Hardware Design and Deployment Issues in UHF RFID Systems

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1. Introduction

Recently, radio frequency identification (RFID) have created emerging applications for tracking, sensing, and identifying various targets in wide-ranging areas such as supply chain, transportation, airline baggage handling, medical and biological industry, and homeland security. RFID systems with a variety of radio frequencies and techniques have been introduced. Among them, ultra-high frequency (UHF) band passive RFID systems that operate in the 860 – 960MHz band have drawn a great deal of attention because of its numerous benefits, such as cost, size, and increased interrogation range. In particular, the interrogation range of the UHF RFID system is comparatively large, due to the use of a travelling electromagnetic (EM) wave to transfer power and data. The increased interrogation range makes it possible for UHF RFID systems to revolutionize commercial processes, such as supply chain management. Several major supply chain companies such as Wal-Mart and Tesco plan to mandate the use of an UHF RFID system in their supply chains (Finkenzeller, 2003).

UHF band passive RFID system based on modulated backscatter has a unique characteristic, quite distinct from those encountered in most other radio systems which involve active transceivers on both sides of the link (wireless LAN, Bluetooth, etc). Because tag has no internal power supply, RFID reader must always supply the power in order to communicate with tags. This puts a different emphasis on the radio link, hardware design, and deployment aspects (Nikitin & Rao, 2008).

In this chapter, we review recent works in current passive UHF RFID systems to provide guidance regarding RFID system design and deployment. We cover the following topics.

- UHF RFID radio links using the link budget concept to calculate forward-link and reverse-link interrogation ranges.
- Hardware design considerations at the reader: phase diversity and quadrature signal combining, phase noise with range correlation effect, and transmitter leakage reduction methods.
- Deployment issues including reader-to-reader interference

The organization of this chapter is as follows. Section 2 analyzes the RFID link characteristics and shows the necessity of link budget concepts to calculate the RFID interrogation range. The hardware issues in an RFID reader are discussed in Section 3 along with recently published research results. Section 4 shows the RFID deployment issues with

emphasis on reader-to-reader interference in dense reader environments. Finally, the conclusions are presented in Section 5.

2. RFID link budget

A communication link, as is well known, encompasses the entire communication path from the transmitter (TX), through the propagation channel, and up to the receiver (RX). In a typical wireless communication system, illustrated in Fig. 1(a), there are forward and reverse links. The forward link is the communication link from a base station (BS) to a mobile station (MS), whereas the reverse link is the opposite communication link, from MS to BS. Because BS and MS can simultaneously transmit data to each other through the forward and reverse links, a typical communication link is called full duplex. In addition, the power levels of the two links have few differences. Therefore, the forward link coverage is almost the same as that of the reverse link, although the transmit power and sensitivity of both links are a little different (Dubkin, 2008).

(a) Typical wireless communication system   (b) RFID system
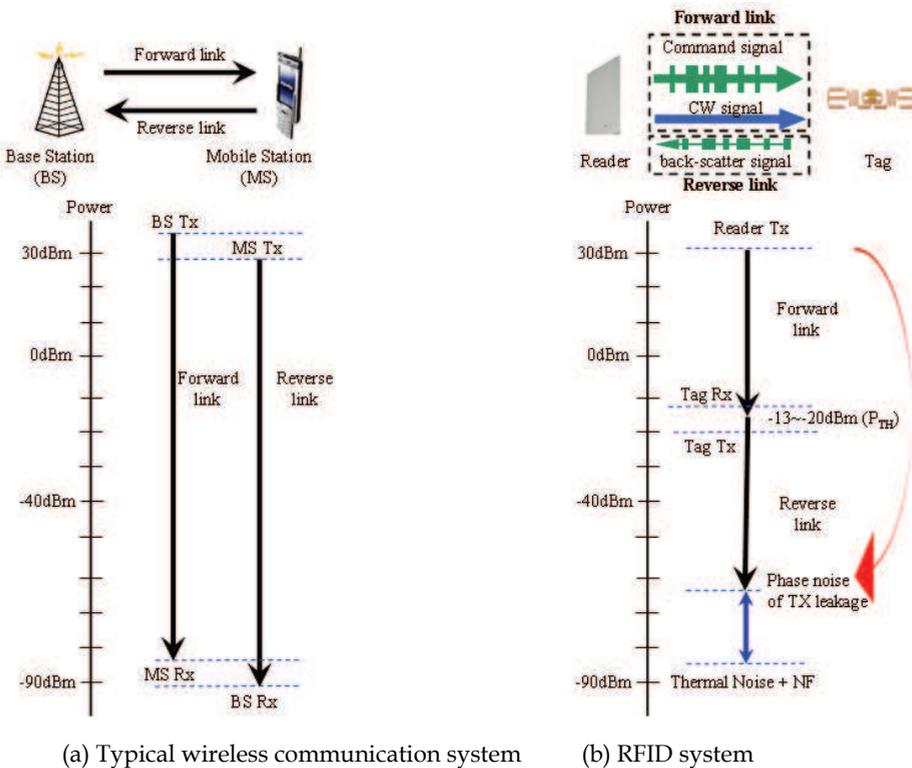
Fig. 1. Comparison of link characteristics between a typical wireless system and an UHF RFID system

On the other hand, UHF RFID links, as illustrated in Fig. 1(b) are different from typical wireless links. An RFID system is generally comprises two components: reader and tag. The reader, sometimes called the interrogator, is made up of a TX/RX module with one or more

antennas. The tag consists of a microchip for storing data and an antenna to transmit stored data. Tags are normally categorized into active and passive types by the presence or absence of an internal power supply. Because the passive tag has no power supply of its own, it obtains energy from the continuous wave (CW) signal transmitted by a reader. In addition, the passive tag transmits its data by backscattering the CW signal. In other words, the data transmission from tags to the reader is done by reflecting the wave energy back to the reader. Therefore, an RFID link is half duplex: reader to tag and then tag to reader. This means that RFID links are intrinsically unbalanced. Moreover, the reverse link is highly correlated with the forward link, because the tag's transmit power is determined by the reader's transmit power (Yoon & Jang, 2008).

These link characteristics of the UHF RFID system can be easily calculated using the link budget concept, which is the wireless communication system designer's primary tool for estimating the cell coverage.

2.1 Forward link budget calculation

In the forward link, the power received by the RFID tag, P_{RX}, can be found by applying the Friis EM wave propagation equation in free space:

$$P_{RX}(r) = \left(\frac{\lambda}{4\pi r}\right)^2 P_{TX} G_T G_R \tag{1}$$

where

λ : the wavelength in free space

r : the operational distance between an RFID tag and the reader

P_{TX} : the signal power feeding into the reader antenna by the transmitter

G_R : the gain of the reader antenna

G_T : the gain of the tag antenna

One portion of the power P_{RX} is absorbed by the tag for direct current (DC) power generation, and the other portion of P_{RX} is backscattered for the reverse link. In order to deliver enough power to turn the tag's microchip on, the absorption power for DC power generation must be larger than the minimum operating power required for tag operation, P_{TH}. For example, the forward link budget which has amplitude shift keying (ASK) backscatter modulation is given by:

$$P_{RX}(r) = \frac{1 - m^4}{(m+1)^2} \left(\frac{\lambda}{4\pi r}\right)^2 P_{TX} G_T G_R \geq P_{TH} \tag{2}$$

where m means the modulation depth.

The forward-link interrogation range (FIR) using the forward link budget calculation is depicted in Fig. 2. The FIR is proportional to the square root of the transmitted effective isotropic radiated power (EIRP), $P_{TX} G_T$, and the tag antenna's gain, G_R, and is inversely proportional to the square root of the tag's power threshold level, P_{TH}. From experience, it is known that the threshold power level required to turn on a tag ranges from 10uW (-20dBm) to 50uW (-13dBm) (Karthasu & Fischer, 2003). The modulation depth, m, is chosen to be an average value between 0.1 and 0.9.
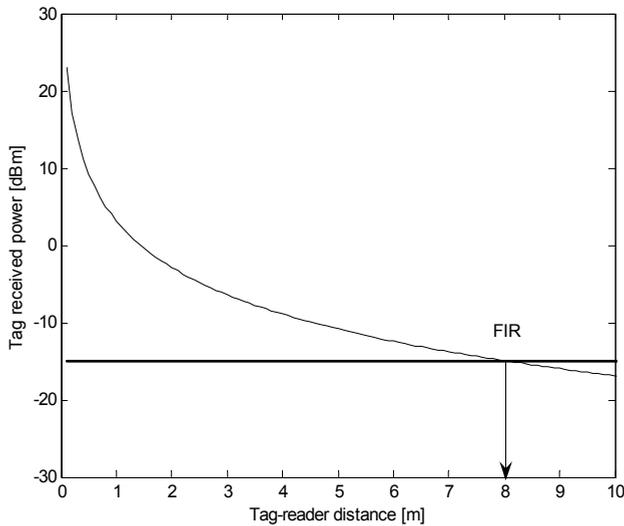
Fig. 2. Forward link budget of an UHF RFID system with center frequency of 915MHz, receive antenna gain of 2.15dBi, of -15dBm, and transmit EIRP of 4W

2.2 Reverse link budget calculation

In the reverse link, the backscattered signal from a tag should be strong enough so that the reader's demodulation output signal will meet the system's minimum signal-to-noise-ratio (SNR_{min}) requirement. This is very similar to typical wireless communication system links. However, because the CW signal always exists in a reverse-link to turn the tag on, the TX leakage level plays an important role in determining the reverse-link budget. Fortunately, the DC offset due to TX leakage is removed from a baseband bandpass filter. Nonetheless, the phase noise of the TX leakage, N_{PN}, on the receiving bandwidth is unfortunately not removed by the filter. Therefore, it may be much stronger than the thermal noise, to a degree that the reverse link budget mainly depends on the phase noise of the TX leakage. On the other hand, in a typical wireless communication system, the phase noise of the TX leakage within the receiving bandwidth is normally not a major problem, because duplexing techniques, such as frequency division duplexing (FDD) and time division duplexing (TDD), are applied.

Figure 3 shows a link budget example in the stationary reader case according to tag-reader distance. The reverse-link interrogation range (RIR) is defined as the maximum distance at which the tag's backscattered signal meets the minimum reader sensitivity condition. As showin in Fig. 3, the forward link is determined by a tag threshold voltage, the reverse link is mainly determined by the phase noise of TX leakage.

2.3 Interrogation range

The performance of an UHF RFID system is usually characterized by its interrogation range, which is defined as the maximum distance at which an RFID reader can recognize a tag. This can be divided into two categories: the FIR and the RIR. Since the actual interrogation
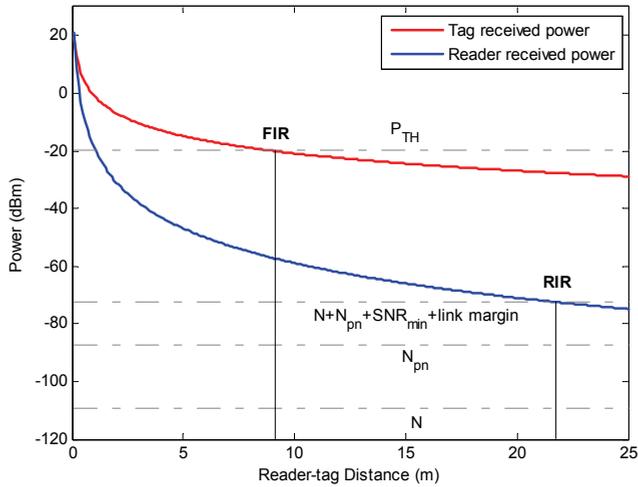
Fig. 3. Reverse link budget of an UHF RFID system (N: thermal noise) (Yoon & Jang, 2008)

range is determined by the smaller value of FIR and RIR, both values should be considered simultaneously when deploying UHF RFID systems. As shown in Fig. 3, FIR has a smaller value than RIR in the case of a well-designed reader. However, RIR may be much more significant than the FIR in environments such as warehouses because of interference from other readers. Also, the interrogation range of a battery-assisted tag is determined by the RIR only.

3. Hardware design issues in the UHF RFID reader

In order to discuss hardware design issues in the UHF RFID reader, let us consider an UHF RFID system model using a direct-conversion I/Q demodulator, as shown in Fig. 4. The reader is composed of local oscillator (LO), a transmitter, a receiver and an antenna. The power amplifier (PA) amplifies the LO signal to achieve a high power level. The amplified
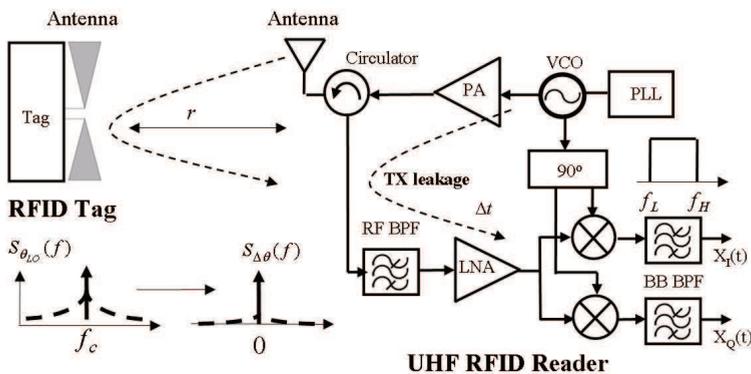

Fig. 4. Architecture of an UHF RFID system and block diagram of a reader and a tag

signal feeds into the reader antenna via the circulator and then radiates into the air. The reader antenna simultaneously receives the backscattered signals from the tag. The antenna can be configured in two ways: two antennas or one antenna with a circulator. The circulator is a non-reciprocal three-port device, where the signals travel from the transmitter port to the antenna port or from the antenna port to the receiver port. In practice, the circulator cannot entirely isolate the transmitter from the receiver, due to the inherent leakage between its ports. Generally, TX leakage is between -20 to -50dB (Jang & Yoon, 2008a).

3.1 Phase diversity and optimal I/Q signal combining

As shown in Fig. 4, the same LO provides two identical frequency signals, one for the transmitter and the other for the receiver. The LO signal for the receiver is further divided using a power splitter to provide two orthonormal baseband outputs, I and Q signals. Because the received signal and the LO signal have the same frequency, the absolute phase of the received signal influences the amplitude of the down-converted signal. Therefore, some sort of phase diversity using I and Q signals should be provided to demodulate the tag signal (Jang, 2008).

Figure 5 shows the simulation results of normalized I and Q signal power at the quadrature receiver for the case of tag moving. For this simulation, the tag located 1 meter below the reader antenna is assumed to move up to 5m away from the reader. The complex plot forms a spiral-like shape due to the periodic received signal power variation.

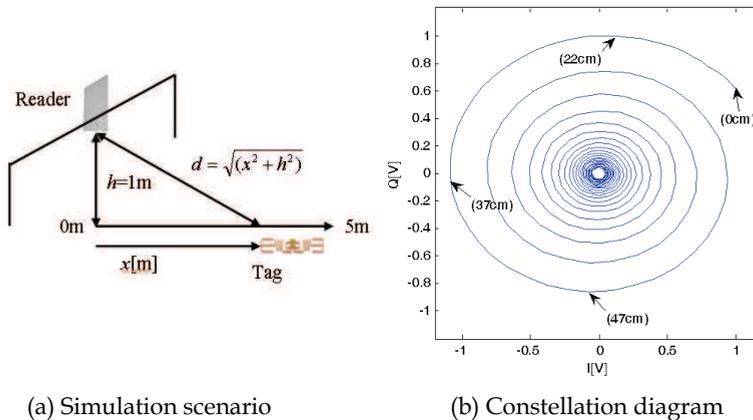(a) Simulation scenario   (b) Constellation diagram

Fig. 5. Received signal variation characteristics of an UHF RFID receiver with respect to the reader-tag distance

Using the quadrature receiver, the demodulator can choose the higher of the tag signals to retrieve the tag's data. This is called selection diversity. Now, the reader can select the better of the quadrature (I and Q) channel outputs and overcome the limitation of a single channel receiver. Figure 6 shows the performance of selection diversity compared with the I and Q channel signals with respect to phase value from zero to π. In selection diversity, two extreme instances, i.e., 'minimum' and 'optimum' occur every $\lambda / 8$ meters, as the tag moves away from the reader antenna. At 900 MHz, these minimum points occur every 4.2cm. For the optimum instance, the tag signal can be demodulated without loss. However, for the

minimum instance, the tag signal can be reduced with a 3dB loss in power. In order to overcome this 3dB loss of selection diversity, various I/Q combining techniques can be used. For example, the power combining technique can be used in the ASK case. On the other hand, signal combining with phase shift keying (PSK) is not as easy as ASK. Recently, arctangent combining and principal component combining (PCC) have been suggested (Jang, 2008).
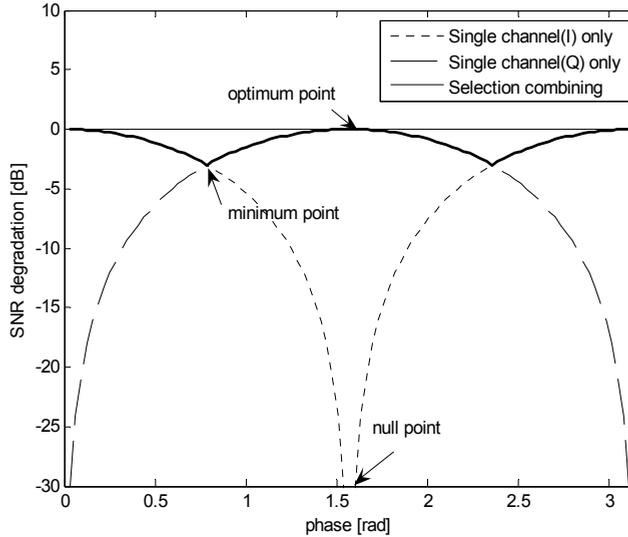

Fig. 6. SNR degradation for various receiver combining techniques

3.2 Phase noise and range correlation effects
Phase noise is an important parameter in designing RFID systems since it can have a significant influence on system performance. Because a LO is generally used for both CW signal generation and the down-converting operation, the phase noise of the received signal is correlated with that of the LO signal. The correlation level is inversely proportional to the time difference between the two signals. In an UHF RFID system, this time difference is very small (several nsec) due to the short tag-reader distance, and so phase noise is reduced by the correlation effect. In an RFID application, this phase noise reduction phenomenon is called the range correlation effect (Jang & Yoon, 2008b).
The baseband power spectral density (PSD), $S_{\Delta\theta(t)}(f)$, for LO phase noise with the offset frequency Δf_c and a round-trip delay of Δt is given by (Droitcour et al., 2004):

$$S_{\Delta\theta(t)}(f) = S_{\theta_{LO}(t)}(f)\,4\sin^2\left(4\pi\frac{r\Delta f_c}{c}\right)^2 \qquad (3)$$

where $\Delta\theta(t) = \theta_{LO}(t) - \theta_{LO}(t - \Delta t)$ and $\theta_{LO}(t)$ is the phase noise of the LO signal.
The term in parenthesis embodies the range correlation effect on the baseband spectrum. Assuming that the typical values for r and f_o are 8m and 160kHz, respectively, the value

of $r\Delta f_c / c$ will be on the order of 10^{-3}. So the range correlation effect will dramatically reduce the PSD of the LO phase noise.

Figure 7 shows an example of a typical PSD of the LO itself and the phase noise reduction effects due to the range correlation with a round-trip delay of 1m. The typical PSD of the LO is selected considering state-of-the-art UHF RFID LO performance. The effect of the range correlation on the phase noise for different offset frequencies was estimated by (3). For example, at an offset frequency of 10Hz, the phase noise is reduced by 130dB.
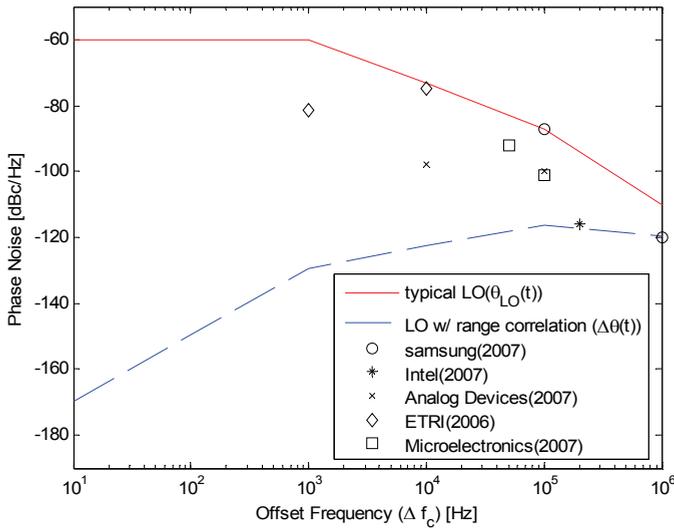

Fig. 7. LO phase noise as a function of offset frequency

In addition, the phase noise may affect the symbol-error-rate (SER) performance in an RFID system. Figure 8 shows the SER performance of the PSK modulation and FM0 coding with phase noise as a function of range correlation. Without the range correlation, the SER performance is worse for the case of typical LO phase noise, as shown in Fig. 7. This degradation is worse for a small modulation phase noise. However, the phase noise of the LO with range correlation effects is almost identical to the SER performance in AWGN environments because of the phase noise reduction by range correlation. For a real LO using a phase-locked loop (PLL), the power spectral density of the phase noise is filtered by the transfer function of the PLL, and the phase noise effects on the error performance are even small. Unlike PSK modulation, phase noise has no effects on ASK modulation, because there is no information in the carrier's phase (Jang & Yoon, 2008b).

3.3 TX leakage reduction methods

Finally, some difficult technical problems arise from TX-to-RX leakage because the RFID reader transmits CW and simultaneously receives back-scattered data from tags. The strong TX leakage into the receiver side degrades the reader performance in relation to the sensitivity of the receiver and its interrogation range. In detail, the low noise amplifier
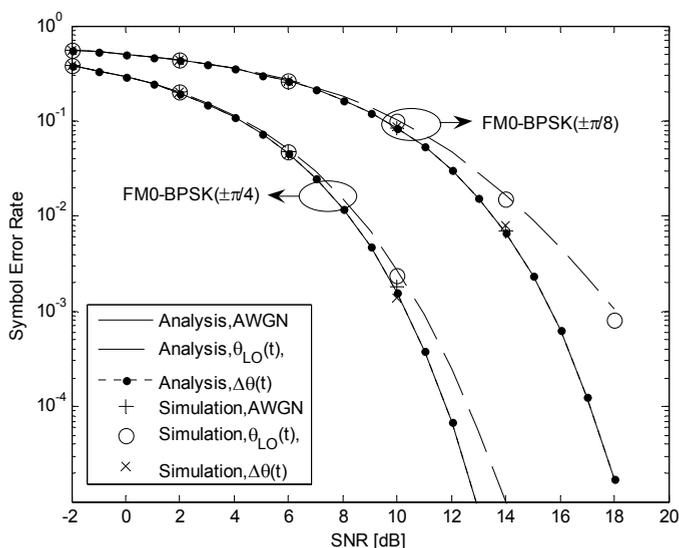
Fig. 8. SER performance of FM0-BPSK signal as a function of phase noise and range correlation effect (Jang & Yoon, 2008b)

(LNA) of the receiver can be saturated by this strong TX leakage, decreasing the dynamic range of LNA. A DC offset problem is also caused by self mixing at the mixer in the reader receiver.

To alleviate the TX leakage problem, the strong TX signal should be separated from the RX signal as much as is possible to achieve higher performance from the RFID reader. The simplest solution is to separate the TX and RX antennas. However, the size and cost of the reader hardware will increase. A circulator of ferrite material or an active CMOS circulator may lighten this burden, but the cost is still high, and isolation of these circulators is insufficient to meet some required criteria. A directional coupler may, therefore, be a better choice given its simplicity and low cost (Kim et al., 2006).

4. Deployment Issues

In supply-chain applications, tens or hundreds of RFID readers will be in operation within close range of each other, which may cause serious interference problems.

There are three types of UHF RFID interference: multiple-tag-to-reader interference (tag collision), multiple-reader-to-tag interference (tag interference), and reader-to-reader interference (reader interference or frequency interference) as shown in Fig. 9.

Multiple-tag-to-reader interference arises when multiple tags are simultaneously energized by a 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 to resolve multiple-tag-to-reader interference (Dubkin, 2008), (EPCglobal, 2004). 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. Multiple reader-to-tag interference can be solved simply by separating reader intterrogation ranges.
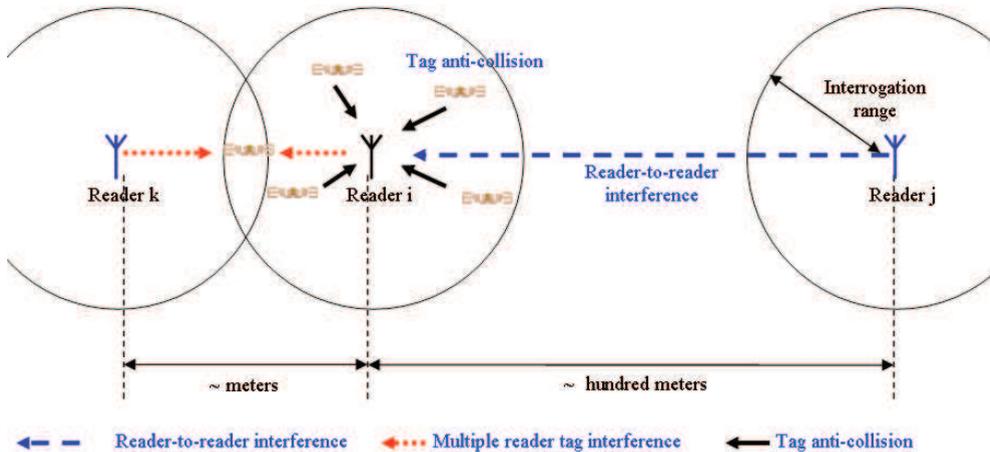

Fig. 9. Three types of Interference in UHF RFID systems

The last type of interference, reader-to-reader interference, is induced when a signal from one reader reaches other readers (Birari & Iyer, 2005). This can happen even if there is no intersection among reader interrogation ranges. As the signal transmitted from distant readers may be strong enough to impede accurate decoding of the signals that are back-scattered from adjacent tags, reader-to-reader interference can cause serious problems in UHF RFID system deployment (Kim et al., 2008), (Kim et al., 2009). 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. 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 an UHF RFID operation in a dense reader environment. According to EPCglobal C1G2, reader transmit signals and tag back-scattered signals are separated in a spectral domain (EPCglobal, 2004).

Additionally, careful consideration of the positioning and type of RFID reader antenna selected are important for reader-to-reader interference (Leong et al., 2006). The situation can also be improved by using reader synchronization and frequency channelling. Actual field testing will be carried out in the future, especially in warehouses, where dense RFID reader environments are most likely to exist

5. Conclusion

In this chapter, we discuss hardware design and deployment issues in current passive UHF band RFID systems. Using the link budget concept, the simple method to calculate forward-

and reverse-link interrogation range is shown. Then, we consider the hardware issues on an RFID reader: phase diversity and signal combining techniques, phase noise with range correlation effect, and TX leakage reduction methods. Finally, three interference problems with an emphasis on reader-to-reader interference encountered in the deployment of RFID systems are presented.

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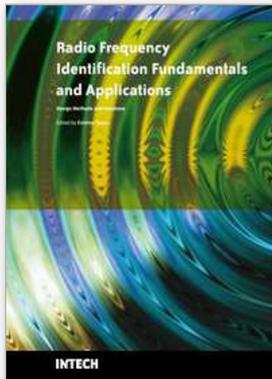
Radio Frequency Identification Fundamentals and Applications
Design Methods and Solutions
Edited by Cristina Turcu

This book, entitled Radio Frequency Identification Fundamentals and Applications, Bringing Research to Practice, bridges the gap between theory and practice and brings together a variety of research results and practical solutions in the field of RFID. The book is a rich collection of articles written by people from all over the world: teachers, researchers, engineers, and technical people with strong background in the RFID area. Developed as a source of information on RFID technology, the book addresses a wide audience including designers for RFID systems, researchers, students and anyone who would like to learn about this field. At this point I would like to express my thanks to all scientists who were kind enough to contribute to the success of this project by presenting numerous technical studies and research results. However, we couldn't have published this book without the effort of InTech team. I wish to extend my most sincere gratitude to InTech publishing house for continuing to publish new, interesting and valuable books for all of us.

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