Conception and Performance Analysis of Efficient CDMA-Based Full-Duplex Anti-collision Scheme

Xiaohua Cao and Tiffany Li

Ultra-high-frequency radio-frequency identification (UHF RFID) is widely applied in different industries. The Frame Slotted ALOHA in EPC C1G2 suffers severe collisions that limit the efficiency of tag recognition. An efficient full-duplex anti-collision scheme is proposed to reduce the rate of collision by coordinating the transmitting process of CDMA UWB uplink and UHF downlink. The relevant mathematical models are built to analyze the performance of the proposed scheme. Through simulation, some important findings are gained. The maximum number of identified tags in one slot is g/e (g is the number of PN codes and e is Euler's constant) when the number of tags is equal to mg (m is the number of slots). Unlike the Frame Slotted ALOHA, even if the frame size is small and the number of tags is large, there aren't too many collisions if the number of PN codes is large enough. Our approach with 7-bit Gold codes, 15-bit Gold codes, or 31-bit Gold codes operates 1.4 times, 1.7 times, or 3 times faster than the CDMA Slotted ALOHA, respectively, and 14.5 times, 16.2 times, or 18.5 times faster than the EPC C1 G2 system, respectively. More than 2,000 tags can be processed within 300 ms in our approach.

Keywords: UHF RFID, CDMA, full-duplex, anti-collision, performance analysis, EPC C1 G2.

I. Introduction

Radio-frequency identification (RFID) technology has been widely applied in many industry areas. A huge number of RFID tags might appear in a reading zone simultaneously. When receiving demands from a reader, all the tags will send signals almost simultaneously. These signals will collide [1]. This is the reason why anti-collision procedures are in existence today. Such procedures are widely used and are designed to prevent tags from broadcasting their information simultaneously. Almost all existing passive RFID systems are based on half-duplex communication (which uses a narrowband radio frequency).

A reader sends an RF carrier signal to a number of tags, and these tags backscatter the data signal by changing the antenna load. In both of the aforementioned signal directions, a narrowband RF signal is used [2]. However, this simple implementation holds some drawbacks. It is sensitive to interference, multipath fading, multiuser interference, and collisions, as well as being susceptible to passive and active attacks.

Existing UHF RFID anti-collision solutions are based on time division multiple access (TDMA) [3]. Figure 1 shows a TDMA method; note that the tags in the reader's field transmit their data at different moments in time.

The Electronic Product Code Class-1 Generation-2 (EPC C1 G2) standard is widely used in UHF passive RFID systems. It utilizes Frame Slotted ALOHA [4], which is based on time slots that synchronize at the start of a transmission. There are two main reasons for the aforementioned standard's low

---

Manuscript received Mar. 27, 2014; revised May 21, 2015; accepted June 25, 2015.

This work was supported by Technology Support Project of Hubei Province (2014BAA033).

Xiaohua Cao (corresponding author, Tomm_cao@163.com) is with the Information Technology Center, Wuhan University of Technology, Hubei, China.

Tiffany Li (xic213@lehigh.edu) is with the Department of Electronic Engineering, Lehigh University, Bethlehem, PA, USA.

http://dx.doi.org/10.4218/etrij.15.0114.0375

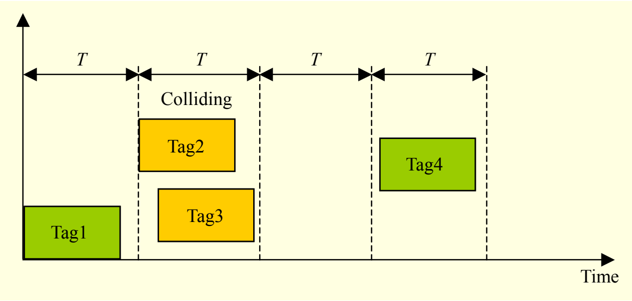

Fig. 1. TDMA anti-collision method.

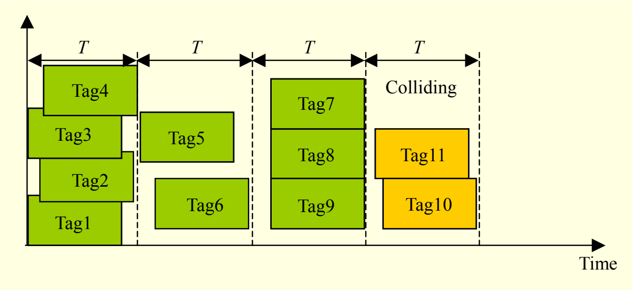

Fig. 2. CDMA anti-collision method.

throughput. Firstly, EPC C1 G2 utilizes backscatter modulation for uplink (tag-to-reader) communication, which limits the data rate to a few hundred kilobits per second (kb/s) and is vulnerable to dense multipath phenomenon and multiuser interference. Secondly, though EPC C1 G2 adopts the Q-algorithm (a dynamic Framed Slotted ALOHA algorithm [5]–[6]) to mitigate tag collisions, it still suffers from severe tag collisions and lacks multiple access capability. In future UHF RFID applications, a UHF RFID needs either a fast recognition capacity for massive RFID tags (more than 1,000 tags) or a shorter recognition time.

Besides a TDMA algorithm, another solution is to introduce code division multiple access (CDMA) to RFID communication systems [7]. A CDMA-based RFID system using semi-passive UHF transponders was proposed in [8], with the reader providing the recognition of multiple transponders simultaneously. This means that the transponders are transmitting data within the same time range and frequency band, as shown in Fig. 2. The results of previous work in the field [9]–[10] have shown that CDMA transmission can be very attractive for RFID systems, due to its good multiple-access capabilities. However, when CDMA technology is applied in UHF RFID, several difficulties arise, such as the fact that CDMA technology is energy hungry, tag costs, and data rates.

Recently, CDMA ultra-wideband (UWB) technology was considered as one promising wireless technique for future RFID systems [11]–[12]. UWB pulse-position modulation (PPM) uses short-duration (in the order of one nanosecond or less) pulses with a very low duty cycle for communications and has the possibility of achieving Mb/s high throughput. If CDMA UWB can be well used as a tag-to-reader link, then it will enable multiple tags to be detected simultaneously. However, only basic architectures for such related CDMA UWB RFID systems have been proposed in previous works [13]–[14].

To reduce a tag's energy consumption, the recognition time, which is closely related to the anti-collision approach, should be as short as possible. So, it is very important to develop an efficient anti-collision approach that is conducive to the likes of the aforementioned systems; such an approach has not been considered in any of the aforementioned works.

In general, almost all of the existing anti-collision approaches are based on semi-duplex communication modes. If CDMA UWB is to be used as a tag-to-reader link in UHF RFID systems, then there are some challenges that need to be overcome to improve the performances of CDMA-based anti-collision approaches. Firstly, RFID anti-collision communication modes have to be compliant with UHF/UWB dual-band system structures and remotely powered tags. Secondly, a reader must be able to accurately estimate the number of unidentified tags. Thirdly, a preferable pseudo-noise (PN) code along with its length must be selected.

II. Literature Review

Many anti-collision methods for UHF RFID systems have already been proposed. The Random ALOHA and unSlotted ALOHA [15] protocols have both been proven; the principle of ALOHA forms the basis of all modern anti-collision protocols. An extension of the ALOHA protocol, called Slotted ALOHA [16], introduced time slots in which a transmitter must send its data at the beginning of a slot. Within this extended protocol, collisions only occur within a full time slot. Most current RFID protocols are based on the principle of Slotted ALOHA and use the EPC standard UHF Class-1 Generation-2 air interface protocol. Improving the current standard anti-collision method by dynamically choosing an appropriate value of Q, for example, was described in [17]–[19]. These works show that the right choice of Q is of great importance for the overall system performance.

However, these Slotted ALOHA methods lack the ability for multiple access within a single slot. Therefore, CDMA anti-collision methods were presented for narrowband RFID systems and are commonly combined with Framed Slotted ALOHA schemes. In particular, Slotted ALOHA CDMA systems and their corresponding performances may be found in [20]–[21]. Other works describe certain CDMA systems that really outperform the TDMA-based systems. The transponders, each equipped with a unique quasi-orthogonal spreading code (for example, Gold codes) (Gold, 1967a) [22], may use the radio channel whenever the transponders are ready to transmit their data (asynchronous CDMA). Gold codes were proposed for RFID systems [23]–[24] because they have much larger code sets than other codes, which means that the number of collisions can be further reduced. On the other hand, longer Gold codes reduce the effective data rate. Thus, PN code lengths must be adapted to other parameters of CDMA-based anti-collision approaches; once again, this has not been researched in any of the aforementioned works.

UWB RFID systems have been proposed recently [25]–[26]. The potential advantages of UWB for RFID include high pulse rate in tag-to-reader communication; low power consumption at the transmitter side; and robustness to multipath and interference. However, a UWB receiver is both area and power hungry, which causes challenges for tags to be remotely powered. Many studies on the designs of UWB transceivers show that UWB technology is a good candidate to achieve low power and low complexity in implementations. In [27], several versions of the ALOHA algorithm are presented to increase the feasibility and efficiency of UWB transceivers. A semi-duplex communication procedure called acknowledgment is required to resolve collisions or failed transmissions. Most of the above methods are improved at either the protocol or algorithmic level of a communication link; however, they usually result in an increase in circuit complexity, chip area, implementation cost, and power consumption.

Dual-band systems have been introduced [28]. They use conventional UHF radio for the forward reader-to-tag link and impulse UWB radio for the backward tag-to-reader link. The reader transmits commands to tags via UHF radio link. Tags are remotely powered by the UHF signals [29]. This solution avoids using a UWB receiver on tags and meets the asymmetric traffic requirements in the forward link (with very few reader commands) and the backward link (with large numbers of tag responses). It mainly focuses on how to design hardware schemes yet hardly on anti-collision problems. However, if there is no efficient anti-collision approach with advisable parameters, even if a UHF RFID system adopts dual-band, then the recognition efficiency will not be obviously improved and tags will need more energy. In addition, the estimating methods of tags used in UHF RFID systems aren't suitable for UWB RFID systems. Reference [24] proposed that the reader makes all tags respond with the same pattern before requesting tag IDs. The reader uses the magnitude of the responses to estimate the number of tags and then adjust the next frame size. However, the effectiveness of this method is low in realistic scenarios because of differences in the backscatter power, channel noises, multipath interference, and others.

In summary, UWB CDMA is a better choice for UHF RFID to solve the tag-collision problem. This paper is to discuss a novel full-duplex anti-collision approach to coordinate the transmitting process of uplink and downlink, and efficiently identify massive tags by combining UHF RFID with CDMA.

III. Our Approach

1. Improvement of Dual-Band RFID

The EPC C1 G2 UHF RFID system is built on the basis of a backscattering communication scheme with semi-duplex mode. It is sensitive to multipath fading, multiuser interference, and collisions. So, a dual-band passive RFID architecture was suggested [30], as is shown in Fig. 3. In this scheme, the reader has a UHF transmitter, a UHF antenna, a CDMA PPM UWB receiver, a UWB antenna, and a micro-controller for logic function and anti-collision protocol. A tag consists of a UHF receiver, a UHF antenna, a CDMA PPM UWB transmitter, a UWB antenna, and a baseband logic module. Tags need neither the modules for backscattering modulation and FM0/Miller encoding nor a UWB receiver. This scheme adopts two asymmetric links including UHF downlink and UWB uplink. The reader transmits commands to tags via UHF downlink at a rate of 160 kbps. A tag is remotely powered by the UHF signals with a minimum input RF power as low as 14.1 μW, and its circuit has been implemented in a 0.13 μm 1.2 V CMOS process. The tag sends information encoded by PN code back to the reader via UWB uplink, which adopts a pulse rate of 10 Mp/s in 0.18 μm CMOS to lower the power consumption and reduce the receiver complexity.

This kind of architecture for dual-band systems is promising [28], [30]. Definitely, tag collisions lead to a large increase in identification time. So, an anti-collision approach should correspond to these kinds of system structures. We take some steps to improve the efficiency of tag recognition with regards to a dual-band scheme. Firstly, the traditional semi-duplex anti-

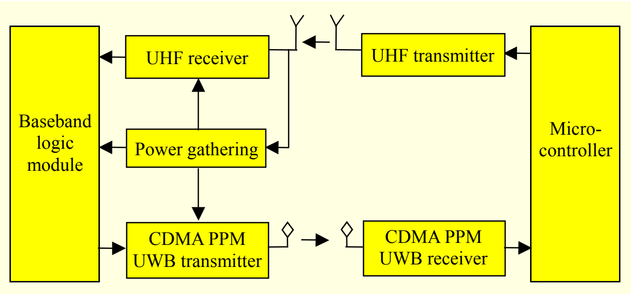

Fig. 3. Dual-band passive RFID scheme.

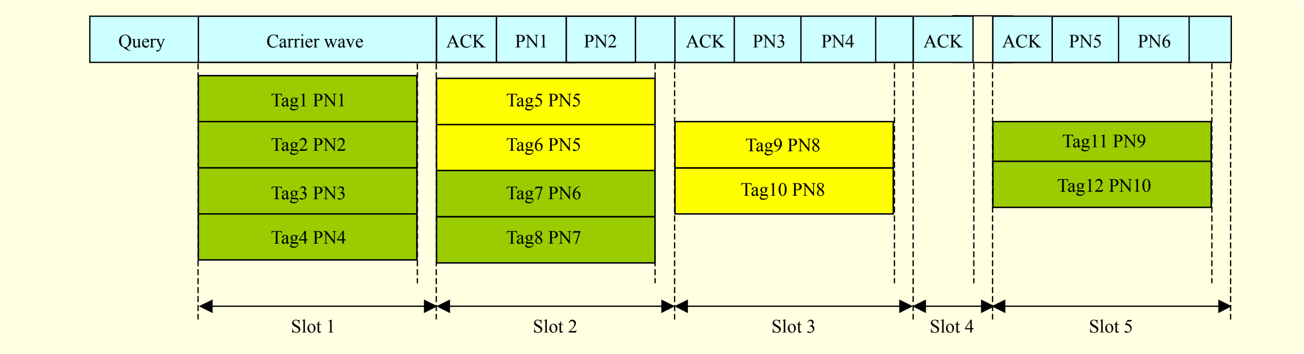

Fig. 4. Semi-duplex communication process in TDMA anti-collision approaches.

collision mode is replaced by a full-duplex one. In this new mode, a reader can coordinate the transmitting process of uplink and downlink and efficiently identify multiple tags. Secondly, a unique PN code is solidified in a single tag to reduce the computation of the anti-collision approach. The unique PN code is stored in the tag's memory, and the generating process of the PN code is removed from all CDMA anti-collision processes. Finally, an accurate estimating method is proposed to advance the performance of the anti-collision approach.

2. Full-Duplex Anti-collision Process

Conventional TDMA anti-collision approaches are based on the semi-duplex mode featured in the EPC C1 G2 standard. A time slot separately includes a tag's response time and a reader's acknowledgement time, as shown in Fig. 4.

However, because our proposed RFID system has significant asymmetry between the downlink and the uplink (UWB data rate is much higher than the narrowband radio data rate), if a conventional TDMA anti-collision approach is used, then the high data ratio and multiple access ability of the UWB channel will be wasted. The acknowledgement from the reader to tags becomes a bottleneck that decreases the network throughput. To improve network throughput, we propose a more efficient full-duplex anti-collision communication scheme to overcome the bottleneck and reduce the recognition time. It transmits uplink and downlink data simultaneously and coordinates commands and responding data with *rhythm*. In addition, it adopts CDMA technology with appropriate parameters in the UWB uplink to enhance multiple access ability. The choice of an appropriate set of PN codes is a key issue when designing CDMA systems.

To describe the full-duplex anti-collision approach, we firstly define a status flag for each tag, ACK, which indicates whether a tag has been identified. Because CDMA technology is used in our approach, the responding processes will spend the same duration even if more than one tag transmits data simultaneously. The length of a slot is determined by which is larger – the duration of ACK or the duration of a tag uploading data. The duration of a tag response is fixed within a frame because all tags have the same length of ID and data. The tags use the same data rate to send information. Generally, the duration for a tag to upload data is set as a *slot* because it is longer than reader acknowledgement time. The proposed full-duplex anti-collision process is given in Fig. 5.

1) *Query* — a command from the reader through UHF downlink. A *Query* command uses a Q value to set the number of slots (frame size).
2) Tags receive a *Query* command and respond immediately. A tag chooses one of the $2Q$ slots to send its ID and data back to the reader with the CDMA UWB. A tag sends data in one slot and receives the ACK in one of the remaining slots.
3) The reader will send an ACK and the PN codes of identified tags to allow the simultaneous acknowledgment of multiple tags if some tags were identified in the previous slot. If a tag transmitted its ID and data in the previous slot and detects its PN code from the ACK command in the current slot, then it means that this tag has been successfully identified and acknowledged.
4) An identified tag will keep silent in the following frames of this inventory round, whereas an unidentified tag will choose a new slot for response in the next frame.
5) The reader estimates the number of unidentified tags at the end of a frame and adjusts the Q value for the next frame.

In this process, the PN codes of identified tags are stored to one buffer of reader memory in the receiving sequence, as show in Fig. 5. These PN codes will be taken out from the buffer in a first-in first-out sequence.

Figure 5 shows an example of these statuses (assuming h = 2). In Slot 1, Tag1, Tag2, Tag3, and Tag4 transmit their IDs and data to the reader with four different PN codes, PN1, PN2, PN3, and PN4, respectively. The reader successfully receives the information from the tags and stores the PN codes to the buffer. In Slot 2, the reader takes out PN1 and PN2 from the buffer and sends an ACK command, PN1 and PN2 to acknowledge

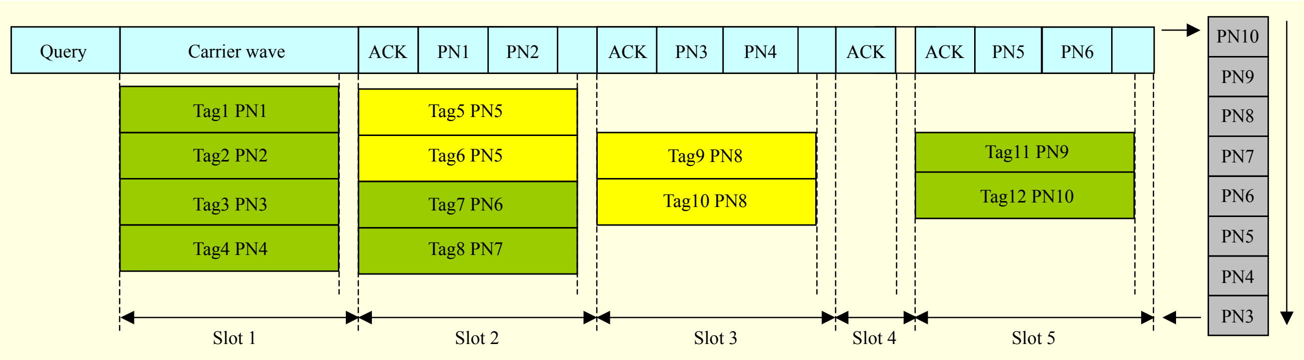

Fig. 5. Full-duplex anti-collision process.

the tags. Tag1 and Tag2 detect their desired PN codes, respectively, and keep silent in the rest of this inventory round. Meanwhile, Tag5, Tag6, Tag7, and Tag8 transmit their IDs and data in Slot 2. Among them, Tag5 and Tag6 choose the same PN code, PN5, and Tag7 and Tag8 have different PN codes, PN6 and PN7. The reader encounters a collision but receives PN6 and PN7 correctly and stores them to the buffer. In Slot 3, the reader takes out PN3 and PN4 from the buffer and sends an ACK, PN3, and PN4 to acknowledge the tags. Tag3 and Tag4 detect their desired PN codes, respectively, and keep silent in the rest of this inventory round. Meanwhile, Tag9 and Tag10 transmit their IDs and data in Slot 3. They choose the same PN code, PN8. The reader encounters a collision and does not receive any tag. Slot 4 is an empty slot without any tag responses and sends only ACK to tags for synchronizing the next slot. Because the global clock is scalable and controlled by the reader, it provides a possibility to shorten idle slots. By detecting the incoming signals at the beginning of each slot, the reader can determine if there is any transmission in this time slot. Therefore, there is a limitation, as follows:

$$T_{\mathrm{ACK}} + hT_{\mathrm{PN}} \le T_{\mathrm{Tag}}, \tag{1}$$

where T_{ACK} is the duration of ACK, T_{PN} is the duration of PN, and T_{Tag} is the duration of tag response. So, the number of fetched PN codes, h, is determined by

$$h \le \frac{T_{\mathrm{Tag}} - T_{\mathrm{ACK}}}{T_{\mathrm{PN}}}. \tag{2}$$

In the full-duplex anti-collision process, one of the following four kinds of statuses could appear in any given slot:

1) All the responding tags have different PN codes or there is only one tag to respond and there is no collision to happen. All the tags can be identified correctly.
2) All the responding tags have the same PN codes and there are collisions to happen. The tags cannot be identified correctly.
3) Some tags have the same PN codes in the responding tags and the others have different PN codes, so collisions will happen but some tags with different PN codes can be identified correctly.
4) There is no tag to respond. It is an idle slot.

3. Estimating Number of Tags

An estimating algorithm that is able to estimate the number of tags and is suitable to our anti-collision approach is necessary to achieve the maximum throughput. In [31], a rough estimator of tags was given, but it performed well for only a small number of tags. The estimator cannot be applied directly to a CDMA-RFID system due to its large error. So, an alternative approach is presented. The receiver contains g pipes of matched filters as shown in [32]. Each pipe corresponds to a single PN code. An *empty* pipe does not detect a tag responding with its relevant PN code in a slot; a *successful* pipe detects a tag with a unique PN code that is different from the codes used by other tags in the same slot; and a *collision* pipe detects more than one tag responding with its relevant PN code simultaneously.

At first, we estimate the expected number of tags per collision pipe. Let m be the number of slots in one frame, n the number of tags, and g the number of PN codes. The probability that a tag chooses a certain slot and a unique PN code is given by

$$P_1 = \frac{1}{mg}. \tag{3}$$

Therefore, the number of tags that choose the same slot and the same PN code is binomially distributed as

$$P_s(i) = \binom{n}{i} \times \left(\frac{1}{mg}\right)^{i} \times \left(1 - \frac{1}{mg}\right)^{n-i}. \tag{4}$$

Let $\partial P_s / \partial m = 0$; the maximum identifying probability can be achieved when $n = mg$. If i is larger than 1 ($2 \le i \le n$), then there are collisions and the i tags cannot be recognized correctly.

If one pipe in a slot is observed as a collision pipe, then the expected value of the number of conflicting tags in one pipe is

$$\mathrm{E}(N_{\text{ctags}}) = \sum_{i=2}^{n} i \times P_{\mathrm{C}}(i) = \frac{n}{mg}\left[1-\left(1-\frac{1}{mg}\right)^{n-1}\right]. \tag{5}$$

The expected value of conflicting probability in a collision pipe is

$$\mathrm{E}(P_{\mathrm{C}}) = \sum_{i=2}^{n} P_{\mathrm{C}}(i) = 1-\left(1-\frac{1}{mg}\right)^{n} - \frac{n}{mg}\left(1-\frac{1}{mg}\right)^{n-1}. \tag{6}$$

Then, the expected value of the number of tags in the collision pipe, ω, is given by

$$\omega = \frac{\mathrm{E}(N_{\text{ctags}})}{\mathrm{E}(P_{\mathrm{C}})}. \tag{7}$$

When the maximum recognition capacity is achieved (that is, $n = mg$), ω can be represented as follows:

$$\omega = \frac{1-\left(1-\frac{1}{n}\right)^{n-1}}{1-\left(1-\frac{1}{n}\right)^{n}-\left(1-\frac{1}{n}\right)^{n-1}}. \tag{8}$$

In practice, a reader can detect collision pipes. Let p be the number of collision pipes in one frame, then the number of unidentified tags among the current frame, N_{e}, can be estimated by

$$N_{\mathrm{e}} = \omega p = \frac{p\left[1-\left(1-\frac{1}{n}\right)^{n-1}\right]}{1-\left(1-\frac{1}{n}\right)^{n}-\left(1-\frac{1}{n}\right)^{n-1}}. \tag{9}$$

In our anti-collision process, the value of n is unknown before the first frame. Assuming that the number of initial tags is large, it may be supposed to be infinite; therefore, the estimated value of the number of unidentified tags after the first frame can be can calculated by

$$\lim_{n\to\infty} N_{\mathrm{e}} = \operatorname{round}\left[\frac{(1-e^{-1})}{1-2e^{-1}}p\right] = \operatorname{round}(2.4p). \tag{10}$$

The values calculated from (10) are compared with the statistical results of the number of conflicting tags in simulation, as shown in Fig. 6. We set the length of a PN code as 15. The statistical values of the number of tags were obtained by taking the mean of 50 statistical values, which were obtained under the same conditions. The results of our two simulations show that the figures obtained by our estimating approach are very close to the simulation statistics when the number of tags is smaller than 2,000 and m is 128 or 256; however, there are obvious errors when the number of tags is larger than 1,200 and m is 64. So, a longer PN code or a greater number of slots can contribute to the accuracy of our estimating method when the number of tags is large (more than 1,000). According to the estimated number of tags, we can adjust the Q value in the next frame. The Q value is set as

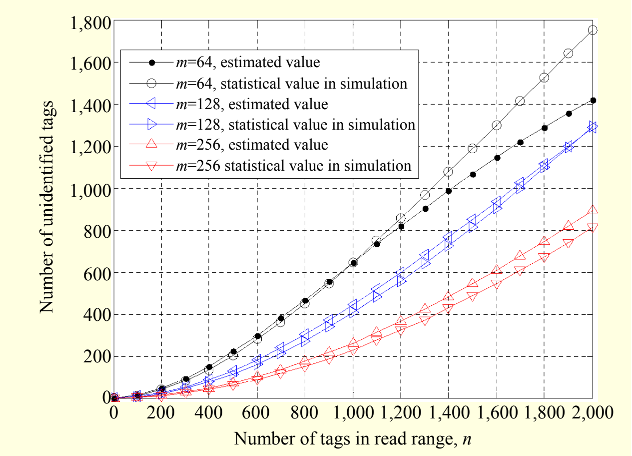

Fig. 6. Comparison of our estimated values with statistical values from simulation.

$$Q = \log_2 \frac{N_{\mathrm{e}}}{g}. \tag{11}$$

IV. Performance Analysis

1. PN Code Analysis

Gold codes appear to be one of the better codes to be used with RFID systems. Assuming that there are g Gold codes with l-level linear feedback shift registers, then these codes can produce the maximum number of different codes as $g = 2^l$. Suppose a tag uses one of the Gold codes in a slot to send its own ID number. If there are other tags using the same spreading code to send their IDs in this slot, then conflicts will occur. The number of tags, i, in a slot is binomially distributed as

$$P(i) = \binom{n}{i} \times \left(\frac{1}{m}\right)^{i} \times \left(1-\frac{1}{m}\right)^{n-i}. \tag{12}$$

When i tags are in a slot, the probability of a tag having a Gold code that is different from those of the remaining $(i-1)$ tags can be computed by

$$P_{\mathrm{d}} = \left(1-\frac{1}{g}\right)^{i-1}. \tag{13}$$

Let k be the number of identified tags from among i tags in a slot. Then, the number of identified tags in this slot can be calculated as follows:

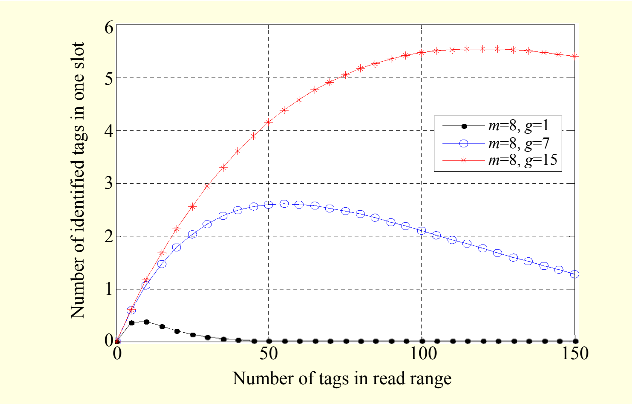

Fig. 7. Number of identified tags in single slot.

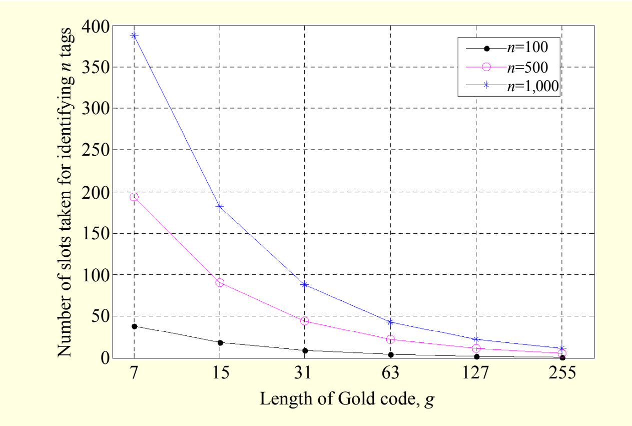

Fig. 8. Number of slots needed for recognizing different numbers of tags.

$$k = i \times P_{\mathrm{d}} = i \times \left(1-\frac{1}{g}\right)^{i-1}. \tag{14}$$

When i varies from 1 to n, the expected value of identified tags in a slot is given by

$$\mathrm{E}(k) = \sum_{i=1}^{n} k \times p(i) = \frac{n}{m}\left(1-\frac{1}{mg}\right)^{n-1}. \tag{15}$$

Let $\partial \mathrm{E}(k)/\partial g = 0$. Then, the maximum number of identified tags can be achieved. We can obtain the condition required such that the number of identified tags reaches a maximum. It is as follows:

$$g = \frac{n}{m}. \tag{16}$$

After substituting (16) into (14), we can obtain the expected value of the maximum number of identified tags in a single slot as follows:

$$K_{\max} = g\left(1-\frac{1}{n}\right)^{n-1}. \tag{17}$$

When n is large and supposed to be infinite, the expected value of the maximum number of identified tags in a single slot will be

$$\lim_{n\to\infty} K_{\max} = \lim_{n\to\infty} g\left(\frac{n}{n-1}\right)\left(1-\frac{1}{n}\right)^{n} = ge^{-1}. \tag{18}$$

Figure 7 shows that the expected value of the number of identified tags in a single slot is related to the number of PN codes. When the number of slots is fixed, the longer the PN code is, and the more the number of identified tags there are in a single slot. The maximum number of identified tags in a single slot is g/e; this occurs when $n = mg$. We set the number of PN codes as 1, 7, 15, 31, 63, 127, and 255, and the number of tags as 100, 500, and 1,000. The analysis results are shown in Fig. 8. The longer a PN code is, the fewer the number of slots there are for recognizing the given tags.

2. Collision Analysis

In our approach, if two or more tags use the same PN code to send their respective ID in the same slot, then conflicts will occur. The number of conflicting tags in a frame is given by

$$N_{\mathrm{C,F}} = mg\mathrm{E}(N_{\mathrm{ctags}}) = n - n\left(1-\frac{1}{mg}\right)^{n-1}. \tag{19}$$

When the maximum capacity is achieved (that is, $n = mg$), the maximum number of conflicting tags is

$$N_{\mathrm{C,max}} = n - n\left(1-\frac{1}{n}\right)^{n-1}. \tag{20}$$

To compare our anti-collision approach with Frame Slotted ALOHA, we set the number of tags as 2,000. Figure 9 shows comparison results on the number of conflicting tags under different combinations of m and g. If $g = 1$ (equivalent to the EPC C1 G2) when the frame size is small but the number of tags is large, then too many collisions will occur and the

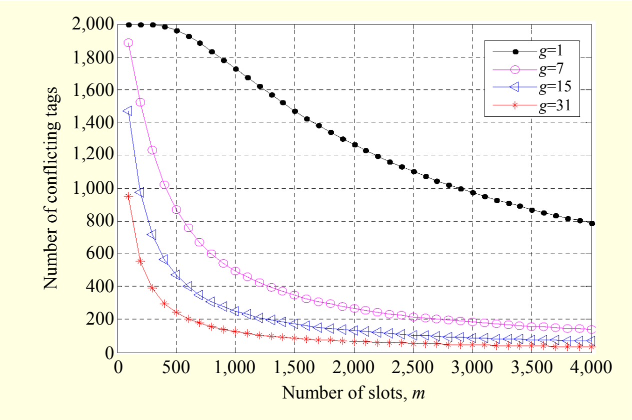

Fig. 9. Comparison results on number of conflicting tags between two anti-collision approaches.

http://dx.doi.org/10.4218/etrij.15.0114.0375

number of identified tags will degrade. When m is fixed and g is larger than 1, then the number of conflicting tags quickly declines with the increase of g. Unlike the Frame Slotted ALOHA, even if the frame size is small and the number of tags is large, there aren't too many collisions if g is enough large; and the larger the number of slots, the smaller the number of conflicting tags. In addition, when g is small but m is large enough, the number of conflicting tags is the same as the case when g is large but m is small. So, we can increase the number of slots to reduce the tag collisions due to the high data rate of the UWB channel. In this way, the limitation of PN resource can be solved well.

3. Recognition Efficiency

The recognition efficiency denotes the number of successfully-identified tags per unit of time; that is,

$$S = \frac{n_S}{T_F}, \tag{21}$$

where n_s is the number of successfully identified tags and T_F is the duration of a single frame. We set the number of slots as $m = n/g$. The number of identified tags in one frame is

$$n_S = n\left(1-\frac{1}{n}\right)^{n-1}. \tag{22}$$

The duration of a single frame T_F can be calculated by

$$T_F = T_Q + (m-m_0)T_{tag} + m_0 T_{ACK}, \tag{23}$$

where m_0 is the number of idle slots. If m is large, then we can ignore the T_Q term and simplify T_F as

$$T_F = (m-m_0)T_{tag} + m_0 T_{ACK}. \tag{24}$$

The number of idle slots in a frame is expected by

$$m_0 = mP_0 = m\left(1-\frac{1}{m}\right)^n. \tag{25}$$

In our anti-collision approach, $m = n/g$. So, T_F is

$$T_F = \frac{n}{g}\left[1-\left(1-\frac{g}{n}\right)^n\right]T_{tag} + \frac{n}{g}\left(1-\frac{g}{n}\right)^n T_{ACK}. \tag{26}$$

To simplify (26), we set the coefficient of duration, α, as T_{tag}/T_{ACK}. Then, T_F can be computed by

$$T_F = \left[1-\left(1-\frac{1}{\alpha}\right)\left(1-\frac{g}{n}\right)^n\right]\frac{n}{g}T_{tag}. \tag{27}$$

If the CDMA Slotted ALOHA in [32] is adopted, then the duration of one frame should be calculated by

$$T'_F = \frac{n}{g}(T_{tag}+T_{ACK}) + n_S T_{PN}. \tag{28}$$

We assume the length of a PN code to be β times that of ACK; that is, $T_{PN} = \beta T_{ACK}$. The duration of one frame can then be calculated by

$$T'_F = 1+\frac{1}{\alpha}+\frac{\beta g}{\alpha}\left(1-\frac{1}{n}\right)^n \frac{n}{g}T_{tag}. \tag{29}$$

If the Frame Slotted ALOHA in the EPC C1 G2 standard is adopted, then the transmitting speed of downlink is the same as in our approach; however, the uplink speeds are different. We assume the uplink speed of our approach to be z times that of EPC C1 G2. The duration of one frame should be calculated by

$$T''_F = m(zT_{tag}+T_{ACK}) + n_S T_{ID}, \tag{30}$$

where T_{ID} is the duration that the reader downloads ID information. In the Frame Slotted ALOHA, $n = m$. We assume the length of an ID code to be γ times that of ACK; that is, $T_{ID} = \gamma T_{ACK}$. The duration of one frame, T''_F, can then be calculated by

$$T''_F = z+\frac{1}{\alpha}+\frac{\beta}{\alpha}\left(1-\frac{1}{n}\right)^n nT_{tag}. \tag{31}$$

From (21), (27), (29), and (31), we can derive the recognition efficiencies of our approach and the two previous approaches.

$$S = \left[1-\left(1-\frac{1}{\alpha}\right)\left(1-\frac{g}{n}\right)^n\right]^{-1}\left(1-\frac{1}{n}\right)\frac{g}{T_{tag}}, \tag{32}$$

$$S' = \left[1+\frac{1}{\alpha}+\frac{\beta g}{\alpha}\left(1-\frac{1}{n}\right)^n\right]^{-1}\left(1-\frac{1}{n}\right)^{n-1}\frac{g}{T_{tag}}, \tag{33}$$

$$S'' = \left[z+\frac{1}{\alpha}+\frac{\gamma}{\alpha}\left(1-\frac{1}{n}\right)^n\right]^{-1}\left(1-\frac{1}{n}\right)^{n-1}\frac{1}{T_{tag}}. \tag{34}$$

According to the systemic hardware and data size in practice, we let $\gamma = 6$ and $\alpha = 10$. If we use 7-bit or 15-bit or 31-bit Gold codes, then β would be 1, 1.3, and 1.7, respectively; correspondingly, z would be 1.95, 0.98, and 0.49, respectively. Figures 10 and 11 show the ratios of maximum recognition efficiencies of our approach to that of the other two approaches. From Fig. 10, when the number of tags exceeds a certain value, our approach with 7-bit Gold codes or 15-bit Gold codes or 31-bit Gold codes operates 1.4 times, 1.7 times, and 3 times faster, respectively, than the CDMA Slotted ALOHA; correspondingly, it operates 14.5 times, 16.2 times, and 18.5 times faster than the EPC C1 G2 system, respectively.

We assume tag data is 512 bits, the uplink speed is 10 Mp/s, and the downlink speed is 160 kbps. If g is 7, then T_{tag} is 0.4 ms, T_{ACK} is 0.1 ms, and α is 4. If g is 31, then T_{tag} is 1.64 ms, T_{ACK} is 0.1 ms, and α is 16. It can be seen from Figs. 12 and 13 that more than 2,000 tags can be processed within 300 ms in

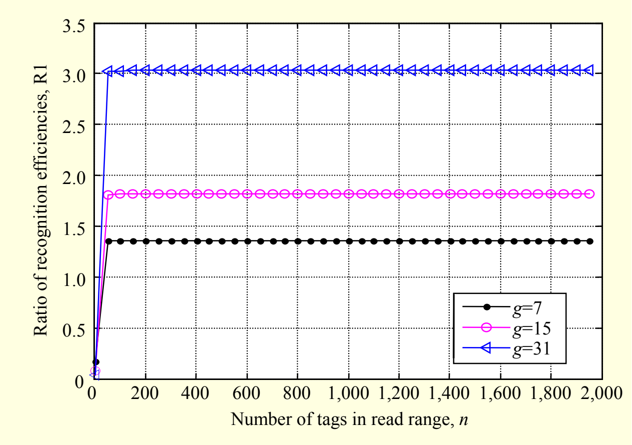

Fig. 10. Comparison of maximum recognition efficiency with Frame Slotted ALOHA.

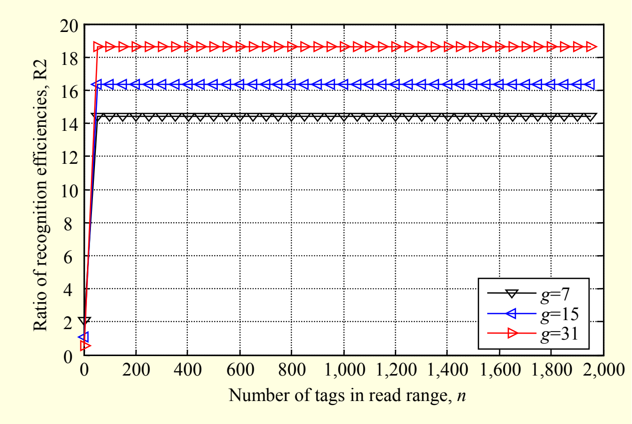

Fig. 11. Comparison of maximum recognition efficiency with CDMA Slotted ALOHA.

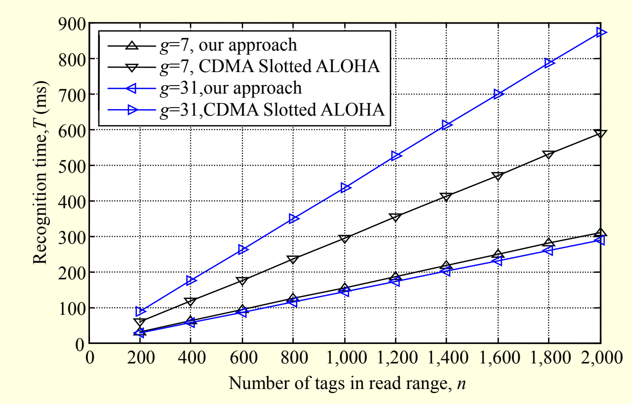

Fig. 12. Comparison of recognition time with CDMA Slotted ALOHA.

our approach when g is 7; comparatively, CDMA Slotted ALOHA requires 600 ms to achieve the same result. If g takes the same value among the different approaches, then it is evident that our approach will need much less recognition time than that of the CDMA Slotted ALOHA approach. In addition, the Frame Slotted ALOHA approach requires 1,950 ms to process 2,000 tags and can recognize about 1,000 tags in one second, which is very much lower than our approach and that of CDMA Slotted ALOHA.

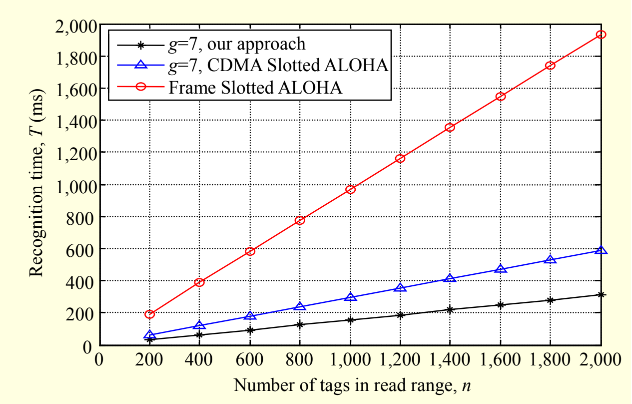

Fig. 13. Comparison of recognition time between three approaches.

4. Complexity Discussion

In our scheme, PN codes are stored in the tag memory (for example, 7-bit Gold codes only occupy 63-bit tag memory) and the spreading process can be achieved by XOR operation on the binary representations of bits and chips. The UWB transmitter in a tag does not need the modules for backscattering modulation and FM0/Miller encoding, which are necessary to UHF RFID. Therefore, adding the CDMA UWB uplink will not greatly increase a tag's complexity. Since the proposed anti-collision approach is implemented by the reader, the complexity is on the reader side. The reader needs to have high computing capability and high processing speed to obtain the signal amplitudes and calculate the inverse of the correlation matrix. All the detection algorithms are accomplished by a digital signal processing block, which can be implemented in an FPGA device. Moreover, thanks to parallel computing capability, the receiver implemented in FPGA will work much faster than any software implementation.

Taken together, the proposed anti-collision scheme has very little impact on the complexity of an overall system, since a typical RFID system uses a great number of tags and only a few reader devices.

V. Conclusion

A dual-band RFID scheme was presented and a feasible structure considered. Based on this structure, this paper proposed an efficient CDMA-based full-duplex anti-collision approach. The main contributions of this paper can be summarized as follows:

1) A full-duplex anti-collision approach has been proposed.
2) Mathematic models for the performance analysis of the proposed approach have been formed.
3) Through simulations, the following important conclusions have been drawn:
   - The number of identified tags in a single slot is related to the number of PN codes. The maximum number of identified tags in a slot is g/e and occurs when $n = mg$.
   - Increasing the number of slots can reduce the tag collisions due to the high data rate of the UWB channel in our approach.
   - More than 2,000 tags can be processed within 300 ms in our approach but 600 ms in CDMA Slotted ALOHA when the number of PN codes is 7.

In the future, we plan to evaluate the power consumption of a CDMA-based RFID system with full-duplex anti-collision approach and compare it against both the EPC C1 G2 system and the CDMA UWB RFID system.

References

[1] S. Sarma, D. Brock, and D. Engels, "Radio Frequency Identification and Electronic Product Code," *IEEE Micro.*, vol. 21, no. 6, Dec. 2001, pp. 50–54.

[2] P.V. Nikitin and K.V.S. Rao, "Theory and Measurement of Backscattering from RFID Tags," *IEEE Antennas Propag. Mag.*, vol. 48, no. 6, Dec. 2006. pp. 212–218.

[3] K.C. Shin, S.B. Park, and G.S. Jo, "Enhanced TDMA-Based Anti-collision Algorithm with a Dynamic Frame Size Adjustment Strategy for Mobile RFID Readers," *Sensors*, vol. 9, no. 2, Sept. 2009, pp. 845–858.

[4] EPCglobal, Class 1 Generation 2 UHF Air interface Protocol Standard V1.0.9, Jan. 2005.

[5] B. Zhen, M. Kobayashi, and M. Shimizu, "Framed ALOHA for Multiple RFID Objects Identification," *IEICE Trans. Commun.*, vol. E88-B, no. 3, Mar. 2005, pp. 991–999.

[6] O. Bang, S. Kim, and H. Lee, "Identification of RFID Tags in Dynamic Framed Slotted ALOHA," *Int. Conf. Adv. Commun. Technol.*, Pyeongchang, Rep. of Korea, Feb. 15–18, 2009, pp. 354–357.

[7] G. Mazurek, "RFID System with DS-CDMA Transmission," *Proc. KKRRiT-2006 Conf.*, Poznan, Poland, June 7–9, 2006, pp. 313–316.

[8] A. Loeffler, F. Schuh, and H. Gerhaeuser, "Realization of a CDMA-Based RFID System Using a Semi-active UHF Transponder," *Int. Conf. Wireless Mobile Commun.*, Valencia, Spain, Sept. 20–25, 2010, pp. 5–10.

[9] E.H. Dinan and B. Jabbari, "Spreading Codes for Direct Sequence CDMA and Wideband CDMA Cellular Networks," *IEEE Commun. Mag.*, vol. 36, no. 9, Sept. 1998, pp. 48–54.

[10] T. Nakanishi and T. Ikegami, "Throughput Performance of CDMA-ALOHA in S-Band Land Mobile Satellite and Stratospheric Platform Channels," *IEEE Int. Symp. Pers., Indoor Mobile Radio Commun.*, London, UK, Sept. 18–21, 2000, pp. 1085–1089.

[11] I. Oppermann et al., "UWB Wireless Sensor Networks: UWEN – A Practical Example," *IEEE Commun. Mag.*, vol. 42, no. 12, Dec. 2004, pp. 27–32.

[12] N. Helleputte and G. Gielen, "A 70 pJ-Pulse Analog Front-End in 130 nm CMOS for UWB Impulse Radio Receivers," *IEEE J. Solid-State Circuits*, vol. 44, no. 7, July 2009, pp. 1862–1871.

[13] Z. Zou et al., "An Efficient Passive RFID System for Ubiquitous Identification and Sensing Using Impulse UWB Radio," *Elektrotechnik Inf. Technik J.*, vol. 124, no. 11, 2007, pp. 397–403.

[14] Z. Zou et al., "A Low-Power and Flexible Energy Detection IR-UWB Receiver for RFID and Wireless Sensor Networks," *IEEE Trans. Circuits Syst.*, vol. 58, no. 7, July 2011, pp. 1470–1482.

[15] K. Mariam et al., "Analytical Study of the Outage Probability of ALOHA and CSMA in Bounded Ad Hoc Networks," *European Wireless Conf.*, Lucca, Italy, Apr. 12–15, 2010, pp. 544–550.

[16] L.G. Roberts, "ALOHA Packet System with and without Slots and Capture," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 5, no. 2, Apr. 1975, pp. 28–42.

[17] Y. Maguire and R. Pappu, "An Optimal Q-Algorithm for the ISO 18000–6C RFID Protocol," *IEEE Trans. Autom. Sci. Eng.*, vol. 6, no. 1, Jan. 2009, pp. 16–24.

[18] P. Pupunwiwat and B. Stantic, "A RFID Explicit Tag Estimation Scheme for Dynamic Framed-Slot ALOHA Anti-collision," *Int. Conf. Wireless Commun. Netw. Mobile Comput.*, Chengdu, China, Sept. 23–25, 2010, pp. 1–4.

[19] L.-C. Wang and H.-C. Liu, "A Novel Anti-collision Algorithm for EPC Gen2 RFID Systems," *Int. Symp. Wireless Commun. Syst.*, Valencia, Spain, Sept. 6–8, 2006, pp. 761–765.

[20] S. Gopalan, G.N. Karystinos, and D. Pados, "Capacity, Throughput, and Delay of Slotted ALOHA DS-CDMA Links with Adaptive Space-Time Auxiliary-Vector Receivers," *IEEE Trans. Wireless Commun.*, vol. 4, no. 1, Jan. 2005, pp. 79–92.

[21] A. Sakata et al., "Throughput Comparison of CSMA and CDMA Slotted ALOHA in Inter-vehicle Communication," *Int. Conf. ITS Telecommun.*, Sophia Antipolis, France, June 6–8, 2007, pp. 1–6.

[22] R. Gold, "Optimal Binary Sequences for Spread Spectrum Multiplexing (Corresp.)," *IEEE Trans. Inf. Theory*, vol. 13, no. 4, Oct. 1967, pp. 619–621.

[23] G. Mazurek, "Active RFID System with Spread-Spectrum Transmission," *IEEE Trans. Autom. Sci. Eng.*, vol. 6, no. 1, Jan. 2009, pp. 25–32.

[24] C. Mutti and C. Floerkemeier, "CDMA-Based RFID Systems in Dense Scenarios: Concepts and Challenges," *IEEE Int. Conf.*

http://dx.doi.org/10.4218/etrij.15.0114.0375

RFID, Las Vegas, NV, USA, Apr. 16–17, 2008, pp. 215–222.

[25] Y.F. Weng et al., "Design of Chipless UWB RFID System Using a CPW Multi-resonator," *IEEE Antennas Propag. Mag.*, vol. 55, no. 1, Feb. 2013, pp. 13–31.

[26] R. Angel, L. Antonio, and G. David, "Semi-passive Time-Domain UWB RFID System," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 4, Apr. 2013, pp. 1700–1708.

[27] S.S. Choi and S. Kim, "A Dynamic Framed Slotted ALOHA Algorithm Using Collision Factor for RFID Identification," *IEICE Trans. Commun.*, vol. E92-B, no. 3, Mar. 2009, pp. 1023–1026.

[28] M. Grilo et al., "Novel Dual-Band RFID Antenna Configuration with Independent Tuning Adjustment," *Microw. Opt. Technol. Lett.*, vol. 54, no. 9, Sept. 2012, pp. 2214–2217.

[29] J.-P. Curty et al., "Remotely Powered Addressable UHF RFID Integrated System," *IEEE J. Solid-State Circuits*, vol. 40, no. 11, Nov. 2005, pp. 2193–2202.

[30] M.B. Nejad et al., "A Novel Passive Tag with Asymmetric Wireless Link for RFID and WSN Applications," *IEEE Int. Symp. Circuits Syst.*, New Orleans, LA, USA, May 27–30, 2007, pp. 1593–1596.

[31] H. Vogt, "Efficient Object Identification with Passive RFID Tags," *Int. Conf. Pervasive Comput.*, vol. 2414, Zurich, Switzerland, Aug. 26–28, 2002, pp. 98–113.

[32] S. Yu and P. Yun, "The RFID Mechanism Design Based on CDMA and Hash Function," *Int. J. Radio Freq. Identification Technol. Appl.*, vol. 3, no. 4, Nov. 2011, pp. 285–293.

Xiaohua Cao received his PhD degree in information technology from Wuhan University of Technology, China, in 2008. He is currently a professor at Wuhan University of Technology. His research interests include information technology and logistics planning. He has held or been holding more than ten major research projects, such as National Natural Science Fund, Support Project of Hubei Science and Technology, Returned Overseas Students Research Fund of National Education Ministry, and Hubei Natural Science Fund.

Tiffany Li received her PhD degree in electrical engineering from the Electrical Engineering Department, Texas A&M University, College Station, USA, in 2012. She is an associate professor with tenure in electrical and computer engineering, Lehigh University, PA, USA. She is a director with the Information and Communication Research Laboratory, Lehigh University. Her research interests include wireless communications/networks and data storage. She was an IEEE Distinguished Lecturer between 2012 and 2013.