AUTO–ID LABS

Anti-Collision Issue Analysis in Gen2 Protocol

Anti-collision issue analysis considering capture effect

Bo Li (Fudan University),
Yuqing Yang (Fudan University),
Junyu Wang (Fudan University)

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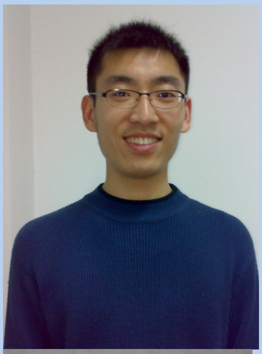
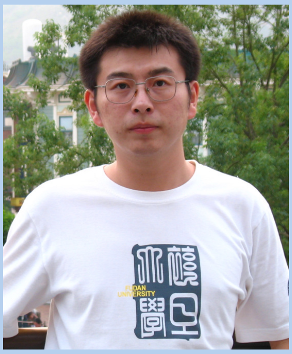


Bo Li
Graduate Student
Fudan University



Yuqing Yang
Doctorate Student
Fudan University

Junyu Wang
Associate Professor
Fudan University

Email: junyuwang@fudan.edu.cn, leebo@fudan.edu.cn

Hardware

Index

1 Introduction ... 4
2 Review of Anti-Collision Schemes Compatible with EPC Gen2 ... 5
  2.1 Tag collision problem in EPC Gen2 ... 5
  2.2 Mathematic fundamentals for anti-collision scheme ... 7
  2.3 Anti-collision schemes compatible with EPC Gen2 ... 7
    2.3.1 Schoute ... 7
    2.3.2 Lower Bound ... 8
    2.3.3 Vogt ... 8
    2.3.4 Q Algorithm ... 8
    2.3.5 C-ratio (Collision) ... 9
    2.3.6 Chen ... 9
    2.3.7 Bayesian ... 10
3 System Model ... 11
  3.1 Reader ... 12
  3.2 Tag ... 13
  3.3 Channel ... 14
4 Capture Probability Analysis ... 15
  4.1 Capture effect ... 15
  4.2 Related works on capture model ... 16
  4.3 Capture probability for passive UHF RFID system ... 17
  4.4 Numerical results ... 18
  4.5 Discussion ... 20
5 Performance Analysis of Anti-Collision Schemes with and without Capture ... 20
  5.1 Schoute ... 21
  5.2 Lower Bound ... 22
  5.3 Vogt ... 23
  5.4 Q Algorithm ... 24
  5.5 Chen ... 25
  5.6 Conclusion ... 26

6 Anti-Collision Scheme Development Considering Capture Effect................................ 26
  6.1 Considerations.. 26
  6.2 Proposed Anti-collision Scheme.. 28
  6.3 Simulation Results and Discussions.. 28
  6.4 System Capacity considering Capture Effect 30
7 Conclusion.. 31
References.. 33

1 Introduction

Radio Frequency Identification (RFID) has been widely applied in a variety of applications where automatic identification of objects is needed. Examples include object tracing, supply chain management and industrial automation. In these domains, RFID system has been proved to be convenient and efficient, since it features contactless communication between readers and tags which brings labour savings for a person to scan the objects, and provides large volume memory which can store more information than other identification technologies.

However, RFID also introduces technical challenges, one of which is multiple tag collision. As the number of RFID tags in the work range of a reader increase, which is especially the case when RFID system is applied in supply chain management and industry automation, tag collision problem becomes significant. Because of the collision of the signals of multiple tags, some tags would not be identified if no anti-collision scheme is introduced.

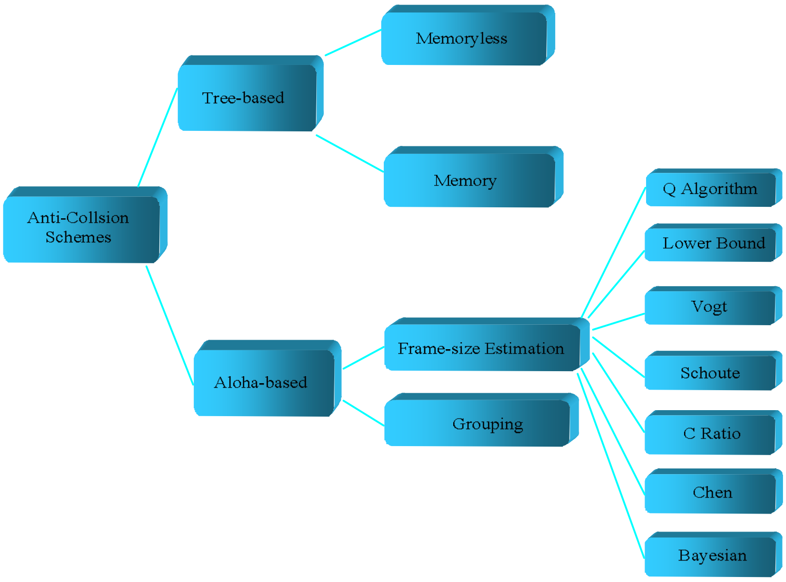


Figure 1: Anti-Collision Schemes for Tag-Collision Problem

The existing anti-collision schemes can be classified to two categories: Tree-based schemes and Aloha-based schemes, as is shown in figure 1. Typical Tree-based schemes include memory-less algorithms, such as Query-Tree scheme (Law, C., Lee, K.,Siu, K.-Y., 2000) which is adopted in EPC Class 1 Gen 1 (C1G1) RFID standard, and also algorithms with memory. Typical Aloha-based schemes include Bit Slot scheme (Kim, C.-S., Park, K.-L., Kim, H.-C., Kim, S.-D., 2004), Grouping scheme, and ID Slot scheme which is adopted in EPC Class 1 Gen 1(C1G2) RFID standard (EPC Global, 2007).

In this whitepaper, we focus on the anti-collision issues in EPC Gen2 Protocol, which is specified for passive UHF RFID system. In this case, we only take ‘Dynamic Framed Aloha’ schemes into consideration.

When signals from more than two tags collide, from the traditional view, reader can not recognize any of them. However, this assumption turns out to be too pessimistic in RFID environment, where the so-called “capture effect” may take place. Capture effect happens when signals transmitted from multiple tags simultaneously arrive at the reader with different power levels, the strongest signal can be successfully received in the presence of collision. This effect will greatly influence the performance evaluation of anti-collision schemes, which is significantly different from the analysis before.

The whitepaper is organized as follows. In section 2, we review the related works. In section 3, we present RFID system model consisting of reader, tag and channel, to simulate reader-tag interaction. In section 4, we analyze capture probability based on the channel model and spatial distribution of tags, and it has shown that when the collision size is small, the capture probability is high, which means in most of the cases when only two or three tags are collided, one tag can still probably be recognized. This gives rise to new considerations for anti-collision scheme development. In section 5, we compare the performance of Q algorithm, Lower Bound, Schoute, Vogt, and Bayesian schemes, with capture effect and without capture effect. In section 6, we discuss about novel Gen2 compatible anti-collision scheme development considering capture effect, before we conclude in Section 7.

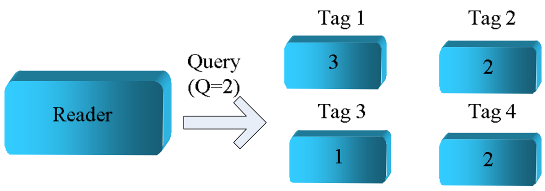
2 Review of Anti-Collision Schemes Compatible with EPC Gen2

2.1 Tag collision problem in EPC Gen2

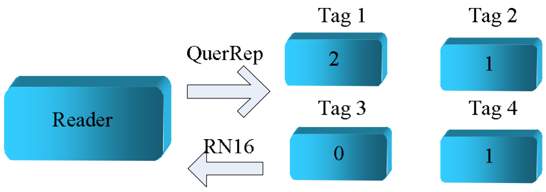
EPC Gen2 protocol (EPC Global, 2007) adopted slotted aloha-based probabilistic algorithm to solve the collision problem. According to the protocol, at first, reader picks a particular portion (or all) of the tag population by the command “SELECT”; Secondly, Reader issues “QUERY”, which contains a Q -parameter to specify the frame size (equal to $L = 2^Q - 1$), then each selected tag will pick a random number within 0 to $2^Q - 1$ and put it into its slot counter. The tag which picks zero as its random number (called slot number) should respond to reader with A RN16. Upon receiving the RN16 from tag, reader will transmit “ACK” containing the received RN16, after which the tag whose slot number is zero will backscatter its EPC to reader. Then reader issues “QUERYREP” or “QUERYADJUST” command to initiate another slot.

In order to query the remainder tags, reader may issue “QUERYREP” or (“QUERYADJUST”), each tag should subtract 1 from its own slot number, or (adjust its Q value and pick a new random number within 0 to $2^{Q'} - 1$ as its new slot number); The tag whose new slot number is zero will response to reader and then backscatter its EPC. There will be three kinds of slot. First, when there is only one tag to reply, called successful slot; Second, when there is no tag to reply, called empty slot; third, when there are more than one tag to reply, called collided slot (see figure 2).

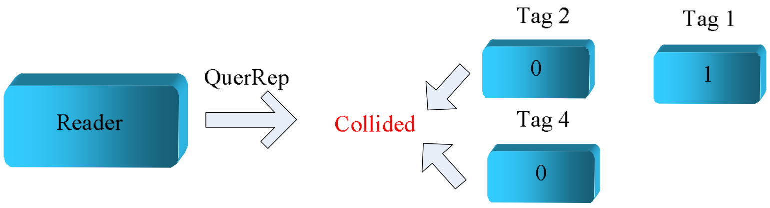
As slot number of each tag is independently chosen, collision happens inevitably. However, we can minimize collision rate and improve the identification efficiency. It is proved that if the frame size ($L = 2^Q - 1$) is equal to the number of tags in the read area, the system efficiency will reach the maximum value, e.g. $1/e$ (Cheng-Hao Quan, Won-Kee Hong, Hie-Cheol Kim, 2006). So the problem of anti-collision is transformed into the problem of estimating the number of tags in the electromagnetic area. Most anti-collision algorithms are designed to resolve this problem. In the next subsection, we will present different schemes.



a) Empty slot



b) Successful slot



c) Collided slot

Figure 2: Empty slot, successful slot, collided slot diagrams in EPC Gen2 Protocol

2.2 Mathematic fundamentals for anti-collision scheme

In the Aloha-based probabilistic scheme, to estimate the number of present tags, Binomial distribution becomes a good method. The distribution (Su-Ryun Lee,Sung-Don Joo, Chae-Woo Lee, 2005) applies to all L slots, thus in a frame with L slots and n tags, the expected value of the number of slots with occupancy number r is given by a_r.

$$a_r = L \times C_n^r (\frac{1}{L})^r (1-\frac{1}{L})^{n-r} \qquad (1)$$

So the expected number of empty slot, representative by h, singly-occupied slot, s, and collided slots c are given by following equations:

$$\begin{cases} h = a_0 = L(1-\frac{1}{L})^n \\ s = a_1 = x(1-\frac{1}{L})^{n-1} \\ c = a_k = L - a_0 - a_1 \end{cases} \qquad (2)$$

The system efficiency is defined as the ratio between successful slot number and frame size. Here, we assume that every slot is of the same length.

$$e = \frac{s}{L} = n\frac{1}{L}\left(1-\frac{1}{L}\right)^{n-1} \qquad (3)$$

It is proved that the highest efficiency can be obtained if the frame size (means the total number of slots in a frame) is equal to the number of tags provided that all slots have the same fixed length:

$$\text{L(optimal)=n} \qquad (4)$$

2.3 Anti-collision schemes compatible with EPC Gen2

2.3.1 Schoute

(F. C. Schoute, 1983) developed a backlog (means the total number of tags that have not been read) estimation technique for framed ALOHA which is exact under the assumption that the frame size is chosen in such a way that the number of stations which transmit in each time slot is Poisson distributed. The backlog after the current frame Bt is then simply given by:

$$Bt = 2.39c \tag{5}$$

where c represents the number of collided slot in the current frame.

2.3.2 Lower Bound

The estimation function is obtained through the observation that a collision involves at least two different tags. So backlog after the current frame Bt is then simply given by:$Bt = 2c$
(6)

where c is the number of collided slot in the current frame.

2.3.3 Vogt

(H. Vogt, 2002) also presents a backlog estimation procedure that selects the tag number estimate which minimizes the error between the observed value, including number of empty slot h, singly-occupied slot s, and collided slot c, and the expected value E(H),E(S),E(C): In order to find the comparative precise backlog, reader should to resolve a complex equation.

$$\min_{N} \left\| \begin{pmatrix} h \\ s \\ c \end{pmatrix} - \begin{pmatrix} E_N(H) \\ E_N(S) \\ E_N(C) \end{pmatrix} \right\| \tag{7}$$

2.3.4 Q Algorithm

The Q frame-by-frame Algorithm (EPCglobal, 2007) represents another transmission control strategy. It keeps a representation of the current frame size which is multiplied by a constant β whenever a collision occurs and which is divided by β whenever an empty slot is detected. While the Q algorithm requires only modest computational resources, it does not specify a method to compute the crucial control parameter β. It only provides a range of suitable values ($1.07 \leq \beta \leq 1.41$).

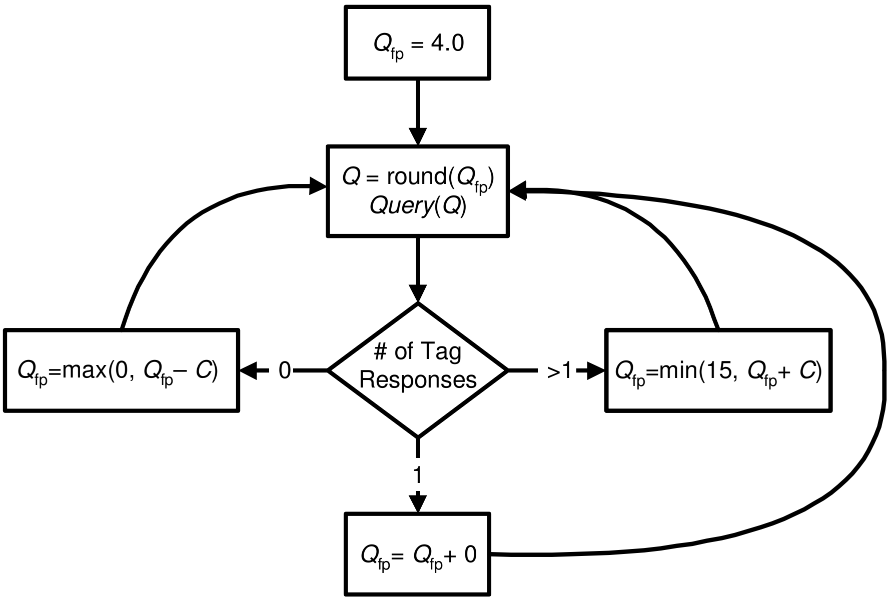


Figure 3: The block diagram of Q Frame-by-frame Algorithm

The performance of Q Frame-by-frame Algorithm can, however, be significantly improved when changes to Q are restricted to incremental changes (Christian Floerkemeier, 2007). Under these conditions the oscillations of the Q algorithm are damped and the simulated throughput is similar to the other frame-based transmission schemes.

2.3.5 C-ratio (Collision)

In order to estimate the number of tags, the collision ratio (C-ratio) is introduced (Jae-Ryong Cha, Jae-Hyun Kim, 2005), which means the ratio of the number of the slots with collision to the frame size, is given by

$$C_{ratio} = 1 - \left(1 - \frac{1}{L}\right)^{n}\left(1 + \frac{n}{L-1}\right) \qquad (8)$$

After a round, we know the frame size and the collision ratio. Based on this information, we can estimate the number of tags.

2.3.6 Chen

Most of the static algorithms estimate the backlog with the number of collided slot. But here Chen1 (Web-Tzu CHEN, 2006) estimate the backlog based on the empty slot information.

We focus on the probability of finding h empty slots after completing a frame.

$$P(h) = \frac{(-1)^h L! n!}{h! L^n} \sum_{j=h}^{L} \frac{(-1)^j (L-j)^n}{(j-h)!(L-j)!n!} \qquad (9)$$

For a given L and h, we want to find a number n such that the above probability is maximum. It is straightforward using the number as the estimate of tag quantity because in this situation (a known frame size L, and the number of empty slots, h), choosing the n has maximum conditional probability.

Chen1 algorithm requires great computational complexity, then is not practical for RFID system.

Chen2 algorithm (Web-Tzu CHEN, 2006) is a simple way to estimate the number of tags, which is illustrated as follows: after completing a frame, the n will be computed by the following equation:

$$n = (L-1) \cdot \frac{s}{h} \qquad (10)$$

If h=0, n is set to a certain upper bound for the tags estimate.

As Chen2 requires less computational complexity and nearly the same performance compared with Chen1, we refer Chen2 as the Chen scheme in the following sections.

2.3.7 Bayesian

The individual steps of the broadcast scheme are adapted to suit the nature of framed Aloha and RFID (Christian Floerkemeier, 2006):

1. Compute the frame size L based on the current probability distribution of the random variable N that represents the number of tags transmitting.

2. Start frame with L slots and wait for tag replies.

3. Update probability distribution of N based on evidence from the reader at the end of the frame. The evidence comprises the number of empty, singly-occupied, and collision slots in the last frame.

4. Adjust probability distribution N by considering newly arriving tags and departing tags including the ones which successfully replied and do not transmit in subsequent slots.

The probability distribution of N is obtained as follows. Let H, S, and C denote random variables indicating the number of empty, success (single-occupied), and collision slots in a single frame with L slots and N tags. After the frame is completed and the feedback in terms of H, S, and C is available, the number of tags that replied is estimated. According to Bayes' rule, the probability that N tags have been transmitting in the frame at time t, given all evidence z1:t including that from the past frame, is then given by

$$P_r(N \mid z_{1:t}) = \alpha P_r(N \mid z_{1:t-1}) \cdot P_r(z_t \mid N)$$

$$= \alpha P_r(N \mid z_{1:t-1}) \cdot P_r(C, H, S \mid N) \qquad (11)$$

where α is a normalizing constant.

Although the evaluation results shows that the Bayesian transmission strategy has a higher throughput than other approaches that only update the estimate at the end of the frame, it costs significant amount of computations, it is therefore not widely applied in RFID systems.

3 System Model

To simulate the anti-collision behaviour of RFID systems, a system model, as shown in figure 4, is built to simulate the transmission and reception of signals, the command set and operation procedure in Gen2 protocol, and corresponding behaviour of RFID tags and wireless channel characteristics, especially the capture effect, which will be analyzed in detail in section 4.

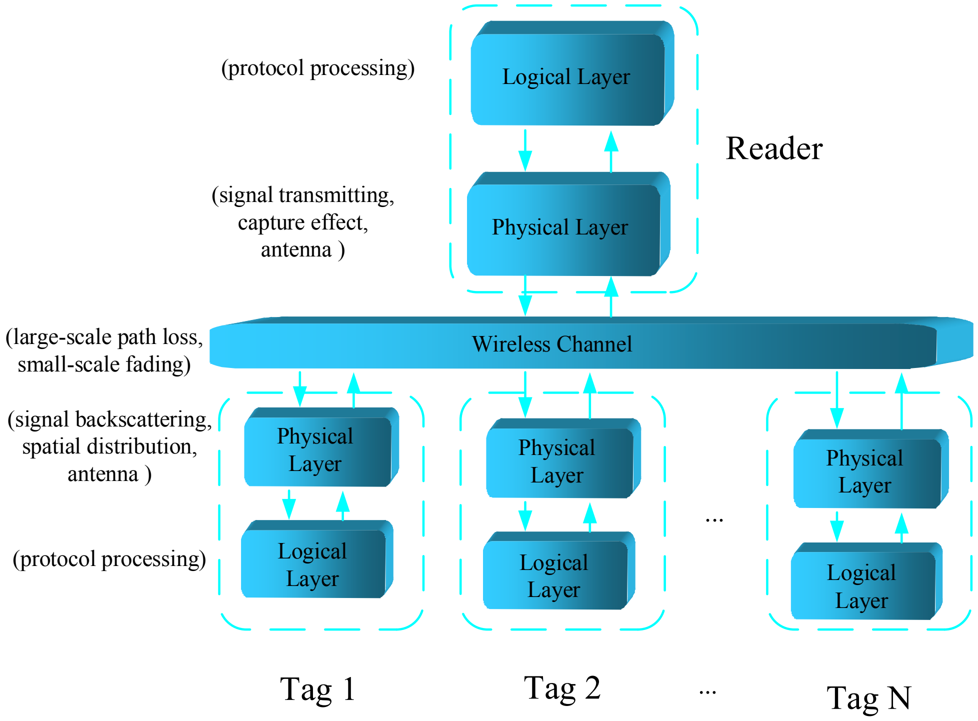


Figure 4: The block diagram of system model

3.1 Reader

As the logical layer, the Reader model features all the select and inventory commands in EPC Gen2 protocol which is necessary in anti-collision operations. This includes commands that Select a subset of the tag population, and Query the tag population to respond RN16, and ACK to acknowledge the successful reception of RN16 and expect further reception of EPC, and QueryRep to start another slot. Reader model also features inventory sequences and link timing, as shown in Fig.5 and Table I.

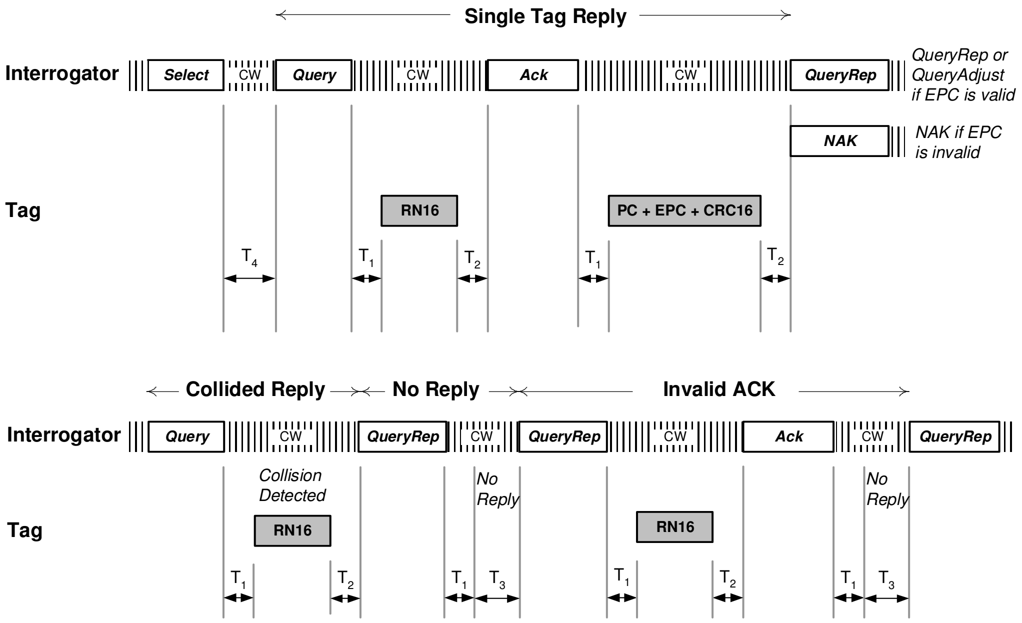


Figure 5: Media access control in EPC Gen2

Table I: Timing parameters applied in System model

Parameter Name	Value
Tari	12.5 us
PIE Data-1	25 us
R-T Data Rate	60 Kbps
T-R Data Rate	80 Kbps
Divide Ratio	8

TRext	0
T1	125 us
T2	62.5 us
T3	62.5 us
T4	75 us

Reader model includes the anti-collision schemes such as Lower Bound, Vogt, Schoute, Chen, and Q algorithm, performance parameters is computed including system efficiency and throughput.

Reader model further features a capture model. Capture effect is a well-known phenomenon in wireless networks that leads to a successful reception despite the simultaneous arrival of other signals. The probability of successful capture will be analyzed in section 4.

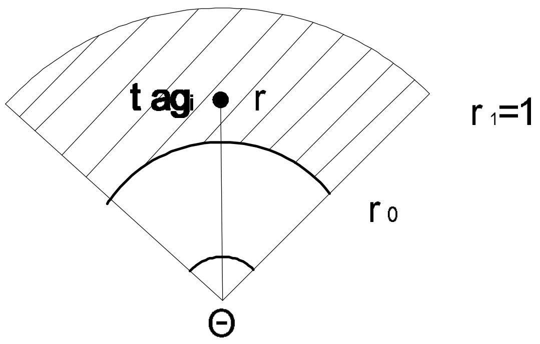
3.2 Tag

According to EPC Gen2, RFID tags will only respond to the reader and never initiate the communication. Upon receiving sufficient power from the reader, the tags power up and wait for incoming commands. Upon successful decoding a command, tags update their states and reply with appropriate messages. These logical operations are all implemented in Tag model.

Tag model specifies the backscattering model in physical layer. The backscattering power from the tag is a function of the incident signal power and backscatter ratio, as shown in equation 12.

$$P_{bs} = P_R \cdot g \cdot e \cdot \eta \qquad (12)$$

Where g is the antenna gain of tag, e is the polarization efficiency which is 0.5 when the reader antenna is circularly polarized with the axial ratio 0 dB and the tag antenna is linearly polarized, η is the backscatter ratio which is a function of the modulation index and modulation type, but here we simply assume it’s a constant.



$$f(r)=\begin{cases}\dfrac{2r}{1-r_0{}^2}, & r_0\le r\le 1\\ 0, & else\end{cases}$$

$$\theta < HP \text{ of reader antenna}$$

a) Distribution Region of Tags *b) Distribution Probability of Tag, Uniform Distribution*

Figure 6: Spatial Distribution of Tags

All tag antennas are assumed to be isotropic. All tags are distributed in a truncated sector as shown in Fig.6 with radius lower bound r0 and upper bound r1, and within the 3dB antenna beamwidth which means the reader antenna gain doesn't change a lot in this region.

3.3 Channel

Channel model specifies propagation characteristics of indoor wireless channel in RFID environment.

Signal propagation in indoor environment has been extensively investigated in literature (H. Hashemi,1993).In such environment, signal fading can be measured both in large scale and small scale, denoted as large scale path loss and small scale fading respectively.

1) Large-scale Path Loss

Large-scale path loss means the signal attenuation in large distance scale, which is caused by the radiation nature of electromagnetic waves and obstruction between transmitter and receiver. Large-scale path loss can be characterized by equation 13 (H. Hashemi,1993).

$$\begin{aligned}&\overline{PL}(d)\propto(\frac{d}{d_0})^n, \text{n is the path loss exponent}\\&\overline{PL}(d)=\overline{PL}(d_0)+10n\lg(\frac{d}{d_0})\end{aligned}\qquad(13)$$

2) Small-scale Fading

Passive RFID systems are typically operated in factories, warehouses and stores. In such environments, significant multipath fading has been measured by researchers (H. Hashemi ,1993). Since RFID communication is relatively narrow-band, e.g., under European legislation the channels are 200 KHz and under U.S. regulations 500 KHz, on the other hand, the typical indoor RMS delay spread is less than 300 ns (Rappaport,2001), which is much smaller than the symbol length. These prove that the RFID indoor channel is a flat fading channel.

Further considering the LOS path is present in typical RFID environment, we model the small-scale fading envelop as Ricean fading distribution as shown in equation 14.

$$P_R = \frac{P_T}{PL(d)} \cdot \frac{R^2}{2} \qquad (14)$$

where $\frac{P_T}{PL(d)}$ is the average received signal power, and R is the Ricien random variable with unit power and pdf shown in equation 15.

$$f(r) = \begin{cases} \frac{r}{\sigma^2} \exp(-\frac{(r^2 + A^2)}{2\sigma^2}) I_0(\frac{Ar}{\sigma^2}), & (A \geq 0, r \geq 0) \\ 0, & (r < 0) \end{cases} \qquad (15)$$

Where σ^2 is the scattering power, and A is the amplitude of LOS component.

4 Capture Probability Analysis

4.1 Capture effect

Capture effect, also referred to as the near far effect, has been extensively studied in literature (L. G. Roberts(1975), D. J. Goodman and A. A. M. Saleh(1987), J. C. Arnbak and W. Van Blitterswijk(1987), M. Zorzi(1997)). As in RFID system, however, very few workes has been done analyzing the capture effect (Christian Floerkemeier, 2009), in this section, we will analyze capture effect in both analytical way and numerical way.

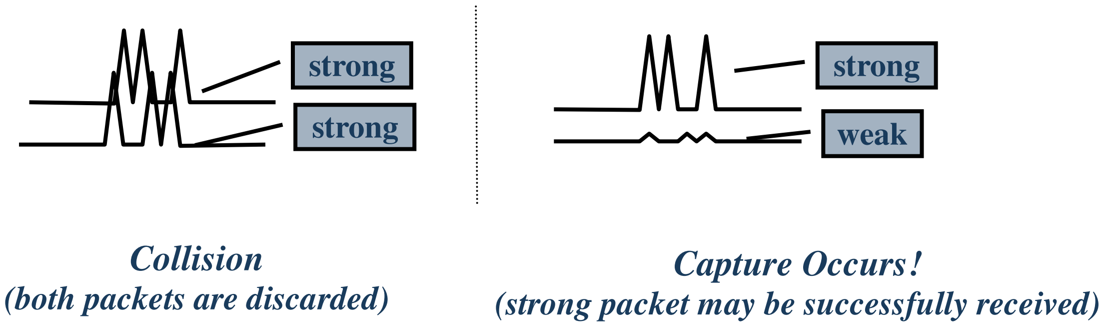


Figure 7: Capture effect in RFID applications

Figure 7 illustrates the phenomenon of capture when two tag signals collide, if the signal power is almost the same, both packets are discarded and can not be recognized by the reader, and if the signal power is of significant difference, then the stronger signal can be successfully recognized and capture occurs.

4.2 Related works on capture model

In order to predict the capture probability, which is the probability of successful reception in the presence of N packets collision, capture models has been built and has been widely adopted in wireless networks.

1) Distance-based model

$$P_{cap}(N) = P(\frac{r_2}{r_1} > a),$$

$$\text{a: capture ratio;}$$

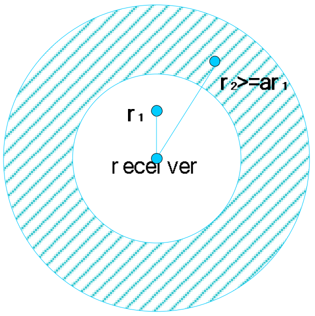


Figure 8: Distance based capture model

In this model, capture effect only occurs when the distance between two mobiles are large enough.

2) SIR-based model

$$P_{cap}(N) = P(SIR > z_0)$$

$$= P(\frac{P_{\text{desired}}}{P_{\text{interference}}} > z_0)$$

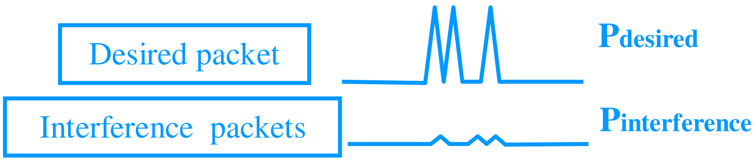


Figure 9: SIR-based capture model

In this model, capture effect only occurs when the signal to interference ratio (SIR) is large enough.

3) BER-based model

$$P_{cap}(N) = (1 - P_b)^L$$

L is the packet length;

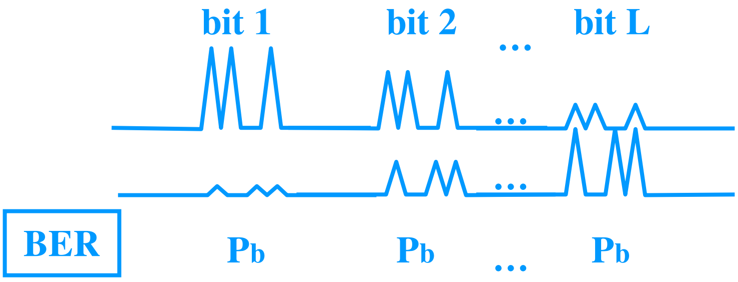


Figure 10: BER-based capture model

In this model, capture effect only occurs when the whole packet is successfully received without bit error.

The comparison of above three models is listed below.

Complexity: Model 1 < Mode 2< Model 3;

Accuracy: Model 1 < Mode 2< Model 3;

4.3 Capture probability for passive UHF RFID system

For the trade-off between complexity and accuracy, we take the SIR-based model as the RFID capture model here, which means the capture probability is determined by the following equations.

$$\begin{cases} P_{cap}(N) = N \cdot P\left(\dfrac{P_i}{\sum\limits_{j=1, j\neq i}^{N-1} P_j} > z_0\right) \\ P_i, or\, P_j = P_T \cdot \left(\dfrac{\lambda}{4\pi d_0}\right)^2 d^{-n} R^2 ge \cdot \eta \cdot g\left(\dfrac{\lambda}{4\pi d_0}\right)^2 d^{-n} R^2 \end{cases} \qquad (16)$$

where Z0 is the capture ratio, g is the antenna gain of tag, e is the polarization efficiency, ŋ is the backscatter ratio, $\left(\frac{\lambda}{4\pi d_0}\right)^2 d^{-n}$ is the large-scale path loss, n is the path loss exponent, R is Riciean fading variable with unit power and pdf as shown in equation 15.

This probability can be analytically evaluated in the case of Rayleigh fading (M. Zorzi, 1994) and in the absence of fading for the bell-shaped traffic model. In general, the computation can be performed efficiently via Monte Carlo simulation

4.4 Numerical results

The Monte Carlo simulation parameters are listed below.

Table II: Capture probability simulation parameters

Parameter Name	Value
Carrier Frequency	866 MHz
r0 (normalized)	0.3
r1 (normalized)	1
n (path loss exponent)	2
Capture ratio	6 dB (typical)
K (Ricean Factor)	6 dB (typical)
Confidence level	95%
Absolute error bound	1%

1) Pcap(N) vs N for different z0

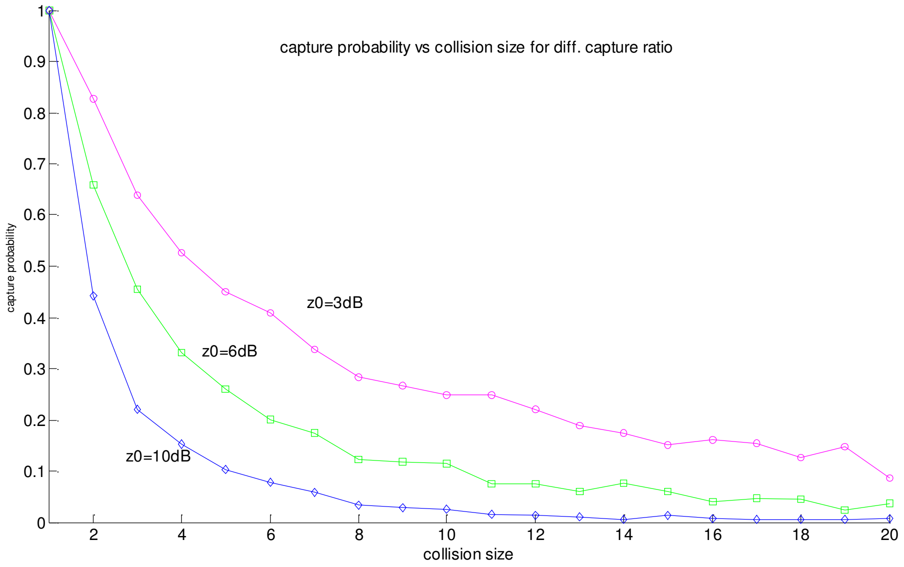


Figure 11: Pcap(N) vs collision size for different capture ratio

From Figure 11, we can see that capture probability strongly depends on the collision size and capture ratio, Pcap decreases when collision size goes high or capture ratio goes high, and increases when capture ratio goes down or collision size goes down.

2) P_{cap}(N)'s sensitivity on Rician factor, K

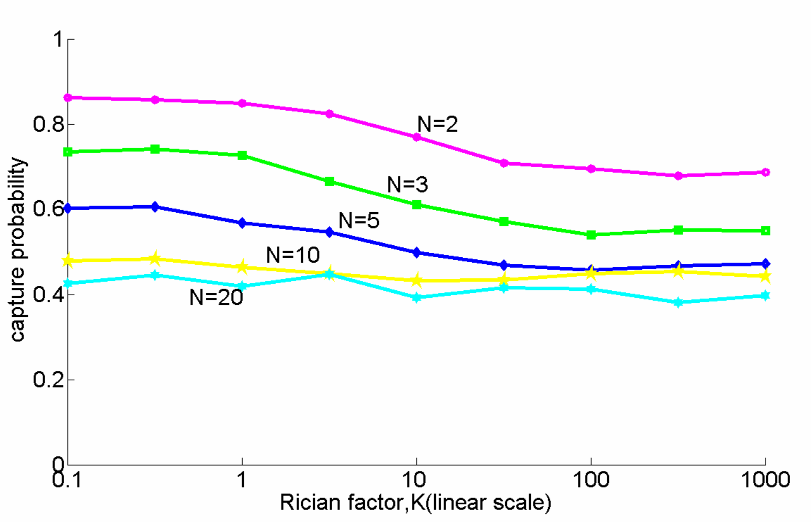


Figure 12: Pcap(N) vs Rician Factor for different collision size

From figure 12, we can draw the conclusion that capture probability is not sensitive on Rician Factor, especially when collision size is large (e.g. larger than 10).

3) Distance dependence of capture probability

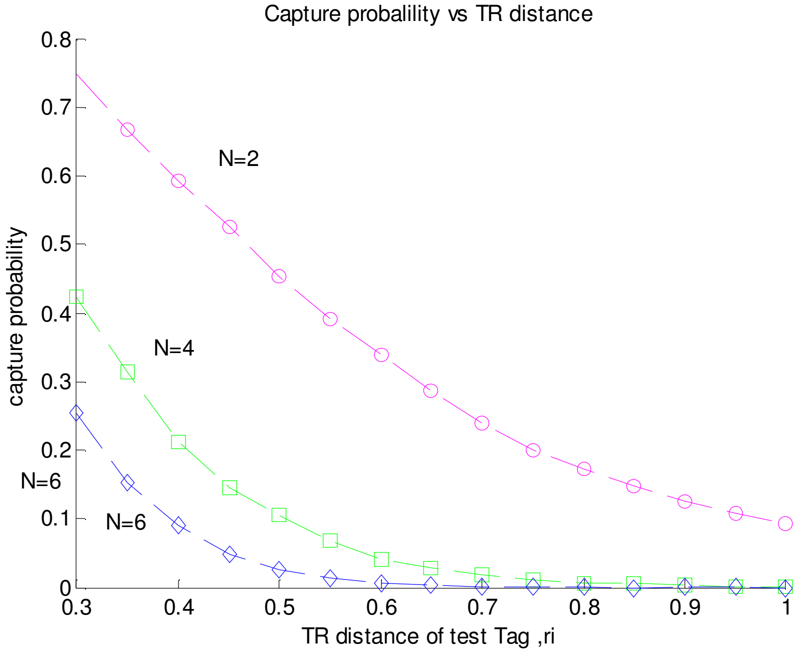


Figure 13: Pcap(N) vs TR distance for different collision size

In Figure 13, N tags are collided, one of them donated as “A” has a TR distance shown in the X-axis, the rest are placed randomly, the curves in the figure show the relation between Pcap(N) and TR distance for tag “A”. We can see that capture probability strongly depends on the collision size and capture ratio.

4.5 Discussion

From section 4.4, we draw the conclusion that when the collision size is small, the probability of successful capture is high. For example, capture probability is more than 60 percent with 2 tags collision and 6 dB capture ratio. This can give rise to significant change to performance analysis and anti-collision scheme development, which will be analyzed in the next sections.

5 Performance Analysis of Anti-Collision Schemes with and without Capture

The following simulation is based on the parameter specified in Table I, Table II and Table III.

Table III: Simulation Parameters

Parameter Name	Value
Amount of tags	100-1000
Initial Q	7

5.1 Schoute

1) System efficiency

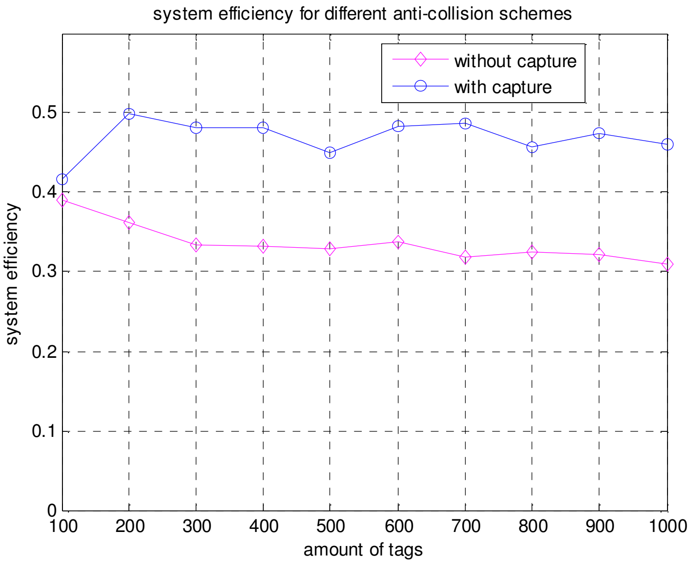


Figure 14: System efficiency of Schoute with and without capture

2) Throughput

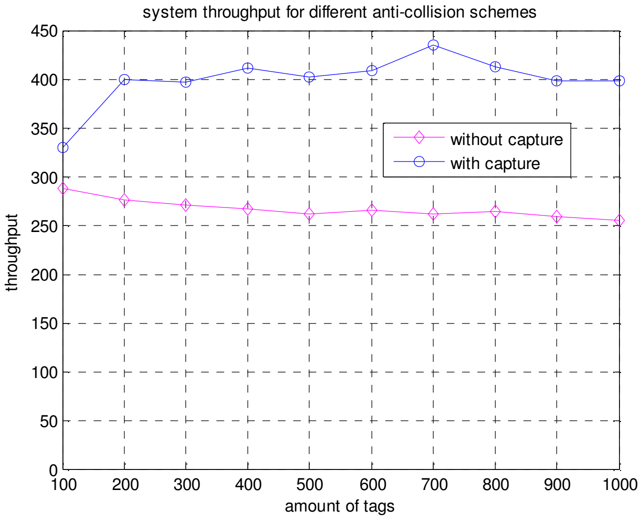


Figure 15: System throughput of Schoute with and without capture

5.2 Lower Bound

1) System efficiency

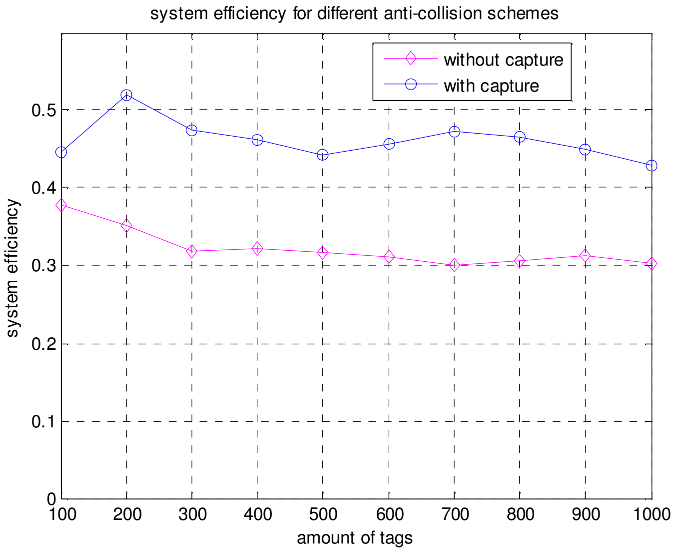


Figure 16: System efficiency of Lower Bound with and without capture

2) Throughput

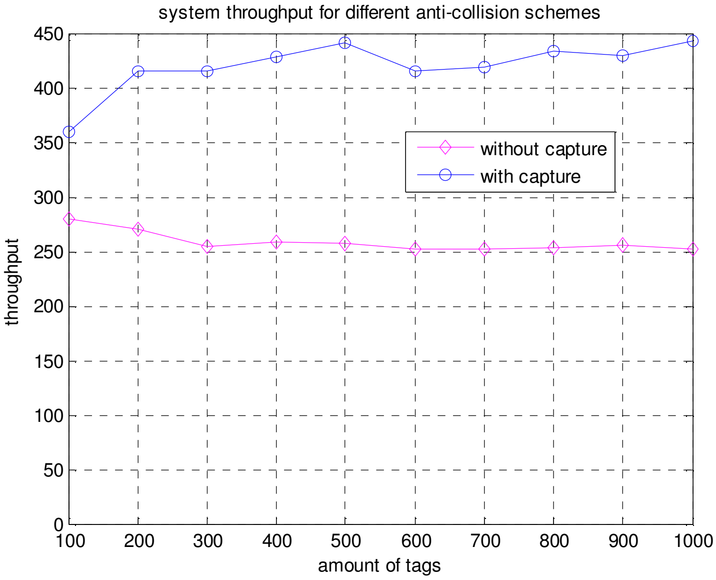


Figure 17: System throughput of Lower Bound with and without capture

5.3 Vogt

1) System efficiency

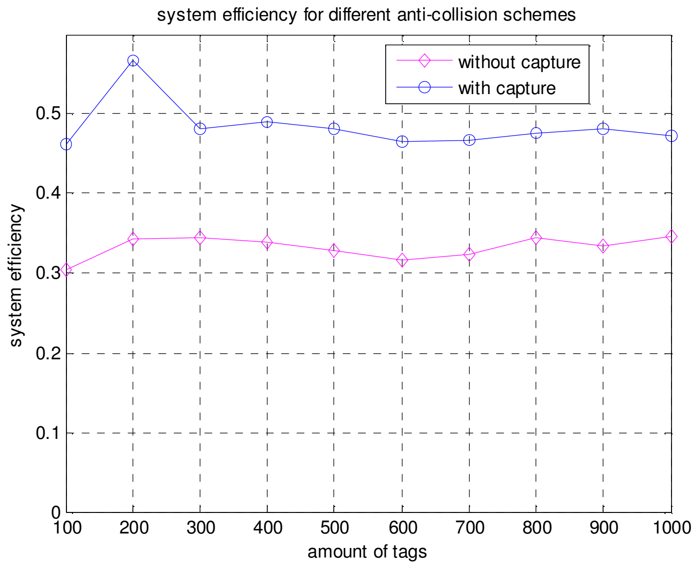


Figure 18: System efficiency of Vogt with and without capture

2) Throughput

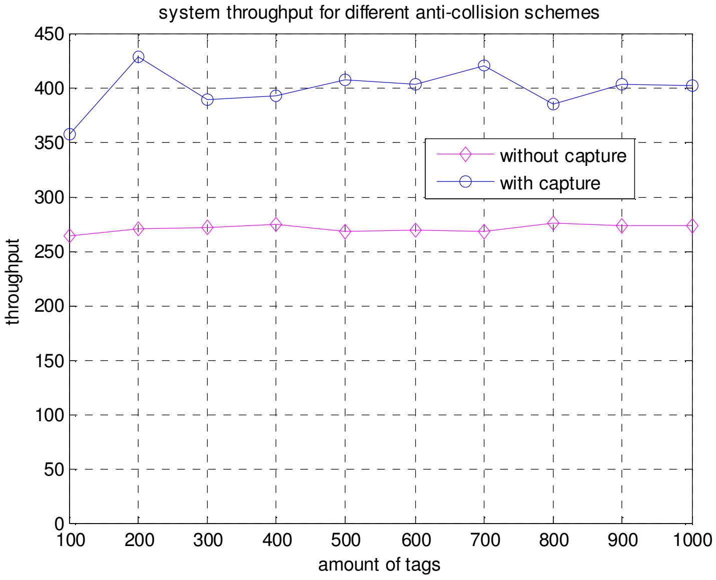


Figure 19: System throughput of Vogt with and without capture

5.4 Q Algorithm

1) System efficiency

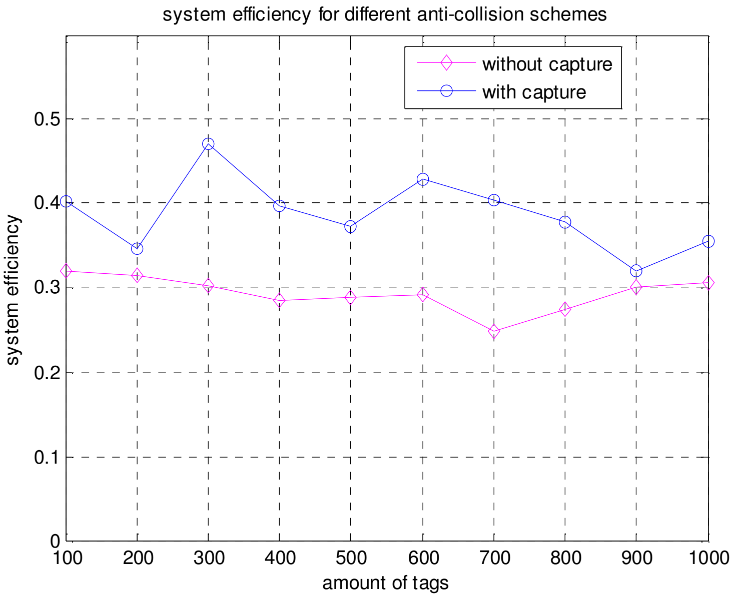


Figure 20: System efficiency of Q Algorithm with and without capture

2) Throughput

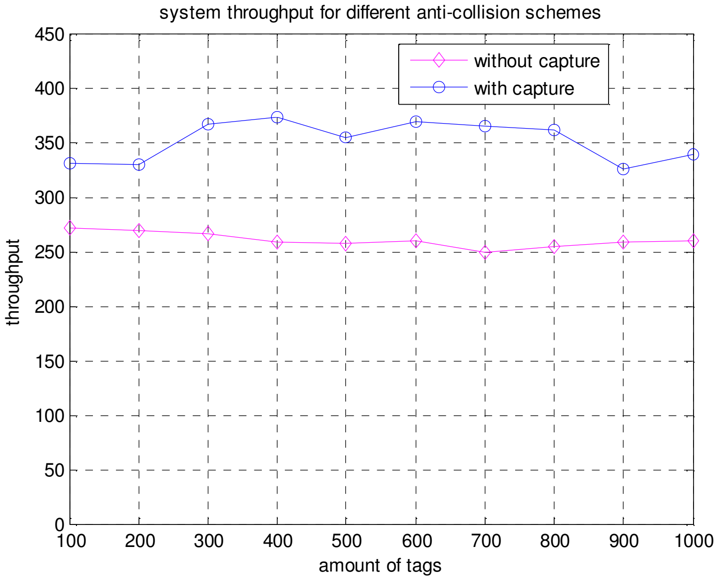


Figure 21: System throughput of Q Algorithm with and without capture

5.5 Chen

1) System efficiency

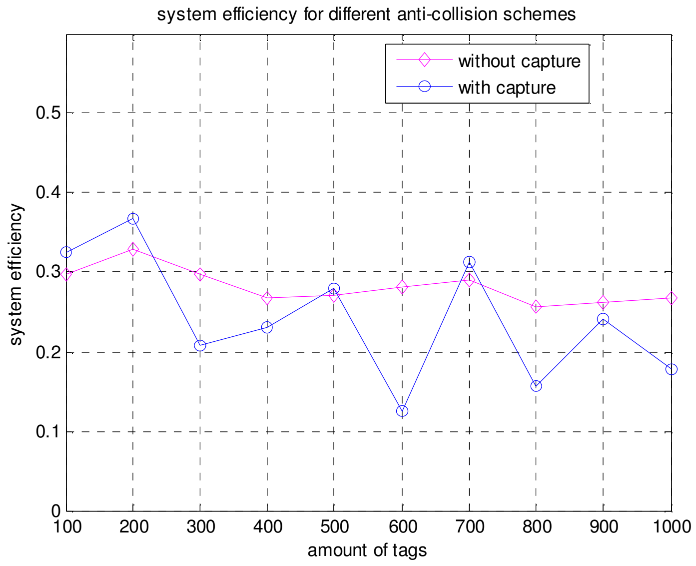


Figure 22: System efficiency of Chen with and without capture

2) Throughput

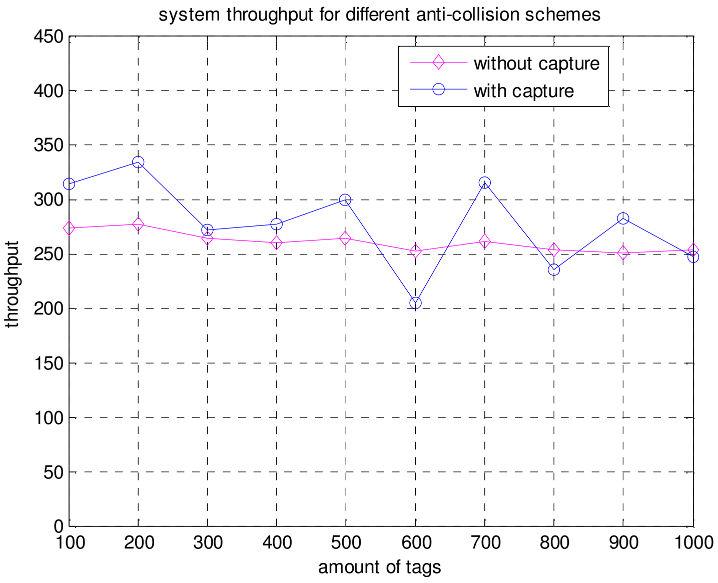


Figure 23: System throughput of Chen with and without capture

5.6 Conclusion

From the simulation results, we draw the conclusion that capture effect can significantly improve the RFID system performance. In average, the system efficiency increases from 30% to more than 40%, which is even higher than the upper bound of slotted aloha system efficiency from traditional analysis, and system throughput increases from 270 to 400 tags/second in average.

Since the anti-collision schemes adopted in above simulations are all developed without considering the capture effect, this situation provides us an interesting way to further improve the system performance, that is to say, to develop an anti-collision scheme which considers the capture effect.

6 Anti-Collision Scheme Development Considering Capture Effect

6.1 Considerations

For anti-collision schemes, there are two major differences depending on capture is considered or not.

1) Tag number estimation

The frame size estimation of traditional anti-collision schemes are based on the assumption that the value of last frame’s c0 (amount of empty slots), c1 (amount of single reply slots), ck (amount of collision slots) is precise, however, because of the existence of capture effect, the values that a reader can only obtain is c0, c1 + cp (amount of captured slots), ck-cp, as shown in equation 17. Then the error between assumption and realistic values occurs, degrades anti-collision performance.

$$\begin{cases} c0' = c0; \\ c1' = c1 + cp; \\ ck' = ck - cp; \end{cases}$$
$$\text{c0,c1,ck is the expected value,and c0',c1',ck' is the obtained value.} \qquad (17)$$

2) Optimum frame size

For the schemes not considering capture effect, the optimum frame size for Dynamic Framed Aloha algorithm is obtained by maximize the system efficiency shown in equation 3,as shown below again. The problem is that when capture is considered, system efficiency is no longer

$e=\frac{c1}{L}$ as shown in equation 3, but $e^{'}=\frac{c1+cp}{L}$ as shown in equation 18. L is the frame size, n is the tag population, c0/c1/ck/cp means number of empty slots, single tag occupied slots, collision slots and captured slots, respectively

$$e=\frac{c1}{L}=n\frac{1}{L}\left(1-\frac{1}{L}\right)^{n-1} \qquad (3)$$

$$e^{'}=\frac{c1+cp}{L} \qquad (18)$$

For the analytical convenience, here we adopt a linear capture model which means $cp=\alpha\cdot ck, \alpha\in[0,1]$.Under this assumption, system efficiency is then in the form of equation 19, as a function of L, n, and α.

$$\begin{aligned} e^{'}&=\frac{c1+\alpha\cdot ck}{L}=\frac{c1+\alpha\cdot(L-c1-c0)}{L} \\ &=\frac{n\left(1-\frac{1}{L}\right)^{n-1}+\alpha\cdot(L-n\left(1-\frac{1}{L}\right)^{n-1}-L\left(1-\frac{1}{L}\right)^{n})}{L} \end{aligned} \qquad (19)$$

To obtain the optimum frame size considering capture, let $\frac{\partial e^{'}}{\partial L}=0$, we get

$$L\_optimum=(1-\alpha)n+\alpha; \qquad (20)$$

Which strongly depends on α, the average capture probability. Figure 24 shows this relationship.

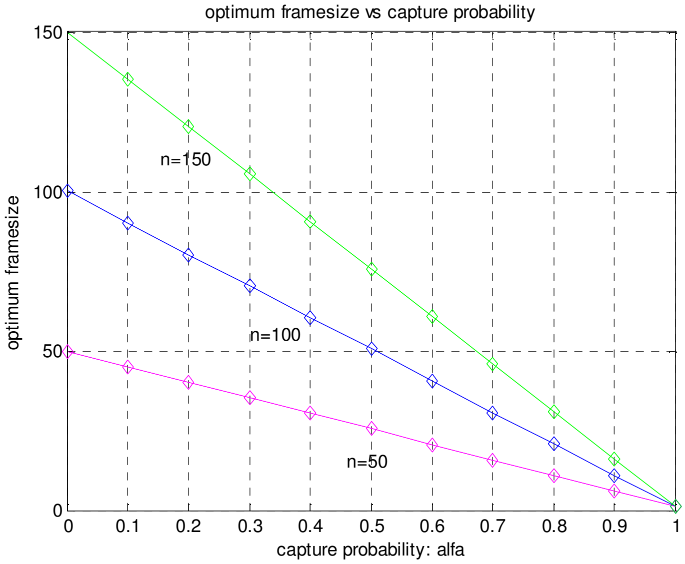


Figure 24: Relationship between L_optimum and n, α

6.2 Proposed Anti-collision Scheme

Based on the considerations in section 6.1, here we propose a improvement scheme for traditional anti-collision algorithms, the modifications are shown as follows.

1) Modified c0, c1, ck estimation scheme

As mentioned before, tag number estimation is the key process for Framed Aloha Anti-collision Algorithms, and the estimation is based on values of c0, c1, ck. Because of the existence of capture effect, the values that a reader can only obtain is c0, c1+cp(amount of captured slots), ck-cp, as shown in equation 17.

To obtain the actual values of c0, c1, ck, we propose this new scheme. Adopting a linear capture model $cp = \alpha \cdot ck$, we can get the actual c0,c1,ck from equation 17 as shown in equation 21.

$$\begin{cases} c0' = c0; \\ c1' = c1 + cp = c1 + \alpha \cdot ck; \\ ck' = ck - cp = (1-\alpha)ck; \end{cases} \Rightarrow \begin{cases} c0 = c0' \\ c1 = c1' - \alpha \dfrac{ck'}{(1-\alpha)} \\ ck = \dfrac{ck'}{(1-\alpha)} \end{cases} \tag{21}$$

c0,c1,ck is the expected value,and c0',c1',ck' is the obtained value.

2) Modified frame size updating scheme

As mentioned in section 6.1, the optimum frame size is no longer $L\_optimum = n$, but

$$L\_optimum = (1-\alpha)n + \alpha; \tag{22}$$

Other operations of the proposed anti-collision algorithm is remaining the same with traditional algorithms such as Schoute, lower bound, vogt, which indicates the compatibility between proposed scheme and traditional ones.

6.3 Simulation Results and Discussions

The following simulation is based on the parameter specified in Table I, II , and III .

1) Performance comparison of proposed scheme and traditional ones

We modified the Lower Bound and Schoute algorithms with our proposal scheme, getting simulation results as follows.

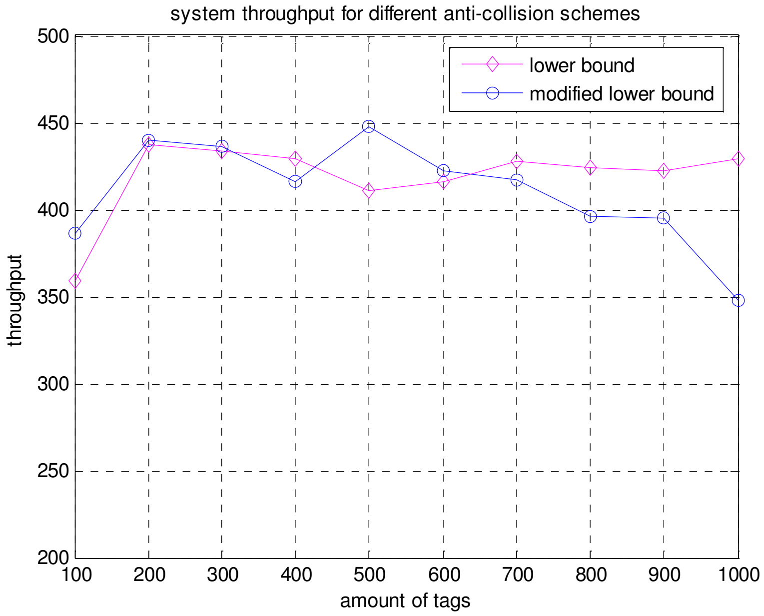


Figure 25: Throughput of lower bound and modified lower bound scheme

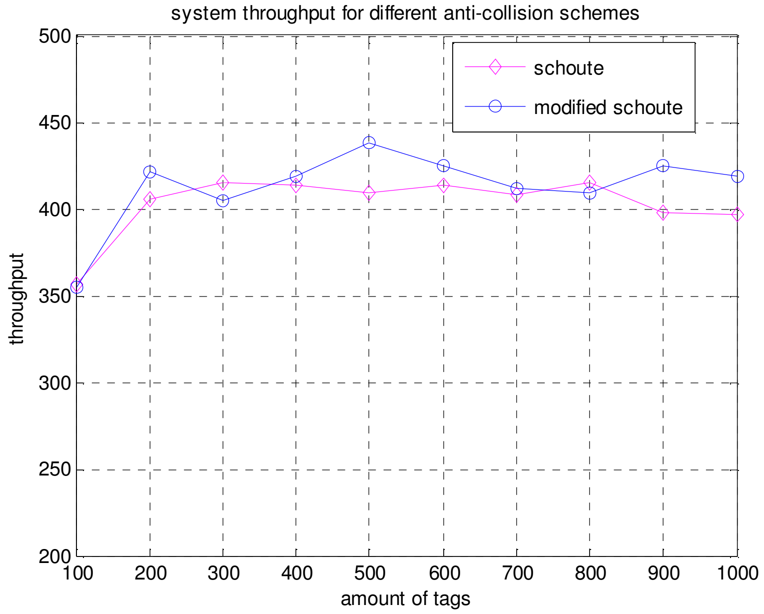


Figure 26: Throughput of schoute and modified schoute scheme

2) Discussions

In figure 25 and 26, it is obvious that there is almost no performance improvement for the proposed scheme, which seems like we get a wrong simulation result, because there should be an improvement based on the above analysis. However, this is a normal result, and we can explain it.

The major reason is the limited number of frame size available in RFID system compatible with C1 Gen2 protocol. The available frame sizes are limited to powers of two, for example, the index is a integer from 0 to 15 in C1 Gen2. This strongly degrades the tag number estimation performance in Anti-collision algorithms, for it can only estimate the index. That explains the situation in figure 25 and 26.

For example, the optimum frame size obtained from the modified Schoute algorithm is 90, and is 120 from traditional Schoute algorithm, these two values have a difference of 30, but they make no difference in C1 Gen2 protocol, because they all have to be changed to a value with powers of two, that is $128 = 2^7$.

According to the above analysis, we can draw the conclusion that the performance of anti-collision algorithms in C1 Gen2 system has almost reached its limit, and can hardly be improved even considering the capture effect. The proposed scheme can get a better performance in other applications, where the frame size can vary continuously.

6.4 System Capacity considering Capture Effect

From equation 3 and 4, we can get the system capacity without capture, which has a value of the well-known '1/e', as shown in equation 23.

$$\lim_{n\to\infty}\eta = \lim_{n\to\infty}\left(1-\frac{1}{n}\right)^{n-1} = \frac{1}{e} \qquad (23)$$

Considering capture effect, and based on the linear capture model, we can get the system capacity considering capture from equation 19 and 20, as shown in 24.

$$\lim_{n\to\infty}\eta' = \lim_{n\to\infty}\frac{c1+cp}{L} = \lim_{n\to\infty}\frac{c1+\alpha\cdot ck}{L} = \lim_{n\to\infty}\frac{c1+\alpha\cdot(L-c1-c0)}{L}$$

$$\overset{L=(1+\alpha)n+\alpha}{=} \lim_{n\to\infty}\frac{n\left(1-\frac{1}{L}\right)^{n-1}+\alpha\cdot(L-n\left(1-\frac{1}{L}\right)^{n-1}-L\left(1-\frac{1}{L}\right)^{n})}{L}$$

$$\lim_{n\to\infty}\eta' = \alpha+(1-\alpha)e^{-\frac{1}{1-\alpha}} \qquad (24)$$

Figure 27 shows the difference between η and η', $\eta=\eta'$ only when α =0.

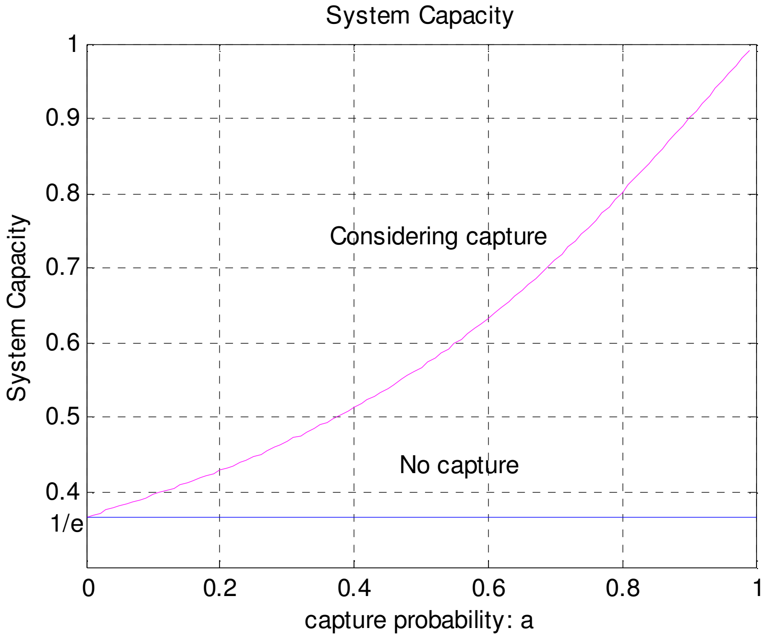


Figure 27: System capacity for no capture and considering capture

7 Conclusion

In this whitepaper, we systematically analyzed the anti-collision issues for C1 Gen2 compatible RFID systems. The contributions and conclusions of this whitepaper are listed as follows.

1) Comprehensive system model based on Matlab is presented

This model not only contains behaviour model of reader and tag, propagation model of wireless indoor channel, but also the tag distribution model and capture model.

This model can support the anti-collision simulation well, and is easy to extend to physical level using Simulink since it is based on Matlab.

2) Capture effect in RFID system is analyzed systematically

Although capture effect analysis is not new in communication systems, the analysis in RFID system is still very limited. In this whitepaper, we presented a capture model, and analyzed the capture probability analytically and numerically.

We also observed that when the collision size is small, the capture probability is high, which means in most of the cases when only two or three tags are collided, one tag can still probably be recognized. This leads us to pay special attention to the anti-collision scheme development considering capture effect.

3) Analysis of anti-collision algorithms in C1 Gen2 RFID system

We presented the mathematical fundamentals of anti-collision algorithms, and compared the performance of widely used algorithms, like Lower Bound, Schoute, Vogt, Q Algorithm, and Chen.

4) Novel anti-collision scheme development considering capture effect

Based on the new considerations of the existence of capture, we proposed a novel tag number estimation scheme and a new optimum frame size equation, which can improve the system performance in theory.

However, because of the limited frame size nature of C1 Gen2 system, the proposed scheme can hardly get remarkable improvement, which indicated that the anti-collision performance of C1 Gen2 system has almost reached its limit now. The limit denoted as system capacity considering capture effect is also presented.

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