“物联网技术导论”课程专题报告

专题1：RFID的识别与估算机制

谢磊 教授

南京大学计算机科学与技术系

主要内容：

一、RFID的基本通信原理

二、基于时隙ALOHA的标签识别机制

三、RFID标签估算机制（ Estimation ）

四、开放性问题(Open Problem ）

五、参考文献

RFID的基本通信原理-1

- Far-Field Propagation and Backscatter Principle

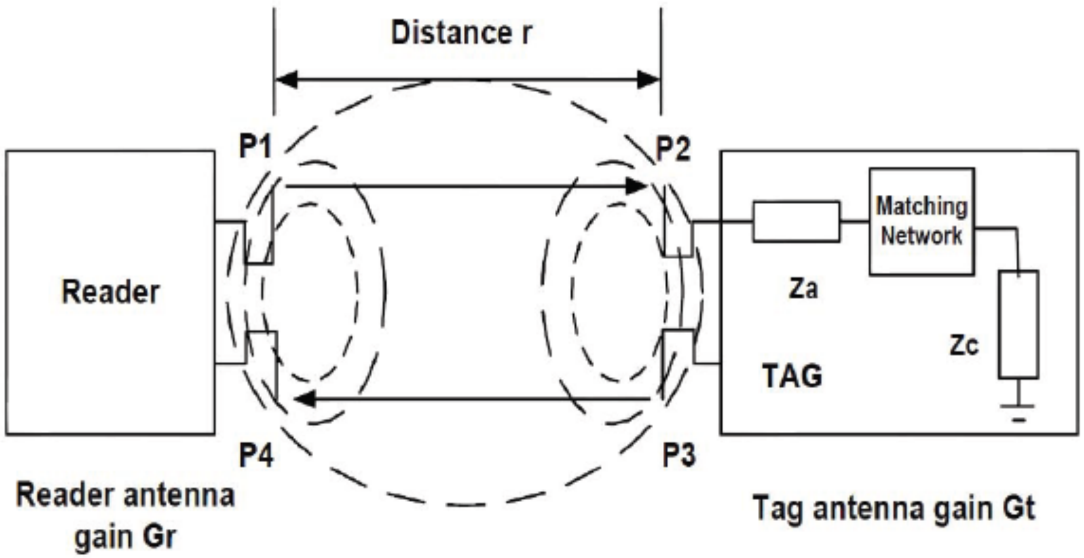


Fig. 1. Far-Field Propagation for RFID system

RFID的基本通信原理-2

- Far-Field Propagation and Backscatter Principle
  - We denote the down-link communication from the reader to a tag as the *forward channel*, and denote the up-link communication from a tag to the reader as the *reverse channel*.

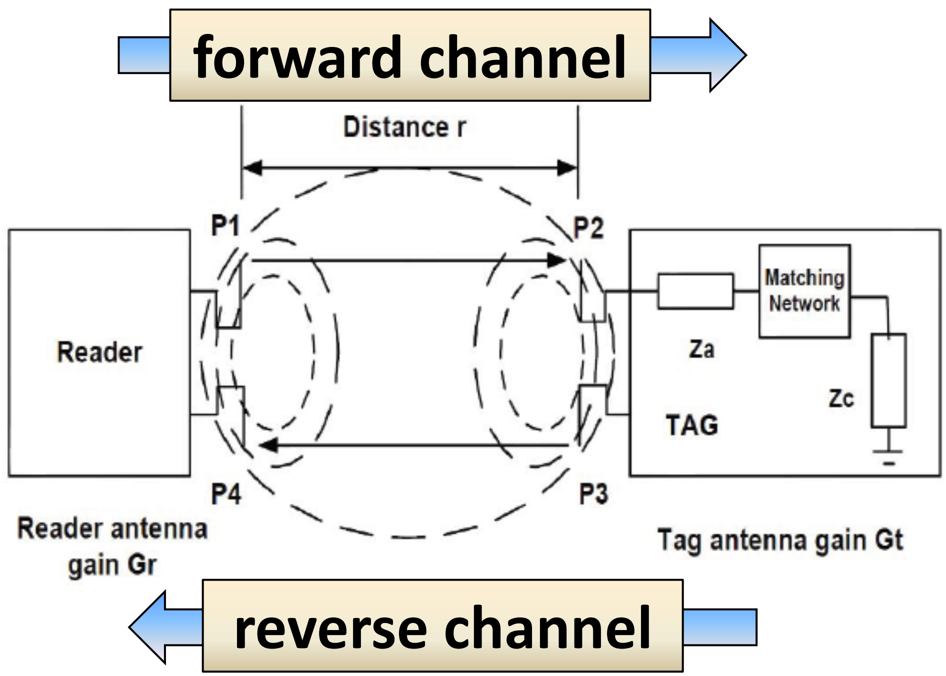


Fig. 1. Far-Field Propagation for RFID system

RFID的基本通信原理-3

- Far-Field Propagation and Backscatter Principle
  - For successful reading of a passive tag with the backscatter scheme, there are two thresholds to meet the physical requirements. The first is the ***tag power (sensitivity) threshold, Pts***. It is the minimum received power necessary to turn on an RFID chip. The second is the ***reader sensitivity threshold, Prs***. It is the minimum level of the tag signal that the reader can detect and resolve.

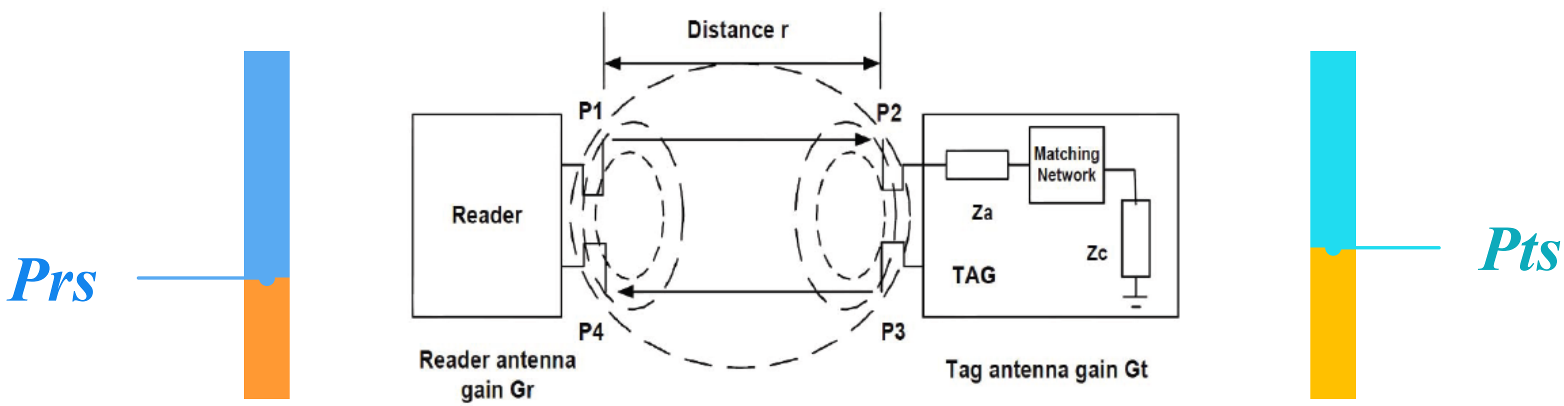


Fig. 1. Far-Field Propagation for RFID system

RFID的基本通信原理-4

- Far-Field Propagation and Backscatter Principle
  - Thus it must satisfy ***P2 > Pts*** for the tag to be powered up and resolve the received signal, and also ***P4 > Prs*** for the reader to detect and resolve the received signal.

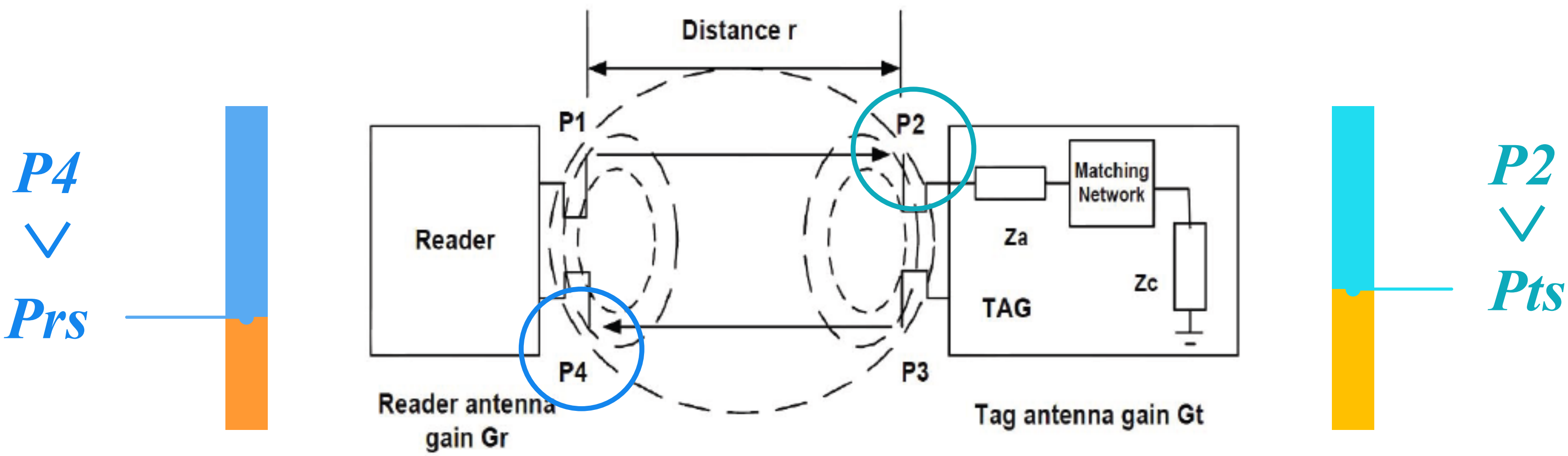


Fig. 1. Far-Field Propagation for RFID system

基于时隙ALOHA的标签识别机制-1

- Tag inventory and access

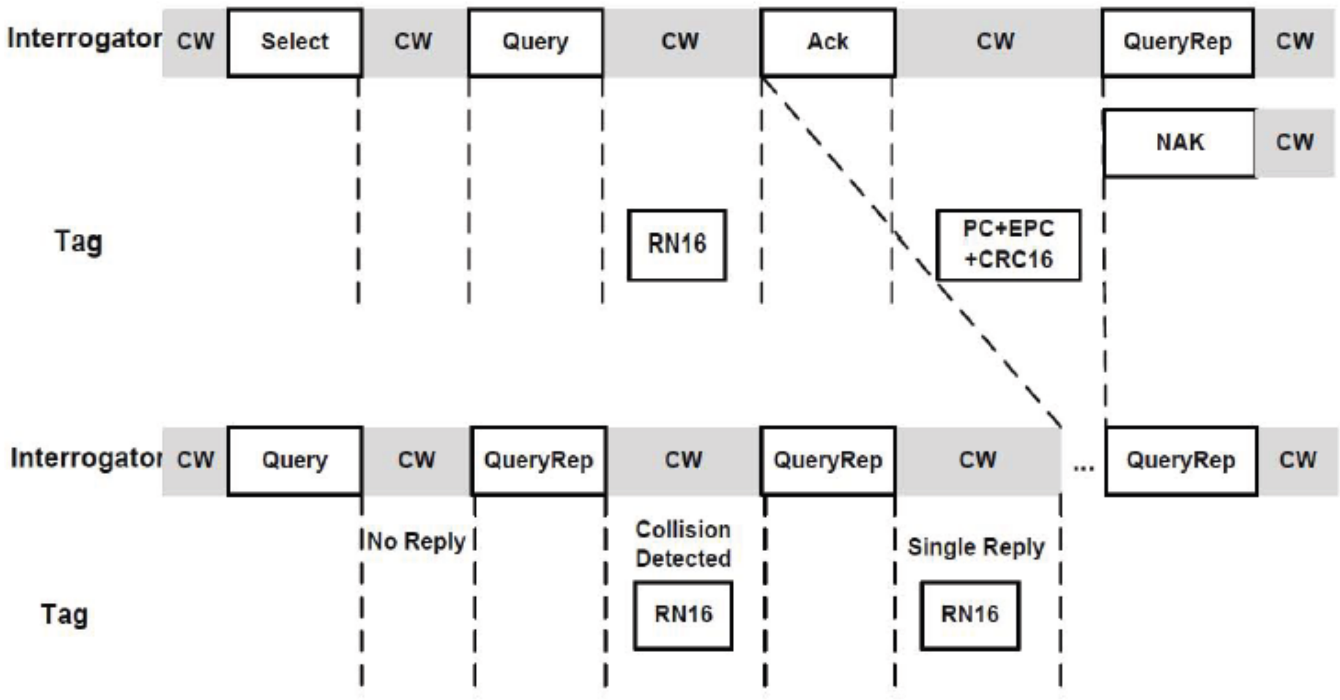
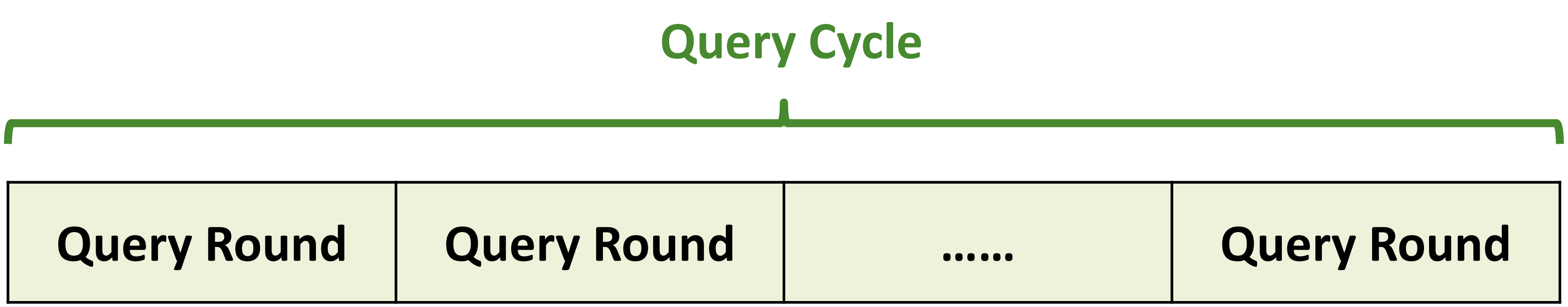


Fig. 2. C1G2 protocol

基于时隙ALOHA的标签识别机制-2

- Tag inventory and access
  - The MAC protocol for the C1G2 system is based on *Slotted ALOHA*, where each frame has a number of slots and each active tag will reply in a randomly selected slot per frame.
  - When a reader (interrogator) wishes to read a set of tags, it first powers up and transmits a continuous wave (CW) to energize the tags. It then initiates a series of frames, varying the number of slots in each frame to best accommodate the number of tags. After all tags are read, the reader powers down. We refer to an individual frame as a ***Query Round***, and the series of ***Query Rounds*** between power down periods as a ***Query Cycle***.



基于时隙ALOHA的标签识别机制-3

- Tag inventory and access
  - For each ***Query Round***, the reader can optionally transmit a ***Select*** command which limits the number of active tags by providing a bit mask. Then a ***Query*** command is transmitted which contains the uplink frequency and data encoding, the ***Q*** parameter determining the number of slots for the following frame, and a *Target* parameter.

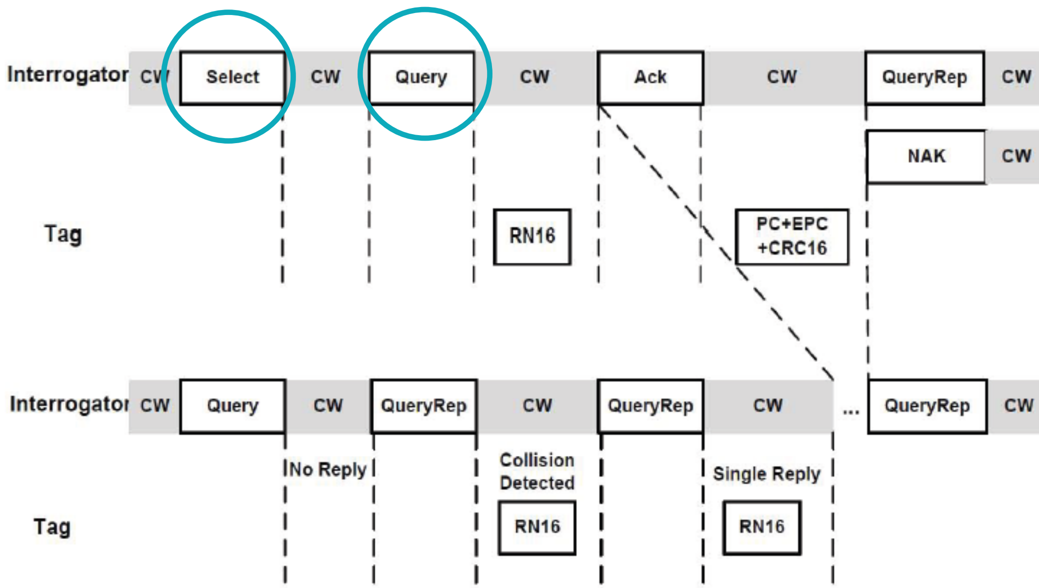


Fig. 2. C1G2 protocol

基于时隙ALOHA的标签识别机制-4

- Tag inventory and access
  - When a tag receives a ***Query*** command, it chooses a random number in the range (0, $2^{Q}-1$), where $\boldsymbol{Q}$ is in the range (0,15), and the value is stored in the slot counter of the tag. If a tag stores a 0 in its slot counter, it will immediately backscatter a 16 bit random number, denoted by ***RN16***.

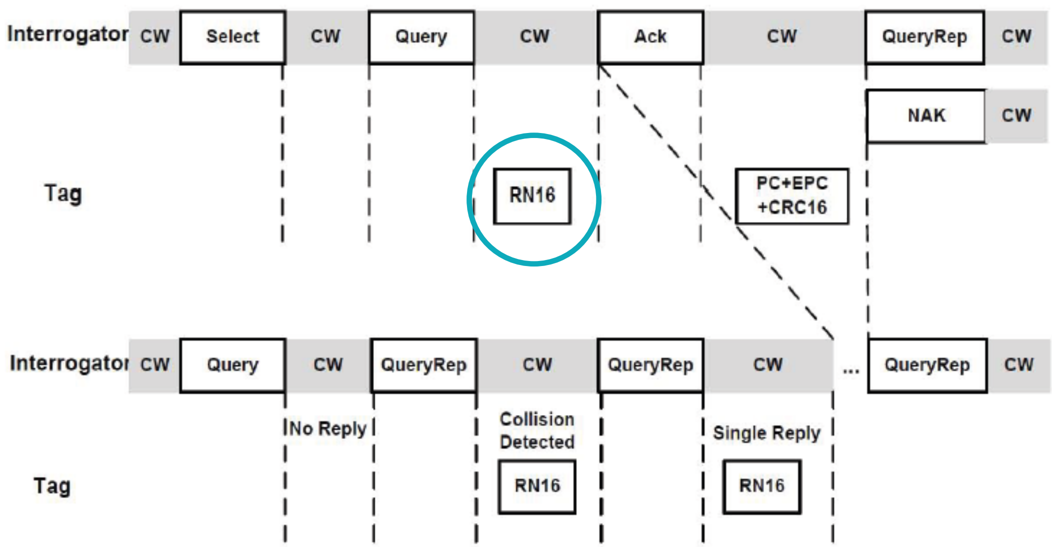


Fig. 2. C1G2 protocol

基于时隙ALOHA的标签识别机制-5

- Tag inventory and access
  - Upon receiving ***RN16***, the reader will echo ***RN16*** in an ***ACK*** command. If the tag successfully receives ***RN16***, it will backscatter its ID information (*PC+EPC+CRC16*). Then a subsequent ***QueryRep*** command will be sent to the tag, signaling the end of the slot and toggling an ***inventoried*** flag in the tag to make it keep silent in the following rounds.

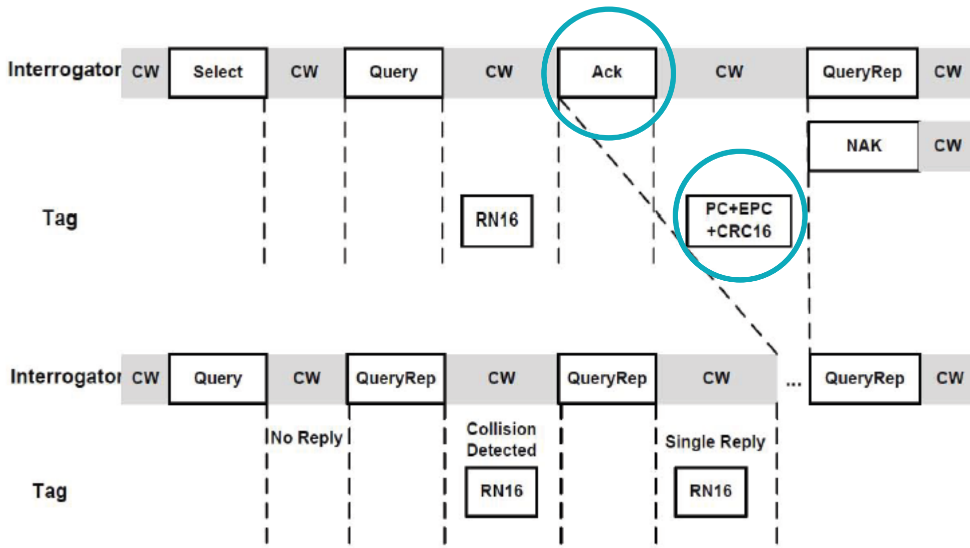


Fig. 2. C1G2 protocol

基于时隙ALOHA的标签识别机制-6

- Tag inventory and access
  - If the ID is not successfully received by the reader, an ***NAK*** command is sent which resets the tag so as to keep the tag active in the next round.
  - Upon receiving the ***QueryRep*** command, the remaining tags will decrement their slot counters, and respond with ***RN16*** if their slot counters are set to 0. When the number of ***QueryReps*** is equal to 2^Q, the current ***QueryRound*** ends.

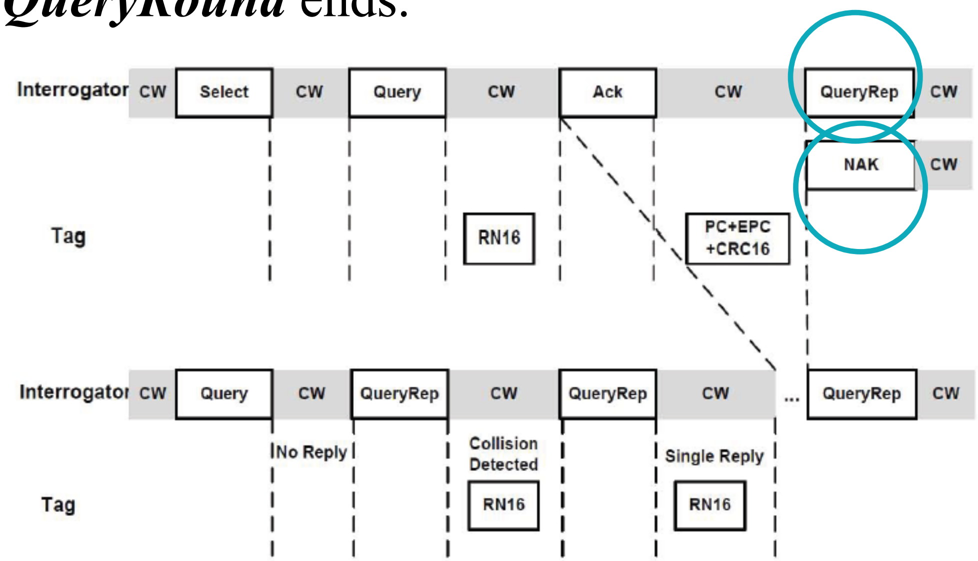
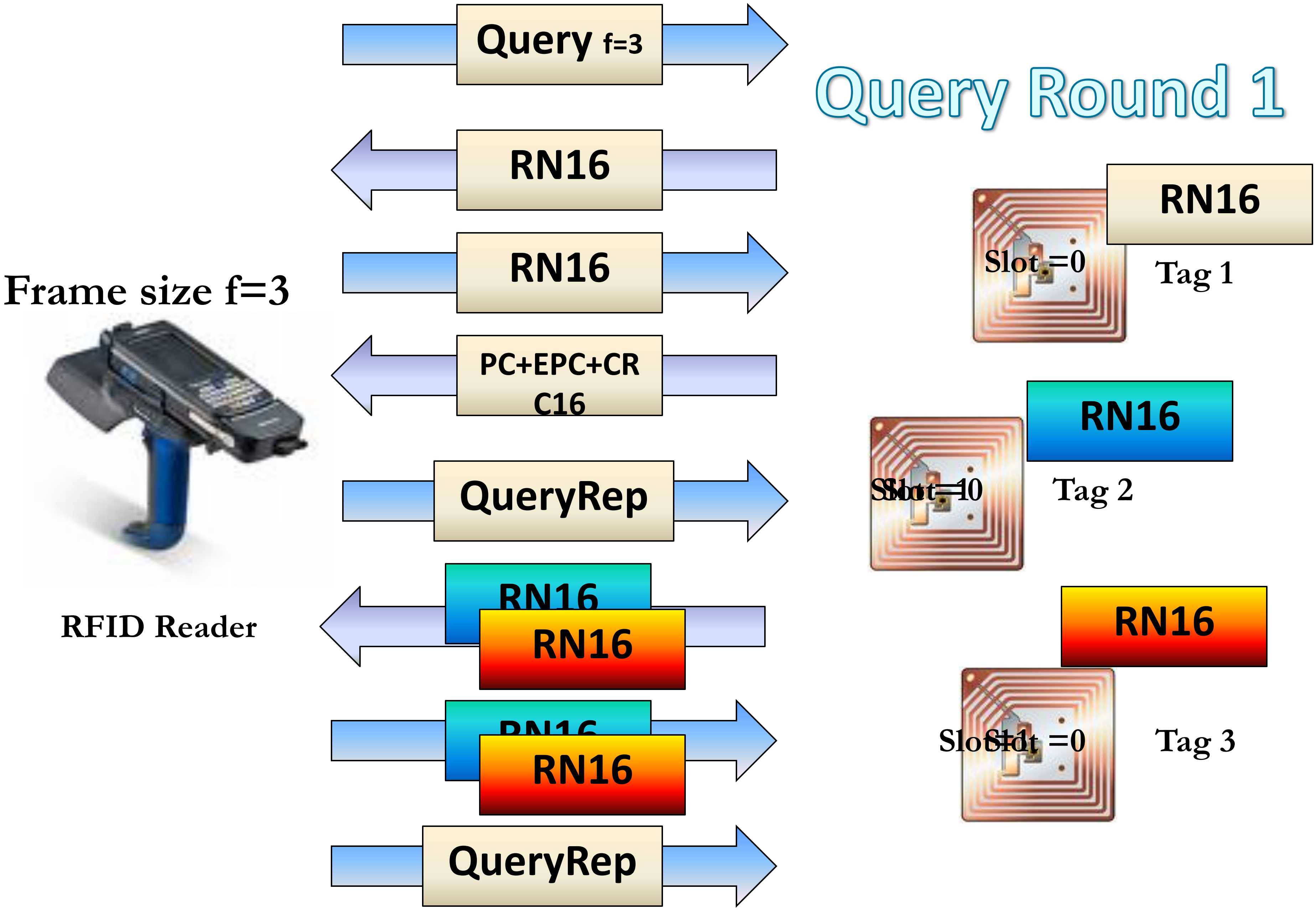
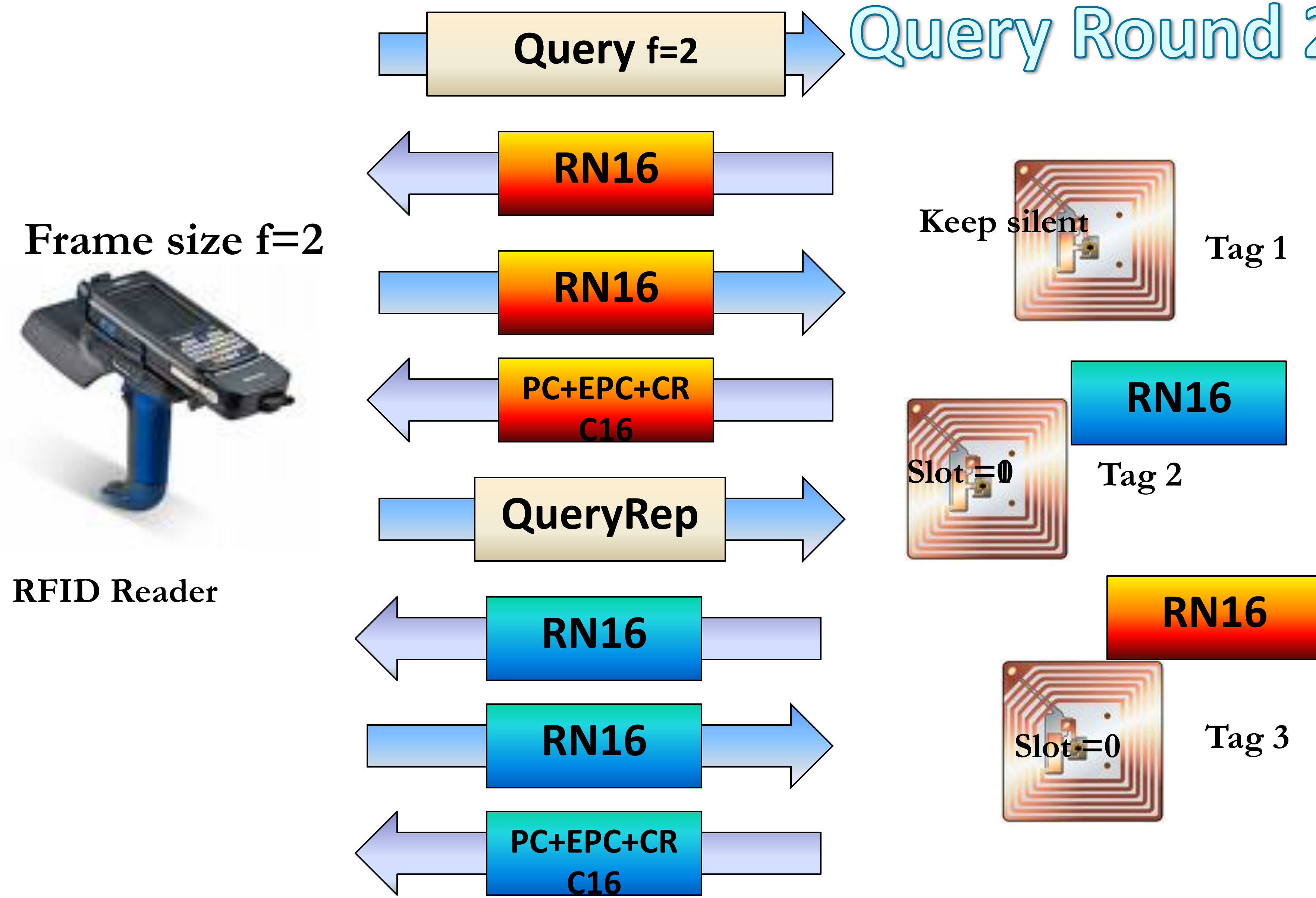


Fig. 2. C1G2 protocol

Query Round 1

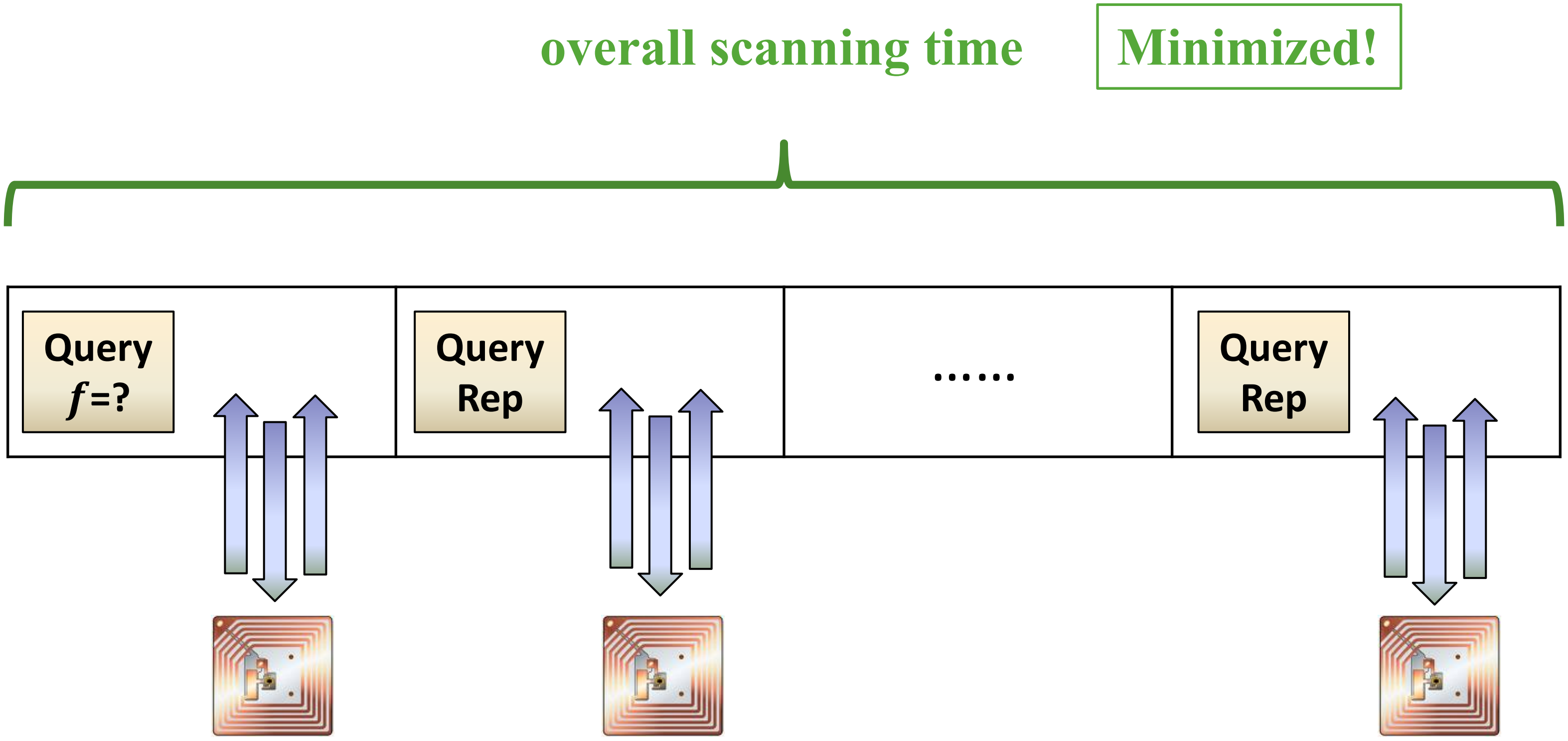


Query Round 2



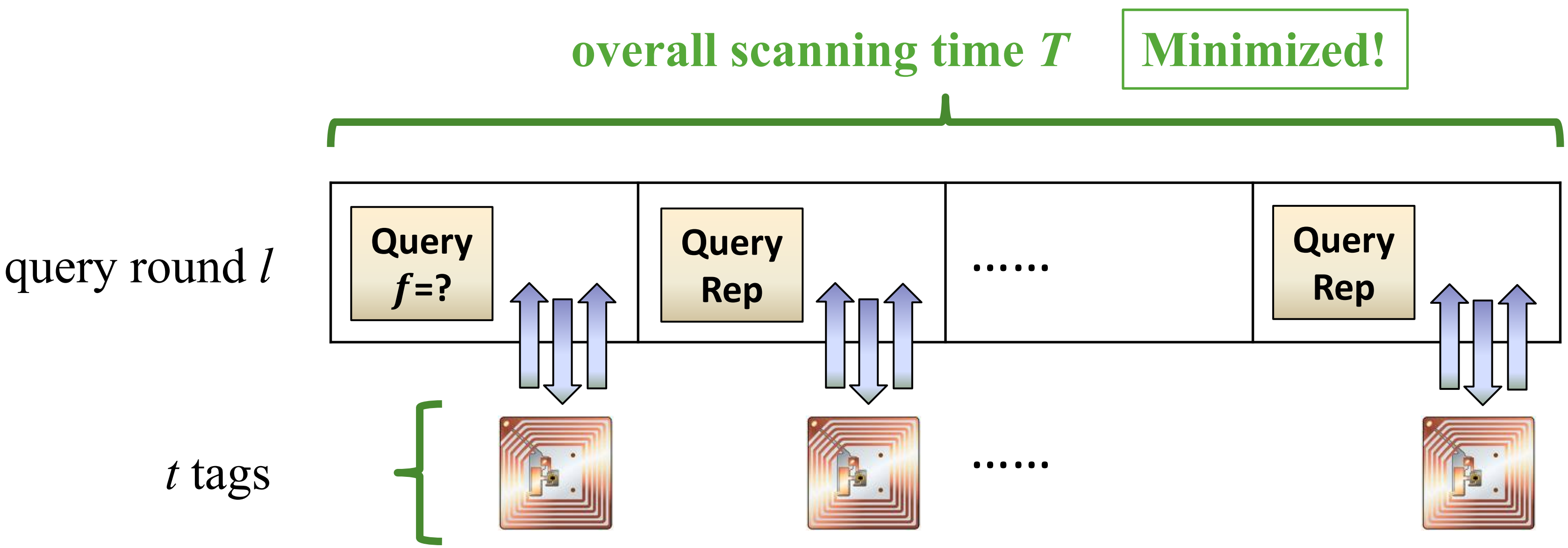
基于时隙ALOHA的标签识别机制-7

- Efficiency Problem:
  - How to select an optimized frame size *f* for each query round such that the overall scanning time can be minimized?



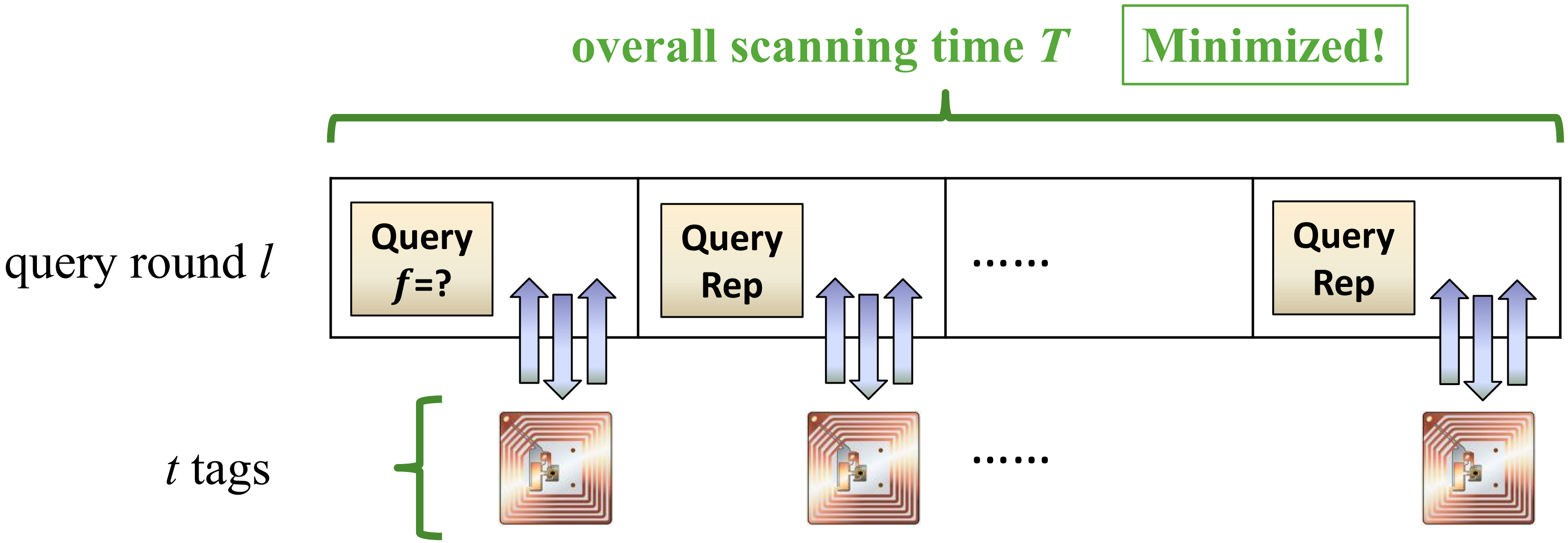
基于时隙ALOHA的标签识别机制-8

- Problem Formulation
  - The reader is essential to issue a number of *query rounds* to finish identifying all tags. Suppose in a certain *query round l*, the frame size is *f*, the number of remaining tags is *t*, the objective is how to set a frame size *f* for each query round, such that the overall scanning time *T* (or: overall number of slots) is minimized while finishing reading all tags.



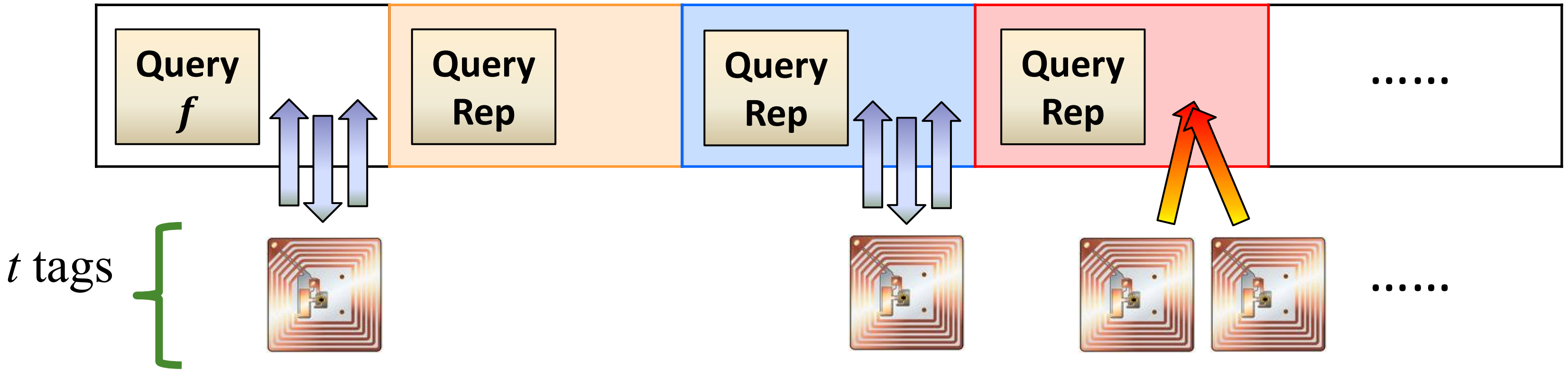
基于时隙ALOHA的标签识别机制-9

- Solution:
  - Modeling
  - Compute the optimal frame size



基于时隙ALOHA的标签识别机制-10

- ***Lemma 1***. Let (*N0*,*N1*,*Nc*) represent the number of time slots with no transmissions, one transmission and collision respectively in a system with t tags and frame size f. Let ρ = t/f. Then
  - $E[N0] \approx f e^{-\rho}$
  - $E[N1] \approx f \rho e^{-\rho}$
  - $E[Nc] \approx f(1 - (1 + \rho) e^{-\rho})$



基于时隙ALOHA的标签识别机制-11

- Proof:

$$\lim_{x\to+\infty}\left(1-\frac{1}{x}\right)^x=\frac{1}{e}$$

- Slot j will be empty if none of the tags transmit in that slot. Therefore, $Pr[X_j = 1] = (1-\frac{1}{f})^t \approx e^{-\rho}$. This implies that $E[N0] = \sum_{j=1}^{f} Pr[X_j = 1] \approx f\, e^{-\rho}$.

- Similarly, $Pr[Y_j = 1] = t\,\frac{1}{f}(1-\frac{1}{f})^{t-1} \approx \rho e^{-\rho}$, and $E[N1] = \sum_{j=1}^{f} Pr[Y_j = 1] \approx f\,\rho\, e^{-\rho}$

- Since $X_j + Y_j + V_j = 1$ for all j, $E[Nc] = \sum_{j=1}^{f} Pr[V_j = 1] \approx f - fe^{-\rho} - f\,\rho\, e^{-\rho}$

基于时隙ALOHA的标签识别机制-12

- The portion of singleton slots inside each frame is $E[N1]/f \approx \rho\, e^{-\rho}$.
- Then in order to maximize the portion of singleton slots inside each frame, we compute $\frac{\partial E[N1]/f}{\partial f} = 0 \rightarrow f^* = t$. In this way, $E[N1]/f^* = \frac{1}{e}$.
- It infers that, during each *query round*, when the frame size *f* is equal to the remaining number of tags *t*, the portion of singleton slots inside each frame is maximized. Then *the local optimum* is achieved.
- Furthermore, as the efficiency over all *query rounds* is $\frac{1}{e}$, which is the upper bound of efficiency among all *query rounds*, thus actually *the global optimum* is achieved.

RFID标签估算机制（Estimation）

- Problem in RFID deployment:
  - **Quick estimation of the number of tags in the field up to a desired level of accuracy**

RFID标签估算机制（Estimation）

- Prior work in this area: focus on the identification of tags
  - needs more time
  - unsuitable for many situations, especially where the tag set is dense

RFID标签估算机制（Estimation）

- Prior work in this area: focus on the identification of tags
  - needs more time
  - unsuitable for many situations, especially where the tag set

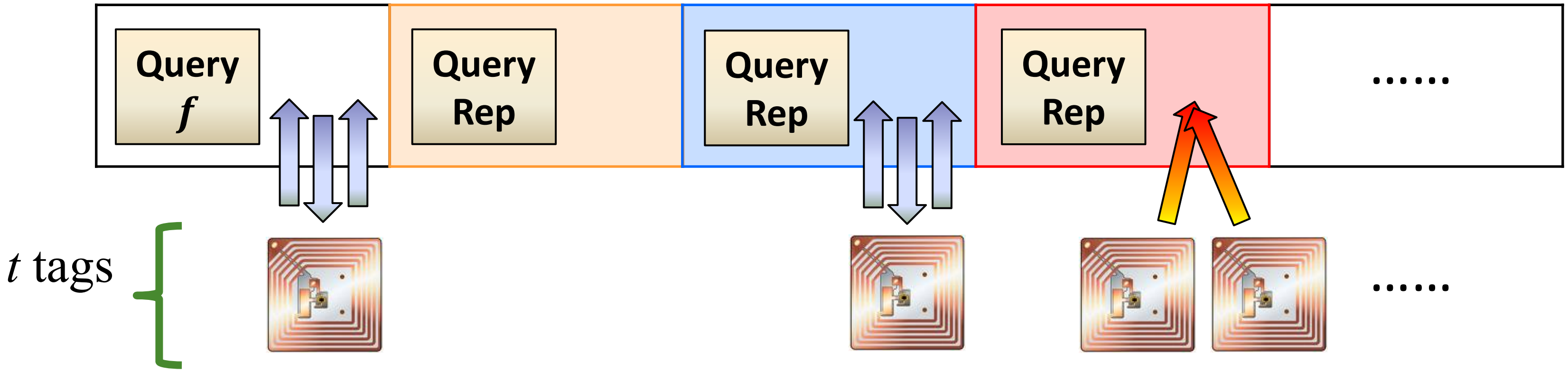
How to **fast estimate** the cardinality of tags based on the number of empty /singleton /collision slots, while **achieving the required accuracy requirement**?

RFID标签估算机制（Estimation）

- Problem formulation
  - Given a set of t tags in the system, the reader has to estimate the number of tags in the system with an confidence interval of width β, i.e., we want to obtain an estimate t' such that $\frac{t'}{t} \in (1 - \frac{\beta}{2}, 1 + \frac{\beta}{2})$ with probability greater than α. In other words, we need maximum error to be at most $\pm\frac{\beta t}{2}$ with probability greater than α.
  - A sample problem would be to estimate the number of tags within $\pm 1\%$ of the actual number of tags with probability greater than 99.99 %.

RFID标签估算机制（Estimation）

- ***Lemma 1***. Let (*N0*,*N1*,*Nc*) represent the number of time slots with no transmissions, one transmission and collision respectively in a system with t tags and frame size f. Let $\rho = t/f$. Then
  - $E[N0] \approx f e^{-\rho}$
  - $E[N1] \approx f \rho e^{-\rho}$
  - $E[Nc] \approx f(1 - (1 + \rho) e^{-\rho})$



RFID标签估算机制（ Estimation ）

- The reader measures ($n0$, $n1$, nc). From Lemma 1, we know that the expected number of **empty slots** is $f e^{-\rho}$, or the fraction of empty slots is $e^{-\rho}$. From the current measurement the reader observes that the fraction of empty slots is $n0/f$. Equating the expected value and the observed value, the reader now determines ρ_0 that solves $e^{-\rho_0} = n_0/f$ and sets $t_0 = f\rho_0$. Similarly, the reader can get estimates for t from the **singleton slots** as well as **the collision slots**. We show the three estimates in Table I.

Estimator	Problem to be Solved
ZE: Zero Estimator t_0	$e^{-(t_0/f)} = n_0/f$
SE: Singleton Estimator t_1	$(t_1/f)\ e^{-(t_1/f)} = n_1/f$
CE: Collision Estimator t_c	$1-(1+(t_c/f))\ e^{-(t_c/f)} = n_c/f$

Table 1: Estimators for t

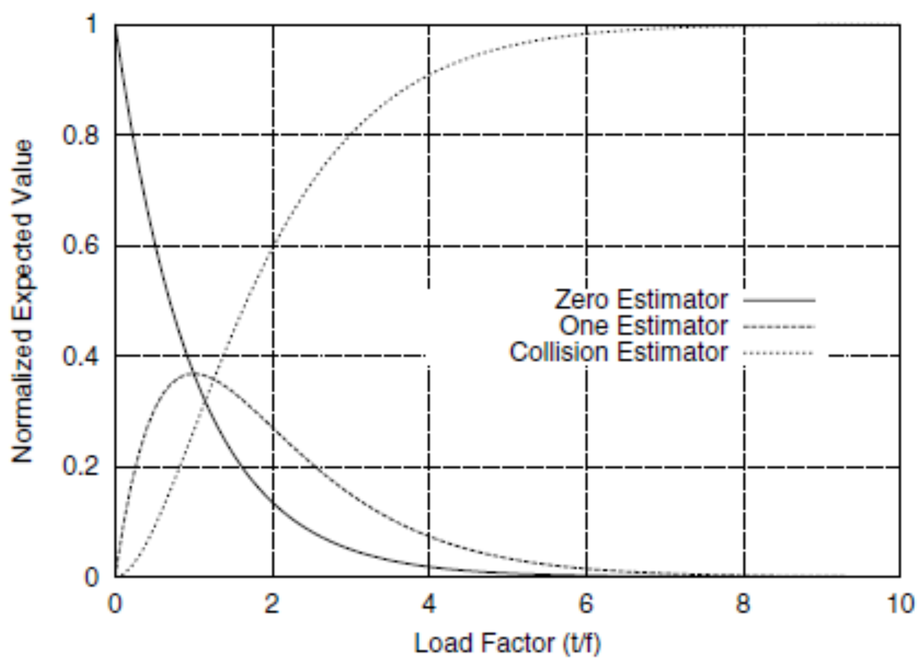
RFID标签估算机制（Estimation）

- It is easy to solve for the estimator *t*0 in **closed form** but the other two estimators involve solving a **non-linear equation** in one variable.
- A simple **bisection search or Newton's method** can be used to solve the equation, since the estimation functions shown above are **well behaved** and therefore both these methods converge very quickly.
- We can also use the fact that the estimate has to be an **integer** to terminate the search once we know the interval of uncertainty is less than one.

RFID标签估算机制（Estimation）

- The three estimators have very different characteristics.
- In Figure 1 we plot the normalized expected values, $E[N0]/f$, $E[N1]/f$ and $E[Nc]/f$ as functions of the load factor ρ. **Note that the curves for empty slots and collision slots are monotonic in ρ but singleton slots is non-monotonic.**

单调性



RFID标签估算机制（ Estimation ）

- **Accuracy of the Estimators**

THEOREM 2. *Let* $t, f \to \infty$ *while maintaining* $t/f = \rho$. *Then*

$$[g_0(N_0) - g_0(\mu_0(t))] \sim \mathcal{N}[0, \delta_0]$$

and

$$[g_c(N_c) - g_c(\mu_c(t))] \sim \mathcal{N}[0, \delta_c]$$

where

$$\delta_0 = t\frac{(e^\rho - (1+\rho))}{\rho} \qquad (1)$$

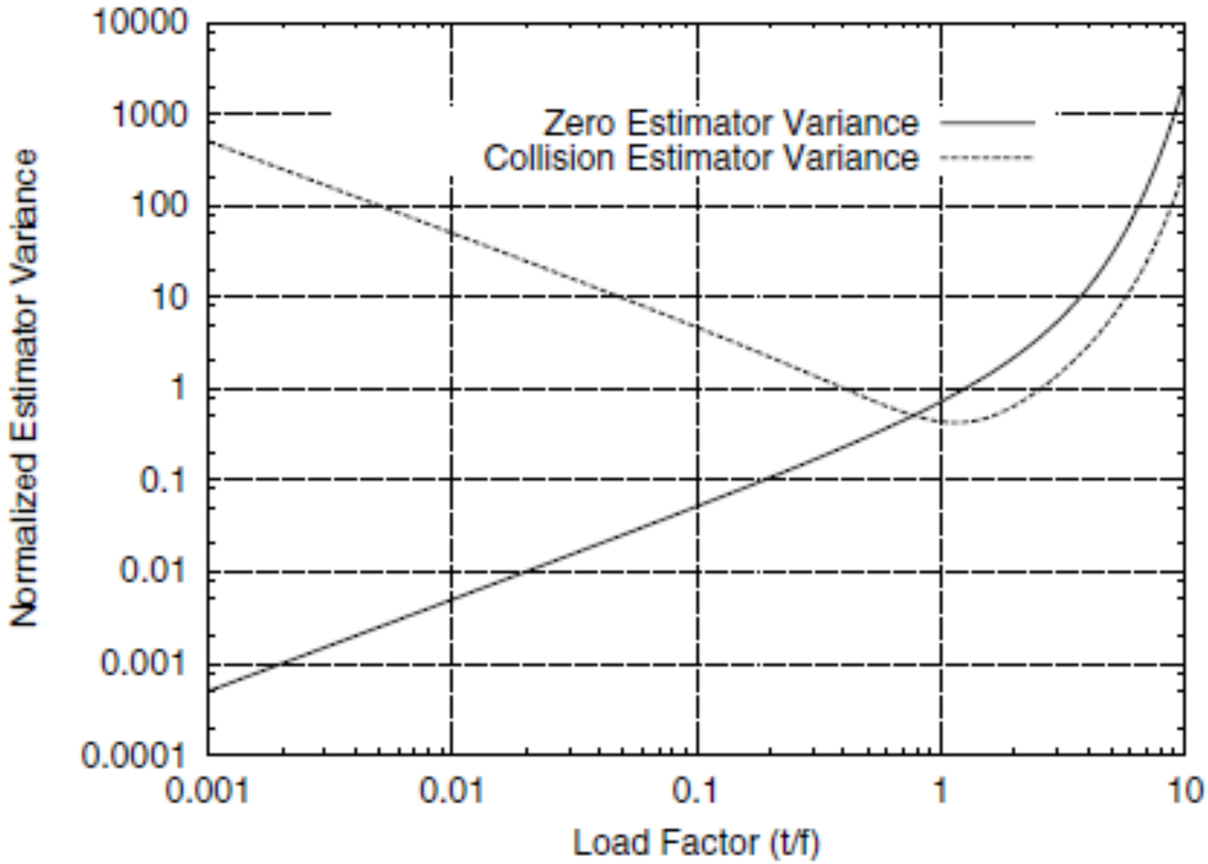
and

$$\delta_c = t\frac{(1+\rho)\,e^\rho - (1+2\rho+\rho^2+\rho^3)}{\rho^3}. \qquad (2)$$

RFID标签估算机制（Estimation）

- **Compare the variances of the two estimators**

精准度



RFID标签估算机制（Estimation）

- **Reducing the Variance of the Simple Estimators**
  - If we want the variance to be less than σ^2, for a given estimate ˆt, we first set

$$\hat{t}\,\frac{(e^{\rho}-(1+\rho))}{\rho} \le \sigma^2$$

    and solve for ρ. We can then set f ≥ ˆtρ.
  - In practice, all systems have some maximum frame size restriction. Therefore, if the frame size computation above leads to a size larger than the maximum permitted, then we use the maximum permitted frame size instead. **This implies that we may have to perform multiple experiments in order to reduce the variance.**

RFID标签估算机制（Estimation）

- **Reducing the Variance of the Simple Estimators**
  - A straightforward way of reducing the variance of an estimator is to **repeat the experiment multiple times** and **take the average of the estimates**.
  - If the final estimate is the average of m independent experiments each with an estimator variance of σ^2, then the variance of the average is σ^2/m.

RFID标签估算机制（Estimation）

- **Computing the Estimate using Combined Simple Estimators**
  - Based on our earlier observation that the two estimators are complementary to each other, we can devise a unified Simple Estimation Algorithm, which uses both estimators, depending on the **frame size** and the **estimated number of tags**.

ESTIMATION PROCEDURE

1. Compute the desired variance, $\sigma^2 = \frac{Z_\alpha^2}{\beta^2}$.
2. Compute the initial frame size f by solving $fe^{-(\bar{t}/f)} = 5$.
3. Energize the tags and get n_0 and n_c.
4. Compute t_0 as in Table 1 and the variance of this estimate δ_0 using Equation 1.
5. Compute t_c as in Table 1 and the variance of this estimate δ_c using Equation 2.
6. If $\delta_0 < \delta_c$ then set $\hat{t} \leftarrow t_0$ else $\hat{t} \leftarrow t_c$.

RFID标签估算机制（Estimation）

- **Estimate the cardinality of tags based on posteriori probability**
  - Consider tags are to be read and a read cycle with a frame length of f time slots. Given one of the time slots, the number of tags allocated in the slot is a **binomial distribution** with ***n*** **Bernoulli experiments** and **1/*f* occupied probability**. The probability of finding r tags in the slot is therefore given by

$$B(r) = \binom{n}{r}\left(\frac{1}{f}\right)^{r}\left(1-\frac{1}{f}\right)^{n-r}$$

  - Accordingly, we obtain the probabilities of empty, successful transmission, and collision for the slot as $p_e = \mathrm{B}(0)$, $p_s = \mathrm{B}(1)$, $p_c = 1 - p_e - p_s$.

RFID标签估算机制（Estimation）

- **Estimate the cardinality of tags based on posteriori probability**
  - **We need to derive the probability of finding the exact *N0* empty slots, *N1* singly occupied slots, and *Nc* collision slots if there are *f* slots.** The problem can be modeled as **a *multinomial distribution* with repeated independent *f* trials**, where each trial has one of three outcomes: empty, successful, or collision.
  - Suppose that the possible outcome in each trial is p_e for empty, p_s for successful, and p_c for collision. In general, the probability is subject to the condition $p_e + p_s + p_c = 1$.
  - The probability that in *f* trials, empty outcome occurs *N0* times, successful outcome occurs *N1* times, and collision outcome occurs *Nc* times is $P(N0, N1, Nc) = \frac{f!}{N0!N1!Nc!}(p_e)^{N0}(p_s)^{N1}(p_c)^{Nc}$

RFID标签估算机制（Estimation）

- **Estimate the cardinality of tags based on posteriori probability**
  - Therefore, for a read cycle with frame length , we have a posteriori probability for the number of tags when empty slots, singly occupied slots, and collision slots are observed, as follows:

$$P(n, N0, N1, Nc) = \frac{f!}{N0!\,N1!\,Nc!} \times \left(\left(1-\frac{1}{f}\right)^{n}\right)^{N0} \left(\frac{n}{f}\left(1-\frac{1}{f}\right)^{n-1}\right)^{N1} \times \left(1-\left(1-\frac{1}{f}\right)^{n} - \frac{n}{f}\left(1-\frac{1}{f}\right)^{n-1}\right)^{Nc}$$

RFID标签估算机制（Estimation）

- **Estimate the cardinality of tags based on posteriori probability**
  - **Based on the a posteriori probability distribution, we attempt to determine tag quantity such that the probability is maximized.** Hence, the decision rule of our proposed tag estimate method is as follows:
  - Set the tag estimate $n = n'$ if $P(n, N0, N1, Nc)$ is **maximum**.
  - This decision rule can be referred to as **the maximum a *posteriori probability* rule.**

开放性问题（Open Problems）-1

Tag Identification in Mobile RFID Systems

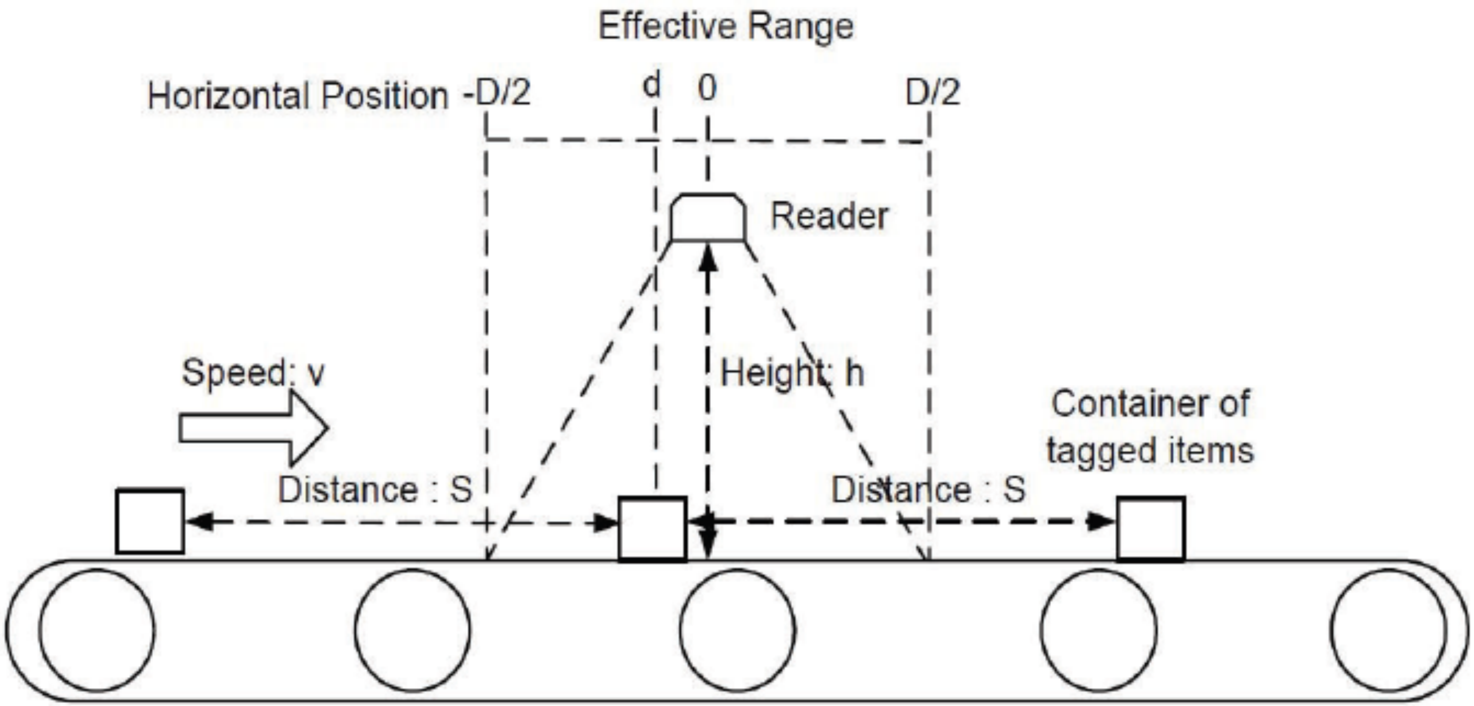


Fig. 1. Reading the moving tags on the conveyor.

Lei Xie, Bo Sheng, Chiu Tan, Hao Han, Qun Li, Daoxu Chen. **Efficient Tag Identification in Mobile RFID Systems**. In Proceeding of IEEE International Conference INFOCOM 2010.

开放性问题（Open Problems）-2

Find the Missing Tags

T. Li, S. Chen, and Y. Ling, “**Identifying the missing tags in a large rfid system**,” in *Proc. of ACM Mobihoc*, 2010.

开放性问题（Open Problems）-3

Continuous Scanning

Bo Sheng, Qun Li, and Weizhen Mao. **Efficient Continuous Scanning in RFID Systems**. IEEE Infocom, San Diego, CA, Mar. 15-19, 2010

开放性问题（Open Problems）-4

Multiple RFID Readers

S. Tang, J. Yuan, X. Y. Li, G. Chen, Y. Liu, and J. Zhao, "**Raspberry: A stable reader activation scheduling protocol in multi-reader rfid systems**," in *Proc. of ICNP*, 2009.

开放性问题（Open Problems）-5

Exploring the Gap between Ideal and Reality through Experimental Study

Lei Xie, Qun Li, Xi Chen, Sanglu Lu, and Daoxu Chen. Continuous Scanning with Mobile Reader in RFID Systems: An Experimental Study. In Proceeding of the 14th ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc 2013). Acceptance Ratio: 10% (24 out of 234).

Continuous Scanning with Mobile Reader in RFID Systems

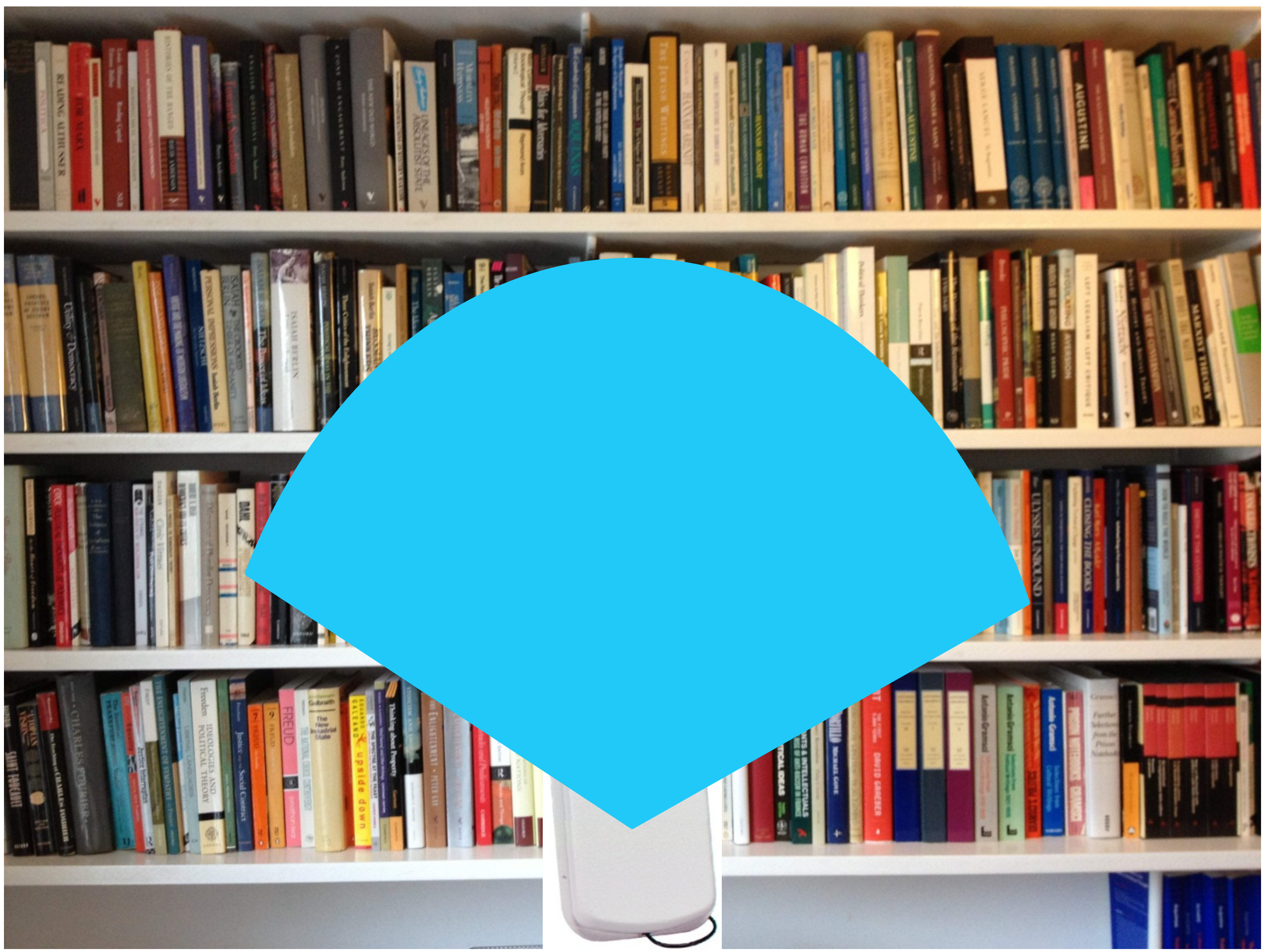
MobiHoc 2013

- **Application scenarios**
  - How to scan books in a library or a bookstore?

Continuous Scanning with Mobile Reader in RFID Systems

Solution 1: Scan the tags with a fixed reader.

Evaluation: Limited scanning range even with the maximum power



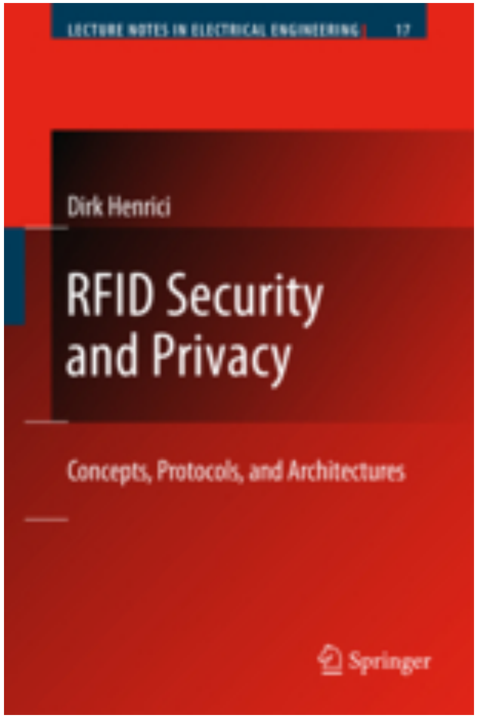
Continuous Scanning with Mobile Reader in RFID Systems

Solution 2: Continuously scan the tags with a mobile reader

Evaluation: the right way for efficient tag identification, effectively compensating for its limited reading range.

开放性问题（Open Problems）-6

Authentication over RFID tags



Lei Yang, Jinsong Han, Yong Qi, Yunhao Liu. **Identification-Free Batch Authentication for RFID Tags**. In *Proc. of ICNP*, 2010.

参考文献

RFID Tag Identification

[1] Lei Xie, Bo Sheng, Chiu Tan, Hao Han, Qun Li, Daoxu Chen. Efficient Tag Identification in Mobile RFID Systems. In Proceeding of IEEE International Conference INFOCOM 2010.

RFID Tag Polling

[2] T. Li, S. Chen, and Y. Ling, "Identifying the missing tags in a large rfid system," in Proc. of ACM Mobihoc, 2010.

RFID Tag Size Estimation

[3] M. Kodialam and T. Nandagopal, "Fast and reliable estimation schemes in rfid systems," in MobiCom '06: Proceedings of the 12th annual international conference on Mobile computing and networking, 2006.

RFID Experimental Study

[4] Lei Xie, Qun Li, Xi Chen, Sanglu Lu, and Daoxu Chen. Continuous Scanning with Mobile Reader in RFID Systems: An Experimental Study. In Proceeding of the 14th ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc 2013).

课程作业1（读书报告）

- **可选择如下之一的课题对相关论文进行阅读，并完成读书报告。要求对两篇以上的论文进行阅读，对论文中的算法、协议以及相关内容进行总结、归纳。鼓励提出创新的研究思路和解决方案。**
  - RFID标签识别机制-冲突以及防冲突算法研究
  - RFID标签数目估算机制研究
  - RFID系统的定位感知机制研究
- **具体要求与论文列表详见课程主页**
  - http://cs.nju.edu.cn/lxie/IOT.htm