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Stochastical Model and Performance Analysis of Frequency Radio Identification

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1. Introduction

RFID (Radio Frequency Identification) can assign a unique digital identifier to each physical item, and provide an efficient, cheap and contactless method for gathering the information of the physical items to enable their automatic tracking and tracing(Finkenzeller 2003). RFID technology serves as the back stone of the "Internet of Things"(Engels 2001), and is reviewed as a main enabler of the upcoming "Pervasive Computing"(Stanford 2003). RFID systems have been widely adopted in quite a lot applications, ranged from "smart box" to world-wide logistics management systems.

A typical RFID system is consisted of some RFID tags, one or more RFID readers and the backend information system. Each RFID tag holds a unique identifier and is attached to a physical item. RFID reader is used to collect the identifiers stored in the RFID tags located in its vicinity and is often connected with the backend information system. During identification, The RFID reader asks the RFID tags to modulate their binary identifiers into signals and transmit these signals back to the reader through the air interface, which is a wireless communication channel for the RFID tag and reader to exchange information. Afterwards, The RFID reader sends the data gathered to the backend information system for further processing and dispatching to various applications.

One of the main issues that affect the universal deployment and application of the RFID system is the collisions occurred during RFID tag identification(Wu 2006). The simultaneous modulated signals broadcasted by the RFID reader and transmitted from the RFID tags will interfere in the air interface, in which case, what the receivers can get is only a collision signal but no useful information. Collisions occurred in the RFID system can be categorized as the reader-reader, reader-tag and tag-tag collisions(Shih 2006).

When two or more RFID readers try to broadcast messages through the air interface simultaneously, reader-reader collision occurs. Due to that they are often connected with the computer system and can be equipped with enough resource to monitor the air interface, RFID readers can detect the collision and coordinate with each other in advance. Reader-reader collision can be avoided and resolved completely with some deliberate designed protocols, such as the ColorWav(Waldrop 2003) and others(Leong 2006).

Source: Radio Frequency Identification Fundamentals and Applications, Bringing Research to Practice, Book edited by: Cristina Turcu, ISBN 978-953-7619-73-2, pp. 278, February 2010, INTECH, Croatia, downloaded from SCIYO.COM

Reader-tag collision can also be avoided easily by asking the RFID reader and RFID tags to broadcast message and transmit identifiers in different time, so that the signals broadcasted by the RFID reader and transmitted from RFID tags will never collide in the air interface and reader-tag collision will never occur.

When two or more RFID tags try to transmit their identifiers simultaneously through the air interface, tag-tag collision will occur. Due to the extreme constraints on computation, communication and energy supply put on RFID tags, especially that in passive RFID system, RFID tag can only get power supply through the reflection of the waveforms broadcasted by the RFID reader, tag-tag collision cannot be resolved easily using existed collision resolution methods, such as CDMA (Code Division Multi Access), FDMA (Frequency Division Multi Access), SDMA (Space Division Multi Access) and TDMA (Time Division Multi Access), proposed in other communication systems(Theodore 2006).

Proposed protocols for RFID tag collision resolution can be classified as the probabilistic frame slotted ALOHA based protocols, the deterministic splitting tree based protocols, and some hybrid protocols, such as the slotted tree protocol (Bonuccelli 2007). The deterministic splitting tree based RFID tag collision resolution protocols suffer from scalability, and perform clumsily in resolving the collision caused by a large amount of RFID tags, while the hybrid protocols are seldom adopted in real RFID systems, so these collision resolution protocols will not be discussed any further in this chapter.

Due to that in a frame, each RFID tag can only choose a slot to transmit its data, the RFID tag collision resolution process using the frame slotted ALOHA based protocols can be viewed as a binomial distribution process, the identification accuracy and the efficiency of the protocol depends seriously on the estimation and choice of some key parameters.

In this chapter, for the probabilistic frame slotted ALOHA based RFID tag collision resolution protocol, based on the binomial distribution model, the accurate estimation of the RFID tag population and the optimal choice some key parameters adopted in the collision resolution protocol are analyzed, the Markov chain and its corresponding transition matrix for RFID tag collision resolution are proposed to determine the amount of frames needed in the identification, and our research is verified by numeric simulations.

The remaining sections of this chapter is organized as follows: section 2 presents the basic assumption we hold in this chapter and reviews briefly the frame slotted ALOHA based RFID tag collision resolution protocols. Section 3 discusses the stochastical distribution model for RFID tag collision resolution based on the binomial distribution and the Markov chain, and some key parameters that affect the performance of the collision resolution protocol are analyzed. Section 4 describes and analyzes the result of the numeric simulations performed to verify our research. And finally in Section 5, we conclude.

2. Basic assumptions and the frame slotted ALOHA based protocols

2.1 Basic assumptions

In this chapter, as presented in (Kaplan 1985) for the analysis of multiple-access protocols, we hold the following basic conventions in the discussions:

- Time is slotted, each time slot can be either a command slot for the RFID reader to broadcast a message or a data slot for the RFID tags to transmit their binary identifiers.
- One RFID tag group is interrogated in a data slot.
- The air interface is perfect, and no signal transmission error or lose occurs in it.
- The air interface is ternary, the interrogation of a tag group reveals the presence of *zero, one* and *two or more* RFID tags.

But unlike (Kaplan 1985), in this chapter, it is assumed that the air interface is instantaneous, not delayed, due to the limited distance between the RFID reader and RFID tags. However, short time intervals are needed for the RFID reader and tags to modulate and transfer a bit through the air interface. As other research work on RFID tag collision resolution protocols, it is assumed that RFID tags remain stable in a collision resolution cycle, neither newly arrived RFID tag enters nor does existed RFID tags leave the interrogation zone of the RFID reader during an identification cycle.

2.2 The frame slotted ALOHA based RFID tag collision resolution protocols

The ALOHA protocol for resolving the collision occurred in wireless communication was originally proposed by N. Abramson from the Hawaii University in the 1970s to enable the terminals distributed in isolated islands to exchange information with the mainframe computer system(Abramson 1970). In this protocol, each terminal can choose a time interval randomly to transmit its data to the mainframe, and if the time interval is occupied solely by the terminal, the data can be received by the mainframe successfully. Otherwise, if the time interval is occupied by two or more terminals and collapses, the data signals from these terminals will interfere, and collision will occur, and each terminal is acknowledged with the collision and will choose randomly another time interval afterward for retransmission.

An improvement of the ALOHA protocol is the slotted ALOHA protocol (Roberts 1975), in which the time is slotted, each terminal can only choose randomly a whole time slot, start data transmission at the beginning of the time slot and finish transmission at the end of it. In such a way, a lot of collisions occurred in the wireless communication channel can be avoided.

Due to its simplicity and easiness of implementation, the slotted ALOHA protocol was introduced to the RFID system to resolve the tag-tag collisions, which are caused by that two or more RFID tags try to transmit their identifiers simultaneously through the air interface, and various frame slotted ALOHA based RFID tag collision resolution protocol have been suggested, such as the standard frame slotted ALOHA protocol, the dynamic frame slotted ALOHA protocol, the extended frame slotted ALOHA protocol and etc. Some frame slotted ALOHA protocols have been adopted as international or industrial standards.

In all these protocols, the overall process that a RFID reader tries to collect the identifiers stored in the RFID tags within its vicinity is called a collision resolution cycle (or an identification cycle), which is consisted of a series of frames. And in each frame there is a command slot and a series of data slots.

In the command slot of a frame, the RFID reader broadcasts a command message to RFID tags in its interrogation zone to indicate the number of data slots (frame length), s, adopted in this frame. Each RFID tag, upon receiving this message and decoding the frame length s, randomly generates an integer i in the range $0..s-1$, modulates its binary identifier into signals and transmits the signals back to the RFID reader in the ith data slot through the air interface. Due to the constraint on computation put on RFID tags, s is often chosen as a integer mean of 2 and in the range $[2,4,8,16,32,64,128,256]$.

Afterwards, the RFID reader gathers information contained in the data slots of the frame. If in a data slot, no RFID tag chooses to transmit its identifier, the data slot is called an idle slot. Else if in a data slot, there is one and only one RFID tag choosing to transmit its identifier, the data slot is called a success slot, the identifier is gathered and the RFID tag is identified successfully. Otherwise, two or more RFID tags choose to transmit their identifiers in the data slot, collision will occur and the data slot is called a collision slot, in such case, what the RFID reader can get is only a collision signal but no other useful information.

If after a frame, the desired identification accuracy of RFID tags specified by the application system is achieved, the current collision resolution cycle can be terminated, and the RFID reader will report the result to the backend information system for further processing and dispatching. Otherwise, another collision resolution frame is needed, and the same identification process is repeated.

3. The stochastical model for collision resolution of RFID tags

3.1 The binomial distribution model for RFID tag collision resolution

In a collision resolution frame, due to that each RFID tag can only randomly choose one data slot to transmit its digital identifier, this procedure can be viewed as a typical binomial distribution process.

Suppose that the population of RFID tags within the vicinity of the RFID reader is *t* and the frame length is *s*, the probability that *n* RFID tags choose a common data slot to transmit their identifiers can be calculated with the binomial distribution as

$$B_{s,\frac{1}{t}} = \binom{t}{n}\left(\frac{1}{s}\right)^{n}\left(1-\frac{1}{s}\right)^{t-n} \tag{1}$$

where $\binom{t}{n} = \frac{n!}{t!(n-t)!}$. And the mathematical expects of this binomial distribution can be calculated with

$$E\left[\!\left[B_{t,\frac{1}{s}}(n)\right]\!\right] = s\binom{n}{t}\left(\frac{1}{s}\right)^{n}\left(1-\frac{1}{s}\right)^{t-n} \tag{2}$$

Suppose that μ_r is a random variable representing the amount of data slots that *r* RFID tags chooses the data slot to respond, where *r*∈*[0,1,..,t-1]*, the distribution of μ_r, according to (Feller 1970), is

$$P(\mu_r = m) = \frac{\binom{s}{m}\prod_{k=0}^{m-1}\binom{t-k}{r}G(s-m, t-rm)}{s^t} \tag{3}$$

where $G(M,m) = M^m + \sum_{k=1}^{\left\lfloor \frac{m}{r} \right\rfloor}\left\{(-1)^k \prod_{j=0}^{k-1}\left\{\binom{m-jr}{r}(M-j)\right\}(M-k)^{m-kr}\frac{1}{k!}\right\}$.

The mathematical expects for the number of idle, success and collision data slots, $C_{0,t,s}$, $C_{1,t,s}$, and $C_{k,t,s}$ achieved in the frame can be calculated as

$$\begin{aligned} C_{0,t,s} &= s\left(1-\frac{1}{s}\right)^{t} \approx s\,e^{-\frac{t}{s}} \\ C_{1,t,s} &= t\left(1-\frac{1}{s}\right)^{t-1} \approx t\,e^{-\frac{t}{s}} \\ C_{k,t,s} &= s - c_{0,t,s} - c_{1,t,s} \approx s\,(1-\left(1+\frac{t}{s}\right)e^{-\frac{t}{s}}) \end{aligned} \tag{4}$$

The values of $C_{0,t,s}$, $C_{1,t,s}$ and $C_{k,t,s}$ for the identification of different amount of RFID tags with fixed frame length *s=256* are shown in Fig. 1. From Fig. 1, it can been observed that for the collision resolution protocol with fixed frame length, as tag population increases, the amount of collision slots also increases rapidly and approaches to the frame length, and the amount of idle slots deacreses rapidly and approaches to 0, while the amount of success slots, after reaches a maximum value, will also decrease rapidly and approach to 0 finally.

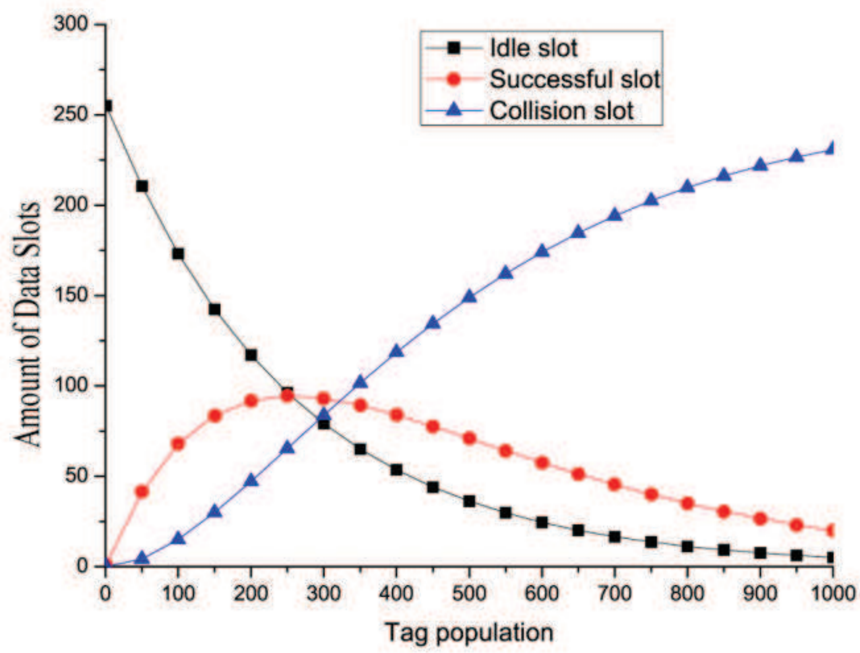

Fig. 1. The Values of $C_{0,t,s}$, $C_{1,t,s}$ and $C_{k,t,s}$ for Different Tag Population and Fixed Frame Length s=*256*

3.2 Estimation of RFID tag population

In typical RFID applications, the population of RFID tags within the vicinity of the RFID reader is usually unknown in advance. For the frame slotted ALOHA based RFID tag collision resolution protocols, accurate estimation of the RFID tag population is a necessity for the calculation of the identification accuracy achieved after a frame and the termination of the current collision resolution cycle.

Proposed methods for the estimation of the RFID tag population adopted in the frame slotted ALOHA based protocols, according to the name of the proposer, can be categorized as the Vogt-1, the Zhen-1, the Cha-1, the Cha-2 and the Vogt-2 methods.

The Vogt-1 method (Vogt 2002) refers to that after an identification frame, if the amounts of idle, successful and collision slots are a_0, a_1, and a_k, due to that a_1 RFID tags respond in the successful slots and that every collision is occupied by the identifiers from at least *2* RFID tags, the overall population of RFID tags that respond in the frame can estimated as t directly with

$$t = a_1 + 2a_k \tag{5}$$

The Zhen-1 method (Zhen 2005) uses the probability that collision occurs in a data slot to estimate the overall population of RFID tags in the vicinity of the RFID reader. The probability that a RFID tag may collide with other RFID tags in a data slot can be calculated as

$$C = \frac{P_{col}}{1 - P_{suc}} = 1 - \frac{(1-\frac{1}{s})^t}{1 - \frac{t}{s}(1-\frac{1}{s})^{t-1}} \tag{6}$$

where P_{col} and P_{suc} refer to probabilities that a data slot result in collision and success. According to the law of large number, the stable of value of C can be achieved when $t \to \infty$, and in such case, C can be calcuated as $C=0.418$. So the overall population of RFID tags that transmits their identififers in the frame can be estimated with

$$t = a_1 + \frac{a_k}{C} = a_1 + 2.392a_k \tag{7}$$

Another method proposed in (Cha 2005) is that the overall population of RFID tags within the vicinity of the RFID reader should be estimated as $t=2.392a_k$, and this method is called the Cha-1 in this chapter.

As proposed in (Cha 2006) according to the binomial distribution of the frame slotted ALOHA based RFID tag collision resolution protocols, the mathematical expects for the amounts of idle, successful and collision slots can be calculated with Eq. 3, if after a frame, the actual number of collision slots is a_k, for the equation $a_k = s\,(1 - \left(1+\frac{t}{s}\right)e^{-\frac{t}{s}})$, for known s, the value of t can be calcuated with the Newton or other literation methods.

This calculation is time consuming, so to ease the calculation, for the framel length s adopted in the protocol, we can calcuated the value of $C_{k,t,s}$for different t, and compare a_k with it to find the approximate RFID tag population t. That is, through seaching t to minize the $|a_k - C_{k,t,s}|$, the appropriate value of RFID tag population can be founded. This method is called Cha-2, and also has been proposed in (Kodialam 2006).

It should be noticed that the search range of t should be limited to $[a_1+2a_k, 2(a_1+2a_k)]$, for that (a_1+2a_k) is the low limit of the tag population, and numeric simulation presented in section 4 shows that the chance is rare for actual RFID tag population exceeds $2(a_1+2a_k)$.

As proposed in (Vogt 2002), accroding to the *Chebyshev's inequality*, the result for random experiment with random variable X is most likely results in the mathematical expects of X, and to resolve the collision caused by different number of RFID tags t with frame length s, the mathematical expects of $C_{0,t,s}$, $C_{1,t,s}$ and $C_{k,t,s}$ achieved in a frame can be calculated in advance. And if after the frame, if the actual amounts of idle, success and collision slots are a_0, a_1, and a_k, the population of RFID tags t can be calculated by minimizing the difference between the tuples $< a_0, a_1, a_k >$ and $< C_{0,t,s}, C_{1,t,s}, C_{k,t,s} >$. That is to find the RFID tag population t, which satisfies

$$Min(f) = Minize \begin{vmatrix} C_{0,t,s} - a_0 \\ C_{1,t,s} - a_1 \\ C_{k,t,s} - a_k \end{vmatrix} \tag{8}$$

The search range of RFID tag population t can also be limited to the range $[(a_1+2a_k), 2(a_1+2a_k)]$, as discussed above.

These methods estimate the population of RFID tags within the interrogation zone of the RFID reader from different views, and the estimation accuracy achieved in each method needs to be examined with further numeric simulations.

3.3 The calculation of the optimal frame size

In the frame slotted ALOHA based RFID tag collision resolution protocols, once the population of RFID tags is known or can be estimated, the choice of the frame length adopted in the protocol affects the efficiency of the protocol and the latency of a collision resolution cycle. The choice of the optimal frame size should take into consideration of both the throughput of the protocol and the efficiency of RFID tag identification.

The throughput of the collision resolution protocol reflects the efficient use of the air interface, and is defined as

$$e_{th} = \frac{c_{1,t,s}}{s} = \frac{t(1-1/s)^{t-1}}{s} \tag{9}$$

where t is the RFID tag population, and s refers to the frame length adopted.

For e_{th} to achieve its maximize value, we need to fix t, and let $\frac{de_{th}}{ds} = 0$. It can be found that when s=t, e_{th} is maximinzed to be $\left(1-\frac{1}{t}\right)^{t-1}$. Similarly, according to the law of large number, the stable maximum value of e_{th} can be calcuated as

$$max\,(e_{th}) = \lim_{t\to\infty}\left(1-\frac{1}{t}\right)^{t-1} = e^{-1} = 0.368 \tag{10}$$

An alternative is to view this collision resolution process as a Poisson distribution process. The probability that t RFID tags transmit their identifiers back to the RFID reader in a time interval $[0\ ,\ \tau]$ is in accordance with the Poisson distribution, and can be calculated with

$$p(X(\tau) = k) = \frac{(\lambda\tau)^k}{k!}e^{-\lambda\tau} \tag{11}$$

where $\lambda = \frac{t}{s}$.

Due to that the frame slotted ALOHA based RFID tag collision resolution protocols divide an identification frame into a series of discrete data slots, and each slot can be viewed as one time unit, if only one RFID tag chooses the time unit to transmit its identifier, no collision occurs and the RFID tag is identified successfully, so the throughput of the frame slotted ALOHA based collision resolution protocol can viewed as $p(X(1) = 1) = \lambda e^{-\lambda}$, and when $\lambda = 1$, p is maximized to be *0.368*. This also verifies that when s=t, the throughput of the protocol is maximized.

The throughputs achieved by the frame slotted ALOHA based RFID tag collision resolution protocols with different frame length in the identification of different amount of RFID tags are depicted in Fig. 2.

In the research of frame slotted ALOHA based RFID tag collision resolution protocols, throughput is often used to determine the optimal frame size adopted in the protocol. But we think that although throughput in an important issue to measure the efficient use of the communication channel, another key factor should be taken into consideration for the calculation of the optimal frame length is to consider the performance of the collision resolution protocol using the identification ratio of RFID tags achieved in a frame, which can be defined as $e_{s,t}$ and calcuated with

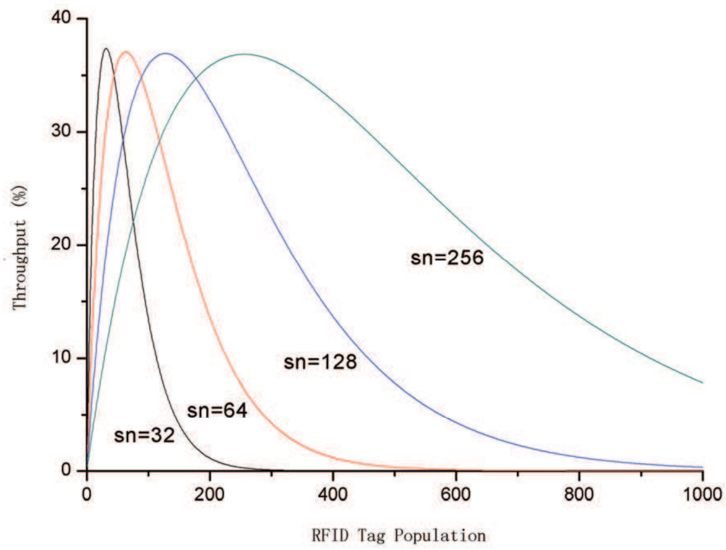

Fig. 2. The Throughputs Achieved by the Frame Slotted ALOHA Based RFID Tag Collision Protocols with Different Frame Length.

$$e_{s,t} = \frac{c_{1,t,s}}{t} = (1 - 1/s)^{t-1} \tag{12}$$

To find the maximum value of the identification ratio $e_{s,t}$, we also need to fix s, calculate $\frac{de_{s,t}}{ds}$, and let $\frac{de_{s,t}}{ds} = 0$, we get

$$\begin{aligned} \frac{de_{s,t}}{ds} &= \left(1-\frac{1}{s}\right)^{t-1} + t\left(1-\frac{1}{s}\right)^{t-1} ln\left(1-\frac{1}{s}\right) \\ &= \left(1-\frac{1}{s}\right)^{t-1}\left(1+tln\left(1-\frac{1}{s}\right)\right) = 0 \end{aligned} \tag{13}$$

and then $s = \frac{1}{1-e^{-\frac{1}{t}}} = 1 + \frac{1}{e^{\frac{1}{t}}-1}$.

According to the discussion presented above for the identification of different amount of RFID tags in the vicinity of the RFID reader, the corresponding optimum frame length for the frame slotted ALOHA based protocol to achieve best identification ratio can be calculated. Due to that the frame legnth adopted in the protocol can only be chosen in the range of *[2,4,8,16,32,64,128,256]*, for the identification of t RFID tags, the appropriate frame length s should satisfy:

- $e_{s,t} > 2e_{\frac{s}{2},t}$, which means that the amount of RFID tags identified in a frame with frame length s should be more than that identified in two frames with frame length $\frac{s}{2}$, and
- $2e_{s,t} > e_{2s,t}$, means that the amount of RFID tags identified in two frames with frame length s should be more than that identified in a frame with frame length $2s$.

3.4 Collision resolution process based on the Markov chain

Suppose that in a collision resolution cycle of the frame slotted ALOHA based RFID tags collision resolution protocol, after the ith frames, the amount of identified RFID tags is $f(i)$, then after the next frame, the amount of RFID tags identified should be $f(i+1)=f(i)+t_i$, where t_i is the amount of RFID tags which are newly identified in the frame $i+1$ but have not been identified in the previous frames. This specifies that the amount of RFID tags identified after frame $i+1$ depends solely on the amount of RFID tags identified after frame i, and this process can be viewed as a homogenous Markov chain.

The Markov chain is often defined using the transition matrix to specify the probability that a state changes to another. The elements of this Markov chain transition matrix for the identification of t RFID tags using the frame slotted ALOHA protocols can be calculated with

$$q_{ij} = \begin{cases} 0 & (j < i) \\ \sum_{r=0}^{i} P(\mu_1 = r) \frac{\binom{i}{r}}{\binom{t}{r}} & (j = i) \\ \sum_{r=j-i}^{i} P(\mu_1 = r) \frac{\binom{t-i}{j-i}\binom{i}{r-j+i}}{\binom{t}{r}} & (j > i) \end{cases} \tag{14}$$

Each elment q_{ij} specifies the probability that the amount of identified RFID tags changes from i to j after a frame.

The first situation specified in Eq. 14 will never occur due to that it is impossible that after a new frame the total amount of RFID tags identified is less than that identified before the frame.

The second situation specifies that the amount of RFID tags newly identified in the frame is 0, which means that all RFID tags which are identified without collision in this frame have been identified in the previous frames, and the current collision resolution cycle should be terminated because that the probability that new RFID tags can be detected in the following frames is also 0. The coefficients for such transition can be calculated with the equation $q_{ii} = 1 - \sum_{j=0, j\neq i}^{t} q_{ij} = 1 - \sum_{j=i+1}^{t} q_{ij}$.

For the third situation, of all t-i RFID tags not identified in the previous frame by the RFID reader, j-i RFID tags choose the success data slot to respond and are identified newly in the frame.

The values for elements in the first row of the transition matrix specifies the initial state of a collision resolution cycle, and should be set to $q_{0j} = \{1,0,\ldots 0\}$.

The Markov chain and corresponding transition matrix specifies the condition that a collision resolution cycle can terminate, and can be used to calculate the number of frames needed for the identification of t RFID tags.

3.5 The deployment of multiple RFID readers

Usually in a dense RFID tag environment, multiple RFID readers are deployed to facilitate the RFID tag identification cycle. Suppose that there are n readers deployed, and each reader resolves the RFID tag collision independently and reader-reader collision is resolved. For the overall identification accuracy α required by the application system, the accuracy γ which each RFID reader should achieve can be calculated as

$$(1 - \gamma)^n \leq 1 - \alpha \tag{15}$$

and we have

$$\gamma \geq 1 - \sqrt[n]{1-\alpha} \tag{16}$$

Table 1. shows that if overall identification accuracy required by the application systems is 99.0%, and multiple readers are deployed, the identification accuracy which each RFID reader should achieve. From Table 1, we can see that the deployment of multiple RFID reader decreases the accuracy requirement for each reader significantly, which will in return, facilitate the identification cycle greatly.

Number of RFID readers deployed	Identification accuracy required for each RFID reader
1	99.0%
2	90.0%
3	78.5%
4	68.4%
5	60.2%

Table 1. Identification Accuracy for Each RFID Reader

4. Numeric simulation and result analysis

4.1 The numeric simulation environment

To verify the research work presented in this chapter, numeric simulations and evaluations are performed. In the simulation, 100 randomly generated data sets are used, in each data set, there are 1000 randomly generated binary strings, and each of which represents the binary identifier of a RFID tag encoded with SGTIN-96 schema. The standard frame slotted ALOHA based RFID tag collision resolution protocols with different frame length are implemented and simulated with the C# programming language in Microsoft Visual Studio .NET 2005 for the measurements of their performances in resolving the collision caused by different amount of RFID tags contained in each data set, the results are recorded and averaged with the 100 data sets.

4.2 The accuracy of RFID tag population estimations

To find the accuracy for RFID tag population estimation of various methods discussed in section 3.1, simulations are performed, in which the frame size of the frame slotted ALOHA protocol is fixed to 256. The accuracies of the RFID tag population estimation methods presented in section 3.2 are measured with the mathematical means and variances of their estimation error ratios achieved in the simulations.

The mathematical means of the estimation error ratios for a RFID tag population estimation method is calculated as

$$\mu_{err} = \frac{\sum_{i=1}^{R} \frac{\hat{t}-t}{t}}{R} = \frac{\sum_{i=1}^{R} \hat{t}}{Rt} - 1 \tag{17}$$

And the mathematical variance of the estimation error ratio for a RFID tag population estimation method is calculated as

$$\sigma_{err} = \sqrt{\frac{\sum_{i=1}^{R}\left(\frac{\hat{t}-t}{t}-\mu_{err}\right)^2}{R-1}} \tag{17}$$

where t and $\hat{t}$ represent the actual and estimated RFID tag populations. R is the number of data sets used the simulation, and in this example, and is fixed to 100.

Fig. 3. shows the mathematical means of the RFID tag population estimation error ratios of the Vogt-1, Vogt-2, Cha-1, Cha-2 and Zhen-1 methods, from which it can be concluded that the Vogt-2 method performs better than other methods with stable means of error ratios around 0.

Fig. 4. shows the mathematical variances of the estimation error ratios of these methods, from which it can also been seen that although the variance of the tag population estimation ratios for Vogt-2 is the greatest, but is still within a satisfactory range.

For the tag population estimation using Vogt-2 and Cha-2, as we have discussed, search on tag population t is needed to find the minimal value of the evaluation function, and the search can be limited in the range $[a_1 + 2a_k, 2(a_1 + 2a_k)]$. In the simulations, we examine the probability that the actual tag population is in the range, and the result is shown in Figure 6. From these simulations, we have observed that if the tag population is less than 3.2 times of the frame size, this upper limit $2(a_1 + 2a_k)$ has never been exceeded.

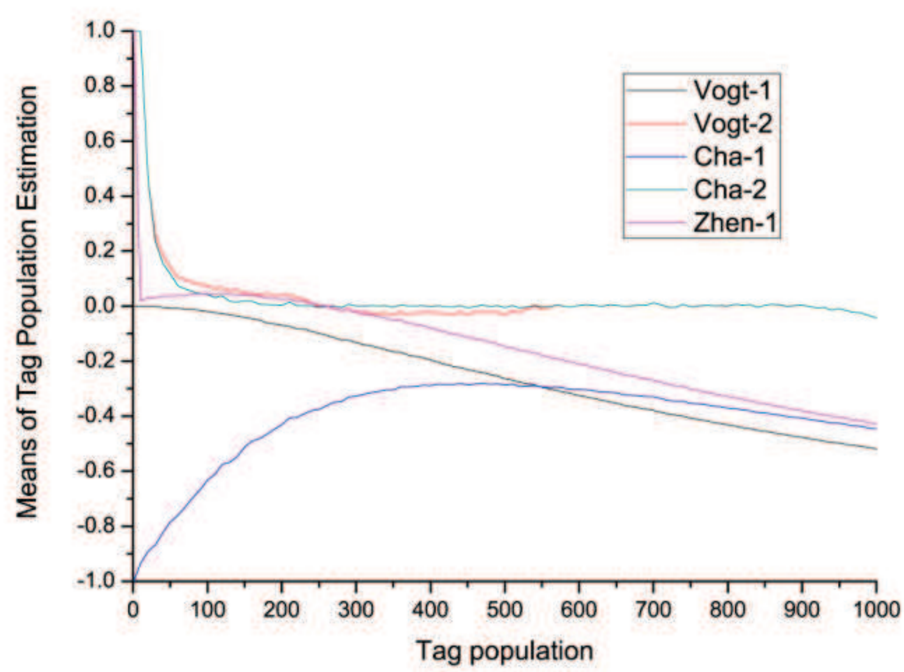

Fig. 3. Mathematical Means of the Tag Population Estimation Error Ratios

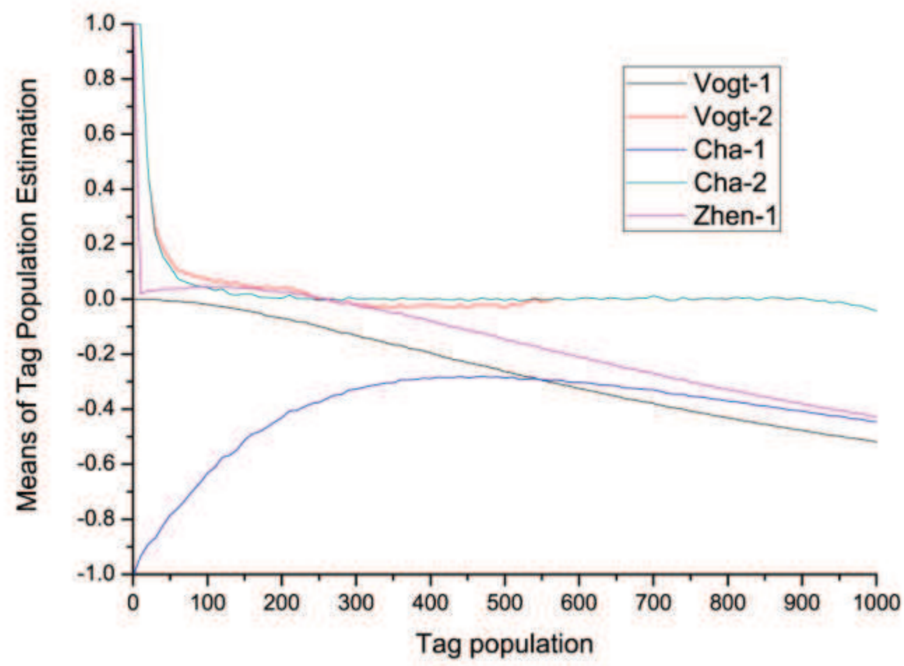

Fig. 4. Mathematical Variances of the Tag Population Estimation Error Ratios

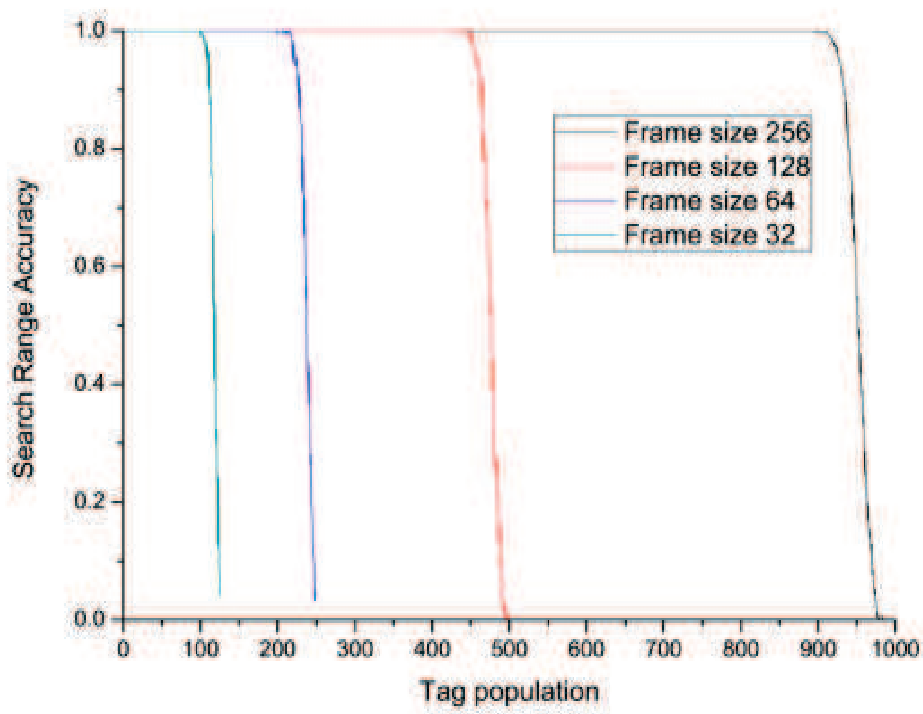

Fig. 5. The Probability that the Tag Population is within the Range

4.3 The efficiencies of the frame slotted ALOHA protocol and analysis

Fig. 6 shows the efficiency of the frame slotted ALOHA protocols with different frame length in resolving the collision caused by different amount of RFID tags. For the convenience of comparison, the protocol with frame length *s* is performed *256/s* frames, for example, the collison resolution protocol with frame size 16 is performed 16 frames. The efficiency is defined as the identification ratio of RFID tags in these frames, calculated with the number of RFID tags actually identified divided by the actual number of RFID tags.
From Fig. 6, it can be observed that as the population of RFID tags increase, the efficiency of frame slotted ALOHA protocol decreases rapidly.

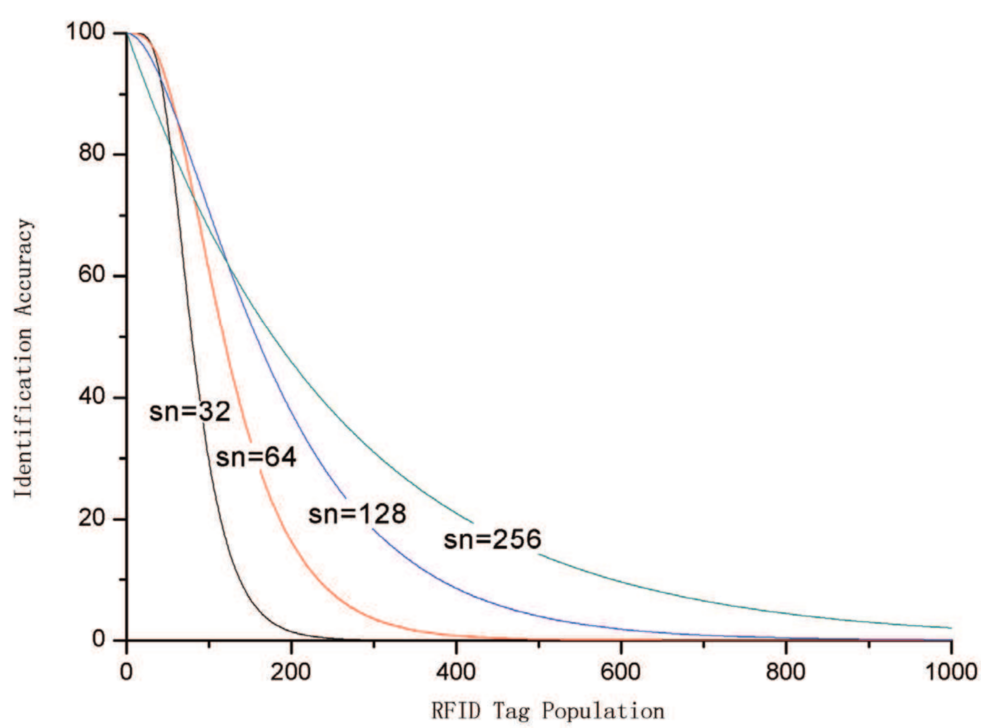

Fig. 6. The Efficiencies of Frame Slotted ALOHA Protocols with Different Frame Length

According to the calculation and simulation, the optimal frame length which the frame slotted ALOHA protocol should adopt in resolving the collision caused by different number of RFID tags is shown in Table 2.

RFID Tag Population	1-14	15-30	31-61	62-124	124~
Optimal Frame Length	16	32	64	128	256

Table 2. Optimal Frame Length for the Identification of Different Number of RFID tags.

4.4 Simulation and analysis of the identification process

Fig. 7 shows the amount of frames needed in resolving the collision caused by different amount of RFID tags using the frame slotted ALOHA based protocols with different frame length. It can been seen that as the RFID tag population increases, the amount of frames needed by these protocol will increase rapidly in exponential order.

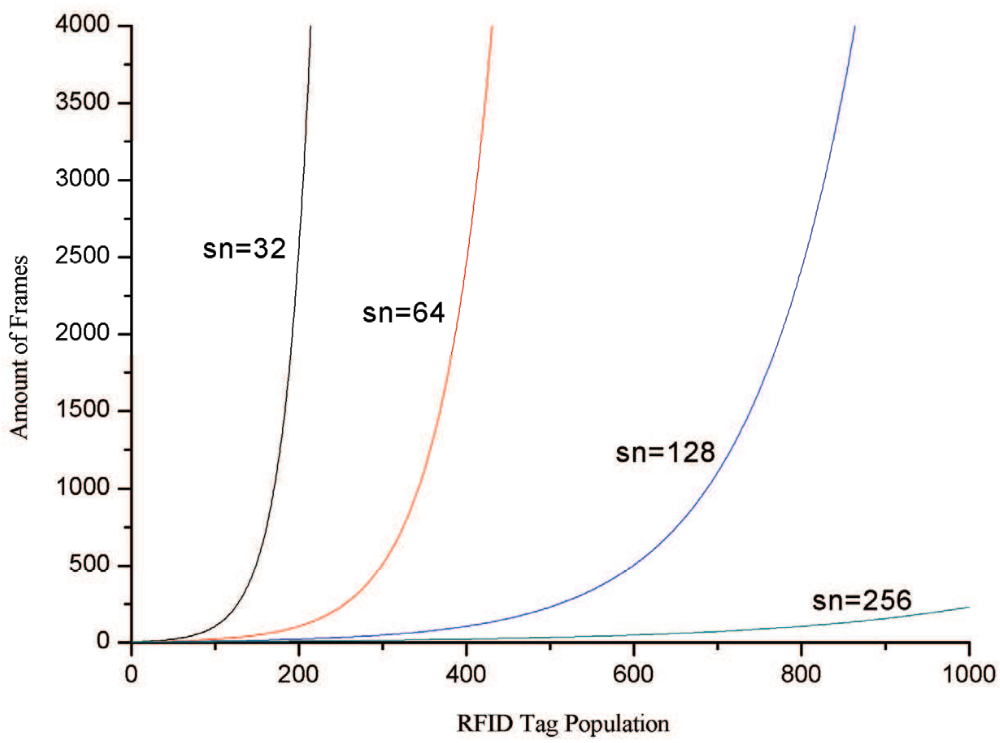

Fig. 7. Amount of Frames Needed for the Frame Slotted ALOHA Protocol with Different Frame Length

5. Conclusion

RFID holds the promise to enable human being to monitor the physical world with much fine granularity and bridge the huge gap between the physical item world with the virtual digital space. However, the collision occurred during the identification of multiple RFID tags prevents this promise to become a reality.

In this chapter, the frame slotted ALOHA based RFID tag collision resolution protocols are investigated, the stochastical distrubution model based on the binomial distrubution and the honomgenous Markov chain for the collision resolution process are proposed, the transisition matrix for the Markov chain is estabilished, vairous methods proposed for the estimation of RFID tag population within the vicinity of the RFID reader are examined and evalutaed. Some key factors that affect the performance of the protocols are evaluated and examined. Numeirc simulations are performed to verify the research presented in this chapter.

6. Acknowledgement

The research work presented in this chapter is partially supported by the Natural Science Fund of China (NSFC) under Grant No. 50625516, the National Fundamental Research Program of China (973) under Grant No. 2009CB724204, and the High Talent Starting Research Project of North China University of Water Conservancy and Electric Power under Grant No. 200923.

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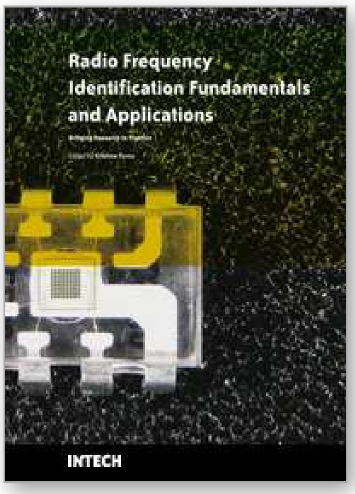

ISBN 978-953-7619-73-2

Hard cover, 278 pages

Publisher InTech

Published online 01, February, 2010

Published in print edition February, 2010

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