Anti-collision Techniques for RFID Systems

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Due to the recent advances in semiconductor technology, the Radio Frequency Identification (RFID) technology is approaching the critical price point for realizing item-level tagging in global supply chain logistics. The ubiquitous deployment of RFID can provide organizations with real-time, accurate product location and other information when combined with the use of Internet.

Among the major issues of RFID technology, the tag collision problem, which is due to the signal collision of simultaneous transmission by multiple tags, needs to be solved. This is necessary for reading a large volume of tags at the same time without physical contact and orientation requirements.

In this thesis, we present two novel anti-collision protocols: (1) Even-Odd Binary Tree (EOBT) protocol and (2) Prefix-Randomized Query-Tree (PRQT) protocol, for multiple tag identification in RFID systems. EOBT partitions tags into different

responding groups based on their previous transmission. The expected tag read time of EOBT is faster than that of framed-Aloha protocol. In contrast to framed-Aloha, EOBT can identify all passive tags with complete certainty when the tag set size is unknown. PRQT builds a query tree based on prefixes randomly chosen by tags rather than using their ID-based prefixes as does by Query-Tree (QT) protocol. Therefore, the tag identification time of PRQT is no longer penalized by the skewness of ID distributions and the length of tag IDs. The expected and worst-case tag read time of PRQT is shown to be significantly smaller than those of QT.

摘要

半導體技術的快速發展使得射頻識別技術 (RFID) 的價格已經下降到足以應用在物流運輸的項目層面 (item-level) 上。在全球的物流供應鏈系統中，搭配現有的互聯網 (Internet) 技術，大規模利用 RFID 技術可以有效地為上游廠商至下游顧客提供各類產品的即時狀況和位置。

在諸多 RFID 的技術困難之中，源於多個標籤 (tag) 同時傳送信息以至互相產生信號沖突的標籤沖突問題 (tag collision problem) 是必須解決的，因為此問題的解決是發揮 RFID 在沒有任何接觸和傳輸指向限制而能同時讀取大量標籤的能力的關鍵所在。

本論文提供了兩個 RFID 系統的防沖突協議 (anti-collision protocol)，其一名為 Even-Odd Binary Tree (EOBT)，而另一名為 Prefix-Randomized Query-Tree (PRQT)。在 EOBT 協議中，標籤會基於它們之前的傳輸結果而被分配到不同的組別進行之後的傳輸，對比 framed-Aloha 協議，EOBT 不但有較短的平均標籤讀取時間，而且在標籤數量 (tag set size) 未知的情況下，EOBT 可以確定所有被動標籤 (passive tag) 都被讀取。在 PRQT 協議中，每個標籤能隨機產生一個前綴 (prefix) 來跟讀取器 (reader) 溝通，而不像在 Query-Tree 協議中要利用標籤自身識別 (ID) 的前綴來進行通訊，這個方法使得標籤讀取時間不再受到 ID 的分佈及長度影響，通過理論和模擬的証明，PRQT 比 Query-Tree 有較短的平均標籤讀取時間和最差標籤讀取時間。

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This work is dedicated to my family.

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Chapter 1

Introduction

The Radio Frequency Identification (RFID) technology has been around us for decades mainly in the form of smart cards for public transportation (Octopus), entrance cards, remote car keys, etc.. These classical RFID applications are quite stand-alone and often only require point-to-point communication between card and card reader. Can we push this technology to next level for more economic benefits? Recently, with the advances in microelectronics and low-power semiconductor technologies, low-cost RFID tags for large-scale deployment become feasible. The price of tags is approaching the critical threshold for item-level tagging, which is done by barcode nowadays. Large-scale deployment of RFID technology is extremely beneficial to the global retail and supply chain management systems. Comparing to barcode labels, RFID tags can store much more item information such as manufacturer, ingredients, expiry date, etc.. Every RFID tag acts as a portable dynamic product information database which realizes real-time product tracking in each stage of supply chain. Moreover, unlike barcode technology, RFID provides object identification in a distance without requiring line-of-sight transmission. In this way, a large number of tags can be read by the same reader at the same time. This advantage can remove large amount of labor-intensive scanning for inventory control and checkout process. In near future, people shopping in the supermarket can directly push the RFID-enabled shopping cart through the RFID-enabled gate to complete the checkout and payment process instantly without waiting in a long queue.

The biggest advantage of RFID technology over other object identification technologies is the ability to identify multiple tags at the same time without physical contact and orientation requirements using anti-collision protocols. In this thesis, we proposed two novel anti-collision protocols for multiple tag identification in RFID systems. They are (1) *Even-Odd Binary Tree protocol* (EOBT) and (2) *Prefix-Randomized Query-Tree protocol* (PRQT). Through detailed analysis and simulation, their performance will be compared with that of existing RFID anti-collision protocols in terms of identification time and reading reliability. Results show that both protocols outperform existing protocols in both speed and reliability.

The remainder of this thesis is organized as follows. In Chapter 2, we overview the state-of-the-art RFID technology and examine the wide range of its applications. In Chapter 3, we review the related work on the tag collision problem of RFID systems and analyze the weaknesses of existing collision resolution solutions. In Chapter 4, we introduce the EOBT protocol with detail protocol description, derivation of expected tag read time, and the performance comparison with framed-Aloha protocol for both the case of known and unknown tag set size. In Chapter 5, the PRQT protocol is proposed and the expected number of polling rounds (expected tag read time) is derived. The optimal initial prefix length is derived for cases where the tag set size is known. For applications where the tag set size is unknown before identification, an initial prefix length adaptation algorithm is proposed to incorporate with the PRQT protocol. PRQT is compared with the Query-Tree (QT) protocol in terms of both average and worst-case identification time. In Chapter 6, conclusions are drawn and future research directions are discussed.

□ **End of chapter.**

Chapter 2

Technology Overview

RFID technology is one of the most important kind of Automatic Identification and Data Capture (AIDC) technologies (other major AIDC technologies include barcode, optical character recognition and infrared identification systems) and is getting increasingly popular in recent years due to advances in microelectronics and low-power semiconductor technologies. The basic operating principle of RFID technology is to attach items with electronic tags, which store various types of item information, and to identify tags with readers to collect item information for different applications.

RFID offers many unique advantages, such as large data storage and multiple tag identification, that other AIDC technologies cannot offer. Moreover, the current price of low-cost RFID tags is very near the critical point for large-scale adoption in supply chain and retail management [2][4]. Retail giants like Wal-Mart in the US, Marks & Spenser in the UK, Metro in Germany, and Mitsukoshi in Japan have all implemented their

RFID solutions for more efficient supply chain management. In foreseeable future, the price of RFID tags will be low enough to realize item-level tagging, thus enabling a new wave of innovative applications. RFID technology, which provides efficient wireless object identification, is envisioned to bridge the physical world and virtual world [1][5].

In this chapter, we first overview the key components of a typical RFID system with a detailed classification of each of them. Then we summarize different frequency regulations and protocol standards. The network architecture of RFID systems are also investigated. Next we discuss the advantages and limitations of the state-of-the-art RFID technology. In the end of this chapter, we summarize the mile-stone industrial RFID implementation examples.

2.1 Components of RFID Systems

Key functional components of a typical RFID system includes:

- **Tag**. The electronic label tagging on different items for storing various types of item information.
- **Reader**. The device to collect data from tags and write data on them based on commands initiated by the software system.
- **Software system**. The system to process, aggregate and extract information from the collected data by readers for

different applications.

- **Communication infrastructure**. The collection of wired and wireless network for connecting the above system components.

2.1.1 Tag

An RFID tag (also called as transponder) is a device consist of an integrated circuit (IC) and an antenna. The IC is mainly for data processing, protocol control and storage while the antenna is for radio communication with readers. Typically, a tag can store data of manufacturer, product category, serial number, shipment record and many other useful information for unique object identification. RFID tags can be classified into three types in terms of the availability of on-board power supply. There are passive tags, active tags and semi-passive tags.

- **Passive tag**: A passive tag does not have on-board power source so that its longevity is not limited by energy. It relies on the continuous radio power emitted from the reader to process commands received from the reader, generate results and transmit data back to the reader. The communication between a passive tag and a reader is normally using backscatter modulation (high frequency passive tags) or load modulation (low frequency passive tags) [6]. After receiving the continuous radio wave from the reader, the tag modulates the wave to encode data on it and then transmits it back to the reader antenna. The communication range of a passive tag is from 2.5 cm inch to 10 m [2]. Due to its simple structure and lack of power source, passive tag is typically smaller than the other two types of tags and is the cheapest among the three. As a result, the economic potential of passive RFID tags is envisioned to realize item-level tagging.

- **Active tag**: An active tag has an on-board power source, which consists mainly of batteries. It uses its power source for command processing and data transmission so that its longevity is limited by the stored energy. Active tags broadcast signal periodically to discover nearby readers and communicate with them. Electronic circuits of active tags are normally more complex than those of passive tags and with a larger size and a higher price. They can support more complicated communication protocols and perform more complex tasks other than object identification, such as actuation and sensing. Typically, an active tag has communication range from 20 to 100 m [2].

- **Semi-passive tag**: A semi-passive tag has an on-board power source, which consists mainly of batteries, for its command processing and data operation as an active tag does. However, it uses the continuous radio power emitted by the reader for data communication with the reader using backscatter modulation as a passive tag does. The communication range of semi-passive tags can be up to 30 m.

RFID tags can also be classified into three types depending on whether the stored data can be altered or not. They are read only, write once-read many and read-write tags.

- **Read only**: For an read only tag, the data is burned into the tag's circuit at the factory and cannot be modified during its whole life.
- **Write once-read many**: A write once-read many tag can be programmed once, usually not by the manufacturer but by the buyer, for application specific purposes.
- **Read-write**: Data on an read-write tag can be rewritten many times for different application scenarios.

Except for the above two classifications, RFID tags are diversified in many other aspects. For example, tags can have a surface area of 0.3 mm^2 [7] up to several cm^2. Tags perform well when attached to wooden pallets may not be good for metal containers. Therefore, dependent on different applications and different operating environments, various types of tags should be deployed together for efficient system operation. Figure 2.1 shows some commercial RFID tags.

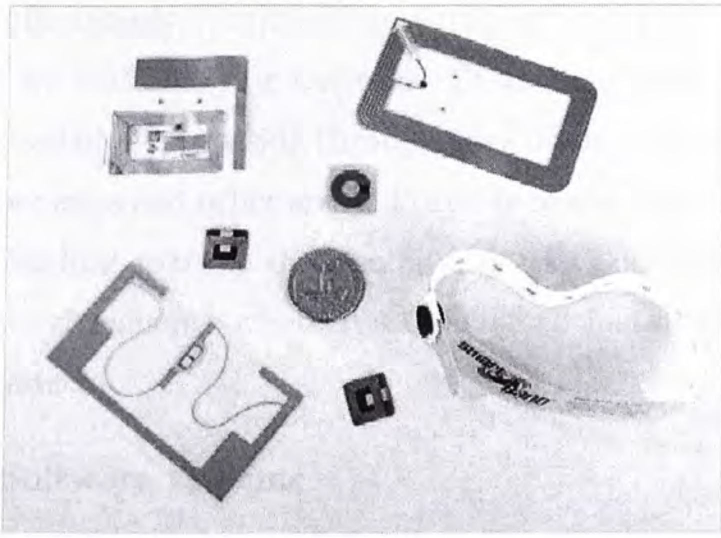

Figure 2.1: Some commercial RFID tags [1].

2.1.2 Reader

An RFID reader (also called as interrogator) is a device to read data from tags and write data on them based on commands initiated by the backend software system. For reading passive tags and semi-passive tags, the reader also plays the role of power supply to energize tags by radio power during the identification process. The RFID reader is the bridge between the application softwares and RFID tags. Key components of a typical RFID reader includes: (1) transmitter, (2) receiver, (3) microprocessor, (4) memory, (5) battery, and (6) the communication interface to backend software system.

RFID readers are of many types. For example, there are readers using single frequency channel and readers using multiple frequency channels for communication. Multiple frequency readers can simultaneously communicate with multiple tags. Readers can also be stationary or portable. Stationary readers can be used to read objects passing through dock doors, conveyor belts, gates, doorways and other areas. Portable readers are more flexible for reading sparsely distributed objects. They can also be used in environments where it's difficult to install stationary RFID readers.

2.1.3 Software systems

The software system commands a reader to read/write tags, process and analyze data collected by readers to advance various business processes. A typical RFID software system includes:

- **Edge interface**: This component connects hardware and software of an RFID system. It can collect data from a reader, control its behavior and aggregate multiple reads of the same object.
- **Middleware**: This component is used for filtering and aggregating the large amount of data produced by RFID hardware. It is based on open standards which can be integrated with other existing software systems. A detailed summary of the state-of-the-art RFID middleware technologies can be found in [8].
- **Enterprise backend**: The enterprise backend uses processed data from the middleware to make meaningful busi-

ness decisions.

2.1.4 Communication infrastructure

The communication infrastructure includes the whole set of connections between different components of the RFID system. It consists of wired and wireless network to ensure the connectivity, security and reliability of the system operation.

2.2 Frequency Regulations and Standards

2.2.1 RFID frequency bands

The frequency bands allocated for RFID systems [9] includes:

- Low frequency 125-134kHz: This frequency range is good for low data rate and short communication range applications generally employed by passive tags. Typical read distance is a few centimeters [6]. Radio waves of this band can penetrate water but not metal.
- High frequency 13.56MHz: This is one of the Industrial-Scientific-Medical (ISM) frequency band suitable for applications with low data rate and short reading distance for passive RFID systems. Radio waves of this band can penetrate water but not metal. This frequency band is used by Philips and Sony RFID products.
- Ultra high frequency 900MHz: This frequency band supports longer read distance and faster data rates. Active

RFID systems normally use this band. The penetration of electromagnetic waves through metal and water is lower than that of the lower frequency bands.

- Microwave frequency 2.4GHz: This is another ISM frequency band. RFID systems of this band are normally used in production lines since they can resist strong electromagnetic interference of electric motors.

2.2.2 Standards

The power level and duty cycle of radio signal at different frequency bands, the type of coding and modulation scheme, the employed communication protocol, and terminology of RFID technology are govern by different standards of different industries of different countries. Nowadays, major RFID standards includes:

- ANSI (American National Standards Institute) standards
- EPCglobal standards
- ISO (International Organization for Standardization) standards
- ETSI (European Telecommunications Standards Institute) standards

Among the above four standardization bodies, ISO and EPCglobal are the major driving forces to build worldwide RFID standards for interconnection of hardware and software products of different vendors. The ISO RFID standards are divided into three families: ISO 14443 series (for contactless systems), ISO 18000 series (for vicinity systems) and ISO 15693 series (specifications of different RFID air-interface). EPCglobal has released five standards, Class 0 to Class 4, that are particulary for supply chain management systems. A detailed summary of ISO standards and EPCglobal standards can be found in [10]. EPCglobal recently released UHF Generation 2 standard [11] targeted for global compatibility of RFID hardware.

EPCglobal has designed a set of technologies called EPCglobal Network, which cooperatively provides real-time object tracking and data sharing for both intra-organization and inter-organization uses. This network architecture is tailor made for RFID based supply chain management systems. The EPCglobal Network includes the following components:

- Electronic Product Code (EPC): A unique identifier for each item of 64 bit or 96 bit length [12].
- EPC tags and readers
- EPCglobal middleware
- EPC Information Services (EPCIS): An EPCIS server associates EPC data with backend servers for various business decisions.

- Object Naming Service (ONS): A service mapping the EPC number and the corresponding EPCIS server for extracting meaningful data.

Figure 2.2 shows the architecture of EPCglobal Network.

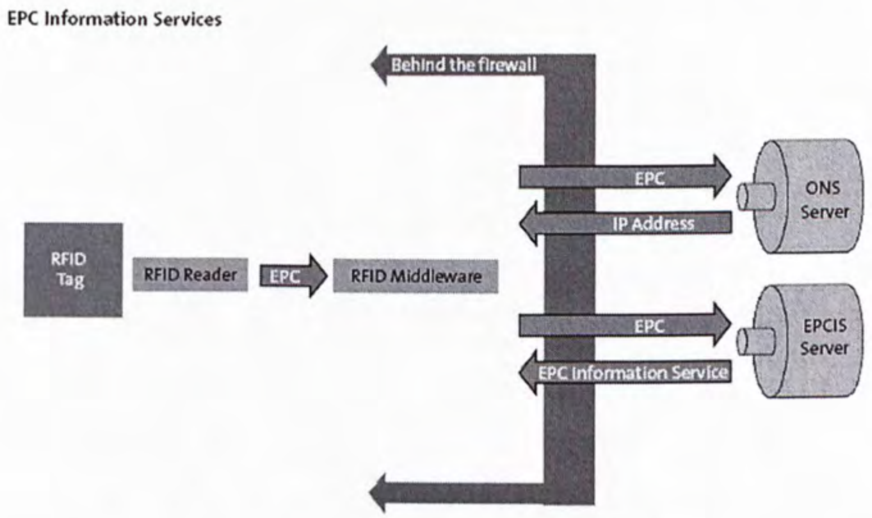

Figure 2.2: The EPCglobal Network architecture

2.3 Advantages and Limitations of RFID Technology

State-of-the-art RFID technology has advantages including:

1. Non line-of-sight: Contactless data transmission without the need for line-of-sight between tags and readers. Tags can be hidden or embedded in items but readers can still read them. This benefit cannot be obtained by using bar-code labels.

2. Multiple tag identification: Line-of-sight transmission is not necessary so that multiple tags within the read range of a reader can be identified simultaneously. This feature is necessary to realize item-level tagging across the supply chain logistics. RFID is the only AIDC technology which supports multiple tag identification.

3. Data storage: RFID tags can store 30 times more product data than barcode labels. Except for the unique identifier of each item, tags can store and update a wide range of real-time data at different stages along the supply chain.

4. Data rewritable: Data on read-write tags can be written and updated many times across the supply chain logistics. Every tag acts as a traveling dynamic database storing the item history in the supply chain. This kind of tag can also be modified for different applications.

5. Communication range: Tags with different communication ranges can be employed in different applications.

6. Reliability: RFID systems can be operated in harsh and dirty environment. Tags can be identified through dirt or soiled packages.

7. Difficult to replicate: Counterfeiters can easily scan and reprint barcode labels. However, the manufacturing process for RFID tags is much more complicated. Counterfeiters

must be familiar with semiconductor technologies and be able to fabricate RFID chips.

8. Sensing and actuation: RFID tags are not static identifiers which only store product serial numbers like barcode labels. Since RFID tags contain semiconductor chips, they can incorporate with different types of semiconductor-based sensors, such as temperature, humidity and pressure sensors, to record environmental data for the tagged item.

State-of-the-art RFID technology has limitations including:

1. Lack of global standard: Frequency regulations for RFID systems of different countries stipulated different frequency spectrum, data rate and radio power level. For example, the US has specified 915MHz while the EU has specified 868MHz for RFID applications. This obstructs the compatibility between products of different vendors.

2. Radio absorbing: Radio power absorbing objects such as metal and liquid can degrade reading performance in terms of both identification speed and accuracy. The level of degradation varies for tags using different frequencies and tags attaching to different kinds of material.

3. Frequency interference: Frequency interference by other communication systems which operating in the same frequency band, for example, the ISM bands. The interference

can degrade the reader-to-tag and reader-to-reader communication significantly.

4. Privacy: Consumer privacy is the biggest barrier for retailers to deploy RFID systems [13]. Customers carrying functioning tags can be tracked easily by readers. How to disable RFID tags after purchasing is a big concern for customers. EPCglobal has recently designed a *kill switch* in a tag for permanently disabling its function.

2.4 Applications

The history of RFID technology dates back to World War II for the allies to distinguish friendly and enemy aircrafts. Since then, the high economic potential of this evolving technology has been proven in many application domains. In the form of smart tags, they are used to improve supply chain management, retail and manufacturing logistics. In the form of contactless smart cards, they are used for speeding up transportation ticketing, toll collection, access control and payment services. In the form of smart keys, they are used to improve security with car immobilization, remote keyless entry, and asset management [14]. Figure 2.3 shows some commercial RFID devices.

Some pioneered industrial examples of RFID system implementations are shown below:

- Wal-Mart pilots its RFID implementations and push its

Figure 2.3: Some commercial RFID devices: a car key with a passive tag (upper left), an EzPass collects highway tolls (upper right), and a SmarTrip card for public transportation (bottom) [2].

major suppliers to follow its RFID standards.
http://www.rfidgazette.org/walmart/

- San Francisco airport has implemented a RFID-based passport checking systems.
http://www.techweb.com/wire/ebiz/175800140

- Hong Kong airport is implementing its RFID system for luggage management.
http://www.rfidjournal.com/article/view/981/1/1/

- Swiss Federal Railway uses RFID technology for vehicle tracking and identification.
http://aimglobal.org/technologies/rfid/casestudy/Swissrailway.asp

- Ford Motor Co. has embedded RFID technology into the battery-charging systems of its electric forklifts for data transmission.
  http://www.rfidjournal.com/article/articleview/1348/1/1/

- FedEx couriers use an automatic keyless entry and ignition system that has RFID tags embedded within a velcro wristband.
  http://www.ti.com/tiris/docs/solutions/solutions.shtml

□ **End of chapter.**

Chapter 3

Background of Research

Active RFID systems have been employed in many applications such as car immobilization and animal tracking for long time. Recently, due to the continuing advances in integrated circuit technologies, extremely small and low-cost passive RFID tags are armed with both computation and communication capabilities [7]. The power required by a passive tag decreases to a few microwatts) with the memory size increases from 200 to 8000 bits.

Since the manufacturing cost of passive tags (13 US cent per tag for a quantity of 1 million tags [2]) is continually approaching the critical price point for item-level tagging (less than 10 US cent per tag), they are increasingly be adopted in the supply chain management systems for object tracking and inventory control in various production and distribution stages [15]. These smart tiny tags provide each item with a unique identifier and other information to make tasks like inventory control, anti-counterfeit, and automated check-out/purchasing process more efficient. Passive RFID systems will likely be the main driving force for the growth of RFID implementations in near future. A detailed analysis of the fundamental constraints including electromagnetic, communication, regulation and physical implementation, for designing passive RFID systems has been presented in [9].

The most unique and compelling advantage of RFID technology over other AIDC technologies is the ability to identify a large number of tags simultaneously without physical contact and orientation requirements. This powerful feature, which cannot be provided by other AIDC technologies, can remove the need of labor-intensive manual scanning in many applications such as warehouse inventory checking and supermarket checkout process. However, the simultaneous transmission of tags cause signal collision, thus degrading the overall identification efficiency.

In this thesis, we develop anti-collision protocols for low-cost passive RFID systems solving the tag collision problem. Since active tags are similar to passive tags except for the availability of on-board power source and other complicated functions, the proposed protocols can also to applied to active RFID systems. The proposed anti-collision protocols are shown to have higher identification efficiency, reading reliability and robustness against unknown tag set size, ID length and ID distribution, when compared with existing RFID anti-collision protocols. Moreover, the complexity of these protocols should be as low as possible for the simple structure of passive tags.

3.1 Anti-collision methods for RFID systems

When multiple RFID tags are under the interrogation zone of a reader and being queried for their stored information, they may respond to the reader at the same time with internal energy (for active tags) or external energy powered by the reader (for passive tags). These simultaneous responses cause mutual interference with each other and thus leading to data loss. The reader cannot obtain any correct information from tags and all tags must transmit their information again. The mutual interference between tags' simultaneous responses is referred to as a signal collision and leads to a failed transmission. In order to decrease these collisions so as to increase the identification efficiency, anti-collision protocols must be employed in RFID systems.

The multiple tag identification problem of RFID systems is similar to the classical multi-access communication problem with solutions such as Tree-based protocol, Aloha-based protocol and Carrier Sense Multiple Access (CSMA) protocol families. However, due to the cost and size issues, anti-collision protocols of RFID systems are constrained by low computational capability and small memory size of simple tiny tags. In addition, they must be optimized for low power operation to increase the communication range in the case of passive tags, or to increase the battery life in the case of active tags. The limited power supply, memory and computing capability of low-cost RFID tags, especially for passive tags, rule out the use of complicated anti-collision algorithms.

Classical anti-collision methods can be classified into four domains: time, frequency, code, and space [16]. The system should assign one of the four types of resources to users for their transmission. Each user is then able to use different time, frequency, code, or space for collision resolution. There are communication systems using a mix of the four resources, for example, Global System for Mobile Communications (GSM) system uses a combination of Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) scheme for collision resolution. In the case of RFID systems, frequency and code domain anti-collision protocols are not feasible due to their complex and costly implementations. For frequency domain, FDMA requires tags to have accurate selective bandpass filters for receiving signals on different carrier frequencies. This is difficult to implement in low-cost RFID systems. For code domain, Code Division Multiple Access (CDMA) has complicated time and frequency synchronization requirements for Spread Spectrum. Moreover, the bandwidth limitations of RFID systems also rule out the use of CDMA.

In space domain methods, the reader can adjust its communication range (for active tags) or emitted power level (for passive tags) during identification to isolate tags at different places. In [17], the author proposed a method to detect tags based on the strongest response at varying communication ranges. In [18], isolating tags is achieved by the location discovery scheme of triangulation. In [6], an array of short range readers are used to isolate one tag at a given time. However, as the number of tags under the reader's interrogation zone increases, the precise control of communication range becomes impractical for low-cost RFID systems.

Currently, the majority of existing RFID anti-collision protocols are time domain methods of either deterministic type or stochastic type. They usually work in a Reader-Talk-First mode, where a reader issues query commands first, and those tags that are within the reading range of the reader will respond with their stored information. Among these anti-collision protocols, framed-Aloha and binary tree protocols have been widely implemented. Type A of ISO/IEC 18000-6 and 13.56MHz EPC Class 1 use framed-Aloha protocol. Type B of ISO/IEC 18000-6 and 900MHz EPC Class 0 use binary tree protocol. To have a deeper understanding of time domain RFID anti-collision methods, we review the related work on both stochastic type and deterministic type in the following sections.

3.1.1 Stochastic Anti-collision Protocols

For stochastic schemes, tags respond to reader's interrogation at randomly chosen time slots. There are a number of variations of these schemes based on the Aloha protocol family. Many commercial RFID systems, such as Philips Icode [19] and BTG SuperTag [20], have implemented Aloha like anti-collision protocols. Philips' Icode uses framed-Aloha protocol while BTG's SuperTag uses pure Aloha protocol with some variations. The ISO 15693 standard supports slotted-Aloha. Among the Aloha protocol family, framed-Aloha is a favorite choice for RFID systems from both theoretical and practical consideration. This protocol is an extension of slotted-Aloha by grouping a number of time slots into a time frame. After the reader broadcasts the reading command, tags are required to send their IDs in a randomly chosen time slot within the frame. There are basic framed-Aloha protocol and dynamic framed-Aloha protocol depending on the flexibility of changing frame size.

In basic framed-Aloha protocol, the frame size (number of time slots in a frame) is fixed during the identification process. Each tag randomly selects a time slot within the frame to transmit its ID to the reader. This procedure repeats until the reader stops the identification. The implementation of this protocol is simple and effective. However, when the tag set size (number of tags) is too large compared with the frame size, tag collision ratio (the number of collided slots divided by the total number of slots) is high and the identification efficiency drops quickly. On the other hand, when a small number of tags transmit in a large frame, there will be many wasted time slots with no response from tags.

In dynamic framed-Aloha protocol, the frame size can be adaptively changed by the reader during the reading process according to the estimated tag set size. These changes aim for the matching between frame size and tag set size so as to increase the identification efficiency. In [6], the reader starts with the minimum frame size. When the number of collided slots is over an upper threshold, the reader updates the frame size to be a larger one. On the other hand, the reader decreases the frame size when the number of collided slots is below a lower threshold. In [21], the author built a Markov model of the dynamic framed-Aloha protocol for multiple passive tag identification. Optimal parameters such as frame size and the number of required communication rounds can be derived according to the estimation of tag set size, which is based on the number of time slots with single response, with no response, and with multiple responses. In [22], the expected identification time of framed-Aloha for reading a number of passive tags was derived under a given missing tag probability. The wireless channel models and capture effect are also taken into consideration in this paper. A modified version of [21] by using a two-functioned tag set size estimation was proposed in [23].

The performance of stochastic anti-collision schemes is not limited by the length and distribution of tag IDs. However, for low-cost passive tags mentioned in [21][22][23], they cannot sense the shared communication medium to know whether their previous transmission is successful or not. Thus, they keep sending their IDs in each frame until the reader terminates the identification process. This leads to that the reader cannot identify all tags with complete certainty if the number of tags is not known before identification. Figure 3.1 shows an example of identifying three passive tags by framed-Aloha with three frames each with four slots. In this figure, shaded boxes represent successful transmission while black boxes represent collided transmission.

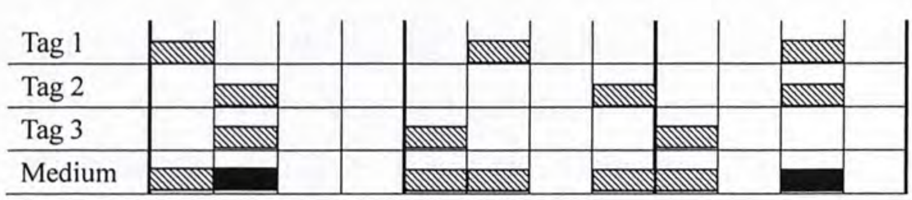

Figure 3.1: An example of identifying three passive tags by framed-Aloha with three frame each with four slots.

3.1.2 Deterministic Anti-collision Protocols

For deterministic schemes, when tags are within the interrogation zone of a reader, the reader broadcasts an initial command requesting certain tags, based on their unique IDs, to respond. It then either sequentially polls a list of tags' IDs or performs some variations of binary search algorithm to completely identify all tags. Texas Instrument's Tag-It uses a variation of binary tree protocol [24]. SCS employs another deterministic anti-collision protocol [25]. Typical polling schemes can be time exhaustive if there are a large number of tags under the reader's interrogation zone. Moreover, the length and distribution of tag IDs can affect the identification time significantly.

In [26], a reader builds a binary tree by continuous querying all tags for the next bit of their IDs. Whenever collision occurs for a query, the reader splits that query into two one-bit longer queries until there is only one tag respond. In [27], an enhanced binary search with cut-through operation to shorten the overall identification time is proposed. In [3], the author introduced an efficient memoryless anti-collision scheme called Query-Tree (QT) protocol for low-cost RFID systems. In this protocol, a reader sends out a prefix in each communication round and tags simply respond with their IDs if the prefix matches with their IDs. If there is a collision for a particular prefix, the reader ignores the response and polls a one-bit-longer prefix later. This procedure continues until there is no collision for any prefix and therefore all tags have been identified successfully. The polling efficiency of this protocol is low when the tag set size is large or the ID address distribution is sparse. This protocol has a worst-case identification time of $n(k + 2 - \log_2 n)$ [3], where n is the number of tags and k is the length of ID string. Figure 3.2 shows an example of identifying four tags using QT. The left side illustrates the communication between tags and reader. The right side is the corresponding binary query tree. Two variations of QT are proposed in [28] and [29]. The first one targets for minimizing the total power consumption and the second one targets for reducing the number of collisions during identification.

ID: {000, 001, 101, 110}

Step	Query	Response
1	ε	collision
2	0	collision
3	1	collision
4	00	collision
5	01	no response
6	10	101
7	11	110
8	000	000
9	001	001

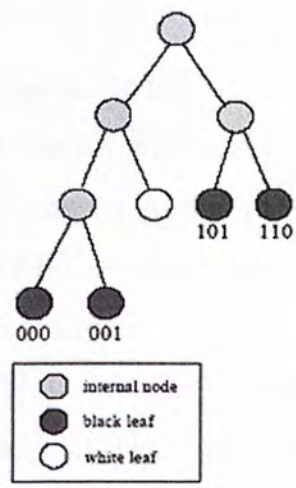

Figure 3.2: An example of identifying four tags using QT. The left side is the communication between tags and reader, and the right side is the corresponding binary query tree [3].

□ **End of chapter.**

Chapter 4

Even-Odd Binary Tree Protocol

In this chapter, we introduce a novel anti-collision protocol, called Even-Odd Binary Tree (EOBT) protocol, for passive RFID systems. This protocol is a variant of framed-Aloha protocol, which is employed by many passive RFID systems due to its protocol simplicity and reasonable performance.

For framed-Aloha used in [21] and [22], the reader determines the frame size F (number of time slots) at the beginning of each communication round (a communication round contains the query command followed by F time slots). Then, it broadcasts a query command with frame size F and all tags randomly choose one of F slots to transmit their IDs. After receiving responses from all tags, the reader obtains the number of slots with single response (successful slot), the number of slots with no response (empty slot) and the number of slots with multiple responses (collided slot). Based on this information, the reader changes the frame size of next communication round dynamically according to the estimation of tag set size. Tags keep sending their IDs in each communication round without knowing their previous transmission is successful or not until the reader terminates the identification process. If the tag set size is not known before identification, the reader terminates the identification process according to some predefined accuracy levels and cannot identify all passive tags with complete certainty. To fix this weakness of framed-Aloha, EOBT targets for the termination condition with 100 percent sure of all passive tags being identified by a little modification of the simple structure of passive tags. The identification efficiency of EOBT is higher than that of framed-Aloha.

4.1 Protocol Description

EOBT is designed under the assumptions: (i) the tag set size is fixed during the identification process, (ii) tags can randomly choose a time slot within the frame for transmission, (iii) tags cannot sense the medium so that they cannot know whether their previous transmission is successful or not, (iv) tags cannot communicate with each other so that they may choose the same slot to transmit, and (v) every tag is able to store the round number of its most recently participated communication round and even/odd slot it used in that round.

The identification process of EOBT consists of rounds of communication between the reader and the set of passive tags. Each communication round has two parts: (1) the reader broadcasts a query command with the current round number and the group of responding tags in this round; (2) a time frame with F time slots for tags' transmission.

In the initial round, the reader broadcasts round number 1 and indicates all tags to respond in the frame with F time slots. All tags store round number 1 and the randomly chosen slot numbers they transmitted in this round. If there are collided slots in round number 1, the reader starts round number 2 with command ordering those tags that have used odd slots in round number 1 to transmit their IDs. Tags transmit in this round store round number 2 and even/odd slot they used. Then, the reader starts round number 3 to collect information from tags that have used even slots in round number 1. Similarly, tags transmit in this round store round number 3 and even/odd slot they used. There will be round number 4 if there are collided odd slots in round number 2 and/or round number 5 if there are collided even slots in round number 2. The same procedure continues until (1) there is no collision if tag set size is unknown, or (2) all unique tag IDs have been collected if tag set size is known. An alternate way to see is that EOBT builds a binary tree for the identification process with each tree node containing a frame of F time slots. Every parent node grows (i) a left child node if there are collisions in its odd slots, or (ii) a right child node if there are collisions in its even slots, or (iii) both left and right child nodes if there are collisions in both odd and even slots.

Figure 4.1 shows an example of identifying eight passive tags, denoted by tag 1 to 8, by EOBT with F equal to 4. The number x in each slot indicates that tag x transmits its ID in this slot. We can see that in round number 1, slots 1, 2 and 4 are collided with tag 1 and 5, tag 4 and 6, tag 2, 7 and 8 respectively. Since there are collided odd slots and even slots in round number 1, tags 1, 3 and 5 are required to transmit in round number 2 while tags 2, 4, 6, 7 and 8 will transmit in round number 3. In round number 2, tags 1, 3 and 5 chooses different time slot without collision. Therefore, round number 4 and 5 are not needed. However, in round number 3, tags 2 and 4 transmit in slot 1 and tags 7 and 8 transmit in slot 4. Therefore, tag 2, 4 are required to transmit in round number 6 while tags 6, 7 and 8 will transmit in round number 7. Since there is no collision in round number 6 and 7, EOBT has used a total of five communication rounds to completely identify eight passive tags.

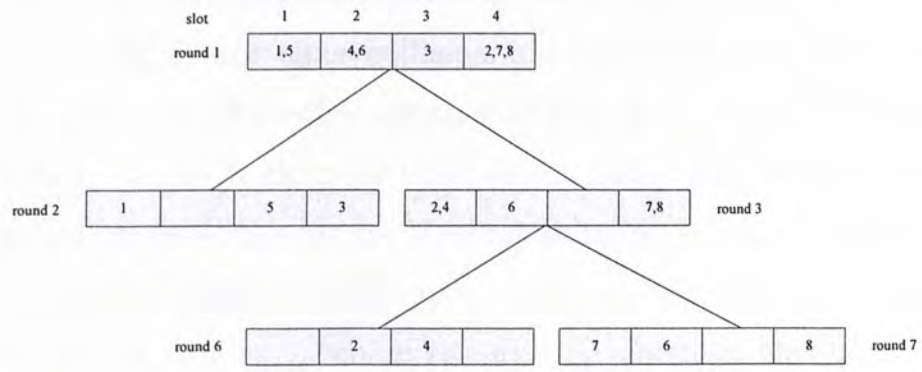

Figure 4.1: An example of identifying eight tags by EOBT protocol with F = 4.

4.2 Time Complexity Analysis

Using computer simulation, the average number of communication rounds used by EOBT to identify 50 tags and 100 tags for different frame size F is found and shown in Figure 4.2. It is noted that the average number of rounds decreases exponentially for larger F since there are less collided slots for larger frame size. The overall tag read time in slots, which is the product of the average number of rounds and frame size F, is shown in Figure 4.3. Each data point of both figures is the average value of 1000 trials of simulation. From Figure 4.3, we note that F equal to 2 gives the minimum overall tag read time in slots with maximum number of rounds for EOBT.

For the reason that $F = 2$ gives the shortest overall tag read time in slots and the derivations of expected number of rounds for F larger than 2 are much more difficult than that of $F = 2$, we only derive the expected number of rounds for $F = 2$ here. Obviously, the expected number of rounds needed for identifying 0 and 1 tag is one since collision will not occur for $F = 2$. We now derive the expected number of rounds r_n with $n \geq 2$ and $F = 2$, where n denotes the tag set size. The derivation is started by conditioning on the first split of the binary tree due to collisions. After the first split, the expected number of rounds is $r_n = 1 + r_i + r_{n-i}$, where r_i and r_{n-i} represent the expected number of rounds introduced by i and $n - i$ tags respectively.

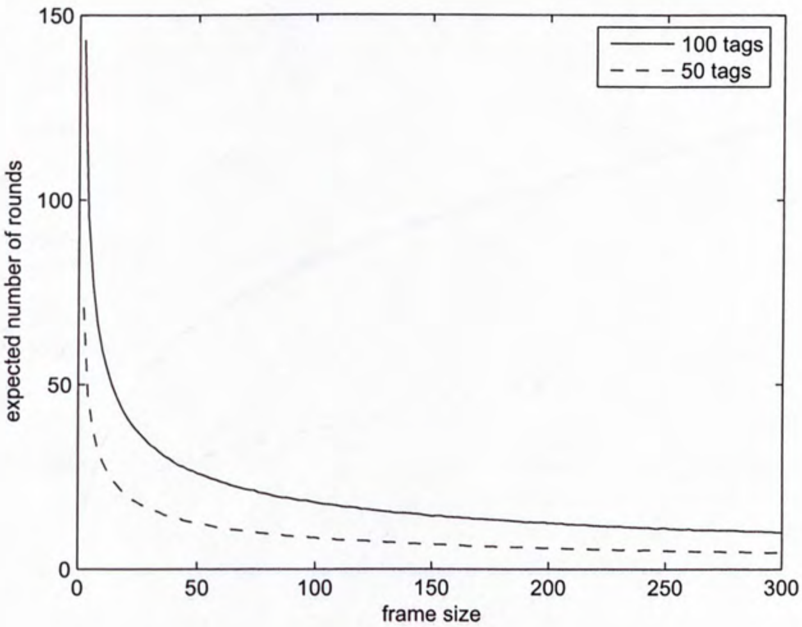

Figure 4.2: Expected number of rounds for different frame size.

Since tag set size 0 and 1 cannot introduce new rounds with $F = 2$, $r_0 = r_1 = 0$. r_n splits into r_i and r_{n-i} with probability

$$p_n(i, n-i) = \binom{n}{i} / 2^n, i = 0, 1, \cdots n \tag{4.1}$$

Summing over all $i \in (0, n)$, we obtain

$$r_n = 1 + \sum_{i=0}^{n} p_n(i, n-i)(r_i + r_{n-i}) \tag{4.2}$$

Substituting (4.1) into (4.2) and rearranging the term r_n, we obtain the recursive formula as follows.

$$r_n = \frac{1}{2^{n-1} - 1} \left[2^{n-1} + \sum_{i=0}^{n-2} \binom{n}{i} r_i \right] \tag{4.3}$$

where $r_0 = r_1 = 0$ and $n = 2, 3, 4, \ldots$

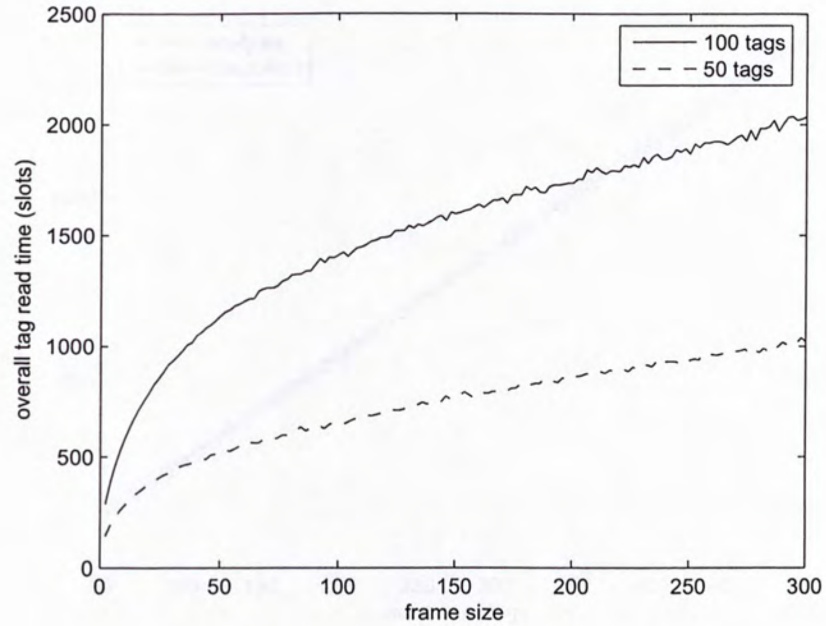

Figure 4.3: Overall tag read time (slots) for different frame size.

For expected number of rounds with $F > 2$, the protocol characteristic makes the derivations of expected number of rounds intractable. Figure 4.4 shows the close matching of the analytical and simulation results of the expected number of slots, which is the product of expected number of rounds and $F = 2$, for different tag set size. The analytical results are obtained by using (4.3) while each of simulation points is the average value of 1000 trials.

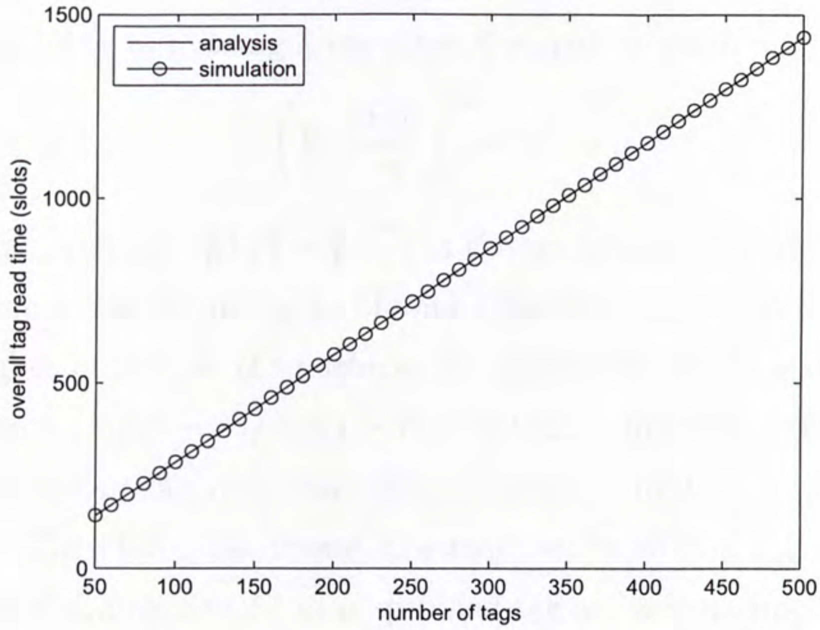

Figure 4.4: Analytical and simulation result of EOBT with frame size $F = 2$ for different tag set size.

4.3 Performance Evaluation

Before we compare the overall tag read time of EOBT with framed-Aloha, let us review the derivation of overall tag read time of framed-Aloha in [22]. Since passive tags keep sending their IDs in every subsequent communication round, the reader is not able to identify all tags with complete certainty when the tag set size is unknown before identification. Therefore, the identification termination condition is dependent on the assurance level α, which is used to indicate that the probability of missing one or more tags after identification is less than $1 - \alpha$.

Given the frame size F, tag set size n and assurance level α, the probability of missing a tag after R rounds is given by

$$\left(1 - \frac{Fp_1}{n}\right)^R = 1 - \alpha \tag{4.4}$$

where $p_1 = \binom{n}{1}\left(\frac{1}{F}\right)\left(1 - \frac{1}{F}\right)^{n-1}$ is the probability of a successful transmission according to binomial distribution. Therefore, the number of rounds R to achieve the assurance level α should be at least $\lceil \log(1-\alpha)/\log(1 - Fp_1/n) \rceil$ [22]. In other words, the least overall tag read time can be obtained by $t_{min} = \min(F * R)$. Therefore, the frame size required to obtain t_{min} is the optimal frame size F^* of a specified tag set size n. In [22], the number of rounds R obtained by (4.4) is shown match closely with the simulation result. Therefore in this section, we use (4.4) to compute the expected number of rounds for framed-Aloha when tag set size is unknown. The overall tag read time is the product of expected number of rounds and frame size.

We now compare the overall tag read time of EOBT and framed-Aloha in two cases depending on whether the tag set size is known or unknown before identification. The assurance level is set to $\alpha = 0.99$ for framed-Aloha in the following performance comparisons. For the case of unknown tag set size, the overall tag read time of both protocols is shown in Figure 4.5. It is noted that the overall tag read time of EOBT is shorter than that of framed-Aloha when F is small. The EOBT curves are obtained by averaging 1000 trials of simulation while the framed-

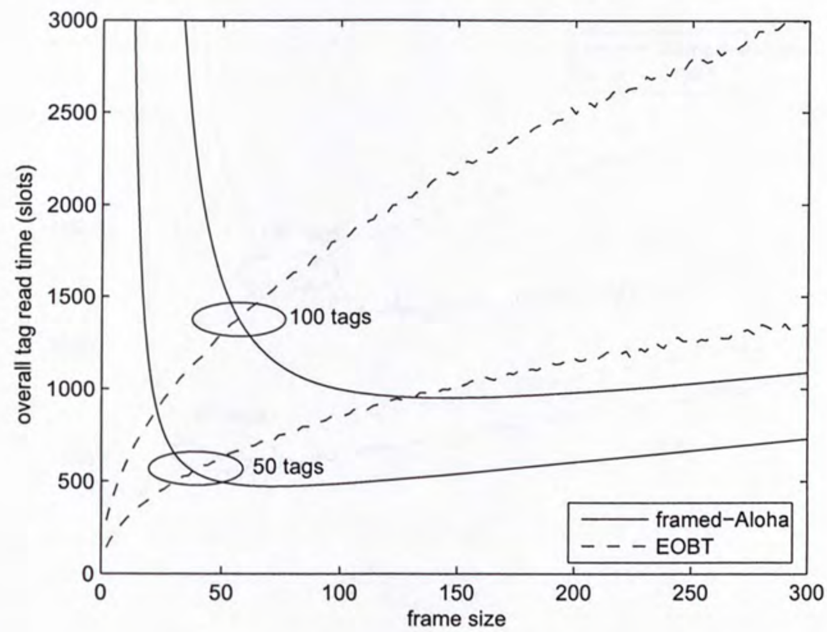

Figure 4.5: Overall tag read time of EOBT and framed-Aloha for different frame size with unknown tag set size.

Aloha curves are theoretical results obtained by (4.4) with $\alpha = 0.99$. EOBT can not only identify the set of passive tags faster than framed-Aloha when frame size is below a critical value F_c but also identify all tags with complete certainty when the tag set size is unknown. For 50 and 100 tags, F_c is 40 and 60 respectively.

For the case of known tag set size, both protocols are able to terminate the identification process with complete certainty when all unique tag IDs have been collected. The comparison of overall tag read time for this case is shown in Figure 4.6. We can see that the overall tag read time of EOBT is shorter

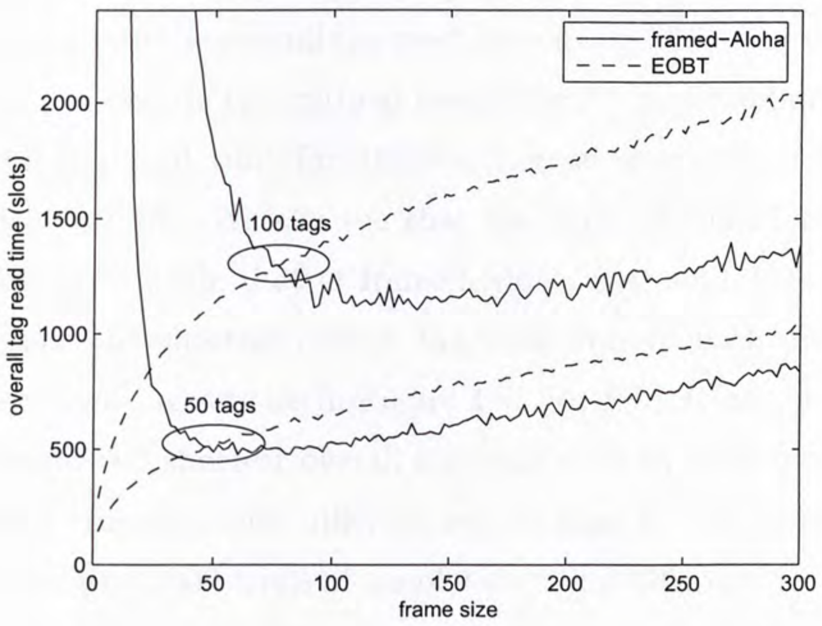

Figure 4.6: Overall tag read time of EOBT and framed-Aloha for different frame size with known tag set size.

than that of framed-Aloha below a critical F value. The EOBT curves and framed-Aloha curves in this figure are obtained by averaging 1000 trials of simulation. Since the tag set size is known, EOBT is able to terminate the identification process without waiting for zero collision. It is noted that the overall tag read time of EOBT shown in Figure 4.6 is uniformly smaller than that shown in Figure 4.5 for the same tag set size.

Next, we compare the shortest overall tag read time of both EOBT and framed-Aloha. In Figure 4.7, we show the shortest overall tag read time of EOBT and framed-Aloha for the case of unknown tag set size. For EOBT, since $F = 2$ gives the shortest overall tag read time, we set $F = 2$ for all tag set size and calculate the overall tag read time using (4.3). For framed-Aloha, we choose the optimal frame size F^* that minimizes the overall tag read time for different tag set size with assurance level $\alpha = 0.99$. We can see that the slope of EOBT curve is around 2.88 while that of framed-Aloha is around 9.59. Next, we show the shortest overall tag read time of both protocols with known tag set size in Figure 4.8. For EOBT, we set $F = 2$ to obtain the shortest overall tag read time by averaging 1000 trials of simulation for different tag set size. For framed-Aloha, by averaging 1000 trials of simulation using different frame size for the same tag set size, we can choose the minimum result as the shortest overall tag read time. The slope of EOBT curve in Figure 4.8 is still around 2.88 while that of framed-Aloha increases to around 14.25.

4.4 Summary

In this chapter, we have proposed a simple modification of framed-Aloha called Even-Odd Binary Tree (EOBT) protocol for multiple tag identification in passive RFID systems. The performance of EOBT is not affected by the ID length and ID distribution of tags as framed-Aloha does. EOBT is shown to outperform framed-Aloha for the ability to read all passive tags with complete certainty when the tag set size is known or unknown.

In EOBT, the reader is capable of partitioning the responding

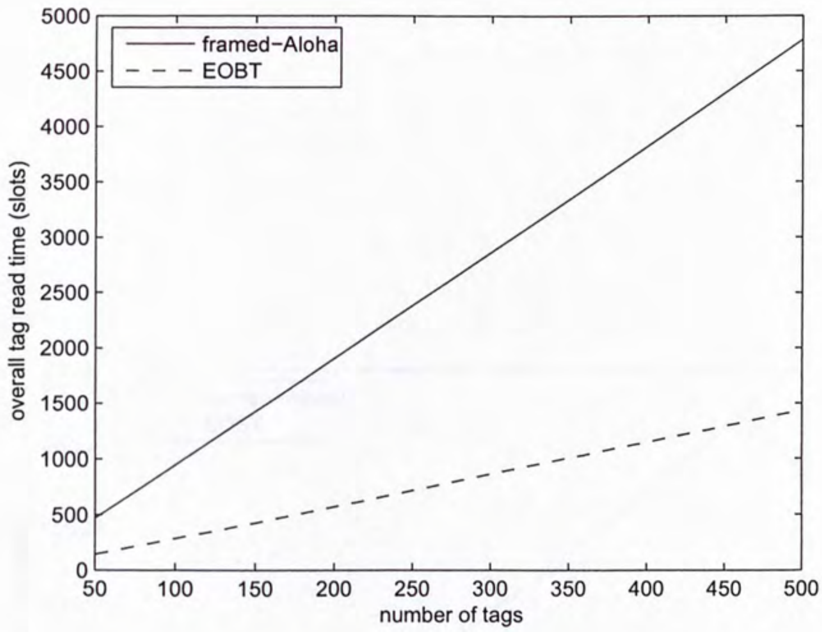

Figure 4.7: Shortest overall tag read time of EOBT and framed-Aloha with unknown tag set size.

tags into different groups based on their previous transmission. This strategy can significantly reduce the number of collisions, thus improving the overall identification efficiency. We have studied the relationship between the frame size and the overall tag read time of EOBT and find out that frame size $F = 2$ provides best reading performance. Through theoretical analysis and simulation studies, we show that EOBT performs better than framed-Aloha in terms of overall tag read time and reading reliability for both cases of known and unknown tag set size.

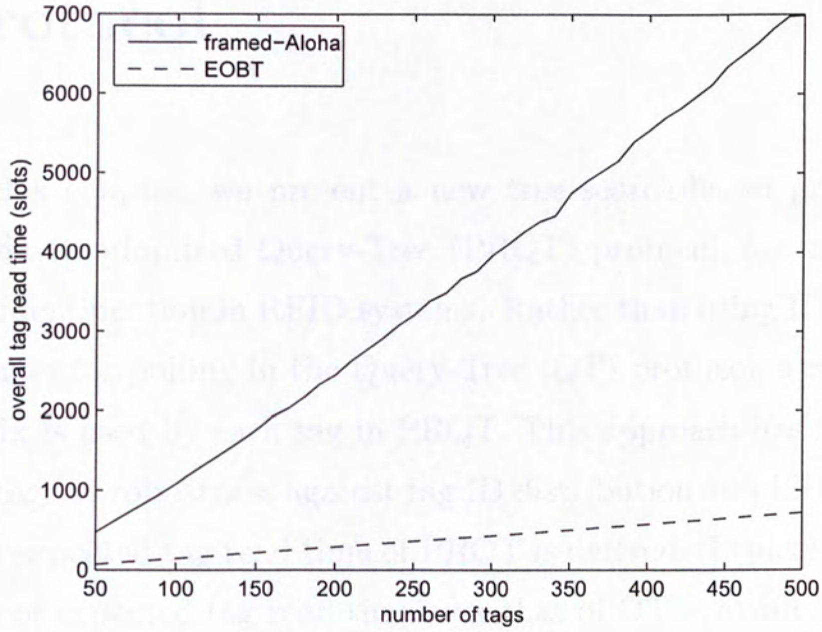

Figure 4.8: Shortest overall tag read time of EOBT and framed-Aloha with known tag set size.

Chapter 5

Prefix-Randomized Query-Tree Protocol

In this chapter, we present a new tree search-based protocol, Prefix-Randomized Query-Tree (PRQT) protocol, for multiple tag identification in RFID systems. Rather than using ID-based prefixes for polling in the Query-Tree (QT) protocol, a random prefix is used by each tag in PRQT. This approach has the advantage of robustness against tag ID distribution and ID length. The expected tag read time of PRQT is derived. Typical reduction of expected tag read time over that of QT is about 30 percent for nonuniform ID distribution and 20 percent for uniform ID distribution. For applications where the tag set size is unknown before identification, an initial prefix length adaptation algorithm is proposed for use.

5.1 Tag Identification - Known Tag Set Size

The Prefix-Randomized Query-Tree (PRQT) protocol is designed under the assumptions: (i) the tag set size is fixed during the identification process, (ii) tags can randomly generate a prefix with a prescribed length, and (iii) tags cannot communicate with each other and they may choose the same prefix.

5.1.1 Protocol Description

The PRQT algorithm consists of rounds of "queries from the reader" and "responses from tags". In the initial round, the reader broadcasts a command with an initial prefix length l ($l \leq L$, where L is the length of tag ID string) which is determined from the tag set size n. After receiving this initial command, each tag generates an l-bit random binary prefix. The reader then polls each of these 2^l prefixes sequentially. In each polling round, tags with prefix matches respond with their IDs. Since tags cannot coordinate the prefix choices, multiple tags may choose the same prefix. Therefore tags with the same prefix will respond to the reader at the same time and cause a collision. After the reader polls all 2^l prefixes, it obtains those prefixes where collision occurs. For each collided prefix f_i, the reader will then broadcast a command asking this group of collided tags matching this prefix to expand f_i by one bit randomly drawn from '0' or '1' and polls the extended prefixes f_i0 and f_i1. If

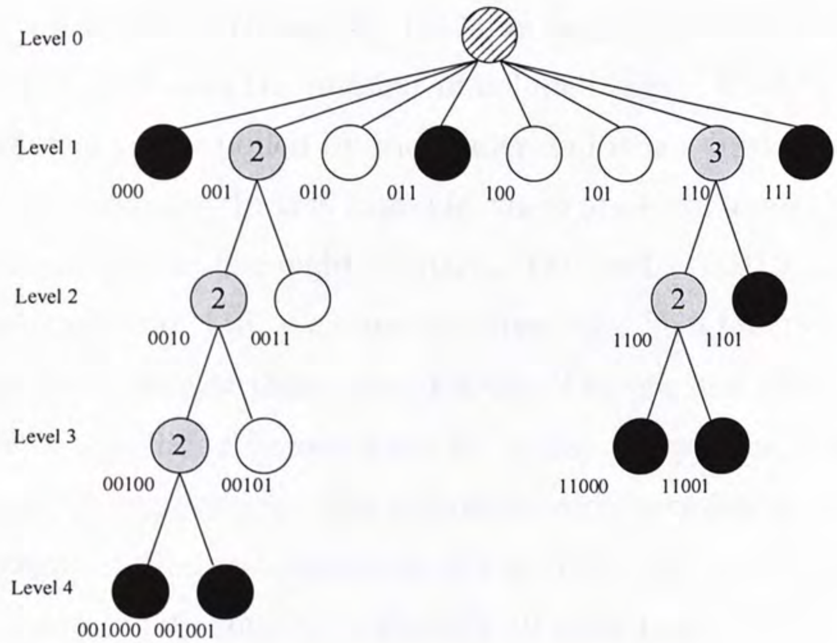

Figure 5.1: PRQT example for identifying eight tags.

collisions occur in these polls, the same procedure is repeated. In essence, PRQT grows a binary query tree from the collided prefix f_i until all tags choosing this prefix are successfully identified. After that, the algorithm returns and continues polling the rest of collided prefixes. The same procedure is repeated until all collided prefixes have been resolved.

In Figure 5.1 we show a query tree of PRQT for identifying eight tags with an initial prefix length of three bits. The shaded root node indicates the broadcasting of the initial prefix length by the reader. A dark node indicates a prefix polled by the reader and is chosen by a single tag (which corresponds to a success response). A gray node indicates a prefix polled by the reader and is chosen by multiple tags (the number inside the circle indicates the number of collided tags). A white node indicates a prefix polled by the reader and is not chosen by any tag (no response). In this example, there are eight level-1 nodes corresponding to the eight prefixes. The prefix '001' is chosen by two tags and '110' is chosen by three tags. So a binary tree is grown from each of these two prefixes. The left and right child nodes of a collided parent node for prefix f_i represent prefixes f_i0 and f_i1 respectively. The communication between the reader and tags for this example is shown in Table 5.1 where PRQT uses a total of 19 rounds to identify all eight tags.

5.1.2 Time Complexity Analysis

In PRQT protocol, tags may choose the same prefix round after round. But this probability drops geometrically as the prefix length gets longer. The classical analysis methods for tree search algorithm [30][31][32] cannot be used here as tags are not guaranteed to generate unique prefixes.

To find the average tree size given the number of tags and the initial prefix length, let us assume the tag set size is n, the initial prefix length is l and therefore the number of level-1 nodes of the query tree is $N = 2^l$. In level-1, some nodes (prefixes) may be chosen by multiple tags as shown in Figure 5.1, which leads to collision when the reader polls these prefixes. Let p_k denote the probability of k tags choosing the same prefix in a level-1

Round	Query	Response
1	$L = 3$	No response
2	000	Success
3	001	Collision
4	010	No response
5	011	Success
6	100	No response
7	101	No response
8	110	Collision
9	111	Success
10	0010	Collision
11	0011	No response
12	00100	Collision
13	00101	No response
14	001000	Success
15	001001	Success
16	1100	Collision
17	1101	Success
18	11000	Success
19	11001	Success

Table 5.1: Communication between reader and tags.

node. Then p_k follows a binomial distribution

$$p_k = \binom{n}{k}\left(\frac{1}{N}\right)^k\left(1-\frac{1}{N}\right)^{n-k} \tag{5.1}$$

Every collision from level-1 node onward causes a split of the query tree. Since each node (excluding the root node) on the query tree represents a round of polling operation by the reader, the expected number of polling rounds needed to completely identify all tags, W, is numerically equal to the size of the query tree excluding the root node. Assuming the amount of time for each polling-response round is fixed, then W is also identical to the *expected tag read time*.

Let t_k denote the average size of a sub-tree with k tags in its root node, then W equals the summation of all sub-tree sizes

$$W = N\sum_{k=0}^{n} p_k t_k \tag{5.2}$$

Obviously $t_0 = t_1 = 1$ because there is no collision in these two cases. To calculate t_k for k from 2 to n, we condition on the first split (level-2) of the collided level-1 node. Suppose i out of k ($i \in [0, k]$) tags choose to expand the prefix by '0' and the rest $k - i$ tags choose to expand the prefix by '1'. This leads to two sub-trees with i and $k - i$ nodes respectively. Therefore, $t_k = 1 + t_i + t_{k-i}$ and this probability is given by

$$p_k(i, k-i) = \binom{k}{i}/2^k, i = 0, 1, \cdots k \tag{5.3}$$

Summing over all $i \in [0, k]$ we obtain

$$t_k = 1 + \sum_{i=0}^{k} p_k(i, k-i)(t_i + t_{k-i}) \tag{5.4}$$

Substituting (5.3) into (5.4) and rearranging the term to the left-hand side, we obtain

$$t_k = \frac{1}{2^{k-1} - 1}\left[2^{k-1} + \sum_{i=0}^{k-1} \binom{k}{i} t_i\right] \tag{5.5}$$

where $t_0 = t_1 = 1$ and $k = 2, 3, \ldots, n$.

Figure 5.2 shows the close matching of the analytical and simulation results of W under different settings of the initial prefix length. Each simulation point represents the average value of 1000 trials.

5.1.3 Optimal Initial Prefix Length

In this section, we derive the optimal initial prefix length for a given tag set size. From (5.1), (5.2) and (5.5) we can see that given n, the expected number of polling rounds (expected tag read time) W is a function of N only. We therefore can minimize W with respect to N. As stated before, the initial prefix length is $l = \log_2 N$.

However, W is not differentiable because N is an integer. To cope with this problem, we relax N to be a real number and introduce a variable $q = 1/N$. Substituting q into (5.1) and

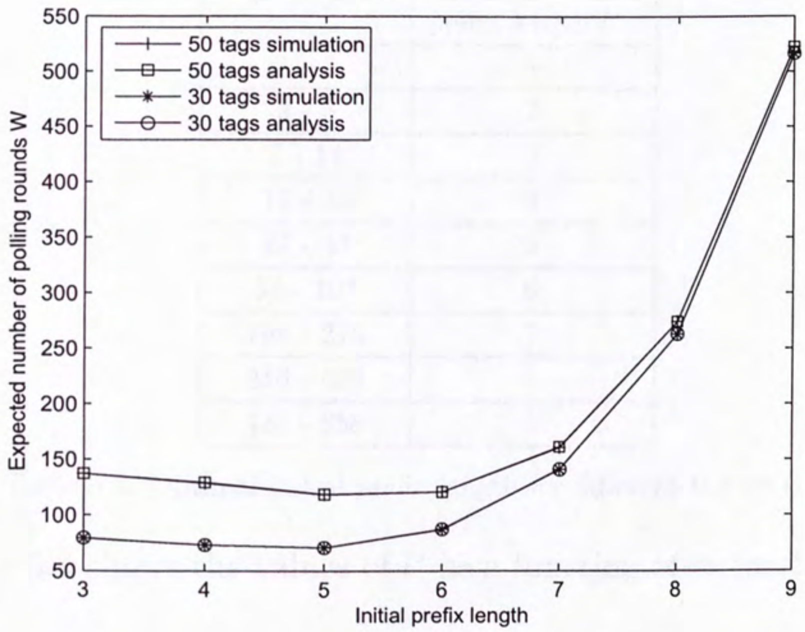

Figure 5.2: Analytical and simulation results of PRQT protocol.

(5.2) we have

$$W(q) = \frac{1}{q} \sum_{k=0}^{n} \binom{n}{k} q^k (1-q)^{n-k} t_k \tag{5.6}$$

Differentiating $W(q)$ with respect to q we have

$$\frac{\partial W}{\partial q} = \sum_{k=0}^{n} \binom{n}{k} (k-1+q-nq) q^{k-2} (1-q)^{n-k-1} t_k \tag{5.7}$$

Let $\frac{\partial W}{\partial q} = 0$, q^* that minimizes W can be found numerically. Since q^* is a real number, the optimal initial prefix length will be either $l^+ = \lceil \log_2(1/q^*) \rceil$ or $l^- = \lfloor \log_2(1/q^*) \rfloor$. Putting them together, the optimal prefix length is given by

$$l^* = \arg\min \{W(l^+), W(l^-)\} \tag{5.8}$$

Tag set size n	Optimal initial prefix length l^*
1 - 3	1
3 - 6	2
7 - 14	3
15 - 26	4
27 - 53	5
54 - 107	6
108 - 215	7
216 - 429	8
430 - 858	9

Table 5.2: Optimal initial prefix length for different tag set size.

Table 5.2 shows the values of l^* as a function of n, for $1 \leq n \leq 858$.

5.1.4 Optimal Number of Level-1 Nodes

Instead of optimizing the initial prefix length, we can optimize the number of level-1 nodes N to shorten the expected tag read time further. In (5.7), let $\frac{\partial W}{\partial q} = 0$, q^* that minimizes W can be found numerically and the optimal number of level-1 nodes N^* can be obtained by (5.9), where $N^+ = \lceil 1/q^* \rceil$ and $N^- = \lfloor 1/q^* \rfloor$.

$$N^* = \arg\min \left\{ W(N^+), W(N^-) \right\} \tag{5.9}$$

In Figure 5.3 we compare the expected tag read time of PRQT using optimal initial prefix length l^* with that using optimal number of level-1 nodes N^*. It is seen that there is a small performance improvement by optimizing the number of level-1 nodes since the choice can now be any integer rather than powers

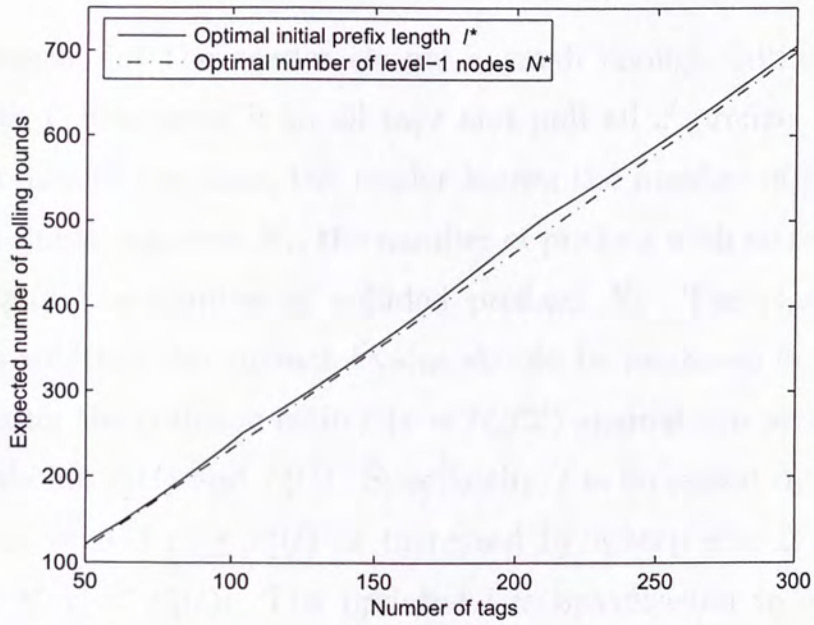

Figure 5.3: Expected tag read time of PRQT by (1) optimal initial prefix length l^* and (2) optimal number of level-1 nodes N^*.

of 2. However, the optimal initial prefix length version of PRQT is simpler and we shall choose it for performance comparisons in the following sections.

5.2 Tag Identification - Unknown Tag Set Size

The PRQT protocol described in previous section requires the knowledge of tag set size for setting the optimal initial prefix length l^* to obtain the best reading performance. In this section, we propose an initial prefix length adaptation algorithm to be used with the PRQT protocol when the tag set size is unknown before identification.

5.2.1 Initial Prefix Length Adaptation Algorithm

To begin, let the reader choose a small enough initial prefix length l, announce it to all tags and poll all 2^l prefixes. From responses of the tags, the reader knows the number of prefixes with single response N_1, the number of prefixes with no response N_0, and the number of collided prefixes N_c. The reader decides whether the current l value should be increased or not by checking the collision ratio r ($r = N_c/2^l$) against two predefined thresholds $r_2^*(l)$ and $r_3^*(l)$. Specifically, l is increased by a step size $\Delta = 3$ if $r \geq r_3^*(l)$ or increased by a step size $\Delta = 2$ if $r_2^*(l) \leq r < r_3^*(l)$. The updated l is broadcasted to all tags again for faster identification time. This procedure is repeated until $r < r_2^*(l)$ and the PRQT protocol is executed with the chosen initial prefix length. Using this method, all previous polling efforts for initial prefix length adaptation are wasted. But being able to use the best initial prefix length (i.e. matches the estimated tag set size) can shorten the overall tag read time. Methods for computing thresholds $r_2^*(l)$ and $r_3^*(l)$ and choosing the optimal step size Δ are presented in the following sections. The following is the initial prefix length adaptation algorithm.

Step 1: $l = 1$.
Step 2: Broadcast l to all tags and poll all 2^l prefixes.
Step 3: Compute the collision ratio r.
Step 4: If $r \geq r_3^*(l)$

$l \leftarrow l+3$, go to **Step 2**.

Else if $r_2^*(l) \leq r < r_3^*(l)$

$l \leftarrow l+2$, go to **Step 2**.

Else if $r < r_2^*(l)$

Execute PRQT with l.

Step 5: End.

5.2.2 Computing $r_\Delta^*(l)$

Let W_l be the expected tag read time with initial prefix length l and $n_\Delta^*(l)$ be the minimum tag set size with which increasing l by Δ leads to a shorter total expected tag read time. After the polling of 2^l prefixes, if the reader increases l by Δ , the total expected tag read time is $2^l + W_{l+\Delta}$. Therefore $n_\Delta^*(l)$ can be obtained as

$$n_\Delta^*(l) = \min\left\{n|2^l + W_{l+\Delta} < W_l\right\} \tag{5.10}$$

Using W_l from (5.2), we obtain

$$\begin{aligned} n_\Delta^*(l) &= \min\bigg\{ n|2^l + 2^{l+\Delta}\sum_{k=0}^{n}\binom{n}{k}(\frac{1}{2^{l+\Delta}})^k(1-\frac{1}{2^{l+\Delta}})^{n-k}t_k \\ &\qquad < 2^l\sum_{k=0}^{n}\binom{n}{k}(\frac{1}{2^l})^k(1-\frac{1}{2^l})^{n-k}t_k\bigg\} \\ &= \min\bigg\{ n|\sum_{k=0}^{n}\binom{n}{k}((\frac{1}{2^l})^k(1-\frac{1}{2^l})^{n-k} \\ &\qquad - 2^\Delta(\frac{1}{2^{l+\Delta}})^k(1-\frac{1}{2^{l+\Delta}})^{n-k})t_k > 1\bigg\} \end{aligned} \tag{5.11}$$

For $n^*_\Delta(l)$ tags, the collision probability $r^*_\Delta(l)$ is

$$r^*_\Delta(l) = 1 - (1 - \frac{1}{2^l})^{n^*_\Delta(l)} - (\frac{n^*_\Delta(l)}{2^l})(1 - \frac{1}{2^l})^{n^*_\Delta(l)-1} \tag{5.12}$$

In the initial prefix length adaptation algorithm, the reader checks the collision ratio r against the collision probability $r^*_\Delta(l)$ to decide if l should be increased by Δ. In other words, if $r \geq r^*_\Delta(l)$, the unknown tag set size is probably larger than $n^*_\Delta(l)$ and hence increasing l by Δ will lead to shorter expected tag read time. Table 5.3 shows sequences of $n^*_\Delta(l)$ and $r^*_\Delta(l)$ for Δ from 2 to 4 and l from 1 to 5.

	l	1	2	3	4	5
$\Delta = 2$	$n^*_2(l)$	7	15	30	60	119
	$r^*_2(l)$	0.9375	0.9198	0.9038	0.8954	0.8894
$\Delta = 3$	$n^*_3(l)$	11	21	43	85	171
	$r^*_3(l)$	0.9941	0.9810	0.9771	0.9724	0.9714
$\Delta = 4$	$n^*_4(l)$	18	36	72	144	289
	$r^*_4(l)$	0.9999	0.9996	0.9992	0.9990	0.9989

Table 5.3: Sequences of $n^*_\Delta(l)$ and $r^*_\Delta(l)$ for Δ from 2 to 4 and l from 1 to 5.

5.2.3 Optimal Choice of Step Size Δ

We now proceed to a three-part argument leading to the conclusion that $\Delta = 2$ or 3 are desirable choices for our algorithm.

Part 1: $\Delta = 1$ is a bad choice.

Let $\Delta = 1$ in (5.10), and compare $2^l + W_{l+1}$ with W_l. Since W_l is at most $2^l + W_{l+1}$, which occurs when all level-1 nodes of the query tree are collided, the condition in (5.10) cannot be satisfied and no value of tag set size will lead to a shorter expected tag read time by increasing l to $l+1$. As an example, suppose the initial prefix length adaptation algorithm starts with $l = 5$, for tag set size ranging between 54 and 107, l^* should be 6 according to Table 5.2. However, we observe from Figure 5.4 that the maximum expected saving of using $l = 6$ over that of using $l = 5$ for identifying 54 tags to 107 tags is 22.5 rounds. This is less than the overhead of 32 polling rounds for going from $l = 5$ to $l = 6$. In other words, if the reader increases l from 5 to 6, the first 32 rounds of polling are wasted but the maximum expected gain is only 22.5 rounds. Therefore, increasing l from 5 to 6 is a bad choice.

Part 2: $\Delta \geq 4$ are bad choices.

From Table 5.3, we can see that larger Δ results in $r^*_\Delta(l)$ closer to 1 for the same l. When $\Delta \geq 4$, $r^*_\Delta(l)$ are all very close to 1. This leads to decision ambiguity when they are used to compare with the collision ratio r. Specifically, if the collision ratio $r = 1$, many values of Δ are suitable. But to avoid the high cost of overshooting l, $\Delta \geq 4$ should not be chosen.

Part 3: $\Delta = 2$ or 3 depending on r.

From the last two parts, $\Delta = 2$ or 3 are the only feasible choices for the algorithm. Its choice depends on the value of

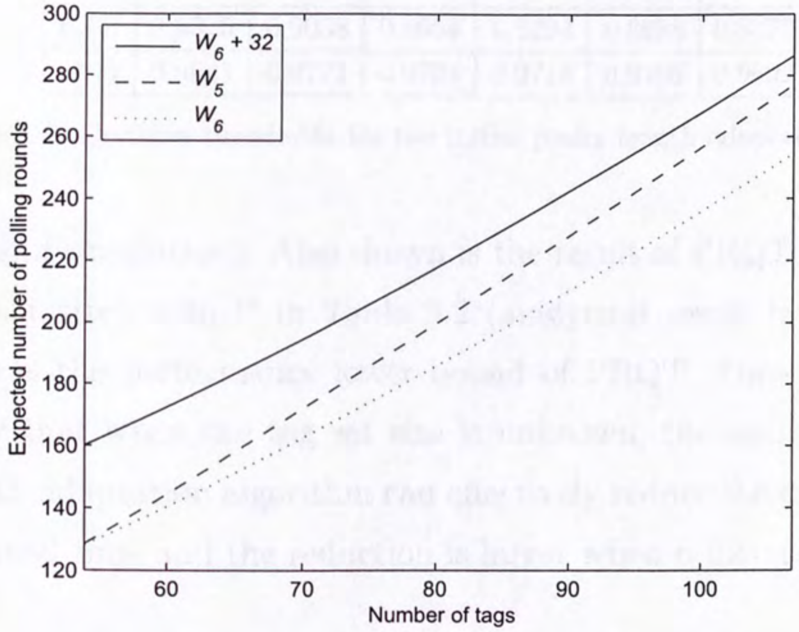

Figure 5.4: Expected tag read time of identifying 54 to 107 tags of (1) $W_6 +$ 32 rounds, (2) W_5 and (3) W_6.

collision ratio r. If $r \geq r_3^*(l)$, l is increased to $l+3$ ($\Delta = 3$). If $r_2^*(l) \leq r < r_3^*(l)$, l is increased to $l+2$ ($\Delta = 2$). Table 5.4 shows the sequence of $r_2^*(l)$ and $r_3^*(l)$ for l from 1 to 7. Note that since the algorithm starts at $l = 1$ and $\Delta = 2$ or 3, an initial prefix length of $l = 2$ is not possible. Therefore the decision thresholds for $l = 2$ is absent in Table 5.4.

In Figure 5.5 we compare the expected tag read time for identifying 1 to 800 tags with two methods: (i) PRQT (unknown tag set size) with fixed initial prefix length $l = 5$ (analytical result by (5.2)), (ii) PRQT (unknown tag set size) with the initial prefix length adaptation algorithm (average result of 1000

l	1	3	4	5	6	7
$r_2^*(l)$	0.9375	0.9038	0.8954	0.8894	0.8888	0.8872
$r_3^*(l)$	0.9941	0.9771	0.9724	0.9714	0.9706	0.9699

Table 5.4: Decision thresholds for the initial prefix length adaptation algorithm.

trials of simulation). Also shown is the result of PRQT (known tag set size) with l^* in Table 5.2 (analytical result by (5.2)). This is the performance lower bound of PRQT. These results show that when the tag set size is unknown, the initial prefix length adaptation algorithm can effectively reduce the expected tag read time and the reduction is larger when n increases.

5.3 Performance Evaluation

We now compare the performance of PRQT with the Query-Tree (QT) protocol. For simplicity, we denote PRQT with the initial prefix length adaptation algorithm as *Adaptive-PRQT* in this section. The expected and worst-case identification time of PRQT, Adaptive-PRQT, and QT (with uniform and nonuniform tag ID distribution) are compared in this section. QT is a deterministic anti-collision protocol with an expected identification time in the range of $(2.881n - 1, 2.887n - 1)$ for n tags with uniformly distributed IDs. However, its worst-case identification time for identifying n tags is $n(k + 2 - \log_2 n)$, where k is the tag ID length [3].

Firstly, we investigate the effect of tag ID distribution on the

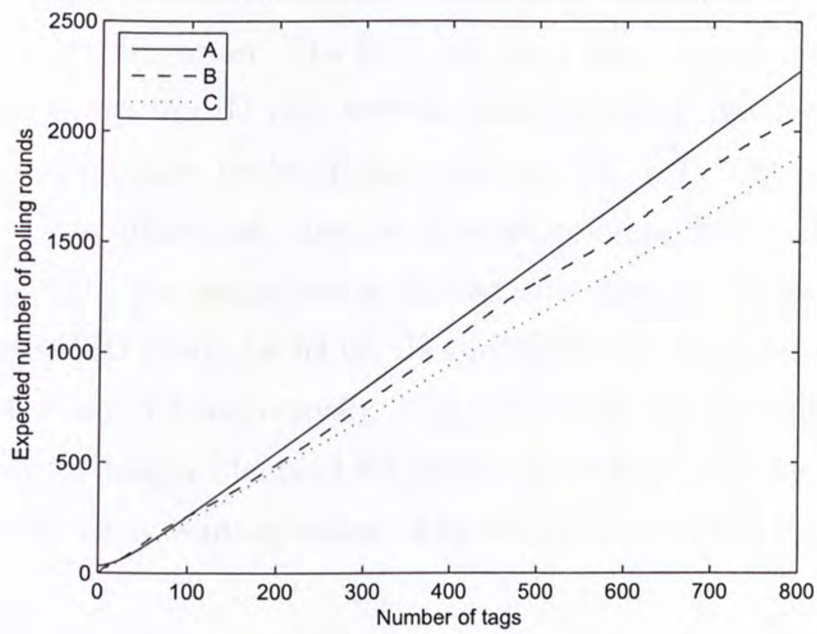

Figure 5.5: Expected number of polling rounds by (1) PRQT (unknown tag set size) with fixed $l = 5$ (curve A), (2) PRQT (unknown tag set size) with the initial prefix length adaptation algorithm (curve B) and (3) PRQT (known tag set size) with l^* (curve C).

average tag identification time of QT by varying the probability of '0's occurring in the ID string from 0.05 to 0.95. The ID length is set to be 64 bits (common used ID length is 64 bit or 96 bit [12]). Each data point shown in Figure 5.6 is the average value of 1000 trials. We can see that the average tag identification time of QT is heavily dependent on the uniformity of tag ID distribution, particularly when the tag set size is large. The performance of PRQT and Adaptive-PRQT, however, is totally independent of ID distribution and ID length.

Another issue affecting the identification efficiency of QT is the length of identical ID prefix shared by the set of RFID tags under interrogation. The EPC tag data encoding schemes partition every tag ID into several fields including Header, Filter value, Company prefix, Item reference, etc. [12]. Often, products being identified have one or more common EPC fields. By using QT, the performance degradation due to the length of identical ID prefix for 64 bit ID and 96 bit ID are shown in Figure 5.7 and 5.8 respectively. It is noted that the degradation is larger for longer identical ID prefix. For PRQT, the identification efficiency is independent of the length of identical ID prefix.

In Figure 5.9, we compare the expected tag read time for four different schemes:

1. PRQT with optimal initial prefix length l^* in Table 5.2 (analytical result by (5.2)).
2. Adaptive-PRQT (average result of 1000 trials of simulation).
3. QT with uniform tag ID distribution (analytical result using the lower bound of its expected tag read time $2.881n - 1$).
4. QT with non-uniform tag ID distribution where Prob('0') = 0.3 (average result of 1000 trials of simulation).

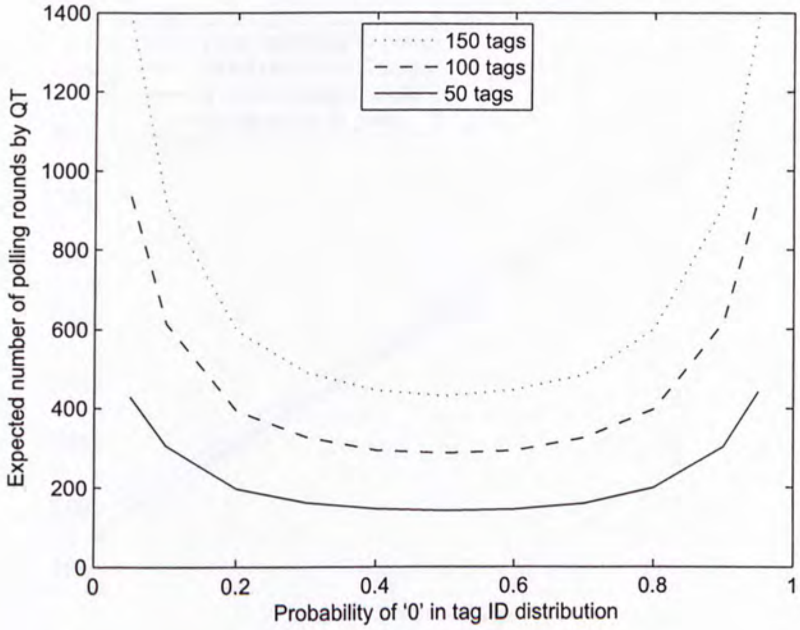

Figure 5.6: Effect of the non-uniformity of tag ID distribution on the average identification time of QT.

It can be seen from Figure 5.9 that the two PRQT schemes have better performance than the two QT schemes for all tag set size. The expected tag read time of PRQT (scheme 1) increases linearly with n with a slope of 2.36. So the average time complexity of PRQT is $O(2.36n)$. The ID length is set to 64 bits for QT in scheme 3 and 4.

In Figure 5.10, we compare the worst-case tag read time of PRQT, Adaptive-PRQT, and QT with uniform and nonuniform (Prob('0') = 0.3) ID distribution, for tag set size equal to 50, 100, and 150 respectively, assuming 64 bit ID length for QT. This worst-case identification time is the worst of 1000 trials

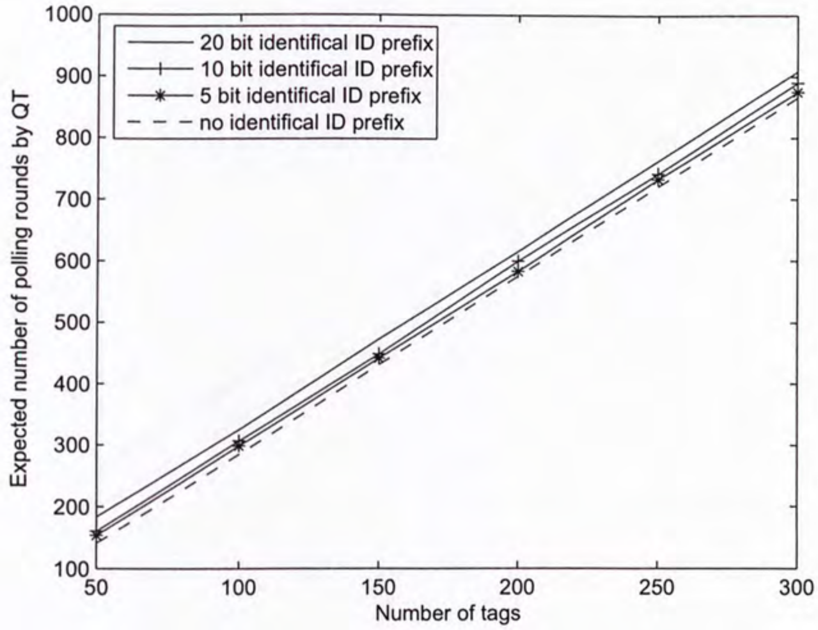

Figure 5.7: Effect of the length of identical ID prefix on the average identification time of QT (64 bit ID length).

of simulation in each of four cases. These simulation results show that PRQT gives increasingly better worst-case performance than QT as the tag set size increases. However, from the theoretical point of view, since PRQT relies on random-prefix generation, its worst-case performance can be as worst as that of QT.

Figure 5.11 shows cumulative distributions of the number of polling rounds to identify 50 and 150 tags respectively. These distributions are obtained by 1000 trials each of PRQT, Adaptive-PRQT, and QT with uniform and nonuniform (Prob('0') = 0.3) ID distribution assuming 64 bit ID length. It is noted that

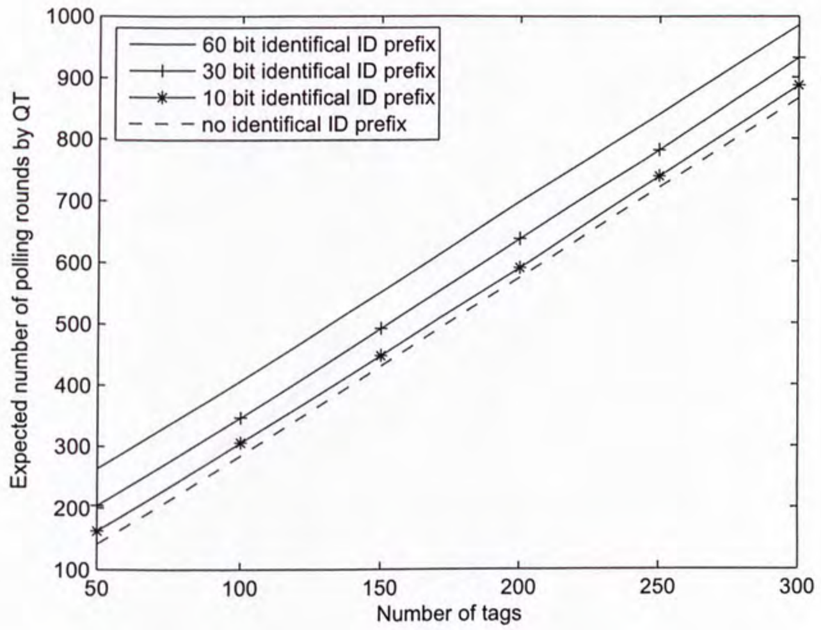

Figure 5.8: Effect of the length of identical ID prefix on the average identification time of QT (96 bit ID length).

PRQT always performs better than QT for the same tag set size and performs increasingly better with the increasing tag set size. As an example, with a set size of 150 tags, the probability of identifying all tags by no more than 400 polling rounds is 0.988 for PRQT, 0.958 for Adaptive-PRQT, 0.158 for QT with uniform ID distribution and 0 for QT with nonuniform ID distribution (Prob('0') = 0.3).

5.4 Summary

In this chapter we propose a Prefix-Randomized Query-Tree (PRQT) protocol for multiple tag identification in RFID sys-

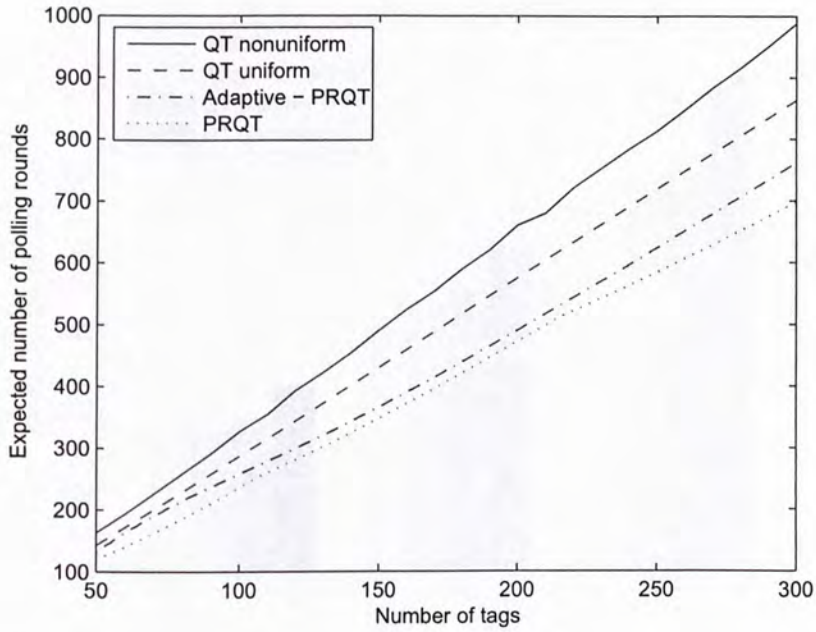

Figure 5.9: Comparison of expected tag read time.

tems. The main feature of PRQT distinguishing from QT is that it uses prefixes randomly generated by tags to match prefixes broadcasted by the reader. Therefore, the identification time of PRQT, contrary to that of QT, is totally independent of the length and distribution of tag ID. Moreover, by using polling, PRQT is capable of identifying all passive tags with complete certainty when the tag set size is unknown.

We have studied the relation of the initial prefix length and the expected tag read time of PRQT and summarize the optimal initial prefix length l^* for different tag set size in Table 5.2. This table can be referenced when the tag set size is known before identification. For applications where tag set size is unknown be-

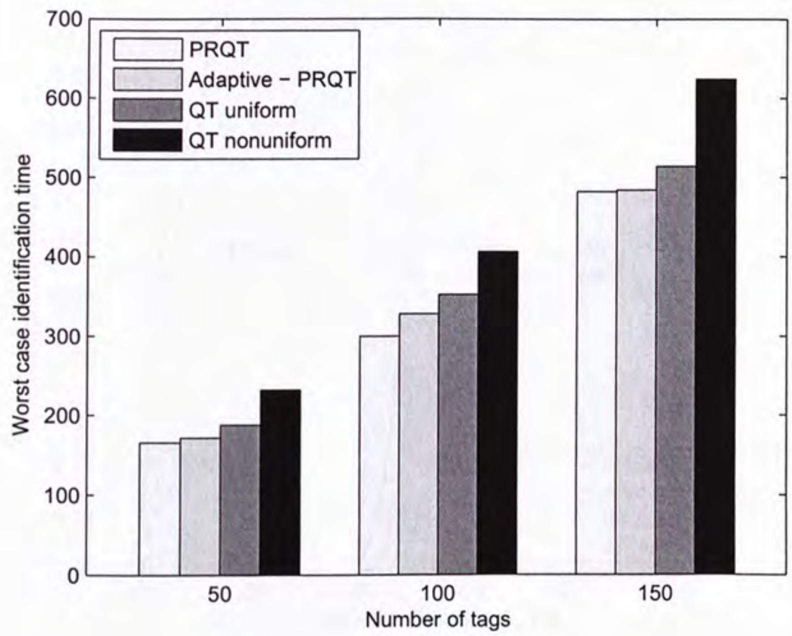

Figure 5.10: Worst-case tag read time among 1000 trials of simulation for 50, 100 and 150 tags.

fore identification, we propose an initial prefix length adaptation algorithm to adaptively increase the initial prefix length based on the collision ratio such that an initial prefix length, which matches the estimated tag set size, can be found for proceeding PRQT to achieve shorter expected tag read time. We derive the sequence of decision thresholds $r^*_\Delta(l)$ and the optimal initial prefix length increment Δ for this algorithm. Through theoretical analysis and simulation studies, we show that PRQT with optimal initial prefix length (known tag set size), and PRQT with initial prefix length adaptation algorithm (unknown tag set size) performs better than QT, with uniform or nonuniform

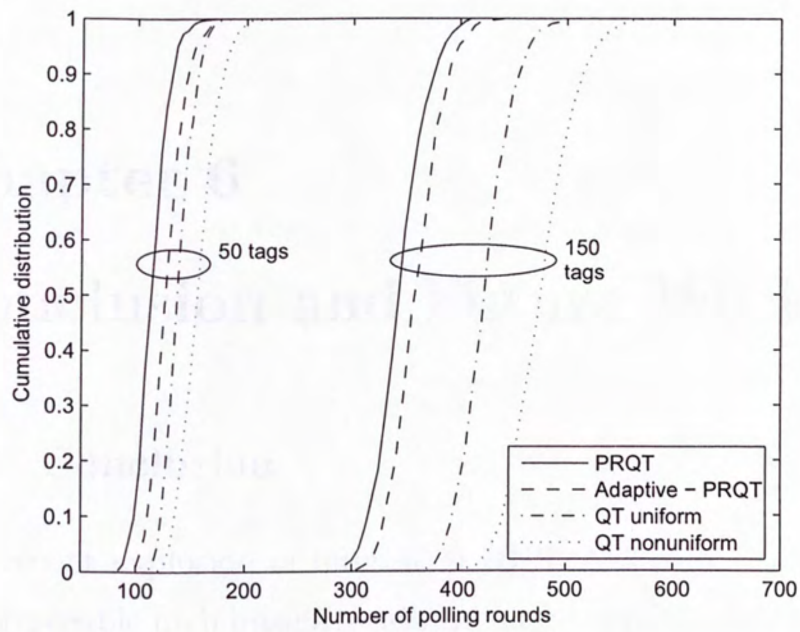

Figure 5.11: Cumulative distribution of the number of polling rounds for 50 and 150 tags.

tag ID distribution, in terms of both average and worst-case identification time.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

The recent explosion of interest in RFID technology is due to its foreseeable high business value in many application domains, especially in the global retail and supply chain management systems. Thanks for the recent breakthroughs in integrated circuit, low-power semiconductor, and MEMS technologies, extremely small and low-cost electronic tags with computation and communication capabilities become feasible. These smart tiny tags are envisioned to attach to every item on earth for seamlessly bridging the virtual world and physical world. By integrating with the Internet, RFID systems can easily enable real time product tracking, inventory control, anti-counterfeit, etc. at different stages of the global retail and supply chain logistics. Therefore, we will soon be able to search any physical object by RFID technology, as efficient as to search any electronic document on the Internet.

One of the unique and compelling advantages of RFID over other object identification technologies, such as barcode, is the ability to read a large volume of tags at the same time without physical contact and orientation requirements. This advantage can reduce or even remove a large amount of labor-intensive scanning in many applications such as warehouse management systems and supermarket checkout counters. However, this multiple tag identification capability requires well-designed anti-collision protocols to solve the tag collision problem. Since low-cost passive RFID systems will be the major driving force of the global RFID implementations in near future, recently proposed RFID anti-collision protocols are optimized for the fundamental constraints of low-cost passive tags, such as low computation power, small memory size and low-power operation.

In this thesis, we have proposed two novel anti-collision protocols: (1) Even-Odd Binary Tree (EOBT) protocol and (2) Prefix-Randomized Query-Tree (PRQT) protocol, for multiple tag identification in RFID systems. These two protocols are time-domain methods which successfully combine the advantages of both deterministic and stochastic RFID anti-collision protocols while remove their respective disadvantages. The complexity of these two protocols is made as low as possible to realize a higher identification efficiency and reliability than those of existing solutions.

EOBT partitions the responding tags into different groups based on their previous transmission, so as to reduce the number of collisions and increase the identification efficiency. Through theoretical analysis and simulation studies, we have shown that EOBT not only has higher identification efficiency than the framed-Aloha protocol, but also can identify all passive tags with complete certainty when the tag set size is unknown before identification. For PRQT protocol, we have studied the relation of the initial prefix length and the expected tag read time. The optimal initial prefix length for different tag set size is also derived for reference when the tag set size is known. For applications where the tag set size is unknown before identification, an initial prefix length adaptation algorithm is proposed to incorporate with PRQT to adaptively increase the initial prefix length for faster identification. It has been shown that PRQT performs better than the Query-Tree protocol in terms of both average and worst-case identification time no matter the tag set size is known or unknown.

6.2 Future Work

The main performance specifications of RFID systems include: communication range, identification speed, read-write speed, data integrity, reading reliability, and compatibility [9]. In this thesis, we focus on the development of efficient and reliable anti-collision protocols for multiple tag identification in RFID systems. The proposed protocols, EOBT and PRQT, have shown faster and more reliable identification when compared with framed-Aloha and QT.

Among all performance specifications of RFID systems, the improvement in anti-collision protocols can significantly increase the identification speed (the other important factor determining identification speed is data rate, which is governed by the operating frequency, carrier power, and operating range specified in different RFID standards) and reading reliability (the propagation of electromagnetic waves of different frequencies through metal, liquid or other radio absorbing material is another challenging issue for reading reliability). For other performance metrics, data integrity improving reading reliability is accomplished by well-designed error control coding schemes. The communication range and read-write speed rely mainly on the semiconductor technology, energy harvesting capability, and compatibility between different standards. In summary, all major performance specifications of RFID systems are closely interrelated and their joint optimization on cost, size, and complexity should be investigated for different RFID applications in future.

In studying the anti-collision protocols for RFID systems, there are many areas deserving future work. Particularly, we would like to explore the reliability issues related to channel model and capture effect. By considering these two issues, we can enhance the robustness of our proposed protocols against tags' movement during identification and the lack of power control between signals from tags at different locations.

Rayleigh and Rician channel model for passive RFID systems have been considered in the design of the dynamic frame size adaptation algorithm in [22]. However, the effect of tags' movement during identification (e.g. tags passing along conveyer belts) on channel model is common in many applications but often being neglected in previous research. A suitable channel model is key to design modulation and coding scheme and understand the characteristic of capture effect. The capture effect [33][34][35] happens when there is no power control among the set of tags under interrogation. Signal from one tag located close to the reader probably masks signal from another tag located far from the reader, thus the reader can decode the strong signal although it is collided with the weak signal. This is a problem for PRQT because if any tag's prefix is captured by another tag's prefix, the reader cannot discover the missing tag any more during the polling process. We suggest to use Manchester coding scheme to solve this problem. In Manchester code, data '0' and data '1' have different phase shift in a time slot. So that the conflict between data '0' and data '1' can be discovered by the reader even the difference of signal energy is significant.

Regarding to the latest EPCglobal standard [11], there is a primitive for the reader to selectively mute the responses of a chosen subset of tags in subsequent rounds. We can implement this feature in EOBT to further improve its performance and analyze the optimal frame size for this tag structure. Similarly, although the EPCglobal standard [11] has used random number instead of tag ID for identification, the initial prefix length adaptation algorithm proposed for PRQT is possible to be implemented as a standard-compliant yet vendor-specific feature for product differentiation.

□ **End of chapter.**

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