Research Article

Numeric Evaluation on the System Efficiency of the EPC Gen-2 UHF RFID Tag Collision Resolution Protocol in Error Prone Air Interface

Xin-Qing Yan, 1 Yang Liu, 1 Bin Li, 2 and Xue-Mei Liu 1

1 School of Information Engineering, North China University of Water Resources and Electric Power, Zhengzhou 450011, China
2 Department of Traffic and Transportation, Fujian University of Technology, Fuzhou 350108, China

Correspondence should be addressed to Xin-Qing Yan; yanxq@ncwu.edu.cn

Received 28 June 2013; Accepted 1 February 2014; Published 9 March 2014

Academic Editor: Chang Wu Yu

Copyright © 2014 Xin-Qing Yan et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Efficient resolution of the tag collisions is the key for the RFID systems to be universally adopted. To resolve the tag collision occurred in the UHF RFID system, the EPC Gen-2 protocol, proposed by the EPCglobal Inc., was adopted as an international standard and have been widely accepted in industry. However, little research work has been taken to evaluate the performance of this protocol in nonperfect and error prone air interface. In this paper, to evaluate the performance of the EPC Gen-2 protocol, a system efficiency model is proposed, and, based on the model, numeric simulations are performed to evaluate the EPC Gen-2 protocol in error prone air interface. Simulation results reveal that the system efficiency of the EPC Gen-2 protocol is seriously affected by the capture and noise effects.

1. Introduction

Radio frequency identification (RFID) uses radio frequency signals to exchange information between the electronic transponders (tags) and the interrogator (reader) and enables the identification of multiple tagged physical items without line-of-sight. As a bridge to connect the physical world and the cyber space, RFID technology is regarded as the main enabler of the “Internet of Things” [1, 2] and ubiquitous computing [3, 4]. In fact, a RFID system can be viewed as a special wireless sensor network, in which each tag (sensor node) can only transmit its digital identifier but no other information to the reader (sink node). The past few years have witnessed the adoption of RFID systems in a lot of systems [5].

Especially in the recent years, the ultra high frequency (UHF) RFID system, which works in the frequency range of 860–920 MHz, gains special attention due to its rapid communication speed, long tag identification range, and low-cost of the passive tags. UHF RFID system is expected to bring a revolution to the logistical and supply chain management systems [6].

Despite of the promising future, the universal adoption of the RFID system is technically affected by tag collision [7]. When multiple tags try to transmit their data simultaneously to the reader, their radio signals will interfere in the wireless communication channel and be garbled at the reader. When tag collision occurs, what the reader can get is only a collision signal but no useful information. Due to tag collision, the RFID system suffers from low tag read rate and long identification delay.

Tag collision is more serious in the UHF RFID system due to the long tag identification distance and therefore more tags will be in the interrogation zone of the reader. Not only does tag collision prolong the tag identification time but also affects the tag read rate. For example, the tag read rate in typical UHF RFID system is only about 60–70% [8].

Due to the extreme constraints on computation and communication put on them, the passive tags can only get power supply by backscattering the radio frequency signals broadcasted by the reader, they cannot detect the collision occurred in the wireless communication channel or coordinate with each other to avoid the collision. Tag collision can only be
arbitrated by the reader with some deliberately designed tag collision resolution protocols.

Proposed tag collision resolution protocols can be basically categorized as the binary splitting tree based and the frame slotted ALOHA based protocols [9, 10]. The binary splitting tree based protocols suffer from scalability and message complexity and are sensitive to the error in the wireless communication channel. So, we will not discuss these binary splitting tree based protocols further in this paper.

Due to their simplicity and robustness, the frame slotted ALOHA based protocols are widely adopted in RFID systems to resolve tag collisions. Especially, to resolve the tag collision occurred in the UHF RFID system, as a variant of the frame slotted ALOHA protocol, the EPC Class-1 Generation-2 air interface protocol (the EPC Gen-2 protocol) was proposed by the EPCglobal Inc. [11] and accepted as an international standard the ISO/IEC-18600C. Now, this protocol has been widely accepted in industry and by main RFID manufactures.

To evaluate and optimize the performance of the EPC Gen-2 protocol, a lot of researches have been taken, such as the performance analysis presented in [12–14], the empirical study presented in [15, 16], and the optimization presented in [17–20]. In a lot of research works, it is assumed that the air interface between the reader and the electronic tags is perfect, without any signal loss or other communication effects. But this assumption may not hold in real UHF RFID system. Due to long tag identification distance, the wireless signalstransmitted from tags and broadcasted by reader may be absorbed, reflected, garbled, and captured in the complex deployment environment; the air interface is far from perfect, and error occurs frequently in the wireless communication channel.

Our motivations in this paper are to evaluate the performance of the EPC Gen-2 protocol in error prone air interface. The main contributions of this paper are as follows. Firstly, a model is proposed to evaluate the system efficiency of the EPC Gen-2 protocol in error prone air interface. Secondly, numeric simulations are performed to evaluate the system efficiency of the protocol in the air interface with different capture and noise effects and to reveal the influences of capture and noise effects on the system efficiency of the protocol.

The rest of this paper is organized as follows. Section 2 introduces briefly the EPC Gen-2 protocol and the Q-adjustment algorithm adopted in the protocol. Section 3 presents a model to evaluate the system efficiency of the EPC Gen-2 protocol in error prone air interface. Section 4 evaluates the system efficiency of the protocol with different capture and noise effects and reveals the influence of these effects on the performance of the protocol. Finally, Section 5 concludes this paper and proposes some works for future research.

2. The EPC Gen-2 Protocol for Tag Collision Resolution in the UHF RFID System

2.1. The EPC Gen-2 Protocol. In the EPC Gen-2 protocol, a tag collision resolution cycle is called a round, which consists of a series of command broadcasted by the reader and responses transmitted by the tag. At the beginning of a round, the protocol asks the reader to broadcast a SELECT command, and only tags which receive this command will respond in the round. Afterwards, the reader broadcasts a Query command to start tag identification. In fact, a tag collision resolution round in the EPC Gen-2 protocol is defined as the interval between two successive Query commands.

In the Query command, there is also an integer Q (with initial value 4) broadcasted by the reader to tags in its vicinity. Upon receiving the Query command, every unidentifed tag randomly generates an integer in the range of \([0, 2^Q - 1]\) and stores the value in its SC register. The tag whose SC equals to 0 will generate a 16-bit SN and transmit the SN to the reader immediately.

If only one tag answers back after the command, the slot is single occupied, the reader can decode the SN and echoes back an ACK command with the SN. Each answering tag compares the SN which it generated with the one it received in the ACK command. If these two SN’s match, the tag transmits its digital identifier to the reader, the tag is identified, and the slot results in successfulness. In such case, the identified tag turns itself into sleep mode and ceases to responding to the following queries, until being aroused by the reader again.

If no tag answers back, the slot results in idle. If two or more tags transmit their SNs, the slot results in collision.

After a single reply slot, the reader broadcasts a QueryRep command and asks every unidentified tag to decrease its SC by 1. The tag whose SC equals to 0 will respond with the randomly generated 16-bit SN, as described above.

After an idle or a collision slot, the protocol may decide whether to adjust the value of Q according to the Q-adjustment algorithm described below. If the value of Q is adjusted, the protocol asks the reader to broadcast a QueryAdjust command with the new value of Q, and let every unidentified tag to regenerate its SC. Otherwise, the protocol asks the reader to issue a QueryRep command to continue asking unidentified tags to decrease their SCs.

We can see that the performance of the EPC Gen-2 protocol is seriously affected by the choice of Q and how to adjust its value.

2.2. The Q-Adjustment Algorithm. As we have introduced, in the EPC Gen-2 protocol, after an idle or a collision slot, the protocol uses the Q-adjustment algorithm to determine whether to adjust the value of Q or not.

In the Q-adjustment algorithm, there is a float number \(Q_{fp}\), representing the float value of Q, with initial value \(Q_{fp} = 4.0\). Besides, the algorithm also uses a float value \(C\) (\(0.1 < C < 0.5\)) to adjust the value of \(Q_{fp}\).

After an idle slot, the value of \(Q_{fp}\) is subtracted with \(C\). After a collision slot, the value of \(Q_{fp}\) is added with \(C\). The value of \(Q\) is set to the integer nearest to \(Q_{fp}\). If the value of \(Q\) is changed, the protocol will ask the reader to issue a QueryAdjust command with the new value of \(Q\). Otherwise, the protocol asks the reader to issue an QueryRep command.
Figure 1: The Q-adjustment Algorithm, extracted from [11].

The Q-Adjustment algorithm works as depicted in Figure 1.

Although it is specified in the EPC Gen-2 protocol that the value of $C$ should be in $(0.1, 0.5)$, small values of $C$ should be used for large value of $Q$, and larger values of $C$ should be used for small value of $Q$. But no optimal choice of $C$ for different value of $Q$ is specified.

Effective Q-adjustment algorithm is also a key for the EPC Gen-2 protocol to resolve the collisions caused by different number of tags efficiently.

3. System Model

3.1. The Imperfect Air Interface. In the UHF RFID system, as other passive RFID systems, tag collision resolution is based on the request/response model. First, a reader sends an interrogation signal to all tags within its vicinity, and tags respond back by backscattering their signals. The backscattering signals are significantly attenuated by distance.

Due to the long identification distance and complex deployment environment of the UHF RFID system, the wireless communication channel between the reader and tags is far from error free. The backscattering signals from tags are typically very weak and can be reflected or absorbed by the environment, and frame errors may also occur due to noise or interference in the air interface.

Errors in the air interface can be classified as the the reader-tag downlink channel error or tag-reader uplink error. In the downlink, a tag may not get the command message broadcasted by the reader, so no response will be transmitted. In the uplink, tag responses, but the reader may miss the signals or misunderstand the information.

Due to the fact that the reader can adjust its signal strength to overcome the error in the downlink channel, but tags cannot, in this paper, we will consider the error occurred in the tag-reader uplink channel; the reader cannot distinguish a collision slot from a successful slot due to the frame error occurred in the uplink.

Furthermore, we can see from the EPC Gen-2 protocol that in the tag-reader uplink channel, the data transmission can be divided into two stages. In the first stage, every tag whose $SC = 0$ will only transmit its 16-bit $SN$ to the reader. If the reader can decode the $SN$, in the second stage, the reader echoes the ACK command and asks the responding tag to transmit its full digital identifier.

In such case, the reader cannot continue identifying the tag even if error occurs in the second stage. Since the responding tag will turn itself into sleep mode and stop responding to the following query commands in the cycle. So, in this paper, we only consider the case that error may occur in the uplink channel when tag tries to transmit its 16-bit SN to the reader.

Due to frame error occurred in the air interface, the protocol may not be able to fully distinguish a successful slot with a collision slot, it sometimes takes a successful slot as a collision slots and occasionally regards a collision slot as a successful slot. But since that there is no signal transmission in the idle slot, the protocol can always distinguish an idle slot from a responding slot.

3.2. Evaluation Model for the System Efficiency of the EPC Gen-2 Protocol. In the EPC Gen-2 protocol, for the identification of $n$ tags using the current value $Q$, according to the Binomial distribution, the probability that $k$ tags responding in a slot can be calculated as

$$p(Q, k, n) = \binom{n}{k} \left( \frac{1}{2^Q} \right)^k \left( 1 - \frac{1}{2^Q} \right)^{n-k},$$

where $\binom{n}{k} = n!/(k!(n-k)!)$. 

$$Q_{fp} = 4.0$$

$$Q = \text{round}(Q_{fp})$$

Query $(Q)$

$0$

Number of tag responses

$>1$

$Q_{fp} = \max(0, Q_{fp} - C)$

$Q_{fp} = \min(15, Q_{fp} + C)$

$Q_{fp} = Q_{fp} + 0$
Especially, the probabilities for a slot to result in idle, single reply or two or more replies can be calculated, respectively, as

\[
p_i(Q, n) = \left(1 - \frac{1}{2^Q}\right)^n,
\]

\[
p_s(Q, n) = \frac{n}{2^Q} \left(1 - \frac{1}{2^Q}\right)^{n-1},
\]

\[
p_c(Q, n) = 1 - p_i(Q, n) - p_s(Q, n)
= 1 - \left(1 - \frac{1}{2^Q}\right)^n - \frac{n}{2^Q} \left(1 - \frac{1}{2^Q}\right)^{n-1}.
\]

The probability for a slot to result in nonidle, \(p_{\text{SC}}(Q, n)\), is \(p_{\text{SC}}(Q, n) = 1 - p_i(Q, n)\). We can see that for a fixed \(Q\), as tag population \(n\) increases, \(p_i(Q, n)\) keeps decreasing, while \(p_{\text{SC}}(Q, n)\) keeps increasing. For a given tag population \(n\), it has been reported that in the perfect air interface, when \(Q = \lceil \log_2 n \rceil\), the probability for a slot to result in single reply (successful), \(p_i(Q, n)\), is maximized. On the other hand, in the perfect air interface, for a given value of \(Q\), the suitable tag population range \([\min(Q), \max(Q)]\) can be calculated. When the tag population is in the suitable range, the minimum and maximum probabilities for a slot to result in idle and nonidle (successful or collision) can also be calculated, as shown in Table 1.

As presented in [21], the system efficiency (SE) of the protocol is defined as the ratio between the number of tags identified in a round (also the number of successful slot), \(n\), and the total number of data slots, \(S\), needed in the round, \(SE = n/S\). In the EPC Gen-2 protocol, since that the protocol can abandon a frame and starts a new one according to the \(Q\)-adjustment algorithm, the number of data slots in a frame is not fixed. But the total number of data slots needed by the EPC Gen-2 protocol in a round can be calculated as

\[
S = \sum S_k,
\]

where \(S_k\) specifies the number of data slots in the \(k\)th frame.

For the \(S_k\) data slot in the \(k\)th frame with \(Q_k\) value, according to (4), the mathematical expectations for the number of idle, successful, and collision slots, \(N_i(S_k, Q_k)\), \(N_s(S_k, Q_k)\), and \(N_c(S_k, Q_k)\) are

\[
N_i(S_k, Q_k) = S_k p_i(Q_k, n),
\]

\[
N_s(S_k, Q_k) = S_k p_s(Q_k, n), \tag{4}
\]

\[
N_c(S_k, Q_k) = S_k p_c(Q_k, n).
\]

Suppose that in the error prone air interface, with probability \(p\), the protocol regards a successful slot as a collision slot, and, with probability \(q\), the protocol regards a collision slot as a successful slot; the system efficiency of the EPC Gen-2 protocol in the error prone air interface, SE, is calculated as

\[
SE = \frac{\sum ((1 - p) N_s(S_k, Q_k) + q N_c(S_k, Q_k))}{\sum S_k}. \tag{5}
\]

For the perfect air interface, we have \(p = 0\) and \(q = 0\), and SE is calculated as

\[
SE = \frac{\sum N_i(S_k, Q_k)}{\sum S_k} = \frac{\sum S_k p_i(Q_k, n)}{\sum S_k}. \tag{6}
\]

## 4. Performance Evaluation

Since that for different value of \(p\) and \(q\), it is difficult to find a closure solution for (5) to evaluate the system efficiency of the protocol, so in this paper, numeric simulations are performed to evaluate the performance of the EPC Gen-2 protocol using the \(Q\)-adjustment algorithms. In the simulations, the tags to be identified by the reader in a round are divided into 2 groups. In the first group, the tag population varies from 1 to 300 with increment 1, and, in the second group, the tag population varies from 300 to 3000 with increment 100. The protocol is required to resolve all tag collisions and identify all tags in a round.

### Table 1: Suitable tag population range for different values of \(Q\).

| \(Q\) | \(\min(Q)\) | \(\max(Q)\) | \(p_i(\min(Q))\) | \(p_i(\max(Q))\) | \(p_{\text{SC}}(\min(Q))\) | \(p_{\text{SC}}(\max(Q))\) |
|------|-------------|-------------|-----------------|-----------------|-----------------|-----------------|
| 1    | 1           | 2           | 0.50            | 0.25            | 0.50            | 0.75            |
| 2    | 3           | 5           | 0.42            | 0.24            | 0.58            | 0.76            |
| 3    | 6           | 11          | 0.45            | 0.23            | 0.55            | 0.77            |
| 4    | 12          | 22          | 0.46            | 0.24            | 0.54            | 0.76            |
| 5    | 23          | 45          | 0.48            | 0.24            | 0.53            | 0.76            |
| 6    | 46          | 90          | 0.49            | 0.24            | 0.52            | 0.76            |
| 7    | 91          | 181         | 0.49            | 0.24            | 0.51            | 0.76            |
| 8    | 182         | 362         | 0.49            | 0.24            | 0.51            | 0.76            |
| 9    | 363         | 724         | 0.49            | 0.24            | 0.51            | 0.76            |
| 10   | 725         | 1448        | 0.49            | 0.24            | 0.51            | 0.76            |
| 11   | 1449        | 2896        | 0.49            | 0.24            | 0.51            | 0.76            |
| 12   | 2897        | 5792        | 0.49            | 0.24            | 0.51            | 0.76            |
| 13   | 5793        | 11585       | 0.49            | 0.24            | 0.51            | 0.76            |
| 14   | 11586       | 23170       | 0.49            | 0.24            | 0.51            | 0.76            |
| 15   | 23171       | 46340       | 0.49            | 0.24            | 0.51            | 0.76            |
In order to gain a fair result, the simulations are performed 100 times. The system efficiencies of the EPC Gen-2 protocol gained in each time of the simulation are recorded and are averaged at last for comparison. In the evaluation, according to (5), we will examine the system efficiency of the EPC Gen-2 protocol with the \( Q \)-adjustment algorithms in the following four kinds of air interface.

(i) The perfect air interface, in which no error occurs in signal transmission, and \( p = q = 0 \).

(ii) The air interface with capture effect, where a tag may be identified even if collision occurs in a slot; \( p = 0 \) and \( q \) varies in \([0, 1)\).

(iii) The noise interface, where a successful slot may be regarded as a collision slot; \( q = 0 \) and \( p \) varies in \([0, 1)\).

(iv) The general error prone air interface, where both \( p \) and \( q \) vary in \([0, 1)\).

In the numeric simulations, as stated in the EPC Gen-2 protocol and the \( Q \)-adjustment algorithm, the initial values of \( Q \) and \( Q_fp \) are set to 4 and 4.0, respectively. Since that the value of \( C \) in the original \( Q \)-adjustment algorithm is only specified in the range of \((0.1, 0.5)\), in this paper, a middle value of \( C \) is chosen, and we set \( C = 0.3 \).

4.1. The Perfect Air Interface. In the perfect air interface, there is no signal transmission error. If in a data slot, only one tag responds; the tag is identified by the reader. If two or more tags respond, collision occurs in the slot, and the reader can only detect a collision signal but no useful information.

In such case, the system efficiency of the EPC Gen-2 protocol can be calculated as

\[
SE = \frac{\sum N_s(S_k, Q_k)}{\sum S_k}. \tag{7}
\]

The system efficiency of the EPC Gen-2 protocol using different \( Q \)-adjustment algorithms is shown in Figure 2.

Especially, when the tag population is less than 300, the system efficiency of the protocol is shown in Figure 3.

Figures 2 and 3 reveal that for the identification of only a few tags, the EPC Gen-2 protocol performs unstably, as its system efficiency varies a little drastically. As the tag population increases, it performs stably with system efficiency varying around 0.33, which means that, in the perfect air interface, about three slots are needed to identify a tag.

4.2. The Air Interface with Capture Effect. In some radio frequency communication channel, a tag can be captured by the reader even if collision occurs in the data slot, and this is called the capture effect.

Capture effect is caused by the fact that responding tags may be scattered in different distances from the reader; the signals from a tag may overwhelm that from other responding tags that can be captured by the reader. Capture effect leads to the fact that there is a probability that a tag can be identified by the reader even if collision occurs in the air interface.

In the air interface with capture effect, the system efficiency of the EPC Gen-2 protocol can be calculated as

\[
SE = \frac{\sum (N_s(S_k, Q_k) + qN_c(S_k, Q_k))}{\sum S_k}, \tag{8}
\]

where \( 0 \leq q < 1 \) specifies the probability that one tag is identified in a collision slot due to the capture effect.

When the tag population is less than 300, the system efficiencies of the EPC Gen-2 protocol with different capture effects, where \( q \) varies from 0 to 90%, are shown in Figure 4. When the tag population is more than 300 and less than 3000, the system efficiencies of the protocol are shown in Figure 5.

Figures 4 and 5 indicate that capture effect can improve the system efficiency of the EPC Gen-2 protocol effectively. Although occasionally, the system efficiency of the protocol in the air interface with small value of capture effect may exceed that with larger value of capture effect, but, in general, as the capture effect \( q \) increases, the system efficiency of the protocol also increases.
We can also see that when capture effect $q$ increases 10%, the system efficiency of the EPC Gen-2 protocol increases about 5%. For example, for the identification of 100 and 1000 tags, the system efficiencies of the protocol with different capture effect $q$ are depicted in Figure 6.

From Figure 6, it can be observed that for the air interface with capture effect, as more tags are within the vicinity of the reader, the system efficiency of the EPC Gen-2 protocol will also increase.

For the air interface with capture effect $q = 1$, which means that in tag responding slot, one tag can always be identified; we can always set the value of $Q$ adopted in the EPC Gen-2 protocol to 0. In such case, the system efficiency of the protocol will be 1.

4.3. The Noise Air Interface. In the noise air interface, a data slot where there is only one tag responding may be regarded as a collision slot, since that the waveforms from the tag may be affected by the noisy signals from the environment and the reader cannot decode the signal correctly.

For the noisy air interface, the system efficiency of the protocol can be calculated as

$$SE = \frac{\sum ((1 - p) N_s (S_k, Q_k))}{\sum S_k},$$

where $p > 0$ specifies the probability that the reader views a single reply slot as a collision slot.

In the simulations, set the value of $p$ in the range of $[0.0, 0.8]$. The system efficiencies of the EPC Gen-2 protocol with noise effect in the identification of 1 to 300 and 300 to 3000 tags are shown in Figures 7 and 8.

Figures 7 and 8 indicate that, in the noise air interface, when there are only a few tags, the EPC Gen-2 protocol performs much drastically and unstably. But when there are a lot of tags, the protocol start to perform stably. As we can observe, as the noise effect increases, the system efficiency of the protocol decreases.

For the identification of 100 and 1000 tags, the effect of the noise on the system efficiency of the protocol is shown in Figure 9.

We can see that for a large number of tags, the system efficiency of the protocol degrades linearly as the value of noise effect increases.

4.4. The Effect of Capture and Noise in the Air Interface. In this subsection, we want to examine the effect of capture
and noise that occurred in the air interface on the system efficiency of the EPC Gen-2 protocol. That is, to determine
which effect influence more significantly on the performance of the protocol. So, in this subsection, we set $p$, $q$ in $[0, 0.8]$, $p = q$ and abandon the extreme cases.

The system efficiencies of the EPC Gen-2 protocol in such cases for the identification of 1 to 300 and 300 to 3000 tags are shown in Figures 10 and 11, respectively.

Especially, for the identification of 100 and 1000 tags using the EPC Gen-2 protocol with same noise and capture effects, the system efficiencies of the protocol are shown in Figure 12. Figure 10 indicates that the noise in the air interface leads to the unstable system efficiency of the protocol when there are only a few tags. But as tag population increases, the protocol starts to perform stably.

Figures 10, 11, and 12 also reveal that the noise plays a more significant role on the performance of the EPC Gen-2 protocol than the capture effect; it may overwhelm the capture effect as its value increases.

4.5 Discussion. From the above subsections, we can conclude that the performance of the EPC Gen-2 protocol is
seriously affected by the capture and noise effects. Although the capture effect can improve the system efficiency of the EPC Gen-2 protocol, but the noise effect can degrade the performance of the protocol significantly.

Besides, we can also conclude that in the air interface with serious noise effect, the performance of the protocol is unacceptable, no matter capture effect exists or not. The performance deterioration may be caused by the following two reasons.

Firstly, due to noise, the reader cannot distinguish the single reply slot with the collision slot and cannot read the responding tag. So, the responding tag will select another data slot in the next frame to respond and may cause more tag collisions.

Secondly, the Q-adjustment algorithm may also be a reason. Since the protocol may mistakenly take the successful slot as a collision slot, the value of $Q_{fp}$ will increase by $C$. In such case, with more probability, the protocol will ask the reader to issue the QueryAdjust command to update the value of $Q$ to $Q + 1$, and more data slots will be consumed in the following frame.

These suggest that for real UHF RFID system deployed in a complex environment, further researches should be taken to optimize the EPC Gen-2 protocol, for example, using biased Q-adjustment algorithm to update the value of $Q_{fp}$ with a pair of distinct values, $C_{idle}$ and $C_{resp}$, when an idle or a responding slot is encountered, such as the work presented in [22].

5. Conclusion and Future Researches

UHF RFID system plays an important role in the upcoming “Internet of Things,” but tag collision prevents the universal adoption of the system technically. Although the EPC Gen-2 protocol has been widely accepted to resolve the tag collision occurred in the UHF RFID system, but its performance is seldom evaluated in error prone air interface.

In this paper, a model is established to evaluate the system efficiency of the EPC Gen-2 protocol in error prone air interface, and numeric simulations are performed to evaluate the system efficiency of the protocol in air interface with different capture and noise effects. It is revealed that the noise in the air interface can deteriorate the performance of the protocol significantly.

A lot of research is needed to be taken in the future, for example, to examine the performance of the protocol in real error prone air interface, to optimize the performance of the protocol in air interface with noise and capture effects, and so forth.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

The research of this paper is sponsored jointly by the Program for Science & Technology Innovation Talents in Universities of Henan Province under Grant no. 2011HASTIT020, the Program for Innovative Research Team in Science and Technology in Universities of Henan Province under Grant no. 13IRTSTHN023, and the National Major Science and Technology Project under Grant no. 2014ZX03005001. The authors appreciate the anonymous referees for their valuable comments and suggestions to improve the presentation of this paper.

References

[1] D. Engels, J. Foley, J. Waldrop, S. Sarma, and D. Brock, “The networked physical world: an automated identification architecture,” in Proceeding of the 2nd IEEE Workshop on Internet Applications, pp. 76–77, 2001.
[2] E. Welbourne, L. Battle, G. Cole et al., “Building the internet of things using RFID: the RFID ecosystem experience,” *IEEE Internet Computing*, vol. 13, no. 3, pp. 48–55, 2009.

[3] V. Stanford, “Pervasive computing goes the last hundred feet with RFID systems,” *IEEE Pervasive Computing*, vol. 2, no. 2, pp. 9–14, 2003.

[4] G. Roussos and V. Kostakos, “rfid in pervasive computing: state-of-the-art and outlook,” *Pervasive and Mobile Computing*, vol. 5, no. 1, pp. 110–131, 2009.

[5] K. Finkenzeller, *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards, Radio Frequency Identification and Near-Field Communication*, John Wiley & Sons, New York, NY, USA, 3rd edition, 2010.

[6] E. Ilie-Zudor, Z. Kemény, F. van Blommestein, L. Monostori, and A. van der Meulen, “A survey of applications and requirements of unique identification systems and RFID techniques,” *Computers in Industry*, vol. 62, no. 3, pp. 227–252, 2011.

[7] D. K. Klair, K.-W. Chin, and R. Raad, “A survey and tutorial of RFID anti-collision protocols,” *IEEE Communications Surveys and Tutorials*, vol. 12, no. 3, pp. 400–421, 2010.

[8] S. R. Jeffery, M. J. Franklin, and M. Garofalakis, “An adaptive RFID middleware for supporting metaphysical data independence,” *VLDB Journal*, vol. 17, no. 2, pp. 265–289, 2008.

[9] T. La Porta, G. Maselli, and C. Petrioli, “Anticollision protocols for single-reader rfid systems: temporal analysis and optimization,” *IEEE Transactions on Mobile Computing*, vol. 10, no. 2, pp. 267–279, 2010.

[10] L. Zhu and T.-S. P. Yum, “A critical survey and analysis of RFID anti-collision mechanisms,” *IEEE Communications Magazine*, vol. 49, no. 5, pp. 214–221, 2011.

[11] EPCCglobal, “Epc radio-frequency identity protocols class-1 generation-2 uhf rfid protocol for communication at 860 mhz-960 mhz,” version 1. 2. 0. 2008.

[12] C. Wang, M. Daneshmand, K. Sohraby, and B. Li, “Performance analysis of RFID Generation-2 protocol,” *IEEE Transactions on Wireless Communications*, vol. 8, no. 5, pp. 2592–2601, 2009.

[13] C. Wang, B. Li, M. Daneshmand, K. Sohraby, and R. Jana, “On object identification reliability using RFID,” *Mobile Networks and Applications*, vol. 16, no. 1, pp. 71–80, 2011.

[14] Y. Maguire and R. Pappu, “An optimal Q-algorithm for the ISO 18000-6C RFID protocol,” *IEEE Transactions on Automation Science and Engineering*, vol. 6, no. 1, pp. 16–28, 2009.

[15] S. R. Aroor and D. D. Deavours, “Evaluation of the state of passive uhf rfid: an experimental approach,” *IEEE Systems Journal*, vol. 1, no. 2, pp. 168–176, 2007.

[16] M. Buettner and D. Wetherall, “An empirical study of UHF RFID performance,” in *Proceedings of the 14th Annual International Conference on Mobile Computing and Networking*, pp. 223–234, September 2008.

[17] L. Zhu and T.-S. P. Yum, “The optimal reading strategy for EPC Gen-2 RFID anti-collision systems,” *IEEE Transactions on Communications*, vol. 58, no. 9, pp. 2725–2733, 2010.

[18] L. Zhu and T.-S. P. Yum, “Optimal framed aloha based anticollision algorithms for RFID systems,” *IEEE Transactions on Communications*, vol. 58, no. 12, pp. 3583–3592, 2010.

[19] X.-Q. Yan, J. Bai, Y. Xu, and B. Li, “An optimized schema to improve the time efficiency of the EPG Gen-2 protocol,” in *Proceedings of the International Conference on and 4th International Conference on Cyber, Physical and Social Computing, Internet of Things (iThings/CPSCom)*, pp. 123–126, October 2011.