

Hardware Design and Deployment Issues in UHF RFID Systems

Byung-Jun Jang¹ · Hyun-Goo Yoon² · Jae-Bong Lim¹

Abstract

In this paper, we discuss hardware design and deployment issues in current passive UHF RFID systems. Using the link budget concept, the methodology to calculate forward- and reverse-link interrogation range is shown. Then, we consider hardware issues: phase diversity, phase noise with range correlation, and TX leakage problems. Finally, three interference problems when deploying RFID systems are presented.

Key words : RFID, Reader, Tag, Antenna, Link budget, Interrogation Range, Interference.

I . Introduction

Recently, ultra-high frequency(UHF) band passive radio frequency identifier(RFID) systems that operate in the 860~960 MHz band have drawn a great deal of attention. It is generally accepted that UHF RFID systems can 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 a UHF RFID system in their supply chains^[1].

A 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 either side of the link(wireless LAN, bluetooth, etc). Tags are powered only by RF energy, and RFID readers must transmit and receive simultaneously in order to be able to communicate with tags. This puts a different emphasis on the radio link, hardware design, and deployment aspects^[2].

In this paper, 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 interrogation ranges.
- Hardware design considerations at the reader.
- Deployment issues including reader-to-reader interference.

The organization of this paper is as follows. Section II analyzes the RFID link characteristics and shows the necessity of link budget concepts to calculate the RFID interrogation range. The hardware issues in RFID readers are discussed in Section III along with recently published research results. Section IV shows the RFID

deployment issues with emphasis on reader-to-reader interference. Finally, the conclusions are presented in Section V.

II . Link Budget

A communication link, as is well known, encompasses the entire communication path from the transmitter, through the propagation channel, and up to the receiver. 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^[3].

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 transmitter/receiver 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

Manuscript received March 1, 2009 ; revised March 18, 2009. (ID No. Invited 20090301-002J)

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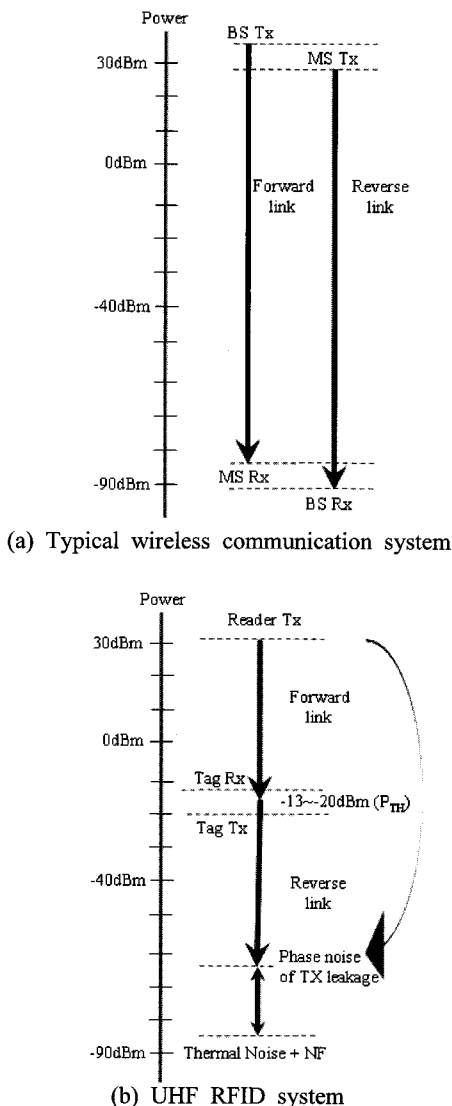


Fig. 1. Comparison of link characteristics between a typical wireless system and a UHF RFID system.

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^[4].

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 electromagnetic(EM) wave propagation equation in free space:

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

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:

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

where m means the modulation depth.

The forward-link budget calculation is depicted in Fig. 2. The forward link budget 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

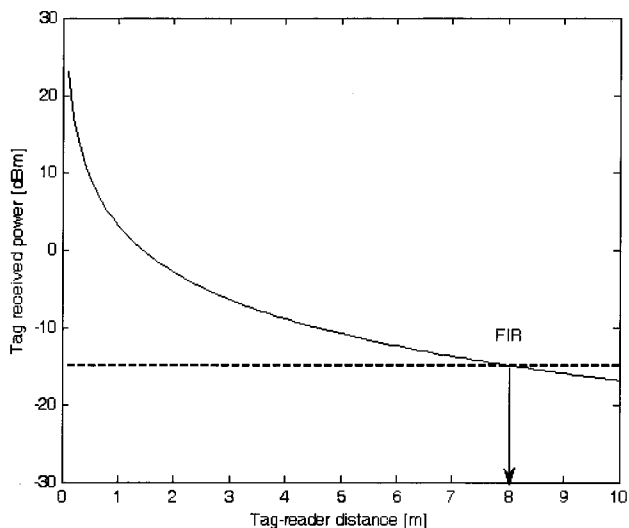


Fig. 2. Forward link budget of a UHF RFID system with center frequency of 915 MHz, receive antenna gain of 2.15 dBi, of -15 dBm, and transmit EIRP of 4 W.

power threshold level, P_{TH} . From experience, it is known that the threshold power level required to turn on a tag ranges from 10 uW(-20 dBm) to 50 uW(-13 dBm)^[5]. The modulation depth, m , is chosen to be an average value between 0.1 and 0.9.

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.

Fig. 3 shows a link budget example in the stationary reader case according to tag-reader distance. While the forward link is determined by a tag threshold voltage, the reverse link is mainly determined by the phase noise of TX leakage.

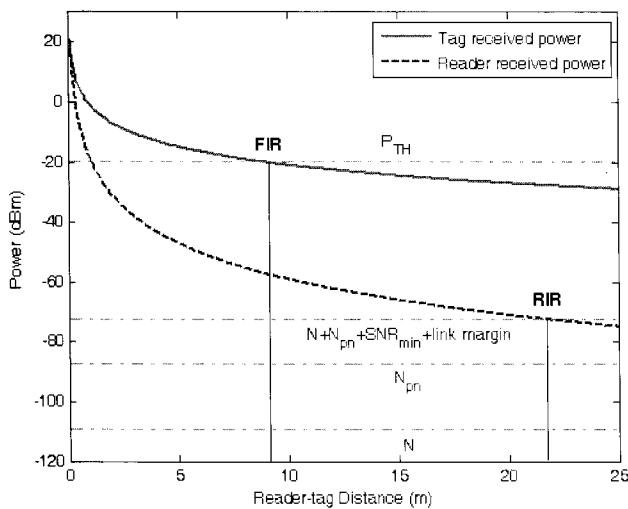


Fig. 3. Reverse link budget of a UHF RFID system(N: thermal noise)^[4].

2-3 Interrogation Range

The performance of a 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 forward-link interrogation range(FIR) and the reverse-link interrogation range(RIR). Since the actual interrogation 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.

III. Hardware Design Issues in the UHF RFID Reader

In order to discuss hardware design issues in the UHF RFID reader, let us consider a 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 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 -50 dB^[6].

3-1 Phase Diversity and Optimal I/Q Signal Combining

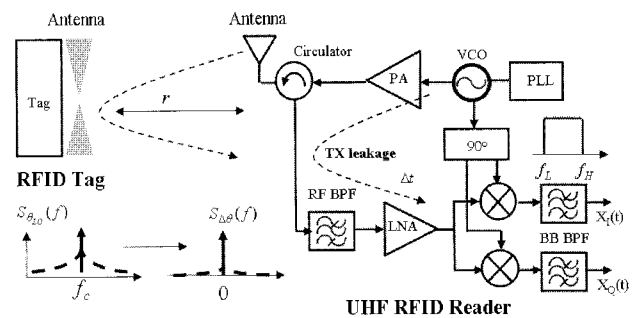


Fig. 4. Architecture of a UHF RFID system and block diagram of a reader and a tag.

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 90° 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 [7].

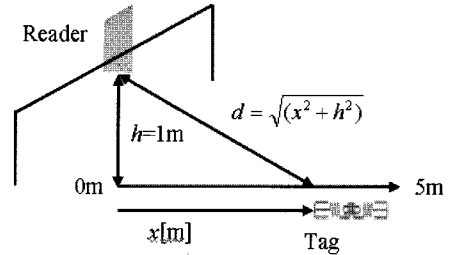
Fig. 5 shows the simulation results of normalized *I* and *Q* signal power at the quadrature receiver for the case of tag moving. For this simulation, the tag located 1 meter below the reader antenna is assumed to move up to 5 m away from the reader. The complex plot forms a spiral-like shape due to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

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. In selection diversity, two extreme instances, i.e., 'minimum' and 'optimum' occur every $8/\lambda$ meters, as the tag moves away from the reader antenna. At 900 MHz, these minimum points occur every 4.2 cm. 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 3 dB 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 [7].

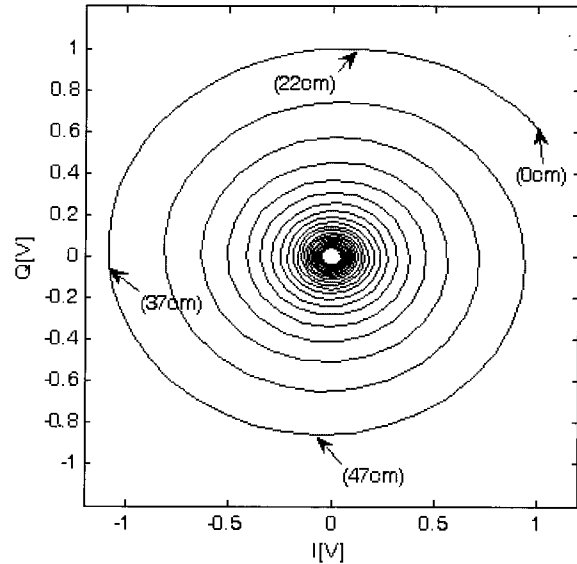
3-2 Phase Noise and Range Correlation Effects

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 a 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 a RFID application, this phase noise reduction phenomenon is called the range correlation effect [8].

The baseband power spectral density (PSD), $S_{\Delta\theta(t)}(f)$,



(a) Simulation scenario



(b) Constellation diagram

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

for LO phase noise with the offset frequency Δf_c and a round-trip delay of Δt is given by [9]:

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

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 8 m and 160 kHz, 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.

Fig. 6 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 1 m. 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

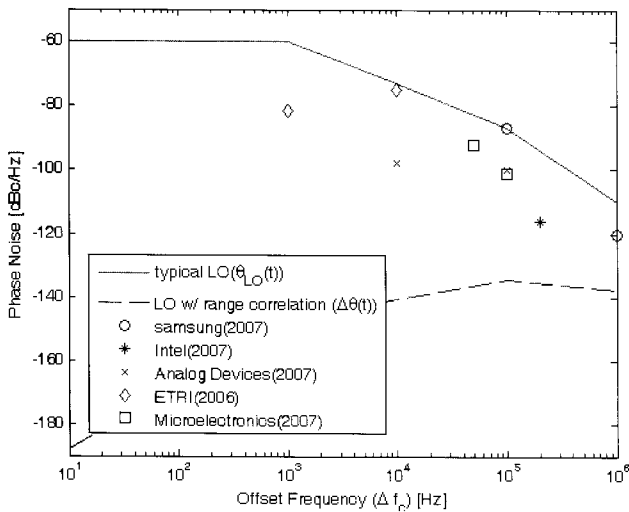


Fig. 6. LO phase noise as a function of offset frequency.

offset frequency of 10 Hz, the phase noise is reduced by 130 dB.

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(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^[10].

IV. 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: tag interference, multiple reader-to-tag interference, and rea-

der-to-reader interference. Tag 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^{[3],[11]}. 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^[12]. 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^{[13],[14]}. 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 a 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^[11].

Additionally, careful consideration of the positioning and type of RFID reader antenna selected are important for reader-to-reader interference^[15]. 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.

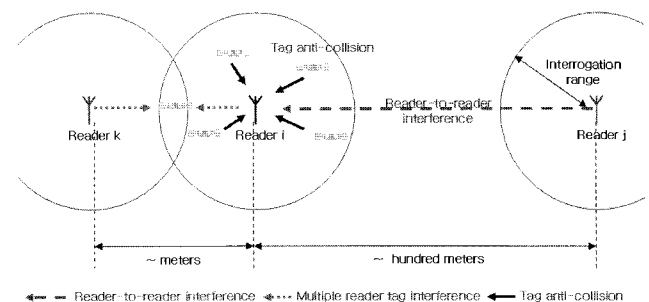


Fig. 7. Three types of interference in UHF RFID systems.

V. Conclusion

In this paper, we discuss hardware design and deployment issues in current passive UHF RFID systems. Using the link budget concept, the methodology to calculate forward- and reverse-link interrogation range is shown. Then, we consider the hardware issues: phase diversity, phase noise with range correlation, and TX leakage problems. Finally, three interference problems encountered in the deployment of RFID systems are presented.

This work was supported by research program 2009 of Kookmin University in Korea

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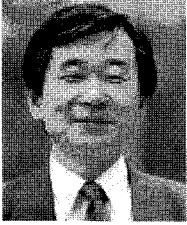
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