show that reader separation distances achieving 0% IRRR, indicating no interference between them, are 1200 m and 35 m for the CCI and ACI cases, respectively. These results show the worst case scenario which considers the possible maximum interference level. In addition, IRRR is inversely proportional to the reader separation distance in both cases. However, comparisons between the two cases show that the interference power for a desired reader decreases more rapidly for ACI than for CCI as the reader separation distance increases. Thus, it is clear that for a large-scale RFID system deployment, the same frequency should not be allocated to adjacent readers if the objective is to avoid CCI.

5. CONCLUSION

By introducing the feature of a UHF RFID system in which a forward and a reverse link are out of balance, interference problems of RFID system are mitigated, providing an important benefit that leads to good performance and stability for real applications. Although there has been much research related to mitigating interference, most did not satisfactorily study the figure-of-merit for a fair comparison of the effect of interference mitigation. Thus, to evaluate the influence of interfering readers on a desired reader quantitatively, a new figure-of-merit, IRRR, is defined as the percentage of a ratio of $R_{max} - R_{red}$ to R_{max}. For applications of IRRR, IRRR simulations for a both line-array model and plane-array model were completed using multiple reader and dense reader environments. From the simulation results, it was shown that the total interference power for a desired reader rapidly decreases more for a dense reader environment than for a multiple reader environment, depending on the reader separation distance. Thus, a dense reader environment requires a smaller supply chain segment than a multiple reader environment. For a two-array model, the IRRR results are shown via simulation and measurement in a multiple-reader environment. Finally, it was concluded that IRRR can provide a reliable and applicable figure-of-merit in analyses of more complex interference problems in actual RFID system deployment instances. Moreover, it can provide important design parameters, including reader positioning and interference mitigation planning.

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REFERENCES

1. Finkenzeller, K., *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification*, John Wiley, Chichester, 2003.
2. Bendavid, Y., S. F. Wamba, and L. A. Lefebvre, "Proof of concept of an RFID-enabled supply chain in a B2B e-commerce environment," *Proceedings of the 8th International Conference on Electronic Commerce (ICEC'06)*, 564–568, 2006.
3. Wamba, S. F., L. A. Lefebvre, and E. Lefebvre, "Enabling intelligent B-to-B eCommerce supply chain management using RFID and the EPC network: A case study in the retail industry," *Proceedings of the 8th International Conference on Electronic Commerce (ICEC'06)*, 281–288, 2006.

4. Leong, K. S., M. L. Ng, A. R. Grasso, and P. H. Cole, "Synchronization of RFID readers for dense RFID reader environments," *Proceedings of the 2006 International Symposium on Applications and the Internet Workshops (SAINT'06)*, 48–51, 2006.
5. Zhou, F., C. Chen, D. Jin, C. Huang, and H. Min, "Evaluating and optimizing power consumption of anti-collision protocols for applications in RFID systems," *Proceedings of the International Symposium on Low Power Electronics and Design*, 357–362, 2004.
6. Engels, D. W. and S. E. Sarma, "The reader collision problem," *Proceedings of the 2002 IEEE International Conference on Systems, Man and Cybernetics*, Vol. 3, 92–97, 2002.
7. EPCglobal, "EPC radio-frequency identity protocols class-1 generation-2 UHF RFID protocol for communications at 860 MHz–960 MHz version 1.0.9," EPCglobal Standard Specification, 2004.
8. ETSI EN 302 208-1 v1.1.1, Sept. 2004. CTAN: www.etsi.org.
9. Cha, K., A. Ramachandran, and S. Jagannathan, "Adaptive and probabilistic power control alogrithms for dense RFID reader network," *Proceedings of the 2006 IEEE International Conference on Networking, Sensing and Control (ICNSC '06)*, 474–479, 2006.
10. Kim, D. Y., B. J. Jang, H. G. Yoon, J. S. Park, and J. G. Yook, "Effects of reader interference on the RFID interrogation range," *Proc. the 37th European Microwave Conference (EuMC'07)*, 728–731, Munich, Oct. 2007.
11. Fan, Z. G., S. Qiao, J. T. Huangfu, and L. X. Ran, "Signal descriptions and formulations for long range UHF RFID readers," *Progress In Electromagnetics Research*, PIER 71, 109–127, 2007.
12. Yarkoni, N. and N. Blaunstein, "Prediction of propagation characteristics in indoor radio communication environments," *Progress In Electromagnetics Research*, PIER 59, 151–174, 2006.
13. Martinez, D., F. Las-Heras, and R. G. Ayestaran, "Fast methods for evaluating the electric field level in 2D-indoor environments," *Progress In Electromagnetics Research*, PIER 69, 247–255, 2007.