Enabling Ultra Large-Scale Radio Identification Systems

by

Kashif Ali

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Abstract

Radio Frequency IDentification (RFID) is growing prominence as an automated identification technology able to turn everyday objects into an ad-hoc network of mobile nodes; which can track, trigger events and perform actions. Energy scavenging and backscattering techniques are the foundation of low-cost identification solutions for RFIDs. The performance of these two techniques, being wireless, significantly depends on the underlying communication architecture and affect the overall operation of RFID systems. Current RFID systems are based on a centralized master-slave architecture hindering the overall performance, scalability and usability. Several proposals have aimed at improving performance at the physical, medium access, and application layers. Although such proposals achieve significant performance gains in terms of reading range and reading rates, they require significant changes in both software and hardware architectures while bounded by inherited performance bottlenecks, i.e., master-slave architecture. Performance constraints need to be addressed in order to further facilitate RFID adoption; especially for ultra large scale applications such as Internet of Things.

A natural approach is re-thinking the distributed communication architecture of RFID systems; wherein control and data tasks are decoupled from a central authority and dispersed amongst spatially distributed low-power wireless devices. The distributed architecture, by adjusting the tag's reflectivity coefficient creates micro interrogation zones which are interrogated in parallel. We investigate this promising direction in order to significantly increase the reading rates and reading range of RFID tags, and also to enhance overall system scalability. We address the problems of energy-efficient tag singulations, optimal power control schemes and load aware reader placement algorithms for RFID systems. We modify the conventional set cover approximation algorithm to determine the minimal number of RFID readers with minimal overlapping and balanced number of tags amongst them. We show, via extensive simulation analysis, that our approach has the potential to increase the performance of RFID technology and hence, to enable RFID systems for ultra large scale applications.

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Statement of Originality

I hereby certify that this Ph.D. thesis is original and that all ideas and inventions attributed to others have been properly referenced.

Kashif Ali

June 8^{th} 2011

List of Acronyms

AFSA	Advanced Framed Slotted Aloha
ALE	Application Level Events
ASAP	Adaptive Slotted Aloha Protocol
ASC	Approximate Set Cover
ASC-LB	Approximate Set Cover with Load Balancing
ASK	Amplitude Shift Keying
BST	Binary Search Tree
CW	Carrier Wave
CDMA	Carrier Division Multiple Access
CMOS	Complementary Metal Oxide Semiconductor
CSMA	Carrier Sense Multiple Access
DCS	Distributed Color Selection
DNS	Domain Name Service
DFSA	Dynamic Framed Slotted Aloha
DR-RFID	Distributed Receiving Radio Frequency Identification
dB	Decibel
dBm	Power ratio in decibel
EBST	Enhanced Binary Search Tree
EDFSA	Enhanced Dynamic Framed Slotted Aloha
EPC	Electronic Product Code
FDMA	Frequency Division Multiple Access
GSM	Global System for Mobile Communications
FSA	Framed Slotted Aloha
HF	High Frequency
HiQ	Hierarchical Q-Learning
Hz	Hertz
IC	Integrated Circuit

IFF	Identify Friend or Foe
IoT	Internet of Things
LF	Low Frequency
LSB	Least Significant Bit
MAC	Medium Access Control
MACA	Multiple Access with Collision Avoidance
MIMO	Multiple Input Multiple Output
MHz	Mega Hertz
MSB	Most Significant Bit
NTE	Neighbors and Tags Estimation
O-PDC	Optimal Power-based Clustering
OD-PDC	Optimal Discrete Power-based Clustering
ONS	Object Naming Service
PIE	Pulse Interval Encoding
PDC	Power-based Distance Clustering
PML	Physical Markup Language
PRQT	Prefix Randomized Query Tree
QT	Query Tree
RCS	Radar Cross Section
RF	Radio Frequency
RFID	Radio Frequency Identification
RRE	Redundant Reader Elimination
SDMA	Space Division Multiple Access
SS	Spread Spectrum
TDMA	Time Division Multiple Access
UHF	Ultra High Frequency
URL	Universal Resource Locator
VDCS	Variable-Maximum Distributed Color Selection
μW	Micro-Watts
WSN	Wireless Sensor Network
XML	Extensible Markup Language

Co-Authorship

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2. W. Alsalih, K. Ali and H. S. Hassanein, "A Power Control Technique for Anti-collision Schemes in RFID Systems", submitted, Computer Networks, May 2011

3. K. Ali, W. Alsalih and H. S. Hassanein, "Set cover approximation algorithms for load-aware readers placement in RFID networks", accepted, to appear in IEEE International Communication Conference (ICC), 6 pages, May 2011

4. K. Ali, W. Alsalih, and H. S. Hassanein, "Using neighbour and tag estimations for redundant reader eliminations in RFID networks", accepted, to appear in IEEE Wireless Communication and Networking Conference (WCNC), 6 pages, March 2011

5. K. Ali, S. Oteafy and H. S. Hassanein, "Energy-efficient parallel singulation in RFID", in proceedings of IEEE International Conference on Communications (ICC), pp. 1-6, May 2010

6. K. Ali and H. S. Hassanein, "Parallel singulation in RFID systems", in proceedings of IEEE Global Communications Conference (Globecom), pp. 5594-5599, Dec. 2009

7. K. Ali, A-E. Taha and H. S. Hassanein, "Medium access control in Radio Frequency Identification", Book chapter in "RFID and Sensor Networks: Architectures, Protocols, Security and Integrations", edited by Y. Zhang, L. T. Yang and J. Chen, CRC press, pp. 3-30, Nov. 2009

8. K. Ali and H. S. Hassanein, "Passive RFID tags and vehicle-assisted information dissemination for ITS applications", in proceedings of 34th IEEE Conference on Local Computer Networks (LCN), pp. 688-694, Oct. 2009

9. K. Ali and H. S. Hassanein, “Distributed receiving in RFID systems”, in proceedings of 34th IEEE Conference on Local Computer Networks (LCN), pp. 69-76, Oct. 2009

10. W. Alsalih, K. Ali and H. S. Hassanein, “Optimal distance-based clustering for tag anti-collision in RFID systems”, in Proceedings of 33rdIEEE Conference on Local Computer Networks (LCN), pp. 266-273, Oct. 2008

11. K. Ali, H. S. Hassanein and A-E. Taha, “RFID anti-collision protocol for dense passive tag environments”, in proceedings of the 32nd IEEE Conference on Local Computer Networks (LCN), pp. 819-824, Oct. 2007

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Chapter 1

Introduction

Radio Frequency IDentification (RFID) is a prominently emerging automated identification technology. An RFID system is typically composed of an application, reader, and a set of passive tags. A passive tag has neither a physical power source nor a transceiver as it utilizes the energy-harvesting and reflection based communication, for power and communication, respectively. RFID has an edge over other identification systems such as barcode systems, optical character recognition systems, smart cards, biometrics (voice, fingerprinting, retina scanning) ... etc., in that it requires no line-of-sight for communication, is robust to harsh physical environments, allows simultaneous identification, in addition to being cost and power efficient. RFID seamlessly turns everyday objects into mobile network nodes that can be tracked, traced and monitored. This emerging and rapidly evolving technology has the potential to revolutionize the way we interact with physical objects. However, performance of an RFID system, defined in terms of reading range, reading rate and reading coverage is affected significantly by the magnitude of ultra large scale applications, e.g., Internet of Things (IoT). Such performance constraints need to be addressed in order to facilitate efficient RFID continuing adoption. Coping with these challenges and hence

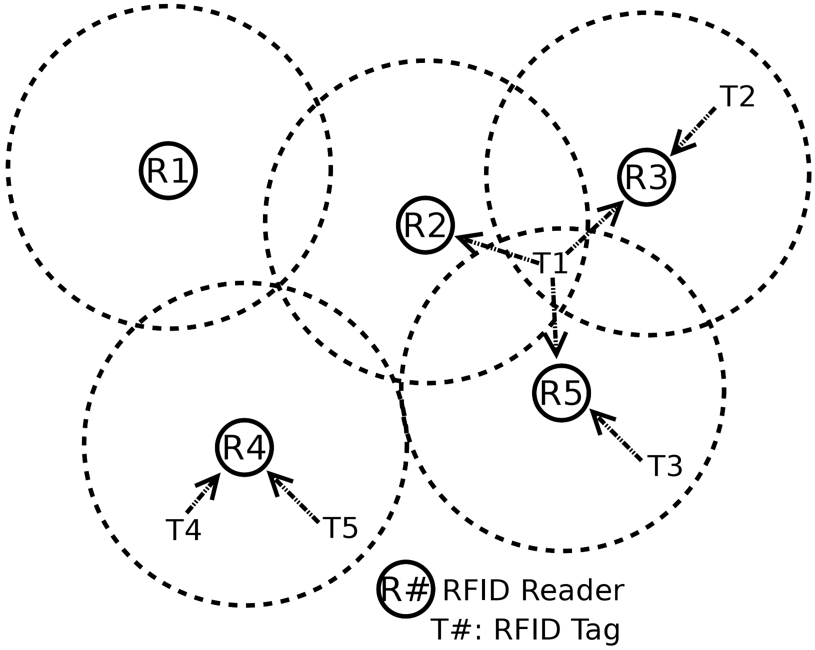


Figure 1.1: Tags and readers collision for a typical RFID system

enabling ultra large scale RFID systems is the main focus of this research.

In the rest of this chapter, we present the motivations behind our research, highlight the thesis contributions and outline the thesis document.

1.1 Motivations

The nature of a tag's reflection based communication dictates failure of the usage of the conventional wireless Medium Access Control (MAC) techniques in RFID systems; as tags cannot sense the medium, detect collisions, or sense the presence of other channel traffic. This means that neither collision avoidance nor collision resolution mechanism can be implemented in tags. Hence, MAC in RFID systems is confined to resolving collisions only at the reader; anti-collision algorithms are needed for both tag collisions and reader collisions.

Tag collisions occur when more than one tag is within the reader's interrogation zone and attempt to reply to the reader's requests at the same time. This is illustrated in Fig. 1.1 as tags $T4$ and $T5$ are within reader $R4$'s interrogation zone. Tag collisions are the most devastating, especially when passive tags, with their limited communication functionalities, are involved. Reader collisions occur when one tag is interrogated by more than one reader, as illustrated in Fig. 1.1 wherein the tag $T1$ is interrogated by readers $R2$, $R3$ and $R5$. Tag collisions and reader collisions result in reduced reading rates, waste of reader's available power; eventually affecting the network lifetime.

Considering tag simplicity, the existing anti-collision algorithms usually employ the Aloha-based contention avoidance schemes. However, these algorithms, because of the centralized reader and tag communication architecture and the probabilistic nature of their executions, are capped by theoretical upper bounds on reading rates. Furthermore, mobility limit the number of tags that can be physically monitored within the interrogation zone of an RFID reader. Therefore, existing anti-collision algorithms do not scale to ultra large RFID applications having 10-100 thousands of tags and thousands of readers.

In addition, reflection based communication also imposes limitations on the reading range of RFID tags. The reflected signal strength faces significant attenuation as it propagates twice the distance between the tag and reader, back and forth, hence capping the upper bound on the operational range of passive tags to some tens of meters. The operational power requirement of upcoming passive tag circuitry and the maximal allowable Carrier Wave (CW) signal strength, in addition to attenuation, also limit the operational range of a passive tag to a few meters. Existing approaches fail to provide significant enhancements to reading rates of RFID tags; therefore forcing more readers to maintain required coverage which further escalates the collisions.

Deploying more readers to cover the required interrogation area will result in redundant readers. For instance, readers $R1$ and $R2$, in Fig. 1.1, are both redundant readers. $R1$ is redundant as it does not cover any tag. Whereas, $R2$ is redundant as the only tag it covers ($T1$) is also covered by its neighboring readers $R3$ and $R5$, both of which cover other tags as well, $T2$ and $T3$, respectively. The overlapping tags need to be interrogated multiple times, individually by each reader. Such redundant interrogations translate into unnecessary energy consumptions, hence lower reading rates thereby affecting network lifetime.

1.2 Thesis Contributions

Our research aims primarily at enabling RFID for ultra large scale applications and improving the performance of existing RFID systems; mainly in reading range, reading rate and reading coverage. The main contributions of this thesis are:

1. Tags within the interrogation zone of a reader cause immense "in-the-air" data collisions, and hence, jeopardize their readability. In general, a reader interrogates tags within its zone using maximal power; mainly to cover as many tags as possible. This conflicts with the objective of minimizing tag collisions. We overcome this problem by devising an optimal power stepping scheme that minimizes tag collisions while covering the required interrogation area. We formulate the problem as a closed-form optimization problem.

2. The centralized reader and tag communication architecture of an RFID system

places fundamental constraints on its performance; namely reading rate and reading range. We overcome these limitations by assigning the existing centralized design of RFID system − the nominal task of receiving tags replies − to spatially distributed devices within the interrogation zones of readers. The goal of the proposed system, named Distributed Receiving RFID (DR-RFID), is enhancing the reading reliability and increasing the reading range and reading rate in a scalable manner.

3. We extend the DR-RFID system and introduce the concept of a micro-zone. In it, the reader's interrogation zone is divided into smaller zones, each of which is managed by a set of distributed devices. We devise an algorithm which determines the reader's power level and alters the strength of the tag's reflected signal; with the objective of confining its readability within a smaller subset, i.e., a micro-zone. They facilitate autonomous interrogation of tags. We propose parallel singulation algorithms for the DR-RFID system. In addition, we also propose both deterministic and probabilistic variations of existing tag anti-collision algorithms. Our parallel singulation alleviates the reading rate bottlenecks.

4. We define and solve RFID coverage as a deterministic as well as random deployment problem. For the former, we propose an approximation algorithm to determine the minimal number of RFID readers required to maintain the requested coverage while having minimal overlapping interrogation zones amongst the readers. We also extend the algorithm to give a load-balancing deployment strategy. We propose a heuristic algorithm to eliminate redundant readers in

random deployments. The goal is to achieve maximal coverage with the minimal possible readers by turning off redundant readers, i.e., readers without additional coverage benefits. This is useful for large scale, dense and random deployments of RFID systems.

1.3 Document Outline

The remainder of this document is organized as follows. Chapter 2 presents the background and literature survey of RFID systems. Chapter 3 presents the power control scheme for tag anti-collision scheme in RFID systems. This includes the basic heuristic scheme, closed-form optimization scheme and discrete greedy optimization scheme. Chapter 4 presents the distributed design for RFID system. The proposed design uses distributed receiving entities to facilitate reading range and reading rates. This also includes our micro-zone concept and parallel singulation algorithms, adopted for both deterministic and probabilistic classes of anti-collision schemes. Chapter 5 presents RFID coverage both as a deterministic and a random deployment problem. It includes the approximation algorithms for load-aware reader placement and the greedy heuristic algorithm for redundant reader elimination, in deterministic and random deployments, respectively. Finally, Chapter 6 concludes this document by highlighting the main issues addressed in this thesis and outlining some of the future research directions.

Chapter 2

Background and Literature Survey

2.1 Background

In this section, we briefly present the history of RFID technology, the enabling technologies, fundamental system architecture and prominent underlying communication protocols.

2.1.1 History

The roots of RFID can be traced back to World War II when Germans enhanced upon the Scottish physicist Sir Robert Alexander Watson-Watt radar to differentiate between the enemy and their own planes. The approach was to enable pilots to roll their planes as they returned to base, allowing the reflected signal to alter in its amplitude. This method would allow the ground crew to differentiate between the German planes and the Allied planes. This was conceptually the first single ID-bit passive RFID system. During same era, the British, under Watson-Watt secret project, developed the first active Identify Friend or Foe (IFF) system which involves deploying an active transmitter on each of the British plane. The transmitter, when it received signals from radar stations on the ground, begins broadcasting signal which helps to identify it as a friendly plane. These two systems were conceptually the first single bit passive and active RFID system.

Advances in radar and RF communications systems continued throughout the 1950s and 1960s. These advancements aided into commercialization of the 1-bit RF based identification resulted in to electronic article surveillance tags, still use in goods theft protection. The bit, depending on the successful payment, is either on or off to detect any forgery or theft. The early RFID technology also found its way into military applications. In 1970s, Los Alamos National Laboratory developed the first transponder reader system to detect the trucks carrying nuclear materials in and out of the secure facilities. The reader wakes up the transponder which then will respond with its serial number and stored information. This system was commercialized in mid 1980s, since then it is adopted for the automated toll payment system for roads, bridges and tunnels across the globe. This identification system, advanced with a passive Low-Frequency (LF) 125 KHz RFID tag, was then adopted in various other applications, e.g., animal tracking and building access. Later on, due to unregulated and unused spectrum, High-Frequency (HF) 13.56 MHz RFID tags were introduced. These HF tags offered relatively faster data transfer rates. Today, the HF 13.56 MHz RFID systems are used for access control, payment systems (e.g., speed-pass) and contact-less smart cards for secure access control.

In the early 1990s, IBM engineers developed an Ultra-High Frequency (UHF) RFID system which offered longer range and faster data transfers however, suffers from wide adoption-scale adoption due its high associated cost. These high costs were mainly due to low sales volume, uncertainty in return-of-investment and lack

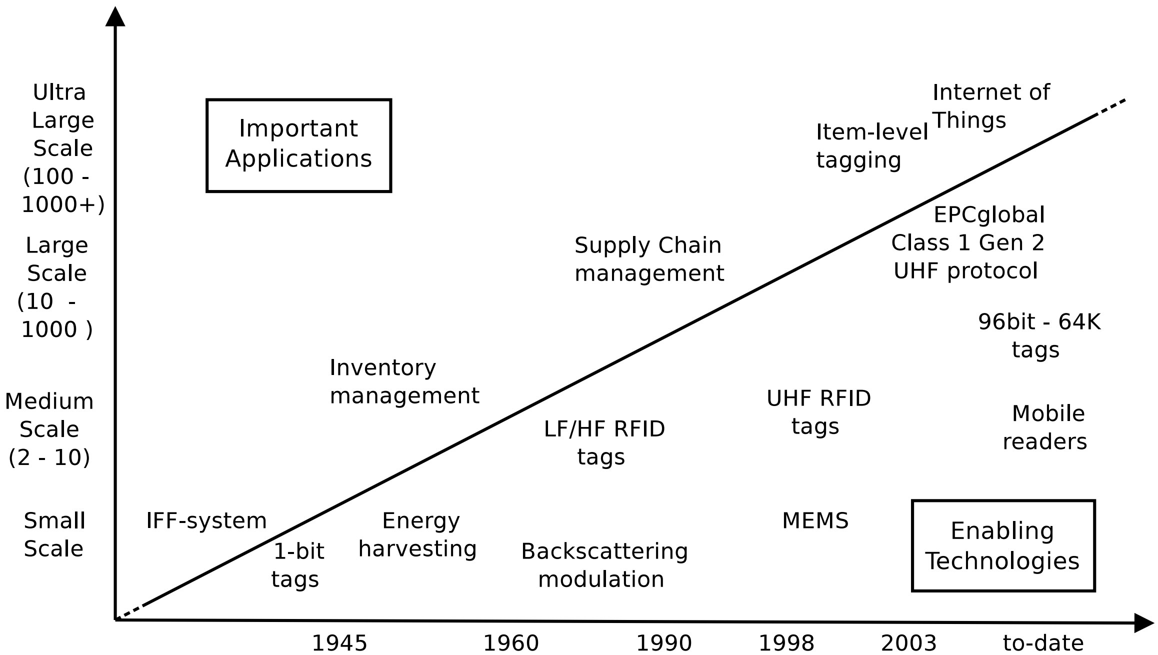


Figure 2.1: History timeline of advancements in RFID technology, highlighting the key applications and enabling technologies.

of international standardizations. However, this changed with the establishment of Auto-ID centre, at the Massachusetts Institute of Technology, which introduced storing the serial number on a small microchip. This approach enabled low-cost RFID tags which can then be placed on products to be tracked throughout the numerous manufacturers supply chain.

Between 1999 and 2003, the Auto-ID Centre, with support of more than 100 large end-user companies, key RFID vendors, and U.S. Department of Defence, developed two important air interface protocols (Class 0 and Class 1), the Electronic Product Code (EPC) numbering scheme and a network architecture to lookup tag data over the network. The standardization of RFID, especially with evident of the second generation standard, currently known as EPCGlobal Gen2, enable large-scale deployments and adoption of RFID solutions. Some of the world biggest retailers, e.g., Metro, Target, Tesco, Wal-Mart, and U.S. Department of Defence are evaluating the EPC Gen2 technology for goods tracking in their supply chain. Other industries such as pharmaceutical, automotive, defence, aviation, and many more are also deploying prototype systems to evaluate the technical feasibilities of RFID systems within their business process. The major RFID related historical events are summarized in Fig. 2.1.

2.1.2 Enabling Technologies

Advancements in energy harvesting, backscatter modulation and micro electro mechanical systems present the foundation of low-cost identification solutions provided by RFID. The energy harvesting yields battery-less RFID tags which enables minimal maintenance, longer lifetime and low cost RFID solutions. The backscattering yields transceiver-less RFID tags which enable minimal power and low cost RFID solutions.

Energy scavenging (harvesting) technique harness incident radio waves and facilitate the operation of battery-less RFID tags. These incident radio waves, after interacting with the antenna, produce high-frequency voltage which is rectified using a diode. The rectified signal is smoothed out using a storage capacitor to provide constant voltage. The voltage is then used to power the tag's logic unit and nonvolatile memory space. A similar circuitry with a smaller capacitance is used to de-modulate the data transmitted by the reader. Using this process, known as envelope detection, the tag processed the reader's query request and acts accordingly. The schematic of a simple energy harvesting scheme and envelope detection of a typical RFID tag is

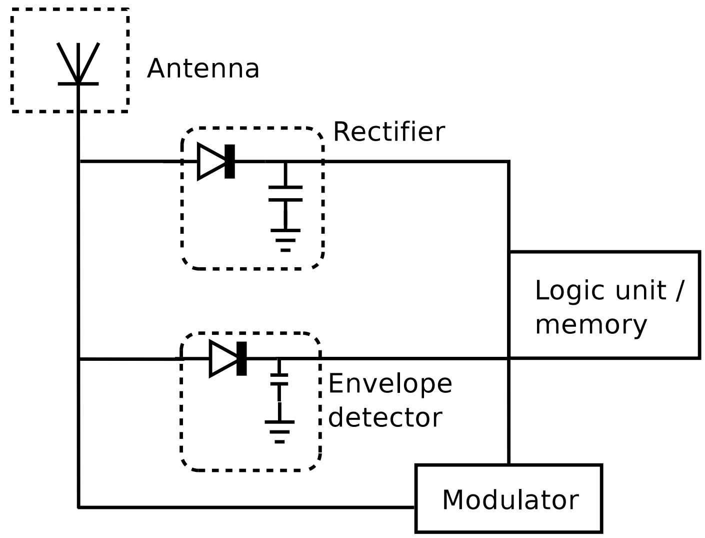


Figure 2.2: Schematic of an exemplary RFID tag.

shown in Fig. 2.2. Radio frequency based energy harvesting enables a cost effective solution as the tag circuitry does not require sophisticated signal processing blocks, e.g., crystal frequency reference, synthesizer, power amplifier, low-noise amplifier and batteries.

Backscattering reflects and modulates incident radio waves and facilitates transceiver-less RFID tags. The tag modulates the signal scattered by the antenna to communicate with the reader. Conceptually, for the modulated backscattering, the RFID tag iterates between three different states, namely normal operation, open circuit and short circuit. These three states are depicted in Fig. 2.3. In the normal state, the tag's antenna is matched with the IC load to allow maximum possible power delivery to the IC. This power, as is explained above, is used by the rectifier to charge up the tag's circuitry. The tag is guaranteed a continuous unmodulated carrier wave, to harvest upon, by the reader, as it stays in this state for a maximum allowable time. To modulate the backscattering signal the tag transits between short and open state. In the short state, the current flow steadily to the ground plane. The flow of the signal to the ground, as is not used by the rectifying unit, scatters with minimal resistance, resulting in detectable power signal at the reader. On the other hand, in the open state, the signal path to the ground is blocked. This results in no current flow in the antenna and hence, minimal radiation is reflected back. These two state, i.e., short and open, allow a tag to modulate the bit as '0' or '1', respectively. Backscattering modulation enables a cost effective solution as the tag does not require a transceiver to communicate with the reader.

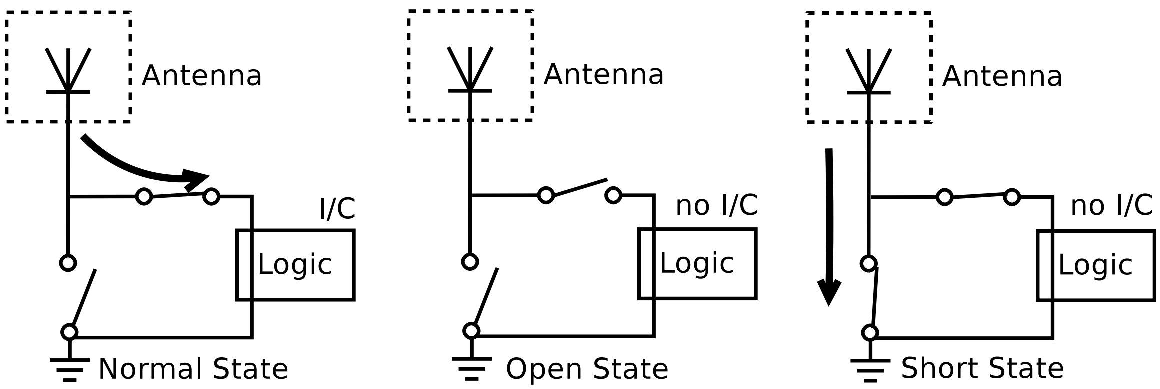


Figure 2.3: Backscattering modulation concept of RFID tags [36].

2.1.3 System Architecture

An RFID system is typically composed of an application host, a reader and a set of tags. A tag is designed to store certain information, the size of which varies between 96 bits and 64K bytes. Tags can be either passive, semi-passive or active. A passive tag has no physical power source and no transceiver as it uses the energy-harvesting and backscattering modulation techniques for power source and communication, respectively. While most common in the RFID market, the passive tag has limited

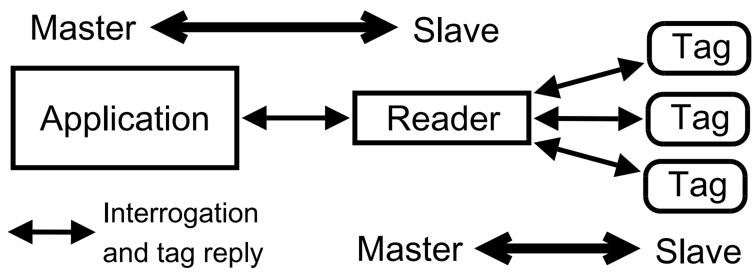


Figure 2.4: Master-slave architecture in RFID systems.

functionality for processing and communication. It processes simple state machines and has no medium sensing capabilities. A semi-passive tag has an on-board battery, use to power its circuitry, but no transceiver hence, relies on backscattering modulation for communication with the reader. An active tag, on the other hand, has both on-board battery and transceiver and may also carry certain sensing capabilities for example temperature or pressure. The RFID tags are listen-first devices, i.e., they does not initiate communication unless are interrogated by the reader.

Tags targeted by a certain reader are said to be with in that reader's interrogation zone. Specifically, an interrogation zone is the physical distance within which the strength of the electromagnetic waves, generated by the reader, is able to power the tags, receive the tags' signals, and successfully decode them — a process known as singulation. At any arbitrary instant, a reader can only read one tag within its interrogation zone and a tag can only be read by one reader. An RFID reader acts as a master for the tag and a slave for the application host. Upon application request, an RFID reader will interrogate the tags within its interrogation zone. The master-slave architecture of the RIFD system is shown in Fig. 2.4. The read tag data is then passed onto the middleware application where it is filtered accordingly.

RFID reader operates in wide UHF frequency ranges, i.e., between 860-960 MHz

Region	Radio frequency band
Argentina, Chile, Costa Rica, Dominican Republic, Uruguay	902-928 MHz
Australia	918-926 MHz
Brazil	902-907.5 MHz & 915-928 MHz
Canada and U.S.A	902-928 MHz
China	917-922 MHz
EU and Russia	865-868 MHz
Hong Kong	920-925 MHz & 865-868 MHz
Japan	952-954 MHz
Korea	908.5-914 MHz
Malaysia	866-869 MHz & 919-923 MHz
Mexico	915 MHz
New Zealand	864-868
Singapore	923-925 MHz & 866-869 MHz
South Africa	865.6-867.6 MHz & 917-921 MHz
Taiwan	922-928 MHz
Thailand	920-925 MHz

Table 2.1: World-wide UHF RFID Frequency Allocation.

and 2.4-2.45 GHz. The worldwide spectrum regulates within the 860-960 MHz is complex, as it competes with cellular hence, the different RFID spectrum varies for different region. For instance, in North America and European Union the allowed RFID frequency is between 902-928 MHz and 865-868 MHz, respectively. The world-wide UHF band allocation for RFID systems is summarized in Table 2.1. The 2.4-2.45 GHz band is an attractive alternate because of its unlicensed spectrum. However, it receives high interference from other devices, e.g., Zibgee and WiFi, and has reduce reading range (1-3m at 2.4 GHz vs. 2-10m at 900 MHz).

RFID readers collect large amounts of data, most of which are redundant or irrelevant for the time instance. An RFID middleware filter out the redundant and irrelevant data to be allowed as input for localization and tracking, managing the tagged-object historical data, trigger associated events and so forth. The middleware also encodes the data, to pass on to the reader, so it can be stored in proper format within the tag memory. According to the EPCglobal standardization efforts, the following components are the required modules to properly associate the middleware applications with the tagged object. The EPC network architecture, along with components and layers, is shown in Fig. 2.5.

1. *Electronic Product Code:* Electronic Product Code (EPC) is the tag data which frequently is polled by the reader(s) on a regular basis. Due to frequent nature of these polling, the EPC data needs to be filtered by the middleware to remove duplicate codes.

2. *EPC Middleware:* The middleware facilitate the exchange of data between the RFID reader, or a network of readers, and an RFID application. The middleware instructs reader(s) for singulation, accumulates and filters the raw EPC data. For instance, after initial interrogation, the middleware needs only to maintain the database for those existing or new tags which are either leaving or entering, respectively, within the interrogation zone of the reader. The processed and useful EPC data is then passed onto the RFID application.

3. *Application Level Events:* The Application Level Events (ALE) is an Interface definition that defines the interface between the EPC-enabled RFID application and the EPC-enabled RFID reader or a network of readers.

4. *Object Naming Service:* The Object Naming Service (ONS) translates the bytes in the EPC tag data into the web address (URL) of the object data, i.e., returns the network-addressable endpoints mapping to a particular EPC code data. The

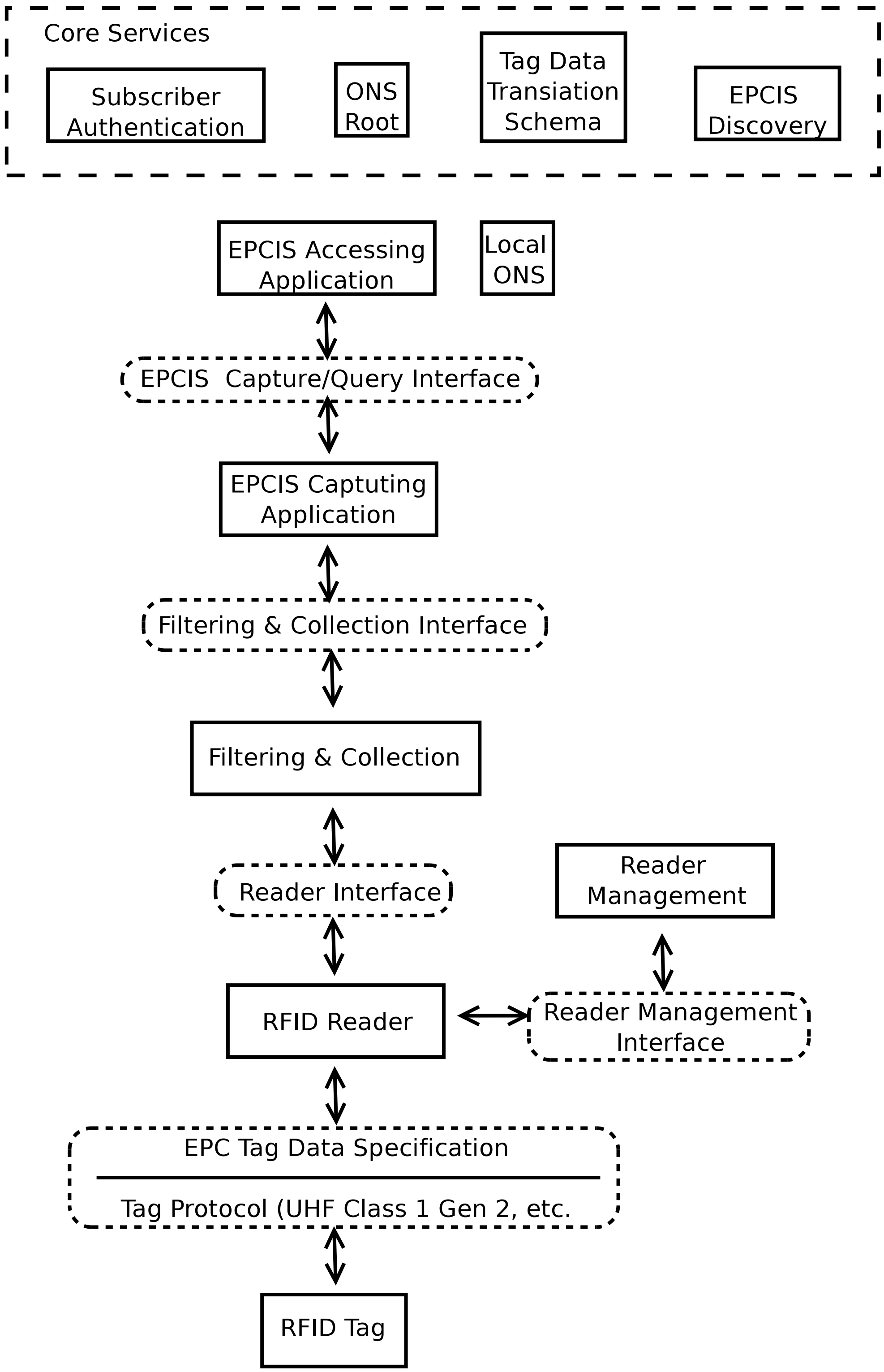


Figure 2.5: EPC Network Architecture (reproduced from [40]).

ONS is an automated network service, allowing the end-user to execute Domain Name Service (DNS) like queries. In order to use DNS to find information about an item, the items EPC must be converted into a format that DNS can understand, which is the typical, dot delimited, left to right form of all domain-names. The ONS resolution process requires that the EPC being asked about is in its pure identity URI form as defined by the EPCglobal Tag Data Standard [EPC] (e.g., urn:epc:id:sgtin:0614141.100734.1245).

5. *The Physical Markup Language:* In a supply chain application, the data needs to be available to multiple participating organizations, and it makes sense to store it in an XML-based format that can be read consistently by all parties, regardless of their information systems. The Physical Markup Language (PML) provide this service to the participating application. The PML, based on XML, provides a format for storing and retrieving data about objects that can be parsed by multiple RFID applications.

6. *EPC Information Services:* The EPC Information Service is an inter-application data exchange standard that defines a secure, web services based data exchange mechanism. The information service is one of the core service and allow the business partners to access and search for EPC data. The EPC Discovery Service is the search engine for the EPC related data which returns the URL locations that have the requested data. Multiple discovery service may be run, each with limited scope (regional, facility wide, local, etc.)

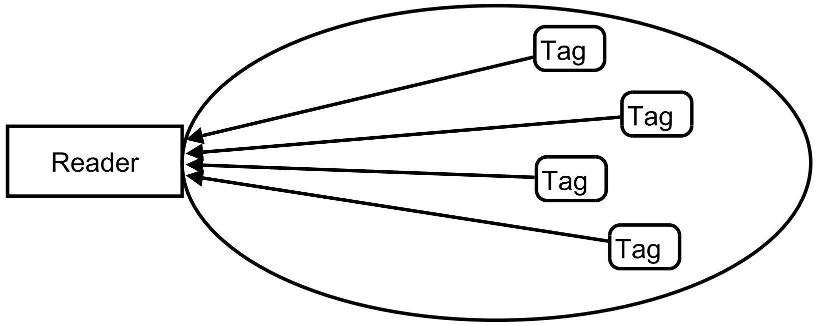


Figure 2.6: Multiple tags-to-reader collisions.

2.1.4 Communication Protocols

The simultaneous wireless medium access results in collisions that undermine a RFID system's overall performance. To sustain system operability, efficient mechanisms for Medium Access Control (MAC) are required. As with other radio-based systems, the main objective of mechanisms aimed at regulating medium access, is to reduce collisions, be it in a proactive or a reactive manner. Proactively, collisions are avoided by distributing sufficient information about the access requirements of elements sharing the medium. Reactive mechanisms respond to collisions and attempt to speed the system's recovery from a collision stall. Conventional collision avoidance methods, such as Carrier Sense Multiple Access (CSMA) cannot be adopted for RFID systems, especially when passive tags are used due to power limitations and its basis of reflection-based communication, i.e., use of backscattering modulation. Avoidance mechanisms also carry the risk of increasing the overall cost of tags and shrinking the potential interrogation zone for a reader. Proposals for RFID systems have therefore favoured reactive approaches to alleviate collisions. Specific to RFID systems, collisions can be classified based on the type of entities involved:

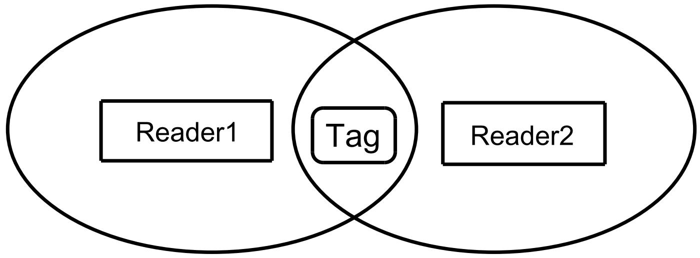


Figure 2.7: Multiple readers-to-tag collisions.

Tags-to-reader Collisions: Occur when more than one tag within a reader's interrogation zone attempts to reply to the reader's requests at the same time, depicted in Fig.2.6. Tags-to-reader collisions are the most devastating, especially when passive tags are involved. They result in reduced reading rates, wasted resources, and increased delay.

Readers-to-tag Collisions: Occur when one tag is interrogated by more than one reader, as shown in Fig. 2.7. In such a scenario, multiple readers try to singulate a single tag which results in corruption of the tag's internal state. As a result, the tag may not be detectable.

Reader-to-reader Collisions: Are result of the conventional frequency interferences, i.e., multiple readers within each other's interference zones are locked on the same frequencies. Existing mechanisms such as frequency-hopping, dynamic frequency allocation and dynamic power adjustment are utilized to hinder these collisions.

Tag collisions, both Tags-to-reader and Readers-to-tag, are the most common source of collisions in RFID systems and are resolved by the reader utilizing techniques collectively known as anti-collisions schemes. These anti-collisions schemes are classified in literature to be either *deterministic* or *probabilistic* [42, 96].

Deterministic anti-collision scheme

In deterministic mechanisms the reader splits and identifies a set of tags to respond in a given time. Splitting is based on contention information obtained from the previous interrogation cycle and attempts to reduce contention for the next cycle. Deterministic anti-collision mechanisms fall under the general algorithmic classification of *tree-based* algorithms because of their splitting approach. The deterministic mechanisms utilize either tags' serial numbers (identification codes) or randomly generated numbers to be used for splitting of the tree branches. The tree-based algorithm is a 2-way handshake algorithm involving sequences of interaction between the reader and the tags, known as the interrogation cycle. The objective of these interrogation cycles is to split the tags, using their serial numbers (IDs) or randomly generated numbers, into a more manageable set of tags. The splitting of the tree, mostly binary trees, into two branches (leaves) is based on the bit collisions and their respective positions; the location of which is obtained from the previous interrogation cycle. Obtaining collision information at the bit level requires that the precise bit position of collision is identifiable by the reader. For this particular reason, normally, either the Manchester coding or the NRZ (non-return-to-zero) bit coding is used by the RFID reader.

In order to understand the deterministic tree-based algorithm, we trace the execution of the conventional binary search tree algorithm [102]. The objective of using the binary search algorithm with multiple interrogation cycles is to singulate a tag from a larger set. The 2-way handshakes during each interrogation cycle (iteration) are the commands that the reader broadcasts based on its previous iteration for the following iteration. The set of commands constitutes four main commands, which are as follows.

1. REQUEST: Carries a serial number to the tag as a parameter. If a tag's own serial number is less than or equal to the received serial number, the tag sends its own serial number back to the reader. Otherwise, the tag will not respond.

2. SELECT: Carries a serial number to the tag as a parameter. Only a tag with an identical serial number is selected for the processing of other commands, e.g. reading and writing data. Only the selected tag will continue to respond to the reader commands.

3. READ_DATA: The selected tag sends stored data to the reader.

4. UNSELECT: Cancels the selection of an up-until-now active tag, i.e. *mutes* the tag. Beyond this, the unselected tag becomes completely inactive and does not respond to further REQUEST commands until is reset by the reader.

Let us assume that there are three RFID tags within the interrogation zone of the reader with 4-bit IDs of 1010_b, 1011_b, and 1110_b. The singulation process starts with the RFID reader sending the highest possible serial number. The purpose is to make all tags respond so that the exact bit collisions among all the tags' ID's could be determined. In our example, shown in Fig. 2.8, the first iteration of the algorithm begins with the reader transmitting the REQUEST command with the serial number 1111_b as an argument. The serial number 1111_b is the highest possible in this case. As the serial number of the tags in the interrogation zone is less than the requested serial number, all three tags reply back with their IDs. This first iteration results in collisions (C) at position 0 and 2, starting from the Least Significant Bit (LSB), i.e., $1C1C$.

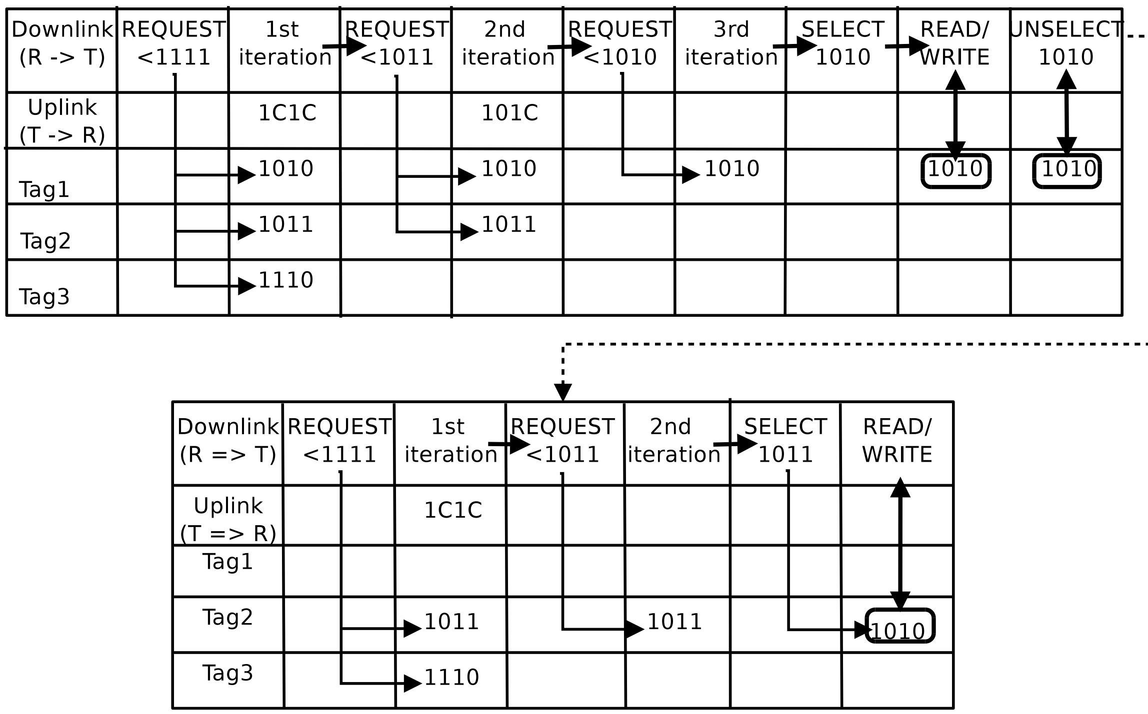


Figure 2.8: Execution trace of the binary search tree anti-collision algorithm using three tags and a single reader.

The third bit is the highest valued bit at which the collision has occurred during the first iteration. This implies that there is at least one tag between 1100_b and 1011_b. The binary search algorithm at this point splits the search into two subsets in an attempt to limit the search zone for subsequent interaction. The algorithm sets the third bit of the request to 0, i.e., 1011_b. The least significant bits after the third bit are all set to 1 in an attempt to capture all the tags whose two most significant bits are 10. The reader now broadcasts the command REQUEST with argument 1011_b. Two tags fulfill the command's criteria, i.e., `tag1` and `tag2`. The response back from these two tags causes collision at the bit position 0, i.e., $101C$. The reader, repeating the same splitting procedure, now chooses 1010_b as the requesting string for the subsequent iteration, i.e., the second iteration. This request is fulfilled by only

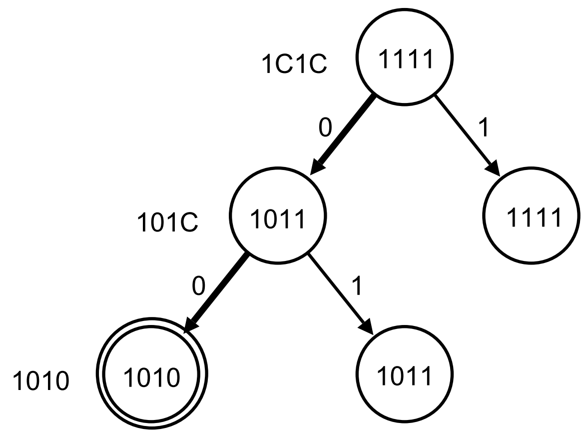


Figure 2.9: Singulation tree for the example RFID system.

one tag `tag1` which is now singulated. For now, no further iterations are required, as the reader has successfully detected a single tag without collision. Using subsequent SELECT commands, `tag1` is selected using the detected tag ID address and can now be read or written by the reader without interference from other tags. At this point, other tags are silent as the READ_DATA command is selective. The tree, from the *request* point of view, is shown in Fig. 2.9. The string shown in the tree nodes are requested and sent by the reader, whereas the string next to each circle is the received response. The node splits into two children nodes, appending 0 and 1 at the Most Significant Bit (MSB) collision, to the left and right child node, respectively. This process continues until tag 1010_b is singulated, which is distinguished in the figure by a double concentric circle.

After the completion of the required read/write operation, the selected tag (`tag1`) is muted by the use of the UNSELECT command. The muted tag is completely inactive and does not reply to any further REQUEST commands. Muting the tags reduces the number of responding tags in the subsequent iteration of the singulation process, therefore resulting in lower collisions and less iterations. Referring back to

Fig. 2.8, the singulation of the tag (`tag2`) requires one less iteration, compared with `tag1`'s singulation. The muting of `tag1` has created a positive impact by yielding low collision as its serial number; otherwise, it would have collided with the `tag2` serial number.

Probabilistic anti-collision scheme

In the probabilistic mechanisms the reader communicates the frame length and the tag picks a particular slot in the frame for transmission. The reader repeats this process until all tags have been successfully transmitted at least once. Reader controlled synchronization is necessary as the tag has to transmit within its slotted time frame. The frame size may be adjusted based on the collision, idle and successful frame information from a previous interrogation cycle for the subsequent cycle. This encourages frame adaptability according to tag density and distribution, thereby reducing idle and collision frames. The probabilistic approach is faster in comparison to the deterministic approach because of its low overhead. However, it may suffers from tag starvation syndrome.

We will now illustrate the details of the conventional slotted Aloha anti-collision procedure [42] using the last example. Consider again three tags with IDs of 1010_b, 1011_b and 1110_b. Similar to the deterministic approach, the probabilistic approach is a chit-chat protocol that uses a sequence of interactive commands. The set of commands are as follows:

1. REQUEST: Synchronizes and prompts all tags to transmit their serial number to the reader using one of the time slots that follow. For our sampler RFID system, there are three available time slots.

2. SELECT: Sends a specific serial number to the tag as a parameter. Only the matching tag, i.e., the tag whose serial number matches with the passed parameter, is flagged for further operation, allowing it to read and write. Tags with conflicting serial numbers however, are still responsive to the REQUEST command.

3. READ_DATA: The selected tag sends stored data to the reader. In real RFID systems, other commands will also be available but they are omitted here for the purpose of simplicity.

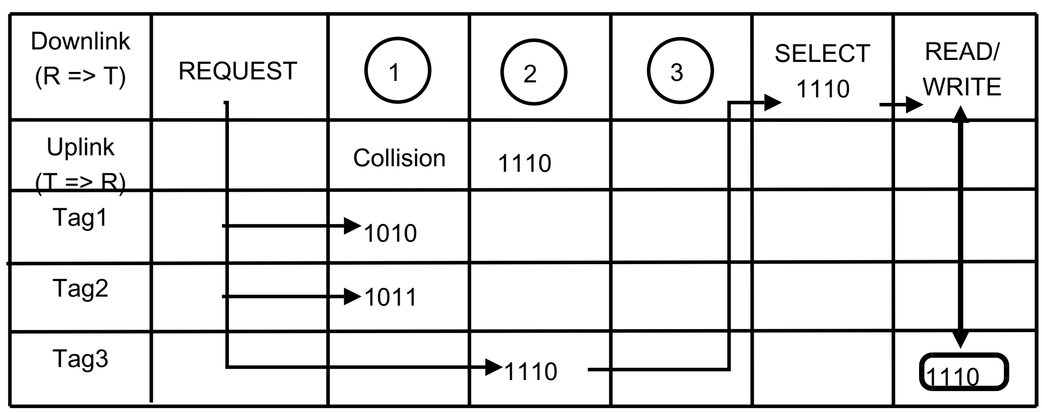


Figure 2.10: Execution trace of the conventional slotted Aloha protocol, using example RFID system of three tags and a single reader.

The execution trace of the slotted Aloha protocol is shown in Fig. 2.10. After a certain time interval, the reader periodically transmits the REQUEST command. After receiving the REQUEST command, the tag randomly selects one of the three available slots. The tag uses the slot to transmit its serial number back to the reader. Due to a random slot selection method, there is a collision between `tag1` and `tag2` in slot1. Only tag3 is successful in transmitting its serial number back to the reader. The successful tag is selected for subsequent reading and writing after it is been selected using the SELECT command. If no transmission was successful, the REQUEST command is iteratively repeated until the serial number can be received successfully and no collision is observed in the frames. As we've witnessed, in the probabilistic anti-collision algorithms, the tag randomly selects a slot number in the frame and responds to the reader using the slot it selected. When the number of tags is small, the probability of tag collision is low, and the time used to identify all tags is relatively short. As the number of tags increases, however, the probability of collision becomes higher and the time used to identify the tags increases rapidly. Therefore, the probabilistic algorithm performance depends significantly on the number of tags within the interrogation zone of the reader.

EPC Class-1 Gen-2 RFID standard

The EPCglobal UHF Class-1 Gen-2 protocol defines the standard physical and medium access requirements for the passive RFID tags. According to the defined standard, the reader communicate with tag using RF modulation. The tags receives its operating energy, using the unmodulated Continue RF Wave (CW), and communication link, both down-link (forward) and up-link (backward), from the reader's RF signal. We will now explain the physical and medium access layer as is described the EPCglobal.

The specification defines a number of physical layer options for both forward-link and backward-link. All forward-link communication uses Amplitude Shift Keying (ASK), where bits are indicated by brief periods of low amplitude, and Pulse Interval Encoding (PIE). The time between low amplitude periods differentiates a zero or a one, and the reader can choose pulse durations that result in down-link rates ranging from 26.7 kbps to 128 kbps. The backward-link rate is determined partially by the forward-link preamble and partially by a bit field set in the Query command which starts each query round, allowing for the backward-link frequency ranging from 40 kHz to 640 kHz. Along with setting the backward-link frequency, the reader also sets one of four up-link encodings, namely FM0, Miller-2, Miller-4, or Miller-8. When using FM0, one bit is transmitted during each cycle and the data rate is equivalent to the link frequency. However, FM0 is highly susceptible to noise and interference which motivated the addition of the Miller encodings. While these are more robust to errors with a higher number being more robust, their link rates are reduced by a factor of 2, 4, or 8, depending on the encoding.

The specification also defines the medium access control protocol, based on Framed Slotted Aloha (FSA). In FSA scheme, each frame has a fixed number of slot and the tags response by randomly picking the slot from each frame. The tag interrogation process starts off by reader transmitting the CW to power-up the tags within its interrogation range. The reader, afterwards, initialize the number of frames and slots within each each frame. The number of frames and slots are dynamically selected according to tags population. In literature, the individual frame is known as Query Round. The sequence of interrogation commands, i.e., Query, Ack, Query Rep, etc. that make up the Query Round, for a single tag, is shown in Fig. 2.11.

At the beginning of a Query Round, the reader can optionally transmit a Select command which limits the number of active tags by providing a bit mask, as only tags with IDs (or memory locations) that match this mask will respond in the subsequent round. A Query command is then transmitted which contains the fields that determine the backward-link frequency and data encoding, the Q parameter which determines the number of slots in the Query Round, and a target parameter. When a

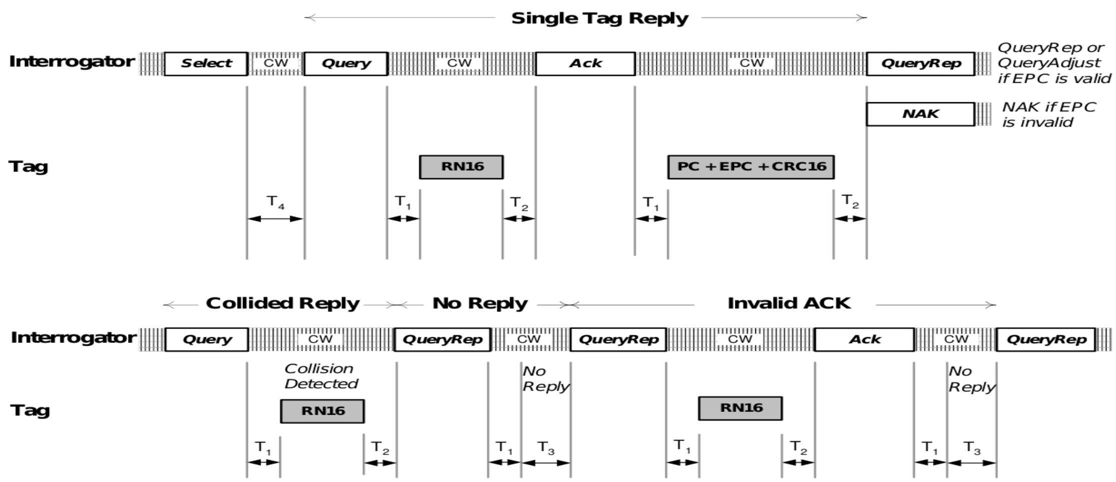


Figure 2.11: Query round for a single RFID tag (reproduced from [40]).

tag receives a Query command, it chooses a random number in the range $(0, 2^Q - 1)$, where 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 transmit a 16 bit random number (RN16). Upon receiving the RN16, the reader will echo the RN16 in an ACK packet at which point, if the tag successful receives the ACK with the correct random number, the tag will backscatter its ID (referred to as EPC in Fig. 2.11). While powered up, tags maintain an Inventoried flag which can be in one of two states, A or B. In the Query command the Target parameter is set to either A or B, and only tags with a matching Inventoried flag will respond during the round. After a tag transmits its ID, a subsequent QueryRepeat command will cause the tag to toggle its Inventoried flag. If the ID was not successfully received by the reader, a NACK command is sent which resets the tag so that a subsequent QueryRepeat will cause the flag to change. In this case, the tag will be active in the next round.

Along with toggling the Inventoried flag of a tag, a QueryRepeat signals the end of the slot. On receiving the command the remaining tags will decrement their slot counter and respond with a RN16 if their slot counter is set to 0. The process then repeats, with the number of QueryRepeats being equal to the number of slots set using the Q parameter. Of course, tags may choose the same random number initially with the result that multiple tags reply during a slot. In this case, a collision occurs and the tags will not be ACK'ed during the round. However, these tags will be active in the next round, where they will choose a new random number. In the lower half of Fig. 2.11, a scenario is shown with three tags, two of which choose an initial random value of 0 resulting in a collision in the first slot, and one which chooses an initial value of 2 and so responds after the second QueryRepeat. If there are no tags with a slot counter of 0, a slot will go empty.

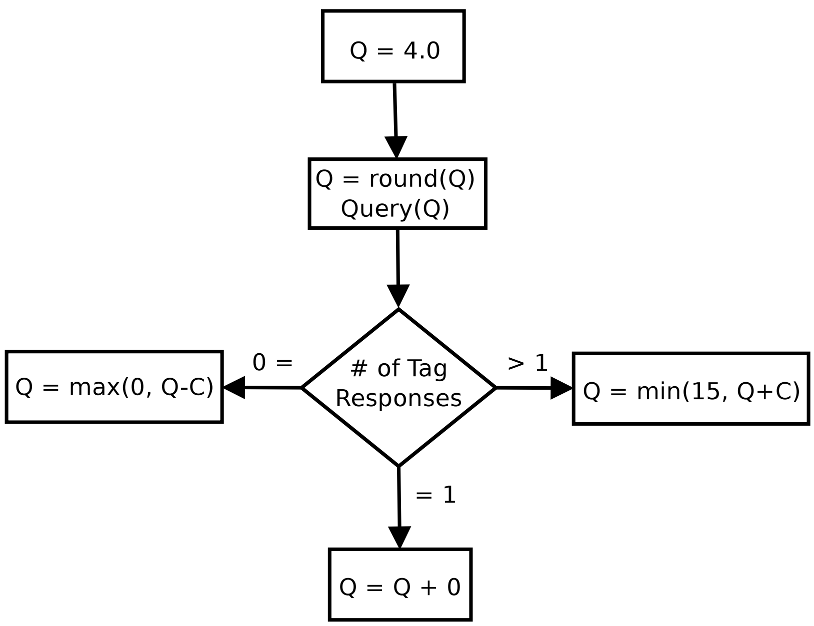


Figure 2.12: Counter execution flow chart of the Q-algorithm (reproduced from [40]).

To reduce empty slots and collisions, the reader changes the Q parameter for every Query Round in order to best accommodate the number of tags remaining to be read. The algorithm, known as Q-algorithm, achieves this by determining the number of empty slots, slots with collisions, and slots with only a single tag reply during the course of the Query Round. The execution flow chart of the Q-algorithm is shown in Fig. 2.12. The Q-algorithm evaluates the tags' replies, for the current frame, to determine the next frame size. The Q-algorithm classifies the replies as idle, collision, and successful slots and accordingly update the Q value for the subsequent query cycles. The value of Q parameter is added and subtracted by a fixed constant C if current slot resulted in collision and idle, respectively. In case of successful slot, the Q parameters remains unchanged. The slot are updated, incremented or decremented, to avoid mis-match between the number of slots and number of tags. For instance, in case of idle slot, the number of slots are decremented as it imply that the number of available slots exceed the number of tags. Similarly, in case of collision slot, the number of tags exceeds the number of slots. In [72], it is shown that the optimum is seen when the number of slots is set equal to the number of tags, and approximately 35% of the slots would see only a single tag response.

2.2 Literature Survey

In this section, we will survey RFID literature for system designs, tags anti-collision and readers anti-collision protocols.

2.2.1 System Design

RFID is a dynamic and active research area. System level development includes antenna designs, RFID IC with enhanced RF sensitivity, ultra low power tag IC, low-power backscattering modulation technique and so forth. The antenna design involves tradeoff between antenna gains, impedance and bandwidth while satisfying numerous requirements such as size, form, reading range, support for mobility, cost and reading reliability [91]. Various antenna configurations such as patch antenna [42], folded dipole antenna [108], asymmetric antenna [27] and use of multiple tag antenna [49] have been proposed in literature. A detailed comparative performance evaluation of various antenna configurations can be found in [45, 91, 101]. Low-power IC design for passive tags [34, 36, 42, 57], as low as $2.7\mu W$, has been proposed in the literature to enhance the operating range of the passive RFID tags. Improvements in the backscattering and modulation techniques are also proposed in the literature. Various analytical studies on the Radar Cross Section (RCS), an important parameter of in determining the quality of the backscattering communication, for the passive tags [81], its differential scalar scattering [82] and to enhance the bit error rate [46], have been performed. Energy-aware modulation techniques [13, 67, 98] also been proposed to reduce tag's energy consumption while using backscattering communication. Wireless Sensor Network (WSN) and RFID integration provides multi-hop communication to the network of RFID readers [70]. In such a setting, the WSN node and RDID reader individually sense, read tags and perform multi-hop data communication with other interrogating readers.

2.2.2 Medium Access Control

In a radio based system, MAC protocols provide mechanisms for channel access control, allowing multiple devices to share the same physical medium. The most prominent MAC techniques are based on the Carrier Sense Multiple Access (CSMA), Multiple Access with Collision Avoidance (MACA), or the Aloha protocol. RFID systems use half-duplex, point-to-point communication links in which communication between the reader and the tag is based on backscatter modulation. In backscattering, the tag sends its serial number by adjusting the antenna reflectivity to modulate the reflected signal. The nature of reflection based communication results in failure of conventional MAC techniques; as tags cannot sense the medium, detect collisions, or sense the presence of other channel traffic. This means that no collision avoidance or resolution mechanisms could be implemented at the tags. Hence, MAC in RFID systems is confined to resolving of collisions only at the reader, resulting in anti-collision algorithms for both tag collisions and reader collisions, mainly employing Aloha-based contention avoidance schemes.

RFID systems exhibit very short durations of very high bursty activity followed by relatively long durations of inactivity. Generally speaking, four different approaches exist in the literature in handling multi-access issues in radio technologies. The approaches regulate access based on time, space (location), frequency, or code. Code Division Multiple Access (CDMA) supports high-rate data multiplexing using the spread-spectrum (SS) technique. In conventional SS, each user encodes data packets using an orthogonal spreading code, allowing successful transmission by multiple users. However, complex receiver design and higher computational and energy requirements restrained adaptation of CDMA technology in RFID systems. A combination of TDMA and CDMA based schemes has been investigated recently [75]. However, the CDMA scheme is a largely unexplored area in RFID systems.

Space Division Multiple Access (SDMA) [42, 99] spatially reuses the channel. The philosophy behind the SDMA procedure is that practically at any given time there will be a limited number of RFID tags spatially co-located at the same position, independent of the total number of tags that may be present in the overall interrogation

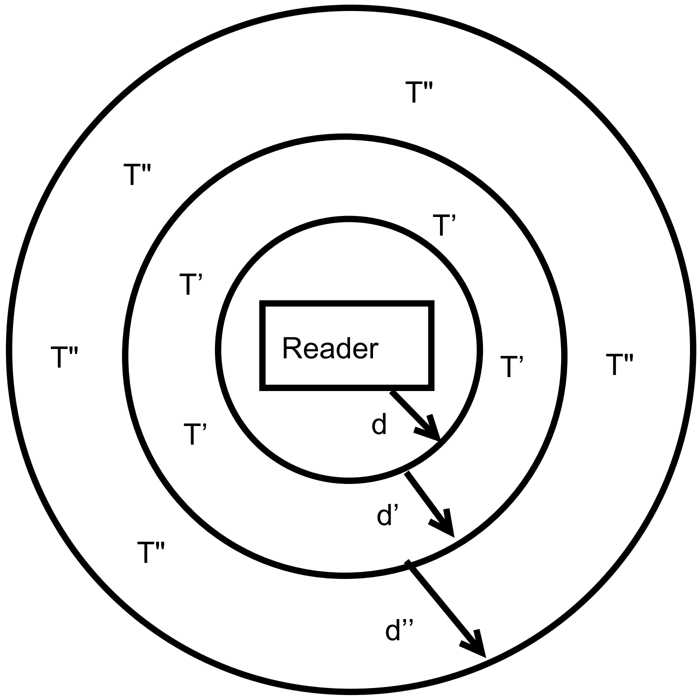


Figure 2.13: Clustering based on the distance between the reader and the tags, using reader's power levels to adjust its interrogation zone.

zone. Therefore, by spatially isolating the tags, the interference caused by other tags can be minimized. Numerous spatial isolation techniques exist with the most notable ones being: adjusting the reader power levels (power control) [10, 12, 60], using adaptive arrays and Multiple Input Multiple Output (MIMO) antennae [65], as well as the use of electronically controlled directional antenna [42].

The power control cluster-based algorithm [10, 12] divides the interrogation zone into smaller clusters based on the distance to the reader by adjusting the reader's power levels. Tags in each cluster are read separately. Since the number of tags in a cluster is less than that in the whole interrogation zone, collisions are minimized. An example of such a partitioning is shown in Fig. 2.13, where the interrogation zone is divided into three clusters: d, $d^{'}$, and $d^{''}$. When the reader sends a request, only those tags in the current cluster respond. For instance, assume the reader has read the tags from cluster d and has just sent a request to cluster d'. In that instance only tags from cluster d', i.e., tags marked as T', will respond to that request. After all tags marked as T' have been read, they are put into a sleep mode. Then, the reader's zone is increased to d'' and a new request is sent, and so on. Similar transmission control schemes have been used for reader collision avoidance [60], where reader's power levels are adjusted to reduce the interrogation overlaps.

Smart antenna techniques such as adaptive array antenna and MIMO antenna [65] are used to maximize system throughput by reducing the collisions. The antenna array adaptively nullifies interferences from other array elements, i.e., one element receives the desired signal whereas other array elements are used to remove the interference in order to maximize the received signal strength. With MIMO, however, each antenna element receives a superposition of the multiple transmitted streams with different spatial signatures. These differences are used to separate multiple streams with signal processing at the receiver. These two techniques lower tag collisions, but with significant increase in the reader complexity and monetary cost.

Electronically controlled directional antennas [42] are used to adaptively adjust the directional beam of the RFID reader at subset of tags, one at a time. Such techniques are commonly known as adaptive space division multiple access and are depicted in Fig. 2.14. To read a specific tag or all the tags within the interrogation zone, the reader scans the area using the directional beam until the desired tag is detected or, in the latter case, when all the tags have been read by the reader. The SDMA technique is effective in reducing collisions but with a relatively high implementation cost because of sophisticated antenna systems, and is therefore restricted to a few specialized

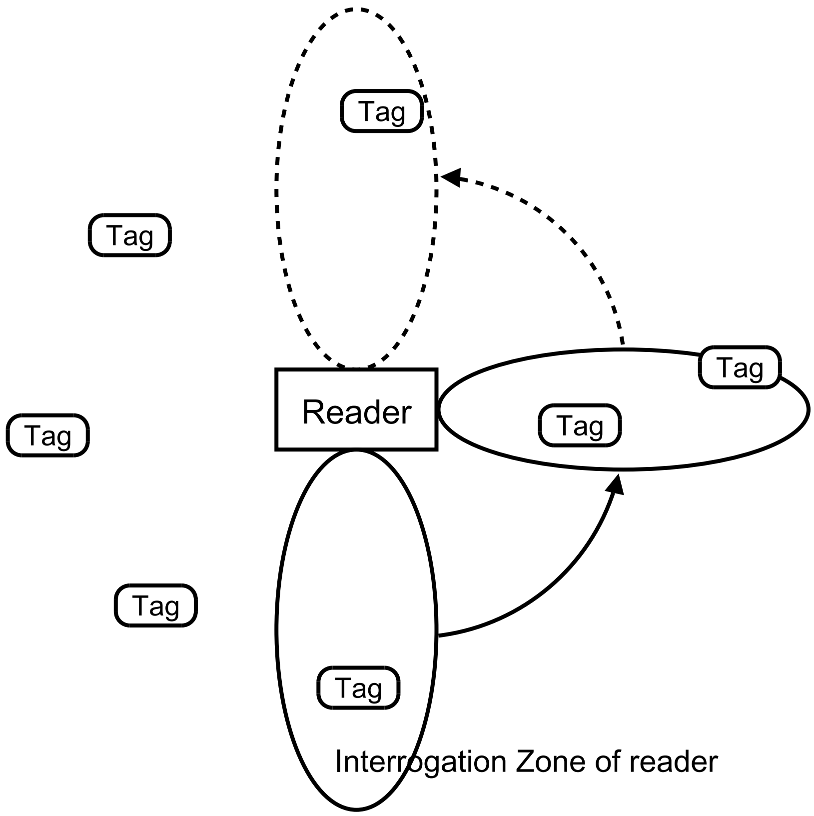


Figure 2.14: Adaptive SDMA with an electronically controlled directional antenna.

applications. One exceptional approach is the aforementioned power control scheme [10], which is low in cost and is effective in reducing both reader and tag collisions.

Frequency Domain Multiple Access (FDMA) proposes the use of multiple channels, each with distinct carrier frequencies for communication. In the context of RFID systems, this implies the availability of broadcasting frequency for the reader and several frequencies for the tags that they can lock on to. The reader, using the broadcasting frequency, synchronizes and issues the interrogation commands. The tags reply to the reader using one of the many available frequencies, shown as f_1, f_2, f_3 and f_4, in Fig. 2.15. The advantage of FDMA is the availability of non-interfering frequencies for concurrent communication by multiple tags and readers. The FDMA

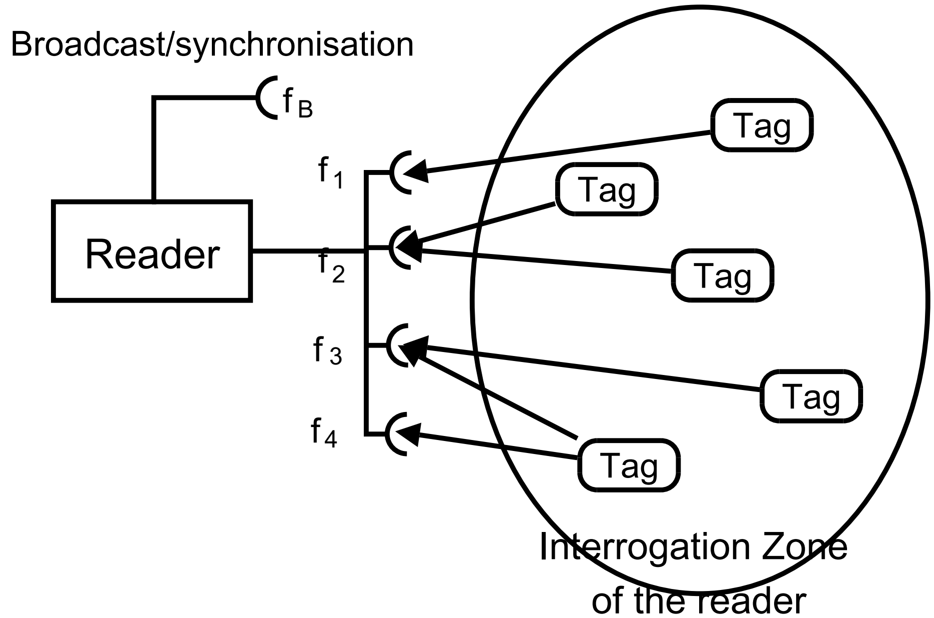


Figure 2.15: Frequency domain multiple access.

technique has not been significantly utilized in RFID systems. The reason is the impracticality for tags and relatively high cost of the readers as a dedicated receiver must be provided for every reception channel, restricting the use of FDMA for limited and specialized applications.

Time Domain Multiple Access (TDMA) relates to techniques where the available channel is divided, along the time dimension, between potential participants. TDMA, in a modified and mostly hybrid manner, is used in other prominent networks, e.g., GSM, Bluetooth and IEEE 802.16 (WiMax). The TDMA technique is by far the most dominant medium access protocols in RFID systems. This is because of TDMA simplicity, low processing overhead for passive tags and low complexity (computational, processing, and monetary cost) compared with other available procedures such as

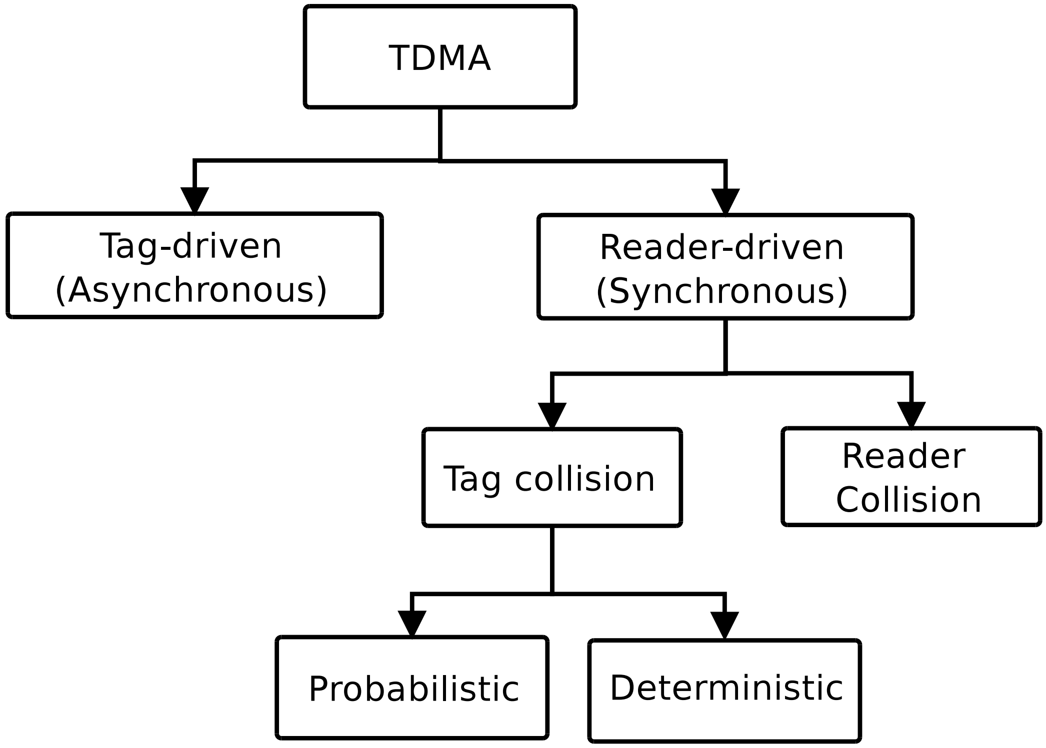


Figure 2.16: Classification of the time division multiple access procedures.

FDMA, CDMA, SDMA, etc. In the context of the RFID system, the TDMA procedure is further classified into tag-driven and reader-driven, as is shown in Fig. 2.16. The tag-driven procedure operates in an asynchronous fashion as the reader does not control the data transfer. Tag-driven procedures are naturally very slow and inflexible with limited applicability. Most of the TDMA procedures are therefore based on the reader-driven approach. The reader-driven approach is a synchronous mechanism, with all the tags' data transfer handled by the reader, i.e., control when the tags transfer data and selects which ones, amongst the tag population, will transmit its data at any given time. This selection process, i.e., isolating an individual tag from a large group of tags, is known as the singulation process. The reader-driven approach is used to tackle the collisions in RFID systems.

Tag collision schemes usually involve a logical partitioning of the tag population using tree-based algorithms or probabilistic-framed Aloha schemes, into a more manageable set of tags. Reader collisions employ conventional contention resolution approaches such as scheduling, interference learning, and coloring schemes to tackle reader collisions, i.e., reader-to-reader and readers-to-tags collisions. The various collision resolution schemes for tags and readers' collisions are classified based on their underlying techniques, and are discussed next, in a sequential manner, in the following sections.

2.2.3 Tag Collisions

Tag collisions are the most common source of collisions in RFID systems. They take place when multiple tags are within the interrogation zone of a reader and simultaneously reply to the reader's commands. The passive RFID tag is by design reader-driven; as it does not have carrier sensing nor inter-tag communication capabilities. Therefore, tag collisions are resolved by the reader utilizing techniques collectively known as tags anti-collision schemes. These anti-collisions schemes are classified in literature, as depicted in Fig. 2.16, to be either *deterministic* or *probabilistic* [42, 96].

In deterministic mechanisms the reader splits and identifies a set of tags to respond in a given time. Splitting is based on contention information obtained from the previous interrogation cycle and attempts to reduce contention for the next cycle. Deterministic anti-collision mechanisms fall under the general algorithmic classification of *tree-based* algorithms because of their splitting approach. The deterministic mechanisms utilize either tags' serial numbers (identification codes) or randomly generated numbers to be used for splitting of the tree branches. Under certain circumstances, the deterministic approach may take a considerably longer time. However, it does not suffer from the tag starvation problem. In tag starvation, a tag may not be identifiable for a long time, and in the worst case, might not be able to be read at all.

In probabilistic mechanisms, the reader communicates the frame length, and the tag, randomly transmits a particular slot in the frame. The frame size may be adjusted, based on the information from the previous interrogation cycle, encouraging adaptability according to tag density and distribution. The frame process is repeated until all the tags have been identified. The probabilistic approach is fast, due to its low overhead, but suffers from tag starvation syndrome.

Deterministic Schemes

Deterministic anti-collision mechanisms are essentially tree-based anti-collision algorithms. The tree-based algorithm is a 2-way handshake algorithm involving sequences of interaction between the reader and the tags, known as the interrogation cycle. The objective of these interrogation cycles is to split the tags, using their serial numbers (IDs) or randomly generated numbers, into a more manageable set of tags. The splitting of the tree, mostly binary trees, into two branches (leaves) is based on the bit collisions and their respective positions; the location of which is obtained from the previous interrogation cycle. Obtaining collision information at the bit level requires that the precise bit position of collision is identifiable by the reader. For this particular reason, normally, either the Manchester coding or the NRZ (non-return-to-zero) bit coding is used by the RFID reader.

We further classify the deterministic anti-collision mechanisms, as shown in Fig. 2.17, based on whether they use a collision tracking or a collision detection approach.

Collision Tracking: In the collision tracking method, both the reader and the tag maintain a certain amount of collision information from the previous interrogation cycle. The information, mostly as pointer to the most recent query, collision bit, or node in the tree, is used to send a subsequent query for the next interrogation cycle. The binary search tree algorithm (explained above using an example RFID system) and its variants [17, 18, 32, 41, 43, 54, 71, 80, 105, 106, 113, 116]), fall under the collision tracking class of the deterministic anti-collision algorithms. The variants of conventional binary tree algorithms differ in their enhancement objectives, i.e., shortening execution time, reducing memory usage, reducing processing overhead or eliminating the unnecessary iterations.

In the conventional binary tree algorithm, when a tag is successfully singulated, read, and muted, the singulation process initiates from the root for the subsequent tag. This was seen, for instance, in our example above where the reader sends out the initial query of 1111_b, i.e., the highest possible serial number, after the first tag, i.e., `tag1`, is singulated and unselected. This results in unnecessary overhead, both from communication and processing perspectives. The overhead can be eliminated, after successful singulation, by setting the starting query point to the queued query from the last interrogation cycle. This translates to selecting either the parent node of the current query node or its sibling node [54, 105]. This simple modification speeds up the interrogation process and reduces overhead by utilizing the saved (queued) information. The conventional binary tree-based algorithm recognizes only a single tag at a time through setting the most significant collision bit to either 1 or 0 during the interrogation process. The work in [32, 71] notes that this results in low performance and claims that without any fundamental change in the tree navigation process two

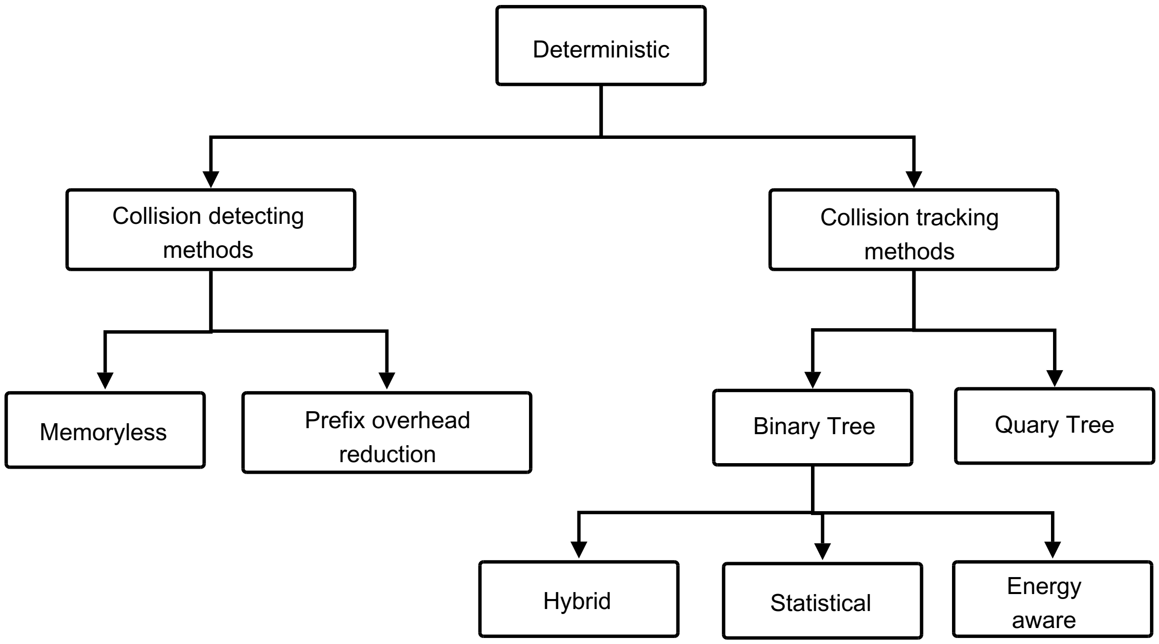


Figure 2.17: Classification of the deterministic TDMA schemes.

tags are identifiable at one time. This takes place during the last bit of the collision sequence, i.e., when the least significant bit collision has been resolved. This is evident, as the least significant bit collision indicates the presence of two tags, i.e., with collision bits of 0 and 1, therefore speeding up interrogation process. The use of other mechanisms such as interference cancellations [112], utilizing the similarities among the tags' IDs [58], using height-oriented, depth-first search algorithms with tag state support [60] and secure variation of the tree algorithms [17, 106] have also been investigated. All these approaches enhance the binary tree algorithm without deterring significantly from the conventional algorithm.

We further classify the collision tracking approach to be either statistical, hybrid, or energy aware, as is shown in Fig. 2.17. The statistical approach exploits information stored in previous interrogation cycles (iterations) to assist in the forthcoming cycle. Adaptive binary splitting algorithms [26, 76, 77] initiate the conventional tree splitting procedure by using the information obtained from the last reading cycle. The fixed tags, i.e., static tags, which have been identified in the previous cycles will be re-identified again by the reader in the next reading cycle. As the reader knows about the fixed tags it can avoid collisions, whereas conventional methods are used to identify the mobile tags. The mobile tag is defined as the tag just coming in, and therefore was not present during the last reading cycle, or has moved out of the interrogation zone of the reader. These adaptive splitting algorithms significantly reduce the number of collisions while supporting mobility but at the cost of substantial storage requirements. In such scenarios, where a significant portion of tags are mobile, the adaptive splitting algorithms will perform no better than the conventional binary algorithm.

The hybrid tree approach [94] is a combination of the deterministic and probabilistic approach. It combines the tree-based protocol with a slotted back-off mechanism. The algorithm uses a 4-ary tree instead of the conventional binary tree, with slotted back-off aimed at reducing the number of unwanted and unnecessary query commands. Upon responding to the reader, a tag sets its back-off timer using a part of its ID. If there is a collision the reader can partially deduce how the IDs of the tags are distributed and potentially reduce the unwanted idle cycles. Like the statistical approach of [76], this approach utilizes the information from previous reading cycles to avoid collision for the static tags and starts the querying process from the root in order to accommodate the tag mobility. In addition to inheriting the drawbacks of the statistical approaches, the hybrid approach increases the tags' cost as it requires additional functionality, e.g., back-off timer.

The MAC scheme's objective of reducing collisions usually comes at the expense of increasing energy consumption. This energy consumption occurs because of additional processing and communication overhead imposed by the MAC protocols. The energy-aware approaches [78, 87, 115, 116] address the energy issues, mainly the tag energy consumption, while maintaining low collisions. The approach in [116], while utilizing the conventional binary tree algorithm, involves the reader taking action if bit collision is detected. This translates to the reader sending a special symbol to the tags to stop sending data back. Fewer bits are thus sent by the tags, indirectly reducing energy consumption, by reducing communication overhead. More efficient schemes [90] use multiple time slots per tree node and three different anti-collision protocols. The motive is that in order to detect the tags, the binary tree algorithm relies on the collision as it transmits redundant queries to the tags. This is important in the conventional binary tree algorithm as it needs to determine which sub-tree to query in the subsequent interrogation cycle. The tags are allowed to transmit responses within a slotted time frame, thereby avoiding collisions. The queries are used to find colliding sub-trees as well as to read the tags. These two mechanisms help to read more tags with fewer queries, thereby reducing the energy consumption at the tags.

Collision Detection: Collision detection methods are stateless algorithms in that they do not exercise tracking. Relative to collision tracking, detection algorithms may take longer to read all tags within an interrogation zone. Their main advantage is in their non-storage requirements, especially for the tags and their comparatively low communication overhead. We classify the collision detection methods into memoryless and prefix reduction, as is shown in Fig. 2.17.

Query tree protocol (QT) [63] and variants [31, 77, 116] are prominent examples of the memoryless approach in which each tag does not need additional memory beyond storing its serial number. This means that no storage is required for random serial numbers, pointers or states, as it was required by the binary tree of the collision tracking algorithms. The QT uses the tag's serial number for the tree splitting mechanism. The reader broadcasts the query, using a string of bits as an argument. The tag receiving the query matches the most significant bit of its own serial number with the broadcasted serial number. If there is a match the tag transmits the remaining least significant portion of its serial number, otherwise, it remains silent. The reader maintains the queue for the transmitted strings of bits. At the beginning of the frame, the queue is initialized with two 1-bit strings, 0 and 1. The reader pops a bit string from the queue and broadcasts to all tags in its interrogation zone. If the tag responses collide, the reader pushes two 1-bit longer bit strings, compared to the last bit string transmitted, into the queue. By expanding the query until there is either a response or no response — all the tags will respond eventually — the query bit string traverses from the most significant to the least significant bits for the possible serial numbers. Contrary to binary trees, a QT imposes simple functions and requires no state or pointer maintenance by the tag. However, the tag reading delay for the QT protocol is significantly affected by the numerical distribution of the tag serial number, in that the reading delay is increased when tags have minimal difference in their serial numbers.

The QT and its variants has noticeable overhead in terms of the number of bits that are sent as query argument, i.e., the string bits. The reason is the string bits have to traverse, from most significant to least significant, equal to the length of the serial number. This results in communication overhead as redundant bits are transmitted, both by tags and readers, during the interrogation cycles.

Prefix overhead reduction algorithms [28, 29, 80, 113] maintain prefix and iteration overhead reduction approaches which enhance the performance of the memoryless mechanisms. Prefix Randomized Query Tree (PRQT) [113], falls under the prefix reduction mechanism and overcomes the limitation of the QT-based algorithm, i.e., create longer reading cycles due to tag length and its distributions. PRQT similar to QT is a stateless approach however, and it differs from QT in that it uses prefixes chosen randomly by tags (rather than using their ID-based prefixes), thereby providing additional memory space. Each tag generates a random length prefix which is then used during the interrogation process. The optimal length prefix depends on an estimate of the number of tags within the interrogation zone. Tag estimation is proposed in the adaptive optimal incremental prefix length algorithm [29]. The algorithm begins by setting a small initial prefix length followed by the polling of all possible prefixes. The initial prefix length is then increased repeatedly until the collision ratio satisfies a prescribed condition. By reducing the prefix overhead, the collision detection mechanisms enjoy a faster reading rate and lower overheads with marginal need of additional memory at the tags.

Probabilistic Schemes

In the probabilistic mechanisms the reader communicates the frame length and the tag picks a particular slot in the frame for transmission. The reader repeats this process until all tags have been successfully transmitted at least once. Reader controlled synchronization is necessary as the tag has to transmit within its slotted time frame. The frame size may be adjusted based on the collision, idle and successful

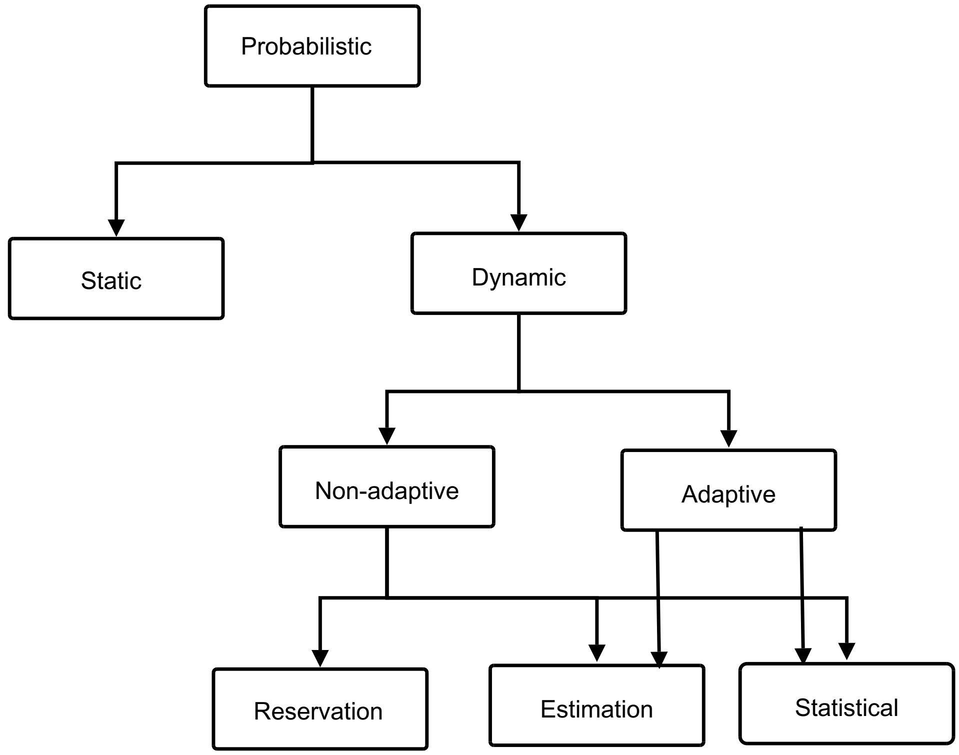


Figure 2.18: Taxonomy of the probabilistic TDMA-based schemes.

frame information from a previous interrogation cycle for the subsequent cycle. This encourages frame adaptability according to tag density and distribution, thereby reducing idle and collision frames. The probabilistic approach is faster in comparison to the deterministic approach because of its low overhead. However, it may suffer from tag starvation syndrome.

Generally speaking, and as shown in Fig. 2.18, we classify the probabilistic mechanisms into two main groups: static and dynamic. The number of slots in the static approach is fixed, making it mostly used in instances of low tag density. An example of static algorithms includes those based on Aloha and framed slotted Aloha. While a fixed frame size leads to a simple implementation, static algorithms risk certain inefficiencies. For example, long frames used with a small number of tags, or vice versa, results in delays and resource underutilization. Such issues are addressed in dynamic approaches in which the frame size is adjusted based on the collision rate from tags within an interrogation zone. For example, the Dynamic Framed Slotted Aloha (DFSA) algorithm [42] determines the frame size based on information such as the number of slots used to identify the tag and the number of the slots with collisions.

Variations of the dynamic framed slotted Aloha algorithm differ in frame size by changing approach. In one such variation, the frame size is adjusted based on some predefined threshold. For instance, the frame size is increased when the number of collision slots exceeds a preset threshold. As the collisions decrease, the frame size is reduced to its previous value. This dynamic adjustment of frame size allows readers to change its frame size depending on the tag density. That is to say, the frame size is increased as with an increase in number of tags increases the collisions, and vice versa.

In another variation, the interrogation cycle begins by setting the initial frame size to two or four. The frame size is incrementally increased with unsuccessful transmissions until at least one tag transmits successfully. If at least one tag is successfully identified, the current reading process is aborted and reinitiated from the beginning at its initial frame size. Despite the general performance of the dynamic framed slotted Aloha and its variants, changing the frame size only may not be sufficient given the number of tags, as the frame size cannot be infinitely increased. For example, in the second variation above, when the number of tags is small the reader can identify all tags without much collision. If the number of tags is large, however, the number of slots needs to exponentially increase since the reader always starts with the initial minimum frame size.

We further classify the dynamic algorithms as adaptive or non-adaptive (see Fig. 2.18). Adaptive algorithms use statistical information for frame size adjustment. Adaptive algorithms accommodate tag mobility more than non-adaptive algorithms because they reduce the probability of tag collisions while simultaneously expediting the identification of the RFID tags. Dynamic algorithms (both adaptive and non-adaptive) can be further classified based on their use of reservation, estimation, or statistical techniques. Estimation based approaches are the most important Aloha based schemes [21,23,59,66,85,86,97,102] and utilize tag count estimation techniques to adjust the frame accordingly. The Advanced Framed Slotted Aloha (AFSA) algorithm [102] estimates the number of tags, prior to initiating the reading process, and adjusts the frame size based on the estimation. However, AFSA has to increase the frame size indefinitely, which is impractical with high tag density.

The Enhanced Dynamic Framed Slotted Aloha (EDFSA) [66] overcomes the limitation of AFSA by bounding the estimation based on maximum frame size, i.e., setting an upper bound on the frame size. EDFSA initially estimates the number of unread tags using the AFSA estimation function and then partitions the unread tags into a number of groups. Only one group of tags is allowed to respond at one time. The number of groups that give output to the maximum throughput for the subsequent reading cycle is calculated and adjusted after every interrogation cycle. The reader transmits the number of tag groups and a random number to the tags when it broadcasts a request. A tag receiving the request generates a new number from the received random number and the tag's own serial number and divides the new number by the number of tag groups. Only the tags having the remainder of zero respond to the request. The estimation and grouping of the unread tags are performed after each read cycle until all the tags have been read. Although EDFSA overcomes the limitation of AFSA protocol, it has longer reading cycles and additional functionality at the tag.

Statistical algorithms [30, 43, 44, 59] exploit statistical information to improve the read time of the RFID systems. Adaptive Slotted Aloha Protocol (ASAP) [59] utilizes information relative to the tag population, from previous interrogation cycles and reading processes, to estimate the number of tags presently within the interrogation zone of the reader. The ML-based estimation algorithm is used for this purpose. The frame size is adjusted optimally to reflect the tag estimation. The mobility is supported by accounting for tag arrival and departure rate, while initiating the estimation and frame adjustment at the beginning of every interrogation cycle. The statistical algorithm resembles the deterministic anti-collision category and shares the same pros and cons.

Discussion

Most of the anti-collision protocols discussed so far in this chapter attempt to maximize specific gains at the expense of other performance merits. In minimizing collision, for example, an algorithm increases the reading rate. This increase, however, comes at the expense of additional memory, overhead communication and processing requirements that may increase the cost of a tag. In what follows, we discuss some of the performance merits traded off in the design of anti-collision algorithms.

1. Speed: the rate at which tags can be read. This is a general objective that is sought by most proposals.

2. Overhead: the communication and processing overhead for the tags and the readers. The communication overhead includes sending additional bits which otherwise would not be sent. The processing overhead includes additional interrogation cycles or data crunching beside the nominal.

3. State: the amount of state that can be reliably stored on the tag. Additional storage means additional memory. A reader may maintain statistical information but the storage cost at the reader is significantly less than at the tag.

4. Mobility: the ability to accommodate tags which enter and leave an interrogation zone during the interrogation process.

5. Scalability: the ability to accommodate high tag deployment densities.

6. Cost: in terms of additional functionality and memory requirements at both tags and reader. Increase in the cost also reflects an increase in the device monetary value.

Table 2.2 and Table 2.3 show the scheme improvements, depicted by a check-mark (✓), and the tradeoffs, depicted by a down arrow (↓), for the deterministic and probabilistic anti-collision algorithms, respectively. A scheme may not affect certain metric but may do so indirectly. This shown by $-$. For instance, the prefix reduction scheme's main objective is to reduce the communication overhead which indirectly reduces the time it requires to interrogate the tags, thereby accelerating the tag reading rate. It is evident from the tables that each of the schemes, either deterministic or probabilistic, come with a tradeoff and the suitability of each varies under different circumstances. Therefore, with diverse sets of RIFD applications, no

Approach	Speed	Overhead	Stateful	Mobility	Scalability	Cost
Energy-aware [78, 87, 116]	✓	✓	-	↓	↓	✓
Hybrid [94]	✓	✓	↓	✓	-	↓
Memoryless [31, 63, 77, 116]	✓	↓	✓	-	-	✓
Prefix [28, 29, 61, 80, 113]	-	✓	↓	-	-	-
Statistical [26, 76, 77]	✓	-	↓	✓	✓	↓

Table 2.2: Comparison of deterministic anti-collision algorithms.

single existing scheme fulfills all performance metrics. For example, in a typical warehouse scenario, the reader deployed at the docking doors or the conveyor belts is to interrogate hundreds of mobile tags, or possibly thousands with item-level tagging, as they move from one section (e.g., docking doors) to another (e.g., sorting) section of the warehouse. Therefore, it is of utmost importance to be able to read all the tags encompassing a certain performance metric, as speed, mobility and scalability matter more than overhead reduction. For such scenarios, the statistical approach is the most promising, compared to other high-speed reading schemes such as hybrid, with its limited scalability or memoryless, with its low support for mobility. An RFID based access control system does not require scalability and high reading rates, therefore any generic tree-based algorithm is sufficient.

Approach	Speed	Overhead	Stateful	Scalability	Cost
Static [42]	↓	✓	-	↓	-
Reservation [107]	✓	↓	↓	-	↓
Estimation [21, 23, 58, 66, 85, 86, 102]	✓	↓	↓	-	-
Statistical [30, 43, 44, 59]	✓	-	↓	✓	↓

Table 2.3: Comparison of probabilistic anti-collision algorithms.

2.2.4 Reader Collisions

Readers with intersecting interrogation zones may interfere with each other's operation to the extent of barring a reader from identifying tags within its reach. As with other radio systems, a reader's operation may also be affected by other readers even if their interrogation zone does not overlap. In either case, a reader collision results [39, 68]. While the use of multiple frequencies may effectively minimize reader collisions, RFID tags are limited functionality devices that are incapable of differentiating between multiple readers and they cannot be mass produced to communicate using multiple frequencies. We classify the reader collision schemes, shown in Fig. 2.19. Multiple mechanisms based on scheduling, coverage and learning are adopted to resolve collisions.

In the scheduling based approach, frequency and an associated time slot is scheduled for the reader. Scheduling can be centralized or distributed, and can support

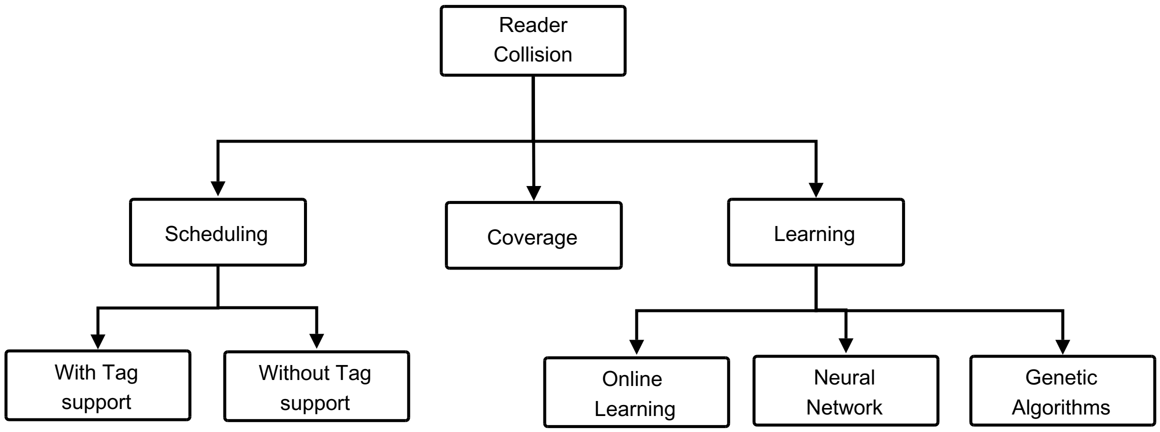


Figure 2.19: Taxonomy of reader collisions schemes.

both static and dynamic frequency assignments. Occasionally, the scheduling is enhanced with tag support, i.e., additional data is stored within tags at the expense of additional memory requirement. However, scheduling without tag support is the most common approach. Algorithms such as colorwave [103] fall under this category. Learning based approaches, on the other hand, are based on hierarchical online learning, genetic algorithms, and neural network methods. The learning approach attempts to minimize collision by learning the collision patterns and assigning frequencies based on the learned pattern. Algorithm such as HiQ [51] falls under this category. Alternate approaches such as the use of beacon channels [15], central cooperators [105], and handling reader collisions as coverage problems [19] also exist in literature.

To achieve optimal frequency channel assignment, a pair of distributed algorithms called Distributed Color Selection (DCS) and Variable-Maximum Distributed Color Selection (VDCS) are introduced [103]. Both DCS and VDCS fall under the scheduling category. An objective of both algorithms, simply known as colorwave, is to color each node of the multiple reader networks using multiple colors in such a manner that the possibility of having two adjacent nodes with the same color is minimized. With color representing different frequencies, the difference between an adjacent node's color could indicate the availability of non-interfering frequencies. Colorwave optimizes the minimum number of colors and therefore frequencies required, up to a predefined maximum value while maintaining a configured successful transmission rate by the readers. Colorwave is a TDMA based approach, wherein each reader randomly selects a time slot to transmit using its assigned frequency. Upon collision, the reader selects a new time slot and informs its adjacent nodes of the selection. If any neighbor is scheduled to use the same frequency (color), it reinitiates itself, selects a new frequency and informs its neighbor of its actions. The process of selecting frequency and scheduling time slot is repeated, as required. The maximum allowable color is increased if the successful transmission rate drops below the configured value. The colorwave reduces the reader collision up to certain network scales, as in practice only a limited numbers of frequencies are available that can be utilized.

The Hierarchical Q-Learning (HiQ) algorithm [51] is a hierarchical, online learning algorithm that finds the dynamic solution to reader collision problems. HiQ, similar to Colorwave, tries to minimize the reader-to-reader collisions by assigning frequencies to each reader over time. The frequency assignment however, is based on learning the collision patterns among neighbors and then assigning the optimal frequency. The optimal or near-optimal frequency assignment is achieved by repetitive environment interaction, i.e., collision patterns and estimation. HiQ utilizes three basic hierarchical tiers, in some form already present in the existing RFID systems, namely: readers, R-servers, and Q-servers. At the lowest tier are the RFID readers. The RFID reader communicates using prescheduled frequency in the reserved time slots. The reader detects the collisions amongst the neighboring readers, i.e., the readers with overlapping interrogation zones. This statistical information, as explained earlier, is utilized for optimal frequency assignments; the decision being made by upper tiers, i.e., the reader-level server (R-server). A one-on-one relation exists between the low-level reader and the R-server. The Q-learning server (Q-server) is the highest tier and is responsible for resource allocation, by finding an optimum scheduling policy based on the underlying readers' learning experience or collision information. The HiQ learning algorithm is distributed at lower-level (readers) with centralized scheduling at the top-most tier. HiQ provides optimal scheduling, resulting in higher throughput, but at the cost of a centralized solution.

Other learning based approaches include neural networks and genetic algorithms. A neural network approach is a fixed channel solution where each neuron represents an RFID reader. The constraint and optimization criteria of the system are translated into an energy function, which the neural network tries to minimize. The outcome of these neurons determines if the channel may be usable for the represented RFID reader. Genetic algorithms are a form of blind local search. In the genetic algorithm approach to the channel assignment, a single solution is an assignment scheme for all RFID readers. The genetic algorithm takes a set of solutions as the population and begins the evolutionary process, which is repeated until a solution is found with no interference.

The learning and scheduling approaches are mainly targeted towards reader-to-reader collision. Alternate procedures such as beacon channels [15] and central co-operators [105] are used to tackle multiple readers-to-tag collisions. The distributed protocol, Pulse [15], is based on the beaconing mechanism. The reader, while reading the tags within its interrogation zone, periodically broadcasts a beacon using the control channel. Any other reader that wants to read the tags, i.e., tags within the overlapping interrogation zone, has to ensure that no beacon has been transmitted on the control channel before it can initiate its interrogation process. The latter reader has to wait until the first reader has executed its interrogation process because the control channel is idle for a specific time period before triggering its own beacon. The pulse protocol however, is inclined toward eliminating the collision caused by mobile RFID readers. In the central cooperative approach [105], a centralized device is responsible for the multiplexing of tags' data to multiple readers. Using a control cooperator, the present 'multiple points to multiple points' collision problem (caused when multiple readers are trying to access multiple tags) translates into the classical problem of 'multiple point to one point' collision. The central cooperator multiplexes multiple reader requests into a single request for the tags. The responses from the tags are de-multiplexed to the individual readers separately. The central cooperator provides an affective approach in handling multiple readers-to-tag collisions. However, it requires a device with all the functionality of a conventional RFID reader.

The reader collision avoidance schemes include frequency assignment scheduling and online learning approaches to avoid reader collisions. Table 2.4 shows a contrast between various algorithms for resolving the collision problem. The algorithms vary and have fundamental differences. For instance, some are centrally controlled, i.e., using central authority for channel assignment and multiplexing the reader queries.

Method	Approach	Centralized control	Distributed control	Fixed Channel	Dynamic Channel
DCS [103]	scheduling	-	✓	✓	-
VDCS [103]	scheduling	-	✓	-	✓
HiQ [51]	learning	✓	✓	-	✓
Neural	learning	-	✓	✓	-
Annealing [69]	learning	✓	- ✓	-	
Genetic	learning	✓	-	✓	-
Redundancy [19]	coverage	-	✓	-	-
CC [105]	coverage	✓	-	✓	-

Table 2.4: Comparison of reader collision algorithm.

Reader collision, especially reader-to-reader interference, is similar to a frequency assignment problem in conventional wireless communication. However, the fundamental difference is that RFID tags, especially passive tags, are unable to differentiate between various readers. Therefore, two readers communicating with the tag must communicate at different time slots or make use of sessions. According to the EPC Gen2 standard, the tag shall provide support for up to four sessions, allowing two or more readers to independently interrogate the tag. The readers, step-by-step, selectively singulate the tags into their respective sessions and move them into other respective sessions upon completion. This allows multiple readers to interrogate common populations of tags. Although effective, this requires extra memory at the tag, increasing the cost.

2.2.5 Coverage

Existing schemes handle coverage and deployment issues for RFID networks in two approaches: planned or random.

In the planned approach, algorithms are developed to find optimal placement of readers in terms of maximal coverage and minimum number of readers, and under some constraints on where readers can be located [25, 50, 83, 92, 93, 104, 110]. In the optimal grid coverage approach [83], readers are deployed in a grid where the distance between two neighboring readers is determined by the interrogation range of readers. After deployment, the reader(s) not covering any tag can be turned off. Another similar approach is the honey grid [110] in which the readers are deployed in rings of different sizes and centred at the centre of the interrogation zone. When rings are numbered based on their radii, the i^{th} ring contains $6i$ readers. Similar to the regular grid approach, after deployment, readers not covering any tags can be turned off. It has been proven that both schemes provide maximal possible coverage. However, that comes at the cost of large number of readers, significant readers collisions and unfair load distribution. Some reader deployment schemes that take into account tags and readers orientation have been proposed [104]. The scheme proposed in [104] finds an optimal number of readers, their locations out of a set of pre-fixed locations and their antennas orientation to maximize readability. The scheme, however, is not generic; it is only being proposed for portal accuracy in supply chain management scenarios. Furthermore, like other schemes in the literature, it considers only placement without load balancing.

In the random deployments, algorithms are devised to find redundant readers in a given deployment strategy [16,52,53]. In the RRE scheme [16], each reader broadcasts a message carrying its own identity and its tag count, which is the number of tags within its region. Each tag stores the identity of the reader having the maximum tag count it received. Access to a particular tag is granted to the reader covering that tag with the maximum tag count (i.e., the reader of the identity stored in the tag). Readers that are not granted access to any tag are marked redundant and are turned off. The RRE scheme has a lot of communication overhead as it requires frequent write operations to the tag. To mitigate this overhead, the LEO and the LEO+RRE algorithms [52] introduce the concept of "first-read first-own" principle: an RFID reader only write its own identity into a tag memory. The reader that manages to singulate the tag and writes the identity first is granted access. In case of the LEO+RRE algorithm [52], upon completion of LEO execution, the RRE algorithm is then used to further eliminate any redundant readers. Various other redundant reader elimination schemes have been proposed in the literature [53, 111], and they try to make enhancements upon the RRE and LEO schemes. A load balancing scheme utilizing tag storage space has also been proposed [37]. The basic idea is that each reader writes its tags count into tag memory space, and the tag picks and responses back to the reader with the lowest load. Various other middleware-based load balancing schemes have also been proposed in the literature [24].

Coverage, in context of node placement, has also been formulated as art gallery problem, Oceans coverage problem, coverage for robots and coverage in wireless sensor networks. In the art gallery problem [84], the problem translate into finding the minimum set of locations for security guard, inside a polygonal art gallery, such that the gallery is visible by at least one of the guard. Various randomized algorithms have been proposed to solve the art gallery problem. The art gallery problem for the $2D$ and $3D$ case is linear and NP-hard, respectively, wherein an approximation algorithm is presented for the later case [73]. The art gallery based coverage problem has many real world applications, such as placement of antennas for cellular telephone companies, and placement of cameras for security purposes in banks and supermarkets. However, the analogy of art gallery problem has limited applications for RFID systems as they have limited coverage, i.e., reading range.

In ocean coverage problem [48], the authors are interested in monitoring the Oceans pigments concentrations, using satellites based remote sensing. Using numerical analysis, the results show that merging data from three satellites can increase ocean coverage by 58% for one day and 62% for four days. The exceptional coverage, using limited satellites was made possible as the satellite nodes had different orbits and therefore was able to sense the same ocean location at different times of day. Such a multi-sensing solutions, due to large associated cost, is justifiable only for large coverage (e.g., Oceans) and hence, can not applied directly to RFID systems.

The coverage concept with regard to the many-robot systems was introduced in [47]. The author herein define three types of coverage: blanket coverage, barrier coverage, and sweep coverage. In the blanket coverage, the goal is to achieve a static arrangement of sensors that maximizes the total detection area. In barrier coverage the goal is to achieve a static arrangement of nodes that minimizes the probability of undetected penetration through the barrier, whereas the sweep coverage is more or less equivalent to a moving barrier. New applications arise in the context of mobile WSNs, where sensors have locomotion capabilities. Thus, the nodes can spread out such that the area covered by the network is maximized and can relocate to handle sensor failures. These solution can be adopted to mobile RFID readers however, is an open research direction.

In wireless sensor networks, deployment of nodes are subject to multiple objectives. The main objectives are to minimize the number of nodes, extending the network lifetime [35] and increasing the network fidelity [114]. These objectives are addressed in the context of area coverage, point coverage and barrier coverage. The most studied coverage problem is the area coverage problem, where the main objective of the sensor network is to cover (monitor) an area, using both centralized and distributed algorithms. Various energy efficient variations of the area coverage also have been proposed in the literature. These variation utilizes diverse techniques such as node duty cycling and node scheduling, connected random coverage, deterministic coverage and k-coverage. The main objective is to minimize the number of nodes required to maintain certain coverage while maintaining network connectivity.

The point coverage scenario considers a limited number of points (targets) with known location that need to be monitored. A large number of sensors are dispersed randomly in close proximity to the targets; mainly is used for surveillance applications. In such applications, requirement is that every target must be monitored at all times by at least one sensor. In [20] authors proposed a solution wherein the disjoint sets are modelled as disjoint set covers, such that every cover completely monitors all the target points. The authors prove that the disjoint set coverage problem is NP-complete and and propose an efficient heuristic for set covers computation using a mixed integer programming formulation. In [56], authors consider the scenario of deterministic point coverage, i.e., the possibility for explicit placement of set of sensor nodes at certain points. Given these set of points, the objective is to determine a minimum number of sensor nodes and their location such that the given points are covered and the sensors deployed are connected. In the barrier coverage [74, 89], the goal is to minimize the probability of undetected penetration through the barrier, i.e., the sensor network. Such coverage involve three tiers mobility, i.e., target mobility, sensor mobility, and data collector mobility.

Unlike RFID, the WSNs node deployment and hence, coverage, is very application dependant. However, similar to RFID, the most common goal is to reduce the number of deployed sensor node while maintaining an acceptable coverage of the event sensing area. Therefore the solutions from the wireless sensor network coverage can be adopted for RFID systems however, is a largely unexplored research area.

2.3 Summary

In this chapter we present the background and literature survey on medium access control and coverage in RFID systems. Energy harvesting and backscattering modulation are the main foundation technologies of low-cost identification solutions provided by RFID. The energy harvesting yields battery-less RFID tags which enables minimal maintenance, longer lifetime and low cost RFID solutions. The backscattering yields transceiver-less RFID tags which enable minimal power and low cost RFID solutions. RFID system employs a centralized communication architecture wherein the reader simultaneously interrogates and process the tags, within its reading range. This centralized and simultaneous interrogations result into collisions.

Due the simplicity of the RFID tags, it is not possible to use the conventional wireless medium access and collision avoidance protocols. To this extend, RFID employes deterministic slotted aloha and probabilistic framed slotted aloha anti-collision algorithms. In the deterministic algorithms, the reader splits and identifies a set of tags to respond in a given time. Splitting is based on contention information obtained from the previous interrogation cycle and attempts to reduce contention for the next cycle. In the probabilistic algorithms, the reader communicates the frame length, and the tag, randomly transmits a particular slot in the frame. The frame size may be adjusted, based on the information from the previous interrogation cycle, encouraging adaptability according to tag density and distribution. Under certain circumstances, the deterministic algorithms may take a considerably longer time. On the other hand, the probabilistic algorithms are fast, due to its low overhead, but may suffers from tag starvation syndrome.

Chapter 3

Power Control in RFID

3.1 Introduction

The focus of our work in this chapter is to overcome tags-to-reader collisions. While several schemes have been proposed to deal with tag collisions in RFID systems, the interrogation delay is still a problem for some applications that involve dense and/or fast moving passive tags. This causes immense data collisions at the reader. A promising opportunity to avoid a significant amount of collisions is to partition the interrogation zone spatially into smaller clusters, and to have tags in each cluster being read separately (i.e., one cluster at a time). Any existing anti-collision scheme can be used to resolve collisions in a single cluster. Such a scheme should reduce the number of collisions as it reduces the number of tags that may respond at the same time. To the best of our knowledge, the proposed Power-based Distance Clustering (PDC) scheme [10] is the first to exploit such an avoidance approach. In PDC, the reader tunes transmission power so that tags within the interrogation zone are clustered based on their distance from the reader. Tags which are being interrogated within the current cluster will not respond to the reader's queries for the subsequent clusters; as once read, these tags are forced into a sleep mode.

We studied the viability and efficiency of the PDC scheme in [10]. However, it was not clear how to find the best partitioning scheme. Indeed, having too many clusters may result in many empty clusters, which is an extra overhead, and few clusters may result in having crowded clusters; both situations affect the performance of that approach significantly.

The contributions of this chapter are as follows. We formulate two optimization problems for finding the clustering scheme that minimizes the number of collisions and, hence, reduces the interrogation delay. The first problem targets an ideal setting in which the transmission power and, hence, the transmission range of the RFID reader can be tuned with high precision. In the second problem, we relax this assumption and consider an RFID reader with finite, discrete transmission ranges. For each optimization problem, we present a mathematical delay analysis and devise an efficient method to find the optimal clustering scheme. Our proposed methods have been designed to adapt to different system environments such as the number of tags and their distribution. We also show the results of several experiments, using the ns-2 simulator [7], which verify the effectiveness and performance improvements of the PDC scheme in terms of number of collisions, reading rates, and delay.

The rest of this chapter is organized as follows. Section 3.2 introduces our PDC scheme. Section 3.3 presents a mathematical analysis and an optimal algorithm for clustering the interrogation zone of an RFID reader whose transmission range can be tuned with high precision. Section 3.4 presents a mathematical analysis and an optimal algorithm for clustering the interrogation zone of an RFID reader with a finite number of transmission ranges. Section 3.5 presents the results of our experiments.

Finally, Section 3.6 summarizes our work.

3.2 The Power-based Distance Clustering (PDC) Anti-Collision Scheme

The PDC is a divide-and-conquer anti-collision scheme in which tags are divided into clusters based on their distance to the reader. Tags in different clusters are then read separately (one cluster at a time). This has the potential to reduce the number of tags which can be concurrently active, lower the collision probability, and, hence, expedite the interrogation process. Partitioning the interrogation zone can be achieved by controlling the readers antenna power level. The reflected power density and the reader range can be computed using the following formulas [42] [115]:

$$S = \frac{\lambda^2 . P_{reader} . G_{Reader} . G_{Tag}}{(4\pi)^2 R^4} \tag{3.1}$$

and

$$R = \frac{\lambda}{4\pi} . \sqrt[4]{\frac{k . P_{reader} . G^2_{Reader} . G^2_{Tag}}{P_{back}}} \tag{3.2}$$

where S is the reflected power density, λ is the wavelength of the emitted electromagnetic wave, P_{reader} is the power supplied to the reader's antenna, R is the distance between the reader and the tag, G_{Reader} and G_{Tag} are respectively the antenna gain for the reader and the tag, and P_{back} is the power received by the reader from the tag. It follows from (3.1) that the power density reflected back by the antenna is proportional to the fourth root of the power transmitted by the reader. Also it follows from (3.2) that the reading distance between the tag and the reader can be changed by changing the power supplied to the reader's antenna while maintaining P_{back}. Hence, the interrogation range of the reader can be reduced by lowering P_{reader}.

An example of the partitioning is shown in Fig. 3.2, where the interrogation zone is divided into three clusters: D_1, D_2, and D_3. When the reader sends a request to a particular cluster, only those tags in that particular cluster may respond. For example, assume that the reader just sent a request (query) to cluster D_2 after it had finished reading tags from cluster D_1. Then only tags from cluster D_2 (i.e., tags marked as t_2) will respond to that request. After all tags marked as t_2 have been read successfully, they are put into a sleep mode. Then, the reader transmission range is increased to cover cluster D_3 and a new request is sent. Now only tags from cluster D_3 (i.e., tags marked as t_3) will respond to the reader requests. This identification process continues until the reader reaches its maximum interrogation range. The flow diagram of the PDC scheme is illustrated in Fig. 3.1. Any anti-collision scheme can be used to resolve collisions within a single cluster.

The scheme is sensitive to the size and the number of clusters. A large number of clusters in a sparse tag environments yields longer delays as a result of many empty clusters and idle cycles. On the other hand, a small number of clusters may result in having too many tags in one cluster which renders the scheme ineffective, especially in dense tag environments.

The Static PDC, which we proposed in [10], divides the interrogation zone into clusters based on a fixed stepping value d. This means that the transmission range of a cluster is more than that of the previous cluster by a fixed value d. While very simple, this scheme does not divide the interrogation zone into equal-size clusters and does not adapt to different tags densities. However, it has the ability to be integrated with any anti-collision scheme and it has shown acceptable improvements as shown in Section 3.5.

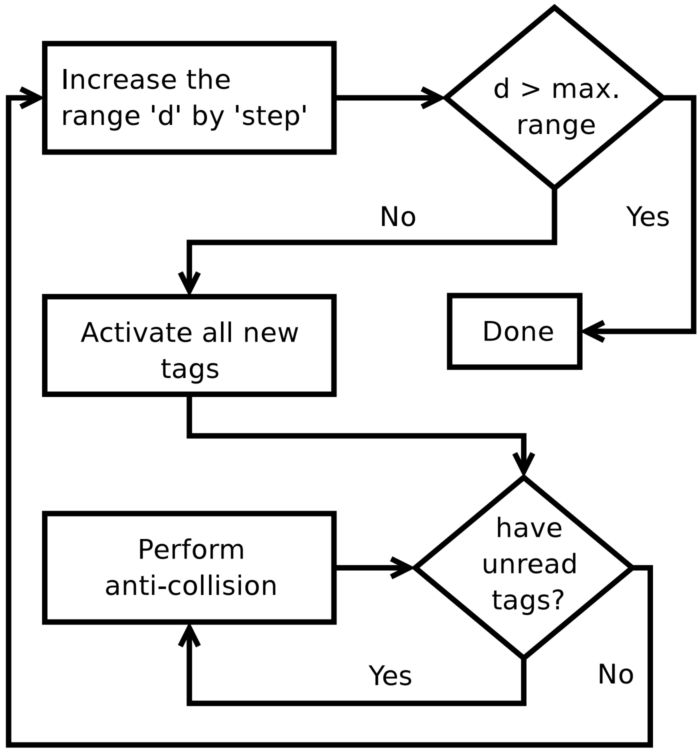


Figure 3.1: Flow diagram of the PDC scheme.

3.3 Optimal Power-based Distance Clustering

In this section we present our theoretical analysis and methodology for finding the Optimal Power-based Distance Clustering (O-PDC) scheme. This scheme targets RFID readers whose transmission power can be tuned with a high precision so that the transmission range can be controlled with high accuracy.

3.3.1 System model and problem definition

We consider an RFID system consisting of an RFID reader and n passive tags. The interrogation zone is modelled as a circle centred at the RFID reader with a radius of R units; the RFID reader can communicate with, and read, all tags located within

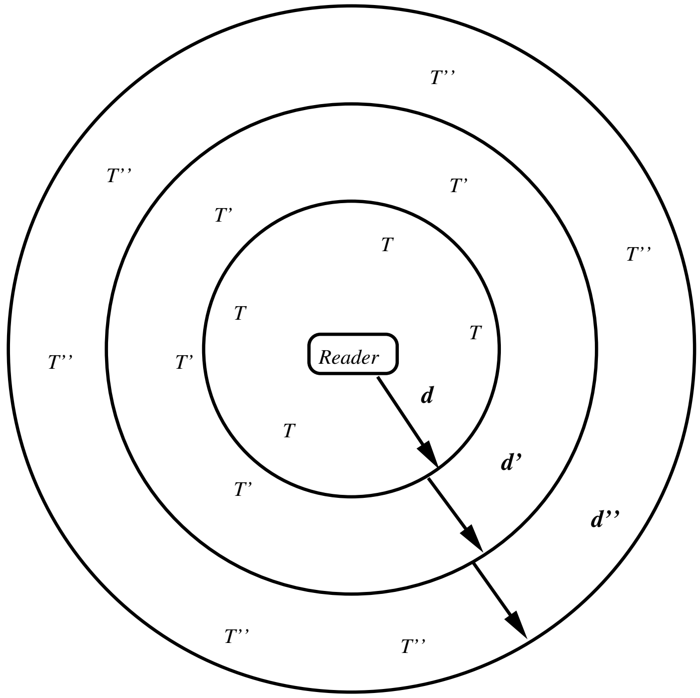


Figure 3.2: An example of an interrogation zone of 3 clusters.

its interrogation zone.

The interrogation zone is divided into k equal size clusters, and tags in each cluster will be read separately (existing protocols use $k = 1$). In general, any anti-collision protocol can be used to resolve collisions in a particular cluster. The RFID reader and tags will go through several cycles during the reading process; in each cycle the RFID reader sends a request and zero, one, or more tags respond to the request by sending their IDs. An idle cycle is one in which no tag responds, a successful cycle is one in which exactly one tag responds, and a collision cycle is one in which two or more tags respond. Upon detecting a collision, the RFID reader will send a more restricted request which excludes some of the colliding tags. Eventually, a tag will be read successfully. This process will be repeated until all tags are read successfully. Now, the problem can be defined as follows:

Find the optimal number of clusters that minimizes the total number of cycles required to read all tags.

3.3.2 Assumptions

To resolve collisions within a single cluster, we use the Query Tree (QT) protocol [64]. Nevertheless, any existing tree-based protocol can be equally used for that purpose. We also assume that tags are uniformly distributed over the interrogation zone. We also assume that the total number of tags is known to the reader; several schemes in the literature (e.g., [62]) are able to find a precise estimation to the number of tags in a negligible time.

3.3.3 Delay analysis

Let $f(n)$ denote the number of cycles required to read a set of n tags, and let $E[f(n)]$ denote the expected value for $f(n)$. For the QT protocol, it has been shown in [64] that for $n \geq 4$,

$$2.881n - 1 \leq E[f(n)] \leq 2.887n - 1 \tag{3.3}$$

To generalize our analysis to other tree-based anti-collision schemes (e.g., the recent work in [95][1]), we will have:

$$E[f(n)] = c\,n - 1, \tag{3.4}$$

where c is a constant.

Now, assume that the interrogation zone is divided into k equal size clusters, and tags are uniformly distributed over the interrogation zone. Let $g(n, k)$ denote the number of cycles required to read a set of n tags uniformly distributed over k clusters and

[1] The scheme proposed in [95] has $f(n) = 2\,n - 1$.

using distance-based clustering. Thereby, we deduce the following lemma.

Lemma 1. *If we have n tags, and the interrogation zone is divided into k equal size clusters, then*

$$E[g(n,k)] = c\,n - k + 2E[s], \tag{3.5}$$

where s is the number of empty clusters (i.e., clusters which do not contain any tag).

Proof. We have s empty clusters and t nonempty clusters. Let n_i denote the number of tags in the i^{th} nonempty cluster. For each empty cluster, we will have a single idle cycle; this results in a total of s cycles. The expected number of cycles required to read tags in the i^{th} nonempty cluster is $c\ n_i - 1$. Therefore, the expected number of cycles required to read tags in all nonempty clusters is $c\ n - t$. Therefore, the expected total number of cycles is $c\,n - t + s$, but $t = k - s$, so we get $c\,n - k + 2s$. $\square$

Now, we deduce the following lemma for the expectation of the number of empty clusters.

Lemma 2. *If tags are uniformly distributed over the interrogation zone, then*

$$E[s] = k\left(\frac{k-1}{k}\right)^n \tag{3.6}$$

Proof. Let P_i denote the probability that the i^{th} disk is empty (i.e., no tag is located in that cluster). Then,

$$E[s] = \sum_{i=1}^{k} P_i \tag{3.7}$$

$$= \sum_{i=1}^{k} \left(\frac{k-1}{k}\right)^n \tag{3.8}$$

$$= k \left(\frac{k-1}{k}\right)^n \tag{3.9}$$

□

The following theorem is a direct result from Lemma 1 and Lemma 2.

Theorem 1. *If we have n tags uniformly distributed over k equal size clusters, then*

$$E[g(n,k)] = c\,n - k + 2k \left(\frac{k-1}{k}\right)^n \tag{3.10}$$

3.3.4 Optimizing the delay

The objective of this sub-section is to find the optimal number of clusters (i.e., the value of k that minimizes $E[g(n,k)]$). We start with the following lemma.

Lemma 3. *$E[g(n,k)]$ is a convex function over the interval $[1,\infty)$.*

Proof. $E[g(n,k)]$ is twice differentiable with respect to k over the interval $(0,\infty)$, and

$$\frac{d^2}{dk^2}\, E[g(n,k)] = \frac{2n}{k^3}(n-1) \left(\frac{k-1}{k}\right)^{n-2} \tag{3.11}$$

Since $n \geq 1$ and $k \geq 1$, $\frac{d^2}{dk^2}\, E[g(n,k)]$ is non-negative. Therefore, $E[g(n,k)]$ is convex over the interval $[1,\infty)$. □

From lemma 3, we know that the optimal value for k is the one at which $\frac{d}{dk}E[g(n,k)] = 0$. Therefore, we need to solve the following equation.

$$-1 + 2\left(\frac{k-1}{k}\right)^{n} + \frac{2n}{k}\left(\frac{k-1}{k}\right)^{n-1} = 0 \tag{3.12}$$

Let x_{opt} denote the solution to equation 3.12. In general, there is no closed-form solution to equation 3.12. However, it can be solved by numerical methods. Moreover, since the number of clusters is integer, we just need to find an integer x_{int}, such that $x_{int} \leq x_{opt} \leq x_{int} + 1$; the optimal number of clusters is either x_{int} or $x_{int} + 1$. The following lemma shows that $1 \leq x_{int} \leq n - 1$.

Lemma 4. *When there are n tags, the optimal number of clusters is at most n.*

Proof. To prove lemma 4, it suffices to show that the expected number of cycles with n clusters is less than that with $n+i$ clusters, where $i \geq 1$, (i.e., we need to show that $E[g(n,n)] < E[g(n,n+i)]$). With $n+i$ clusters, we are certain (with probability 1) that at least i clusters are empty, which results in i idle cycles. Thus,

$$\begin{aligned} E[g(n,n+i)] &= E[g(n,n+i)|\text{at least } i \text{ clusters are empty}] \\ &= i + E[g(n,n)] \\ &> E[g(n,n)] \end{aligned} \tag{3.13}$$

□

Since $E[g(n,k)]$ is convex and the optimal number of clusters is at most n, $\frac{d}{dk}E[g(n,k)]$ is a non-decreasing function. Therefore, one can find the optimal solution through binary search over the set $\{1, 2, \cdots, n\}$. Algorithm 1 finds the optimal number of clusters in $O(\log n)$.

Algorithm 1: Optimal Clustering.

Function Derivative(n,i)
Input: n: the number of tags.
i: an integer between 1 and n.
Output: $\frac{d}{dk}E[g(n,k)]$ at $k = i$.
begin
    return $-1 + 2\left(\frac{i-1}{i}\right)^n + \frac{2n}{i}\left(\frac{i-1}{i}\right)^{n-1}$;
end

Function FindOptimal(n)
Input: n: the number of tags.
Output: the optimal number of clusters.
begin
    $left = 1$;
    $right = n$;
    while *right-left>1* **do**
        if Derivative($n, \lfloor\frac{left+right}{2}\rfloor$) < 0 **then**
            $left = \lfloor\frac{left+right}{2}\rfloor$;
        else
            $right = \lfloor\frac{left+right}{2}\rfloor$;
        end
    end
    if $|$Derivative$(n, left)| < |$Derivative$(n, right)|$ **then**
        optimal $= left$;
    else
        optimal $= right$;
    end
    return *optimal*;
end

3.4 Optimal Discrete Power-based Distance Clustering (OD-PDC)

In the previous section, we presented an exact optimal scheme that is suitable for an ideal setting in which RFID tags are uniformly distributed and the RFID reader has a precisely tuneable transmission range. In this section we present a near-optimal scheme that suits RFID readers with discrete transmission ranges (i.e., a finite number of transmission ranges). To the best of our knowledge, this applies to all today's commercial RFID readers (e.g., SkyeTek's M10 RFID reader [8]). Furthermore, the scheme we present here is not limited to any particular distribution for the tags nor to any particular anti-collision protocol to resolve collisions in single clusters. We present a dynamic-programming algorithm that finds a near-optimal set of clusters for this setting.

3.4.1 System model and problem definition

We consider an RFID system consisting of an RFID reader and n passive tags. The interrogation zone is modelled as a circle centred at the RFID reader with a radius of R units; the RFID reader can communicate with, and read, all tags located within its interrogation zone.

The RFID reader has k discrete transmission ranges $Tr_1, Tr_2, \ldots, Tr_k$; where $Tr_1 < Tr_2 < \cdots < Tr_k = R$. We also use $Tr_0 = 0$ to denote a virtual transmission range. Each transmission range may and may not be used in interrogating RFID tags; this makes it possible to divide the interrogation zone into up to k clusters. A cluster is the area between two consecutive active (i.e., used) transmission ranges as shown in Fig. 3.3. For example, when $k = 3$, we can have 3 clusters if all transmission ranges are active. We may also have two clusters if only Tr_1 and Tr_3 are active, and

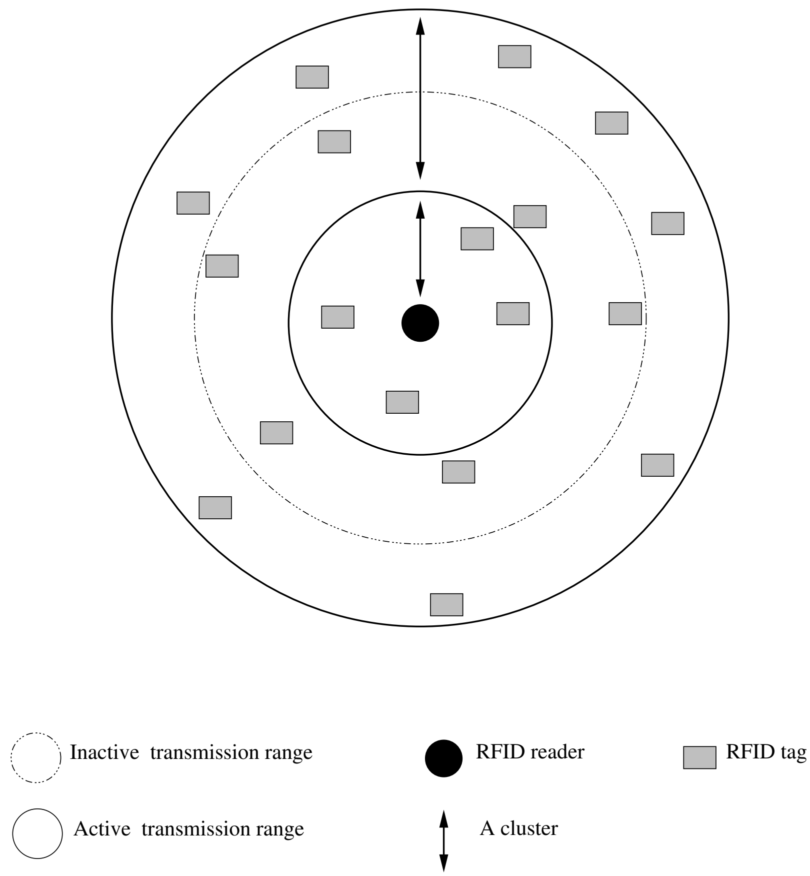


Figure 3.3: An example of 3 transmission ranges and 2 clusters.

we may have only one cluster if only Tr_3 is active. Note that Tr_k must be active in order to cover the whole interrogation zone. A *clustering scheme* is defined by a subset of transmission ranges to be active. A clustering scheme defines the set of clusters used in reading all tags in the interrogation zone. Now, the problem can be defined as follows:

> Find a clustering scheme that covers the whole interrogation zone, such that the total number of cycles required to read all tags is minimized.

3.4.2 Assumptions

To resolve collisions within a single cluster, any anti-collision scheme can be used. We assume that the distribution of tags is known; yet we do not assume a particular distribution. In fact all what is required by this scheme is the probability that a particular cluster is empty of tags; a detailed distribution does not have to be available. We also assume that the total number of tags is known to the reader.

3.4.3 Delay analysis

This subsection explains how each cluster decreases or increases the total number of cycles. A cluster is defined by a pair of transmission ranges that bound it (e.g, the cluster (i, j) is the area between Tr_i and Tr_j). It is obvious that more clusters results in less collisions; we can for example add more clusters until each cluster has at most one tag and, hence, there will be no collisions. However, increasing the number of clusters arbitrarily results in having many empty clusters and, hence, additional idle cycles. Based on this observation, we should maximize the number of non-empty clusters and minimize the number of empty clusters. While the negative effect of an empty cluster is straight forward (which is one additional idle cycle), quantifying the positive effect of a non-empty cluster depends heavily on the anti-collision scheme used within single clusters. To make a general optimization scheme, we assume that an empty cluster adds one extra idle and a non-empty cluster saves d cycles. Therefore, the objective is:

$$\text{MAX} \;\; E[\alpha]d - E[\beta], \tag{3.14}$$

where α is the number of non-empty clusters and β is the number of empty clusters.

For some anti-collision schemes, finding the exact value of d is trivial. For example, the binary anti-collision algorithm with backtracking has $d = 1$ [95]. On the other hand, it is not easy to find the exact value of d for some probabilistic anti-collision schemes. Nevertheless, we can use $d = 1$ to reflect the objective of maximizing the number of non-empty clusters and minimizing the number of empty clusters regardless of the anti-collision scheme being used to resolve collisions within single clusters.

Each cluster will contribute to the objective function in (3.14). Let's give each cluster a rank based on its expected contribution to the objective function, and let $h(i,j)$ denote the rank of a cluster (i,j). $h(i,j)$ can be computed as follows.

$$h(i,j) = P(n_{(i,j)} > 0) * d - P(n_{(i,j)} = 0), \tag{3.15}$$

where $n_{(i,j)}$ is the number of tags located in the cluster (i,j) and $P(e)$ is the probability of an event e, which can be computed based on the distribution of tags. This is based on the fact that a non-empty cluster saves d cycles and an empty one adds an extra idle cycle. When the rank of a cluster is negative, it means that the cluster is expected to add an extra cycle rather than to save cycles. The rank of a clustering scheme cl, which is denoted by $H(cl)$, is the sum of the ranks of clusters composing cl. The optimal clustering scheme is one with the maximum rank.

3.4.4 Optimal clustering algorithm

In this sub-section we present an algorithm that finds the optimal clustering scheme (a clustering scheme is defined by a subset of transmission ranges to be active). In general when there are k transmission ranges, there will be 2^{k-1} possible clustering schemes that cover the whole interrogation zone; it is actually equivalent to the number of all subsets of a set of $k-1$ elements. We present a dynamic programming algorithm to solve this problem. This algorithm finds the clustering scheme whose rank is maximum.

We start with some definitions. Let $CL[i]$ denote the set of all clustering schemes in which Tr_i is active and Tr_j is inactive for all $j > i$. Let $M[i]$ denote the maximum rank of a clustering scheme in $CL[i]$ (i.e., $M[i] = \text{MAX}_{cl \in CL[i]}\ H(cl)$). It is obvious that when we have k transmission ranges, $CL[k]$ will belong to the optimal clustering scheme. The algorithm is described in Algorithm 2.

Algorithm 2: Optimal Discrete Clustering.

```
Function Find Optimal (n, k)
Input:  n: the number of tags.
        k: the number of transmission ranges.
Output: The optimal clustering.
M[0] = 0;
for i = 1 to k do
    Next[i] = 0;
    M[i] = h(i, 0);
    for j = 1 to i − 1 do
        if M[j] + h(i, j) > M[i] then
            M[i] = M[j] + h(i, j);
            Next[i] = j;
        end
    end
end
return (M[k], Next[ ]);
```

3.5 Simulation Setup and Results

In this section, we present the results of a simulation based study we conducted to evaluate the performance of the PDC schemes. We investigate the performance improvements that can be made by the three PDC schemes presented: the static PDC which is presented in Section 3.2, the Optimal PDC (O-PDC) which is presented in Section 3.3, and the Optimal Discrete PDC (OD-PDC) which is presented in Section 3.4. We study the performance of these schemes by generating random RFID networks (topologies) and comparing the performance of a particular pure classical anti-collision scheme (i.e., without PDC) with that of the PDC scheme integrated with the same classical scheme. We may, for example, compare the performance of the pure QT scheme with that of the O-PDC integrated with the QT scheme (i.e., the O-PDC scheme withe the QT scheme being used to resolve collisions within single clusters).

3.5.1 Simulation Setup

We extended the ns-2 simulator [7] to implement RFID. We generate random RFID topologies in which tags are uniformly distributed in a grid of 20×20 m^2. A single reader is located at the centre of the grid. The reader has a maximum transmission range of 10 m. For the PDC scheme, we have a stepping value of 0.5 m (i.e., $d =$ 0.5 m). For the OD-PDC, we have 30 transmission ranges. Tags have randomly generated IDs. In each RFID network, an anti-collision scheme is applied and its operation continues until all tags are successfully identified by the reader. We use several performance metrics to evaluate and compare different schemes. The main metric is the total number of queries (cycles) needed to identify all tags, which is a direct indicator to the performance of different schemes. We also consider the ratio of successful queries, the ratio of collision queries, and the ratio of idle queries. The results are averaged over 20 randomly generated topologies.

Our PDC schemes are compared with three existing schemes, namely the QT scheme, the EBST scheme, and the EPC Q-algorithm. To compare the performance of our PDC schemes with these existing schemes, we show, for each performance metric, the result of the existing scheme without any clustering and the results of the PDC schemes when integrated with that particular existing scheme. This clearly shows the improvements that can be achieved using different PDC schemes. The O-PDC scheme is compared with the QT and EBST schemes only because they meet the assumptions made for the O-PDC scheme. On the other hand, the PDC scheme and the OD-PDC scheme do not have any assumptions on the classical anti-collision scheme being used to resolve collisions in single clusters and, hence, they are compared with the QT scheme, the EBST scheme, and the Q-Algorithm scheme.

3.5.2 Simulation Results

Total number of queries

The main indicator for the efficiency of an anti-collision scheme is the total number of queries needed to identify all tags. Fig. 3.4 shows the improvements made by the PDC schemes when integrated with the QT scheme as compared to the pure QT scheme. The O-PDC scheme saves around 35% of the queries. The OD-PDC scheme saves around 20% of th queries. Fig. 3.5 shows the results of the PDC schemes when integrated with the EBST scheme. The O-PDC scheme saves around 25% of the queries. The OD-PDC scheme saves around 10% of the queries. Fig. 3.6 shows the results of the PDC schemes when integrated with the Q-Algorithm scheme. The OD-PDC scheme saves around 25% of the queries. The static PDC scheme saves around 10% of the queries.

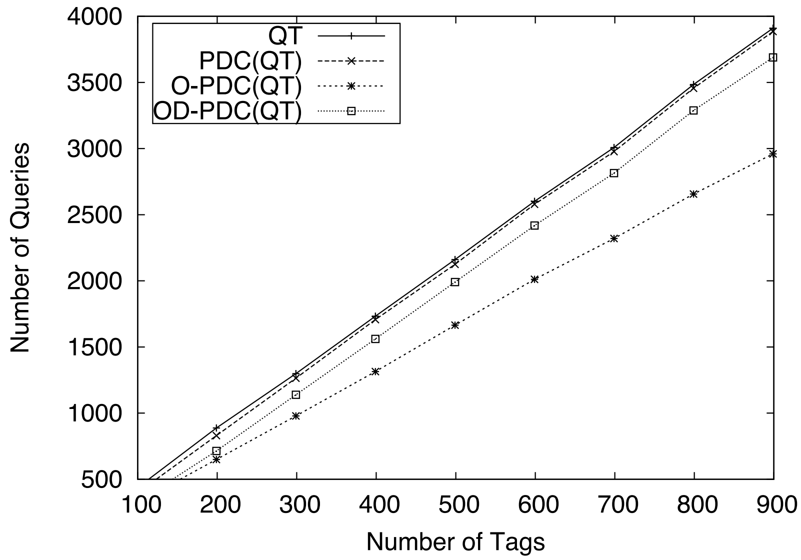


Figure 3.4: Total number of queries with the QT scheme.

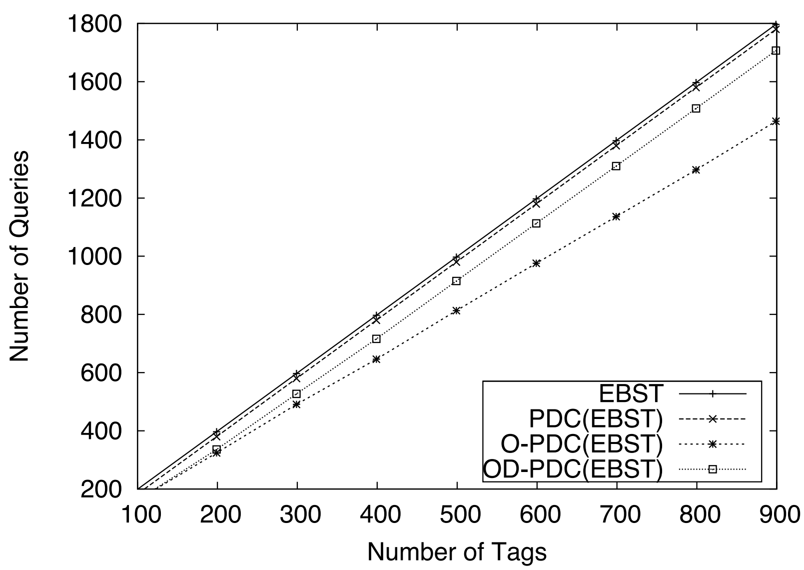


Figure 3.5: Total number of queries with the EBST scheme.

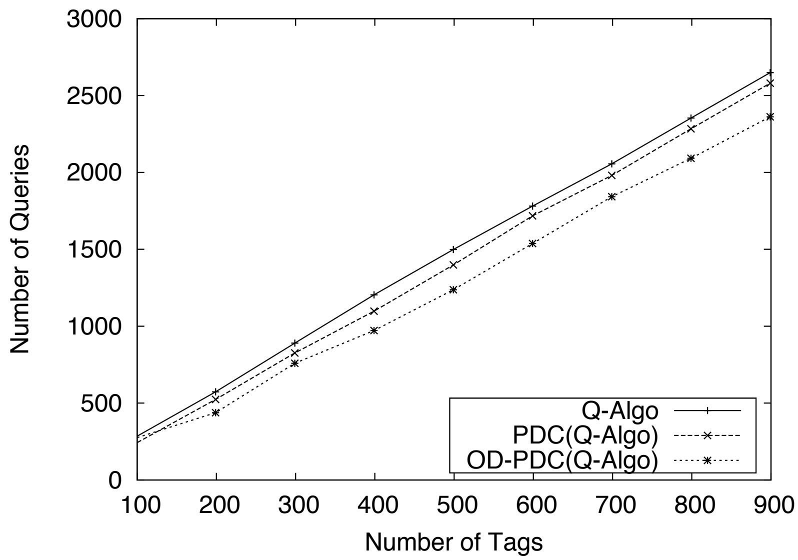


Figure 3.6: Total number of queries with the Q-Algorithm scheme.

Ratio of successful queries

To understand the behaviour of different schemes, we look into the ratio of successful queries to the total number of queries in different schemes. In fact, this metric is inversely proportional to the total number of queries. This is because the total number of successful queries should be the same for all schemes; it is actually the same as the number of tags. However, this metric helps to see how the behaviour of different schemes changes with different tag densities. Fig. 3.7 shows the ratio of successful queries achieved by the PDC schemes when integrated with the QT scheme and that of the pure QT scheme. Fig. 3.8 shows the ratio of successful queries achieved by the PDC schemes when integrated with the EBST scheme and that of the pure EBST scheme. It is not a surprise to see constant ratios for the pure QT scheme and for the pure EBST scheme. The reason is that, for these two schemes, the total number of queries is a linear function of the number of tags. The nice observation here is the

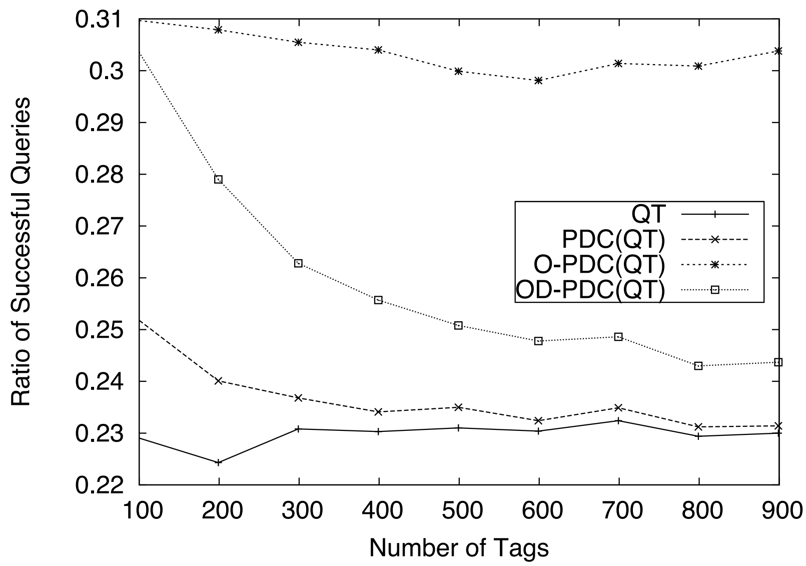


Figure 3.7: Ratio of successful queries with the QT scheme.

stable behaviour of the PDC schemes, and specially the O-PDC scheme. Indeed, this means that the improvements made by the O-PDC scheme are the same regardless of the number of tags. Fig. 3.9 shows the ratio of successful queries achieved by the PDC schemes when integrated with the Q-Algorithm scheme and that of the pure Q-Algorithm scheme. The probabilistic nature of the Q-Algorithm makes the ratio of successful queries less stable than those of the QT and the EBST schemes. This directly affects the stability of the same ratio for the PDC schemes when integrated with the Q-Algorithm. However, as shown in Fig. 3.9, the improvements made by the PDC schemes stay significant regardless of the tags densities.

Ratio of collision queries

Fig. 3.10 shows the ratio of collision queries observed using the PDC schemes when integrated with the QT scheme and that of the pure QT scheme. Fig. 3.11 shows

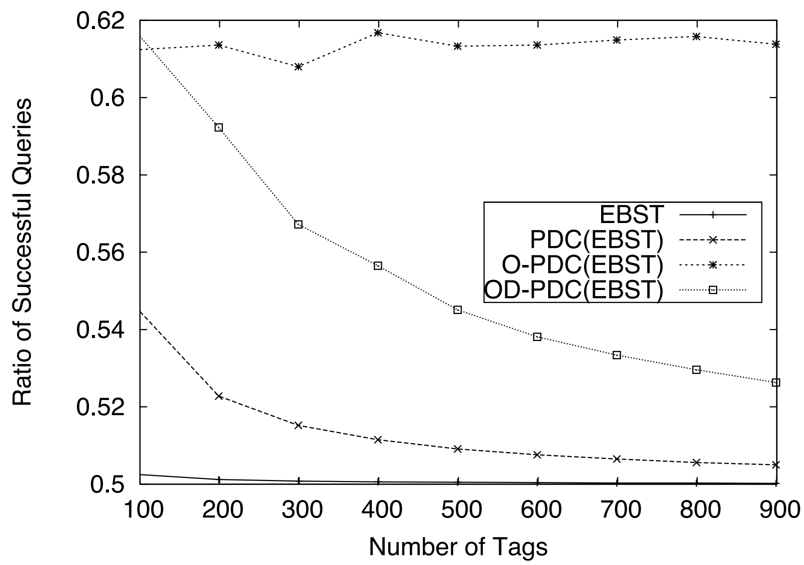


Figure 3.8: Ratio of successful queries with the EBST scheme.

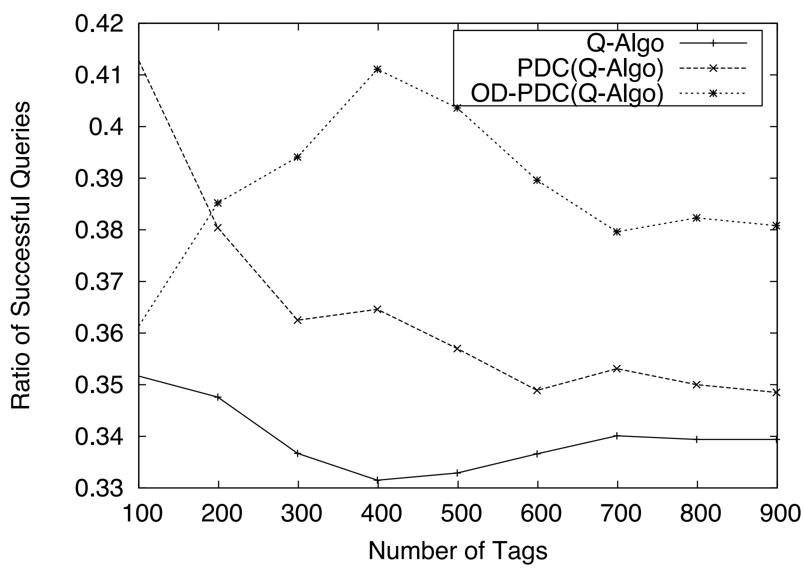


Figure 3.9: Ratio of successful queries with the Q-Algorithm scheme.

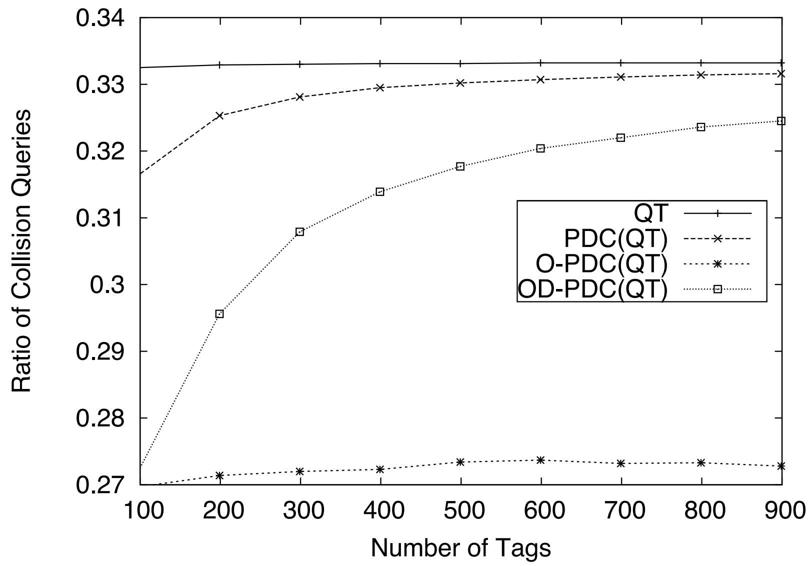


Figure 3.10: Ratio of collision queries with the QT scheme.

the ratio of collision queries achieved by the PDC schemes when integrated with the EBST scheme and that of the pure EBST scheme. These ratios for the pure QT and EBST schemes are almost constant for the same reason mentioned earlier for the constant ratio of successful queries. The PDC schemes also show stable ratios over varying tag densities. Fig. 3.12 shows the ratio of collision queries achieved by the PDC schemes when integrated with the Q-Algorithm scheme and that of the pure Q-Algorithm scheme. Values for this metric has nothing to do with the performance because they are relative to the total number of queries achieved by different schemes.

Ratio of idle queries

Fig. 3.13 shows the ratio of idle queries achieved by the PDC schemes when integrated with the QT scheme and that of the pure QT scheme. Fig. 3.14 shows the ratio of idle queries achieved by the PDC schemes when integrated with the EBST scheme

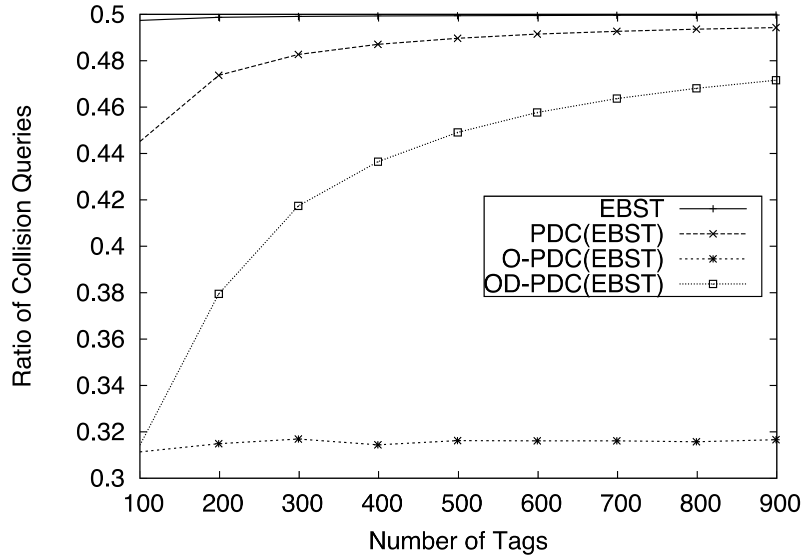


Figure 3.11: Ratio of collision queries with the EBST scheme.

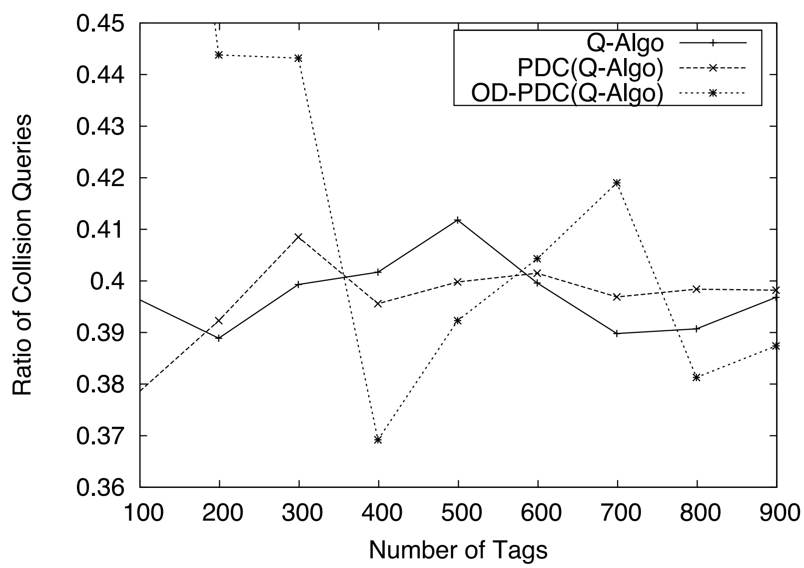


Figure 3.12: Ratio of collision queries with the Q-Algorithm scheme.

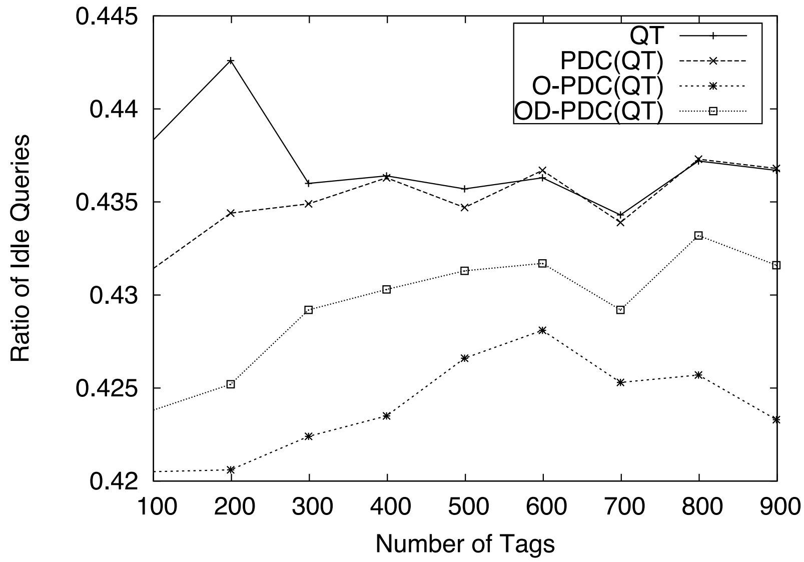


Figure 3.13: Ratio of idle queries with the QT scheme.

and that of the pure EBST scheme. As explained in Chapter 2, the EBST scheme does not have any idle queries. This makes these ratios for the PDC schemes, when integrated with the EBST scheme, very low; idle collisions come only from empty clusters. When the PDC schemes are compared with the QT and the Q-Algorithm schemes, no significant changes are observed between the PDC schemes and the pure classical ones. As is the case of the ratio of collision queries, values for this metric has nothing to do with the performance because they are relative to the total number of queries achieved by different schemes.

3.6 Summary

In this chapter we introduce the power-based distance clustering scheme for tag collision resolution in RFID systems. The main idea in our approach is to divide tags

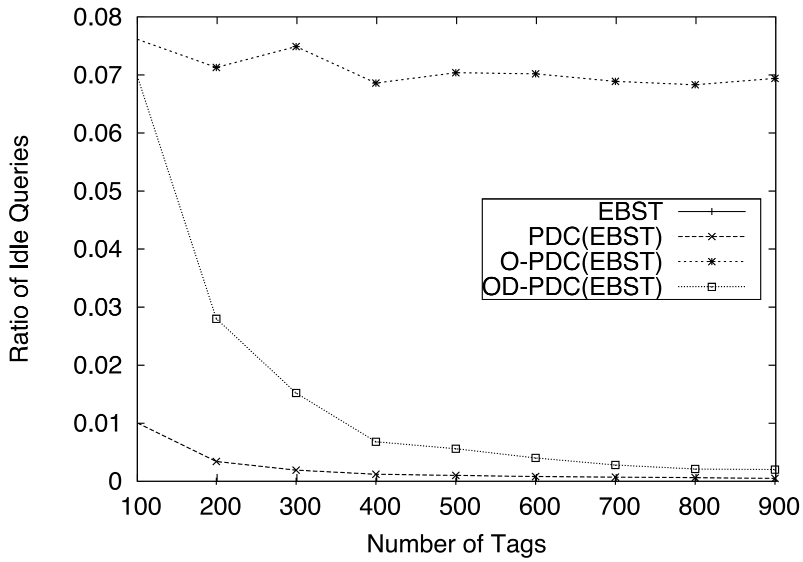


Figure 3.14: Ratio of idle queries with the EBST scheme.

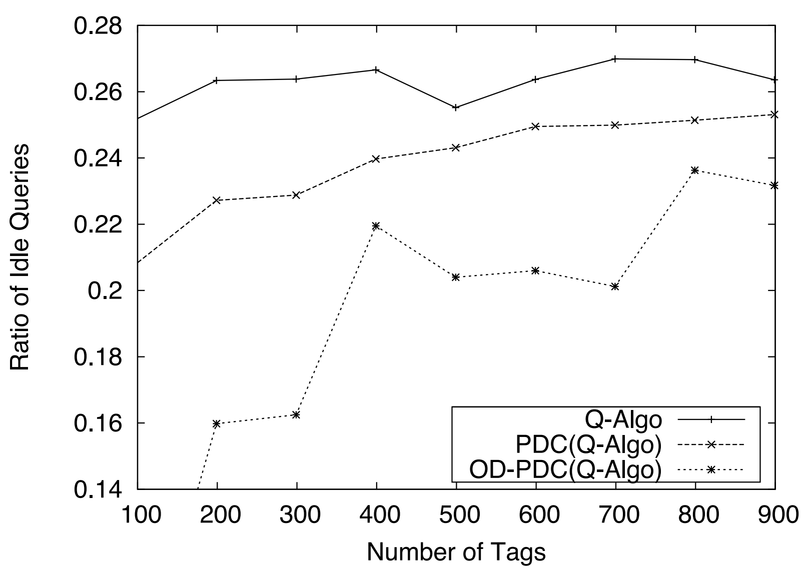


Figure 3.15: Ratio of idle queries with the Q-Algorithm scheme.

into clusters based on their distance to the reader, and read tags in each cluster separately. Since the number of tags in a single cluster is less than that in the whole interrogation zone, the likelihood of a collision is reduced. However, the number of clusters has to be selected carefully, as having too many clusters results in having many empty clusters, which causes a significant number of idle cycles. Our approach finds a balance between reducing the likelihood of collisions and reducing the number of empty clusters by finding an optimal number of clusters. Theoretical analysis and simulations have been presented to verify performance improvements of our approach. Moreover, our approach can be integrated with any existing anti-collision scheme and improve its performance.

Chapter 4

Distributed Receiving in RFID

4.1 Introduction

In RFID systems, a single reader broadcasts the un-modulated signal (on forward link) and receives the backscattered modulated signal from the RFID tags (on backward link). In the forward-link, the RFID reader broadcasts un-modulated Carrier Wave (CW) signals and interrogation queries. Each passive tag, in response to the queries, would harvest its circuitry power from the CW signal incident on its antenna. The operational power requirement of a passive tag circuitry, anywhere between $2.5\mu W - 100\mu W$ [34, 36, 42, 57] and the maximal allowable CW signal power, in addition to attenuation, limit the operational range of a passive tag to a few meters. In the backward-link tags communicate with the reader by reflecting and modulating the incident CW signal on their respective antennas. The reflected signal strength faces significant attenuation as it propagates twice the distance between the tag and reader, hence caps the upper bound on the operational range of the semi-passive tags at some tens of meters.

Furthermore, the inherited centralized architecture coupled with RFID tags' inability to sense carrier channels create collisions at the reader. Collisions are the most prominent hindrance to performance in RFID systems; they lower reading rates, data rates and jeopardize system operational capacity. Currently, numerous solutions have been proposed, both at the system-level and protocol-level, to attain maximal operational performance for RFID systems. For instance, at the system-level, design of low-power circuits [34], higher gain antennas [36], directional antennas [42], etc. have been proposed to enhance the operational range of RFID tags. Similarly, at the protocol-level, energy-aware anti-collision protocols [79, 88, 116], energy-aware modulation schemes [13, 100], sophisticated anti-collision schemes [12, 42, 96], etc. have been proposed to overcome collisions.

However, existing and related proposed solutions are based on centralized communication architectures, therefore inherit their limitations. These limitations place upper bounds on performance, such as reading rate [91], operational range [42], bandwidth [36] and reading reliability [104]. Imminent RFID applications (e.g., intelligent transportation [9]), item-level tagging [14] and mobility demand performance beyond these bounds. It is anticipated that promising trends in CMOS technologies may help in mitigation of some root causes. For instance, reducing the tag circuit power requirements by at least a factor of ten [36], and hence, decoupling passive tags from the performance of the forward-link channel. However, it will also open the door to challenges that require new initiatives; passive tags will be constrained by the backward-link channel performance. In addition, item-level tagging and mobile tags (potentially numbered in thousands [14]) will also prove impossible to interrogate using the existing centralized systems, provoking even stronger advocates to tackle the aforementioned limitations. Indeed, there is a need for new communication models and singulation approaches for RFID systems.

The focus of our work in this chapter is to lessen the limitations and alleviate the bottlenecks imposed by centralized architectures; with the goal of boosting the operating performance of RFID systems to meet both existing and future requirements of ultra large scale RFID applications. To this end, we propose the distributed receiving-based communication architecture, namely Distributed Receiving RFID (DR-RFID) system.

Our main contributions in this chapter are as follows. We introduce our distributed receiving paradigm in RFID systems. In the proposed paradigm, the task of collecting the modulated backscattered signals is dispersed to spatially distributed entities within the reader interrogation zone. This model supports multipoint communication and hence eliminates the redundant interrogation of same set of tags, by overlapping RFID readers. We also present the novel notion of micro-interrogation zones. The micro-zones are formed by dynamically adjusting reflectivity coefficients of RFID tags. Micro-zones spatially isolate tags within the reader's interrogation zone; hence facilitating high bandwidth and data rates. Furthermore, we also devise a parallel singulation algorithm which exploits distributed receiving and micro-zones to mitigate tag collisions. The algorithm singulate tags, from each micro-zone, in a parallel and autonomous manner. Parallel singulation assists in achieving higher reading rate under both dense and mobile tag environments. We evaluate the proposed system, via comprehensive simulations, using the proposed DR-RFID and existing RFID systems, implementation on the ns-2 simulator [7]. The results validate the proposed communication architecture and singulation algorithm, and demonstrate substantial improvement in system performance, usability and enhanced scalability under diverse distribution of tags.

The rest of the chapter is organized as follows. Section 4.2 elaborates on the motivation behind the proposed system. Section 4.3 explains the distributed receiving-based architecture and details its components. Section 4.4 explains the concept of micro-zones and the algorithm formalizing its formation. Section 4.5 explains the parallel singulation algorithm and analyzes its running complexity. Section 4.6 provides detailed information about the simulation methodology and performance analysis. Section 4.7 outlines the work-in-progress on the proposed system. Section 4.8 summarizes our work.

4.2 Motivation

Communication in RFID follows a centralized-control model, usually termed as a master-slave, as is depicted in Fig. 2.4. Although the centralized approach has been widely employed in RFID systems, it has significant drawbacks and limitations, which hinder overall system performance. In this section, we elaborate on the limitations inherently imposed by existing RFID communication architectures.

Reading Range: The least available power for tag circuitry and the strength of backscattered signal are two key requirements in determining the reading range for passive and semi-passive tags; respectively. In addition, in the case of passive tags, other major parameters include reader operating power P_{ERIP} and tag mismatch factor τ. Analytically, the operating distance between a reader and a passive tag is given by

$$d_{(r,t)} = \frac{\lambda}{4\pi}\sqrt{\frac{P_{ERIP}.G_r.G_t.\tau}{P_{min}}} \tag{4.1}$$

As such, under the assumption of a dipole antenna ($G_r = G_t = 1.6$) operating at $900MHz$, a tag with a modest power requirement P_{min} of $16\mu W$ [57] and a mismatch factor τ of 0.5, the maximum theoretical operating distance of the passive tag, following North American regulations, is 15 meters.

The reading range of the semi-passive tag is a function of the strength of the modulated reflected signal

$$P_{rcvd} = \frac{\lambda^2.P_{ERIP}.{G_r}^2.G_t}{(4\pi)^2(d_{(r,t)})^4} \tag{4.2}$$

From (4.1) and (4.2) it is evident that the tag reading range can be increased by adjusting following variables. First, by decreasing the power requirements for the tag circuitry P_{min}. In doing so the tag will be operative at a longer distance however, it is then constrained by the integrity of the received signal (4.2) on by the backward-link. Second, by improving the reader's antenna sensitivity, i.e., $(\frac{P_{rcvd}}{P_{ERIP}})$ by using arrays of antennas, higher gain antennas [36] or directional antennas [42]. However, such solutions, due to their high associated monetary costs, are restricted only to limited applications.

Reading Rate: RFID applications, such as item-level tagging for the supply chain and retail industry, generally involve dense and mobile passive tag distributions. Such environment constitutes potentially thousands of mobile tag within the interrogation zone of a single reader, and as a consequence, causes immense data collisions at the reader [42, 96]. Reading rate is defined as the number of tags that can be singulated per time unit. Lower tags' collisions and the ability of the RFID reader to handle multiple tags at one time imply high reading rates. However, the broadcast nature of the backscattered signal from the tags and reader inability to process them in parallel affect the reading rates of current RFID systems. Furthermore, limited available bandwidth and low data rates further reduce the reading rates. For instance, theoretically, existing RFID reader can only support reading rates of up to 700 tags/second [91]. These reading rates (which may be lower in practice) are not adequate for typical item-level applications involving thousands of moving tags.

Reading Reliability: Reading reliability is the probability a tag is readable regardless of the reader and tag antennas' orientations. Having high reading reliability is of utmost importance for certain applications. For instance, self-checkout counter at a department store – a miss-read tag is lost revenue. The power received by the RFID tag, considering its antenna orientation, i.e., azimuth and latitude angles of the reader (θ_r, ϕ_r) and the tag (θ_t, ϕ_t) [104], is

$$P_{rcvd}^{tag} = \frac{P_{ERIP}.G_t(\theta_t, \phi_t).G_r(\theta_r, \phi_r).\lambda^2}{(4\lambda d_{(r,t)})^2} \tag{4.3}$$

The tag orientation proportionally affects the readability and in some cases, e.g., perpendicular orientation between the tag and the reader antenna, can result in zero readability. Due to the current centralized communication architecture, the CW signal is collected and processed by the emitting reader, which thins out the probability of having decent strength signal for different antenna's orientations and hence throttles readability.

Forward-link: Emerging CMOS fabrication technology promises to significantly reduce the tag's IC power requirements, at least, by a factor of ten. The effect of IC power requirements on the tag reading range is illustrated in Fig. 4.1. The three horizontal lines, from top to bottom, are the minimum power (in dBm) requirement of existing tags; $-10dBm$ $(100\mu W)$ [36] and $-26dBm$ $(2.5\mu W)$ [34] and anticipated

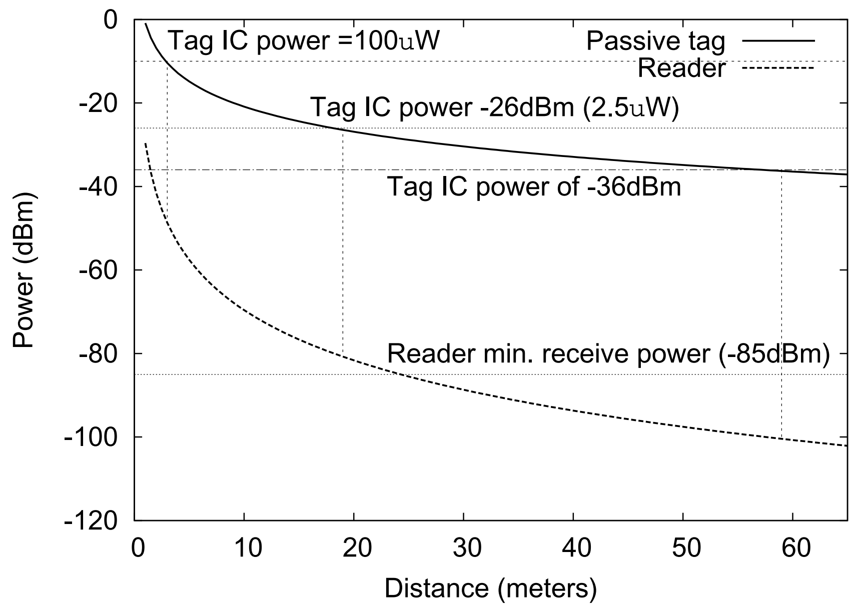


Figure 4.1: Effect of tag circuitry power requirement on the backscattering power and operating range.

tags of $-36dBm$ ($0.25\mu W$). Low IC power translates into longer reading ranges. An existing high-end RFID reader, with receiving sensitivity of $-85dBm$ (lowest horizontal line), may be able to handle the reflected signal of an existing tag. However, it is surely incapable of handling the backscattered signal from the anticipated low-power passive tags as the strength of backscattered signal falls well below (less than $-100dBm$) the reader's receiving sensitivity. In other words, the operating range of the passive tags would be backward-link constraint. This requires new communication architectures and protocols be developed which can adapt to new challenges and constraints.

All of the aforementioned limitations demands that new communication models and singulation approaches be sought out.

4.3 DR-RFID: Distributed Receiving System for RFID

In current RFID systems, the reader acts both as an emanation and an assimilation point. As an emanation point, it broadcasts the CW signal and interrogation queries. As an assimilation point, it receives and processes the modulated backscattered signals from the tags. Such centralized architecture constitutes the master-slave architecture depicted in Fig. 2.4. As explained earlier, it is the centralized nature of communication architecture which is the root cause of degradation in system's performance metrics, viz. reading rate, reading range, reading reliability, bandwidth, capacity and data rates. We propose a novel communication paradigm in RFID – distributed receiving-based communication architecture. The basic idea behind the proposed architecture is to disintegrate the transmission and the receiving components of the existing RFID readers into spatially distributed entities within the concerned RFID interrogation zone. For this purpose a new component, named *fielder*, is introduced in the system. The main tasks of the fielder are collection, processing and relaying of the received data from RFID tags. Distribution of these tasks empowers the reader to tackle multiple tags in parallel at spatially isolated clusters managed by the fielders. Each of the clusters, also known as micro-interrogation zones, is managed by a fielder and is created by dynamically adjusting the fielder's signal receiving sensitivity and the signal reflectivity coefficient of the tags within the prescribed area. This virtually associates a subset of tags to a specific fielder. This association aids in reducing collisions as the reflected tags' signals are now confined within the micro-zones each of which is managed by a separate fielder. It also increases tags reading range as the backscattered signal is multi-hop by the fielder hence sustaining the signal integrity.

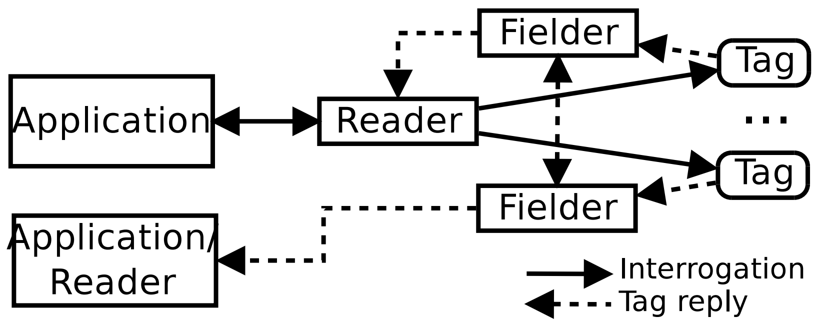


Figure 4.2: Distributed receiving-based RFID architecture.

Furthermore, the autonomous nature of these micro-zones further assists in parallel tags singulation, therefore dramatically increasing the reading rates and reading readability.

The proposed Distributed Receiving RFID (DR-RFID) system uses multi-hop communication as depicted in Fig. 4.2. RFID tag data, once available at the fielder, is replicated and routed to the concerned reader and RFID middleware without initiating a new interrogation process. This eliminates redundant interrogations of the same set of tags by readers, which have overlapping interrogation zones. Purging the system from the overhead interrogations means fewer singulation attempts and thus savings to the scarce wireless resources. Furthermore, with fielder physically associated to a location (micro-zone), e.g., at the docking door in a warehouse, a product tracking application after subscribing to the fielder is notified of items, i.e., with the concerned tag IDs. This results in better product tracking and visibility without any extra equipment, e.g., reader or antenna arrays, for tag localization.

For interoperability with existing RFID systems, the DR-RFID system can functionally accommodate both existing and modified components in multiple configurations. However, not all configurations can harness the benefits assured by the

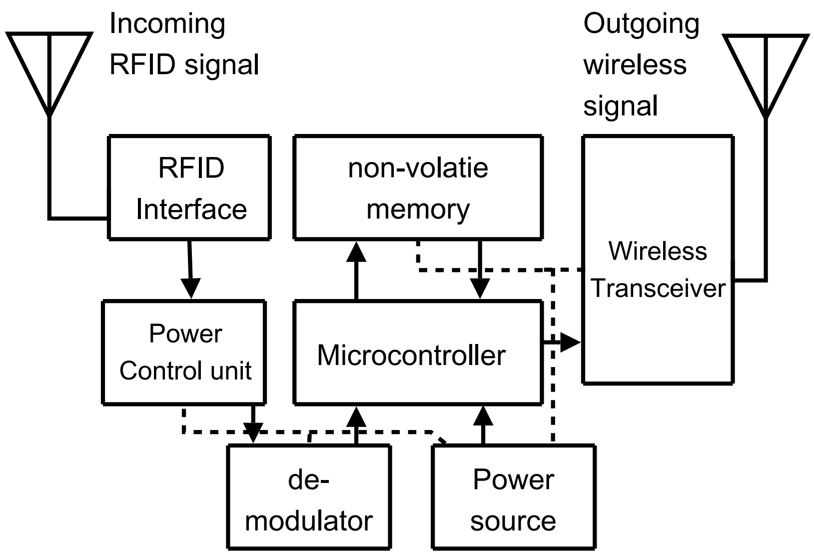


Figure 4.3: Block diagram showing the typical components of fielder in the proposed DR-RFID system.

DR-RFID system. For instance, the operating range, in a configuration involving existing readers and tags, may increase for the semi-passive and active RFID tags but will remain unchanged for the passive RFID tags. This is because an increase in the operating range entails that the passive tag is equipped with functionality to change its reflectivity coefficient, a feature lacking in existing tags. As well conventional readers lack the ability to singulate in parallel hence reading rates will not be increased. Nevertheless, a configuration comprising of a reader with additional functionality, with existing tags, will enhance the support for tag mobility and ability to engage in multi-point communication.

In the remainder of this section, we discuss the system components, i.e., reader, fielder and tag and their comparatively discrete and novel features proposed in the context of the proposed DR-RFID system.

4.3.1 RFID Reader

In a conventional RFID system, source of RF power, task of tag interrogation, processing of backscattered signals, collisions resolution and relaying of data to middleware are all confined in a single entity — the RFID reader. On the other hand, the DR-RFID system disperses some of these tasks into the spatially distributed components of the system, i.e., fielders. The major dispersed task includes dispensation of the backscattered signals and partial relaying of tag data. This requires modifications at the hardware and software levels to RFID readers.

In existing systems, the broadcast of the CW signal and collection of reflected signals is on the same communication channel by the same reader. In the proposed system however, signal broadcast and its collection is on different channels using multiple system components. The reader broadcasts the CW signal on one channel, whereas the fielder relays the received reflected signals on another low power communication channel, e.g., Zigbee or Wibree. Hence, to cope with such an architectural change requires enabling the reader, at the hardware level, to transmit and receive using different communication protocols.

Passive tags within the interrogation zone of multiple readers are singulated, by each reader, individually in an autonomous manner. However, unlike existing RFID systems, the singulation process is shared by the multiple overlapping readers. The tag data processed can potentially be replicated and relayed by the receiving fielders for the overlapping readers, without execution of their singulation mechanism. To support this requires revision in reader's software with ability to subscribe, receive and process tags data without initiation of the singulation process.

4.3.2 RFID Fielder

The fielder, the novel entity of the proposed DR-RFID, is responsible for processing of the tags' reflected signals and relaying of the processed data to the subscribed units. The fielder assists in the formation of micro-zones formation and aid the reader to resolve tags' collisions.

The fielder, conceptually similar to a wireless sensor node, is a low-power and low-cost physical device based on off-the-shelf components. Typical components are shown in Fig. 4.3 and includes wireless transceiver, memory modules, microprocessor and RFID signal receiving interface. The fielder adjusts its Receiving Signal Strength Index (RSSI) threshold to create the virtual micro-zone of a pre-determined circumference. The micro-zone is confined within the reader's interrogation zone and with other micro-zone occupies the entire interrogation field. Each fielder is responsible for processing of the tags that lay within its designated micro-zone.

The functional behavior of the fielders, on receiving of the backscattered signals from the tags, is defined based on their state, namely *silent* state or *forward*. In the silent state, no data is routed to the reader and the converse holds for the forward state. These states are set by the reader and assist in collision resolution. For instance, the reader, upon collision detection, deliberately puts every fielder, except a randomly picked one, into the silent state. The basic idea is to restrain multiple readers, with overlapping reading zones, from interrogating the same set of tags at same time. An overlapping reader not receiving any tag's reply – the silent fielders will not forward the data to their respective readers – avoids competing for tags singulation. The randomly picked fielder, only after successful singulation, replicates and routes the data to the overlapping readers.

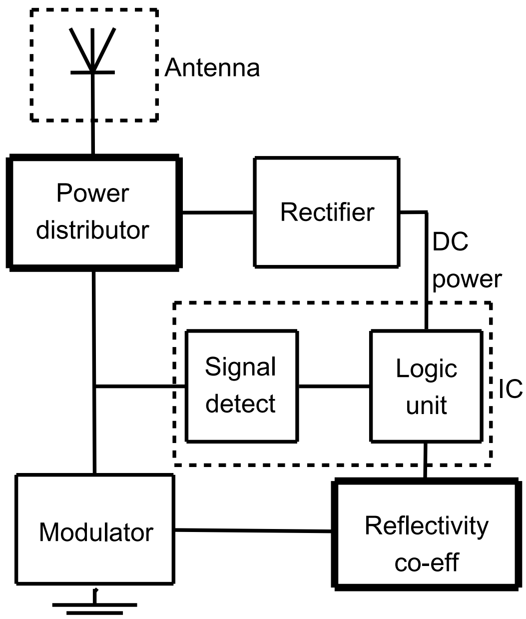


Figure 4.4: Block diagram showing typical components of the passive RFID tag along with highlighted components specific to the DR-RFID system.

4.3.3 RFID Tag

The incident radio waves on the tag antenna facilitate two purposes: first, for the passive tag, to harvest the DC power and second, for both passive and semi-passive tag, to communicate with the reader. The passive tag trades off the signal power between the rectifying unit and the backscattering unit. Existing RFID tags, generally, split the available power equally between the two units. In special cases, however, significant percentage of the power is set for the rectifying unit, hence, tag's circuitry. This will result in lesser power available for the backscattering unit hence, low strength backscattered signal. On the contrary, the tag of the proposed DR-RFID system always distributes significant percentage of the available power to the circuitry unit, aided by the introduced power distributor component (see Fig. 4.4) without the need

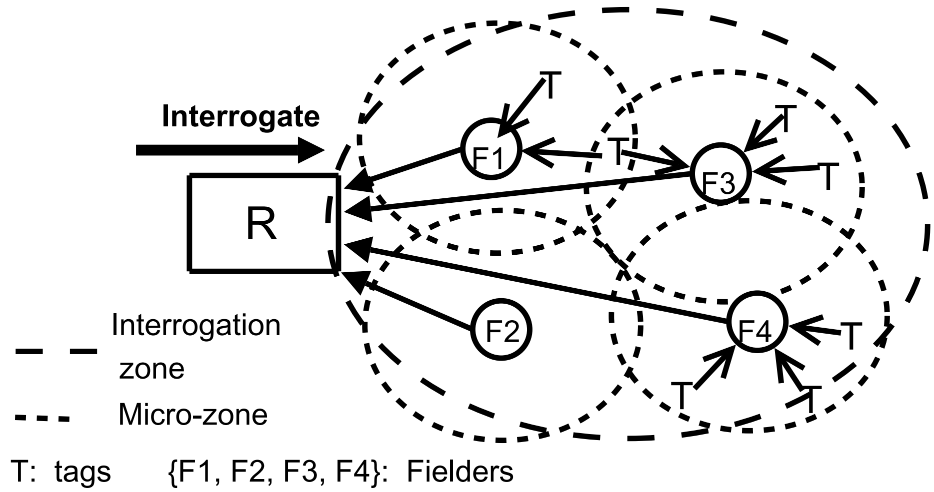


Figure 4.5: Micro-zones in the DR-RFID system.

of high-cost and highly sensitive readers. The fielder minimizes the propagation distance of the reflected signal, therefore, allowing tag's signal integrity to be valid up to the spatially closet fielder. Furthermore, shortening of the backscattered path further facilitate in achieving longer operational range.

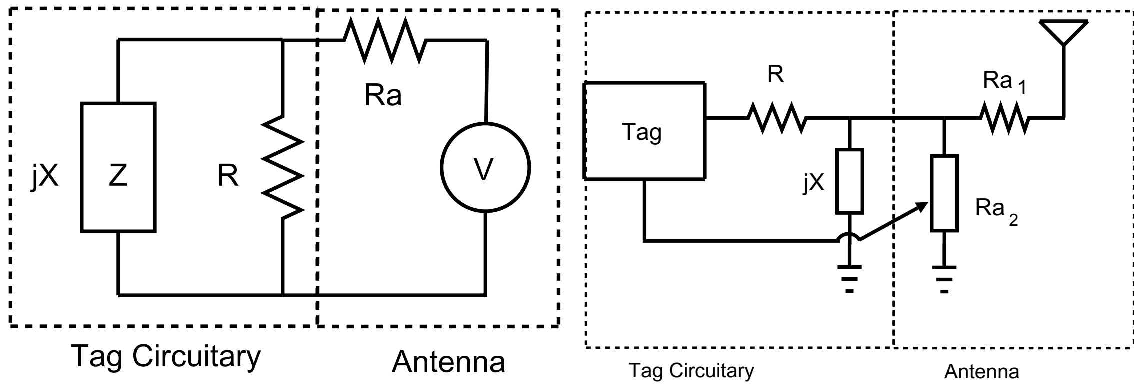
Unlike existing RFID tags, the tag in the proposed DR-RFID system has the ability to dynamically adjust its reflectivity co-efficient. The additional components are shown in Fig. 4.4. Tag adjusts the strength of the backscatter signal to make it decodable within the boundary of its micro-zone, hence, does not interfere with tags from other micro-zones. This significantly reduces tag collisions and enhances the bandwidth of the backward-link channel, a feature not viable in existing tags.

4.4 Micro-Zoning in DR-RFID System

The basic idea of micro-zones, illustrated in Fig. 4.5, is to cluster the tags into micro-zones and interrogate these clusters in an autonomous manner. This reduces the number of tags that needs to be interrogated at one time, reducing collisions and improving tags reading rate. The micro-zones are formed with support from fielders and tags. Fielders simply need to adjust their RSSI threshold such that the signal-to-noise ratio of the spatially close (within the pre-determined area) tags surpasses the tags which are spatially located afar. Tags need to adjust their reflection co-efficient such that the integrity of the reflected signal will only be valid within a confined region and must not be strong enough to interfere outside this region. To this end, the reader, mainly based on the fielder placement, assists the tag in selecting the right value for its coefficient in a way that both tags and fielders are able to form the required number of micro-zones within its interrogation zone. However, due to the nature of a complex indoor environment (e.g., warehouse), wherein the RF signal suffer from multi-path phenomenon, it is possible for the micro-zones to have overlapping interrogation regions. In such a scenario, the tags within these overlapping regions will interfere will tags of more than one micro-zone. However, such conditions will only have minor effects on the overall performance of our proposed system. In the unlikely scenario, wherein the micro-zones are 100% overlapped, our proposed system will not degrade beyond any existing system. We will address this issue further, in Section 4.6, when evaluating the performance of the proposed DR-RFID and existing RFID systems.

4.4.1 Tag Reflectivity Co-efficient

Tag reflectivity depends on the cross-sectional area of its antenna and is modifiable by varying the antenna impedance mismatch, i.e., by changing either the real part R_a or the imaginary part Z for the Amplitude Shift Key (ASK) modulation or the



(a) Current tag schematic (b) Revised tag schematic

Figure 4.6: Tag schematic showing the antenna with the added parallel resistor along with the circuitry imaginary and real part.

Phase Shift Key (PSK) modulation, respectively. The conventional tag with exposes real part and the imaginary part of the circuit and antenna is shown in Fig. 4.6-a.

The tag backscattered power P_{BS} is a function of its distance to the reader $d_{(r,t)}$, the reader transmitted power P_{ERIP} and its radar cross section area σ. Using the Friis equation we get

$$P_{BS} = \frac{P_{ERIP}.G_t}{4\pi D^2_{(r,t)}}.\sigma \tag{4.4}$$

The radar cross section σ of the tag is defined as

$$\sigma = A^e_r.\frac{4R^2_a}{|Z_a + Z_c|^2}.G_t \tag{4.5}$$

where $Z_a = R_a$, $Z_c = R + jX$ and A^e_r is the effective area of tag and is

$$A^e_r = \frac{\lambda^2}{4\pi}.G_t \tag{4.6}$$

Dynamic adjustments to the tag's reflectivity coefficient require to variant the strength of the backscattered signal P_{BS}. To achieve this, we can use a variable resistor R_{a2} in parallel with the antenna resistor R_{a1}, as depicted in Fig. 4.6-b, such that the overall antenna resistance is

$$R_a^{new} = \frac{R_{a1}.R_{a2}}{R_{a1} + R_{a2}} \tag{4.7}$$

Introducing variable parallel resistor gives flexibility to dynamically adjust the antenna coefficient as needed and is controlled by the tag's data signal. The coefficient is adjusted before the execution of singulation algorithm and is made to till is explicitly reset. The modified radar cross-section σ_{new}, after substitution of (4.6) and (4.7) in (4.5) is given by

$$\sigma_{new} = \frac{\lambda^2}{4\pi}.{G_t}^2.\frac{4.R_a^{new}}{|R_a^{new}||R + jX|^2} \tag{4.8}$$

The power density of the reflected signal received by the fielder, with antenna gain of G_f, at distance $d_{(t,f)}$ is

$$S_f = \frac{P_{BS}.G_f}{4\pi.{D_{(t,f)}}^2}.\sigma_{new} \tag{4.9}$$

Substituting P_{BS} and σ_{new} from (4.4) and (4.8) we get

$$S_f = \frac{P_{ERIP}.G_r.G_f.\lambda^2.G_t^2}{(4\pi)^3.D_{(r,t)}^2.D_{(t,f)}^2}.\left[\frac{4.R_a^{new}}{|R_a^{new}||R + jX|^2}\right] \tag{4.10}$$

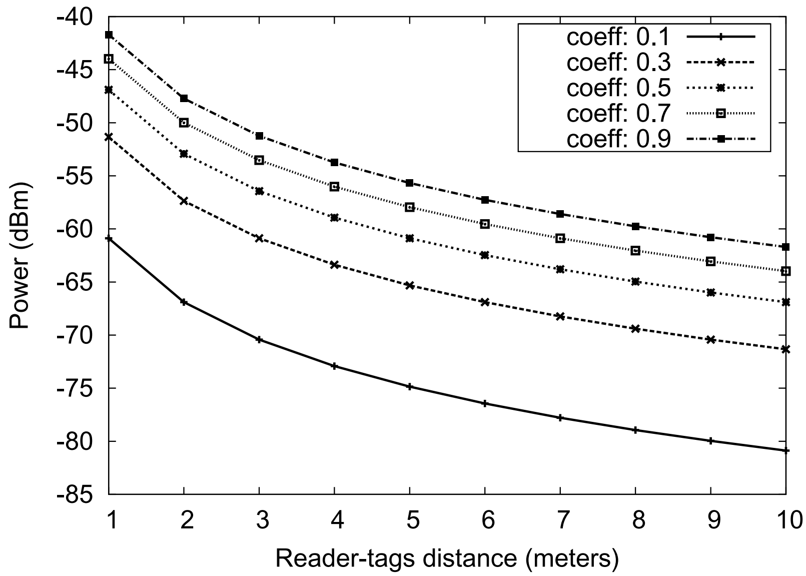
From (4.10), we infer that the strength of the reflected signal depends on three important parameters; distance to the reader, distance to the fielder and radar cross section. Therefore, by adjusting the value of the variable resistor R_{a2}, in accordance with the reader-tag and tag-fielder distance, the strength of the reflected signal can be modified. For instance, Fig. 4.7-a shows the strength of the backscattered signal, seen at the fielder (using 4.10), with P_{ERIP} 4W (North American standard), frequency of

900MHz, antenna gain (G_f, G_t and G_r) of 1.6 and a fixed distance to fielder, $D_{(t,f)}$ of 5 meters. The smaller the distance to the reader $d_{(r,t)}$, the lower the reflectivity coefficient should be.

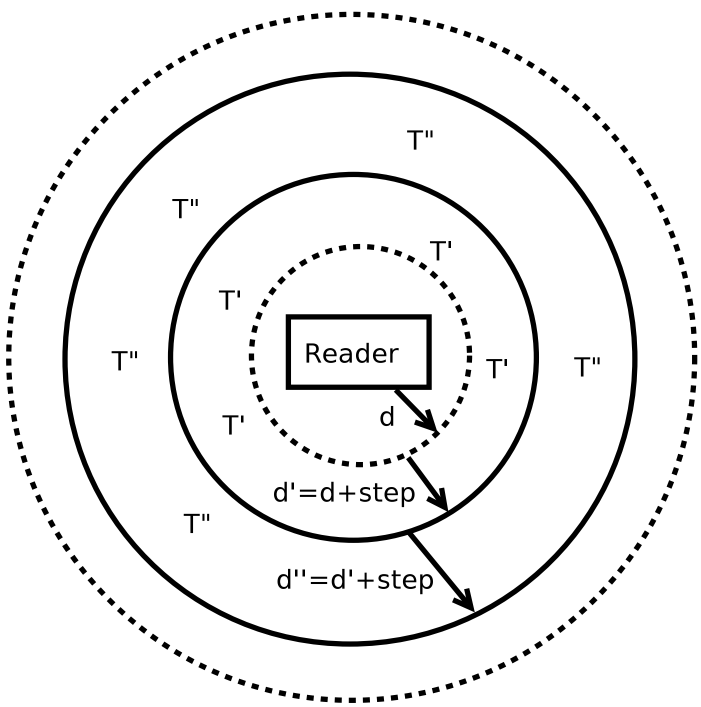
4.4.2 Dynamic Assignment of Reflectivity Index

To calculate the required tag reflectivity co-efficient needs reader-tag and tag-fielder distance. The power-level of the reader is varied in order to calculate the reader-tag distance. Change in the reader's antenna power level clusters the tags based on their distances from the reader [10]. The clustering concept is shown in Fig. 4.7-b, where the reader's interrogation range is divided into clusters d, $d^{'}$ and $d^{''}$ at respective distance of d, $d + step$ and $d + 2 * step$ from the reader. At any time, only tags from same cluster will adjust their reflectivity co-efficient. For instance, assume the reader has already adjusted the tags from cluster d. Then only the tags from cluster $d^{'}$, i.e., tags marked as $T^{'}$ will adjust their coefficients. After these tags, marked as $T^{'}$, have been adjusted the reader then increases its range to $d^{''}$. Now only the tags from cluster $d^{''}$,i.e., labeled as $T^{''}$ will act to the reader requests. In other words, the tag adjusts its reflectivity only once until it is reset. The adjustment process continues until the reader reaches its maximum interrogation range. The stepping distance and thus the number of clusters can be optimized for a given tag distribution [12]. The tag-fielder distance is the Euclidean distance between the boundary intersections of a variable interrogation range and one of the fielders' created micro-zone.

The tag reflectivity co-efficient assignment algorithm is shown in Algorithm 3. In the first step, the intersection points for each fielder's micro-zone f_k with the two



(a) Effect of reflectivity co-efficient on received signal strength (dBm) as function of reader-to-tag distance (meters)



(b) Tag clustering

Figure 4.7: Tag reflectivity coefficient and assignment.

boundaries of the current cluster, d and $(d - \delta)$, (δ is the stepping parameter) is calculated (lines 4-6). The set of intersection points P_k are determined for every fielder k which overlaps with the reader's current interrogation boundary. The tag-fielder distance is the maximum Euclidian distance $\overline{f_k p}$, between the fielder f_k and its intersection points p, amongst all fielders (line 7). The new reflection coefficient σ_{new} is calculated by substituting the tag-fielder distance in (4.9) for a pre-defined S_f and is subsequently broadcast (lines 8-9). Afterwards, the reader power-level is incremented and the aforementioned steps are repeated until the maximum interrogation is reached.

Algorithm 3: The reflectivity assignment algorithm.

1 **Set Reflectivity($\mathcal{F}$)**
  Input: $\mathcal{F}$: set of fielder.
  Output: Adjusted tags' reflectivity
2 **repeat**
3   // for the i^{th} cluster.
4   **foreach** *fielder* f_k *in* $\mathcal{F}$ **do**
5     $\{P\}_k \leftarrow$ 4-intersection points with f_k, using d and (d - δ);
6   **end**
7   d(f,t) $\leftarrow$ max ($\forall$ f_k ϵ {F} | max ($\forall$ p ϵ $\{P\}_{f_k}$ | $\overline{f_k p}$));
8   Calculate σ_{new} by substituting d(f,t) in (4.9);
9   Send (Broadcast, σ_{new});
10   Increment power-level by δ;
11 **until** *Maximum interrogation range is reached* ;

4.5 Parallel Singulation in DR-RFID

Existing anti-collision schemes are based on certain assumptions about the underlying system. First, the reader in a sequential manner interrogates tags within the interrogation zone. In other words, it is only after successful singulation of a tag that the subsequent singulation takes place for the remaining tags. Second, all tags lying within the interrogation zone will cause collisions at the reader. On the contrary, DR-RFID systems have the following important characteristics. First, the interrogation zones are divided into multiple non-interfering micro-zones. Second, the reader only knows and is concerned with the intra-zone collisions. Finally, and most importantly, due to the micro-zones, the sequential singulation is not the only option. To elaborate, since only the intra-zone collisions are possible, each micro-zone can be interrogated independently.

To this end, we propose a parallel singulation algorithm where multiple instances of an existing anti-collision scheme are executed, for each micro-zone, in parallel and autonomous manner. To determine the effectiveness of the parallel singulation approach, we use algorithms from the deterministic and probabilistic class of anti-collision schemes. Although we use simple binary search tree algorithm [42] [95] and the EPC Q algorithm [40] for deterministic and probabilistic, respectively however, yet any other anti-collision algorithm can be used. In this section, we describe the system model, explain the deterministic and probabilistic parallel singulation algorithms and analyze their running complexities.

4.5.1 System Model

Consider an interrogation area A_R enclosed by a single RFID reader R with maximum interrogation range of R_r. The interrogation area is divided into n micro-zones $f_1, ..., f_n$ of area A_{f_1},..., A_{f_n}, respectively. A fielder manages each micro-zone. The fielder selectively relays the received tags' serial numbers to the reader. Assuming the disk model, the reader interrogation area is completely covered by the clusters, i.e., $A_R \leq (A_{f_1} \bigcup ... \bigcup A_{f_n})$. Assuming a uniform distribution, there are k tags within the interrogation area A_R, i.e., t_1,..., t_k, where $k >> n$. Each micro-zone i receives responses only from the tags within its area A_{f_i}. The reader during each interrogation cycle i broadcasts singulation requests $Reqa_{(i,j)}$ intended for the micro-zone f_j. For an interrogation cycle, the maximum number of singulation requests transmitted by the reader equals the number of micro-zone.

4.5.2 The Deterministic Algorithm

The main goal of RFID anti-collision algorithms is to increase the singulation rate by reducing the tags' collisions. In the case of deterministic parallel singulation algorithm, this is achieved in two ways. First, execution of an instance of the deterministic singulation algorithm, for each micro-zone in an autonomous manner. In this section, we use the conventional binary search tree as the candidate deterministic algorithm. Second, by making use of reader and fielders synchronization. Pseudocode for the parallel singulation algorithm is shown in Algorithm 4. The parallel singulation algorithm is composed of four logical components: initialization, concurrent singulation, communication between the RFID components and communication timeout scenarios.

Initialization: The algorithm begins with housekeeping tasks (lines 2-7) which includes setting all fielders states to *FORWARD*, broadcasting the RESET and the initial serial request (REQA) command. Fielders in the forward state always relay tags' serial numbers to the reader whereas converse holds in silent state. The reader, after resetting tags internal state (RESET), broadcasts the initial serial request (REQA)

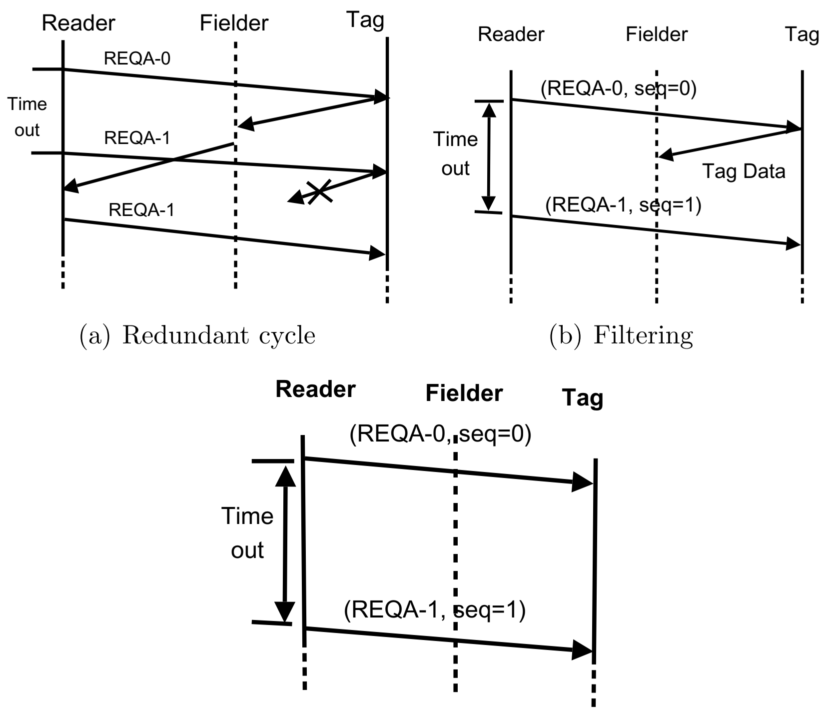
Algorithm 4: Deterministic parallel singulation algorithm.

```
Deterministic Parallel Reading (F)
Input: F: set of fielder.
Output: Singulated tags.
foreach fielder f_k in F do
    s_k = FORWARD;
end
Send (broadcast, RESET);
Adjust the tags reflectivity index using Algorithm 3;
Send (broadcast, REQA_0xffffffff);

// Singulation process for the i^th interrogation cycle.
repeat
    wait until REQA_timeout ;

    foreach fielder f_k in F do
        // Let j be the MSB collision bit, if any.
        if (Collision)_{f_k} then
            REQA_(i,k) ← b_{n-1}...b_j = 0b_{j-1} = 1...b_0 = 1;
            Queue_k    ← b_{n-1}...b_j = 1b_{j-1} = 1...b_0 = 1;
        end
        else if (NoReply)_{f_k} then
            // NULL is returned, if the Queue_k is empty.
            REQA_(i,k) ← Pop from Queue_k;
        end
        else if (NoCollision)_{f_k} then
            // Tag is successfully singulated. Perform tag's read/write
            operations.
            REQA_(i,k) ← Pop from Queue_k;
        end
    end
    foreach fielders f_k in F do
        if REQA_(i,k) ≠ NULL and REQA_(i,k) is Unique for i^th cycle then
            Send(f_k, REQA_(i,k));
        end
        else if REQA_(i,k) = NULL then
            Send(f_k, SILENT);
            s_k = SILENT;
        end
    end
until ∃k|s_k = FORWARD ;
```

command using the highest possible 32-bit serial number as its parameter. This initial interrogation request serves as the root of the singulation tree.

Parallelism: For each micro-zone, the reader maintains an independent instance of the singulation tree and its associated data structures, i.e., singulation tree and queue. An instance of the anti-collision algorithm (listed in lines 15-25) is iteratively executed during each micro-zone's interrogation cycle. In a collision scenario, between the tags of the k^{th} micro-zone, a new broadcast request $REQA_{(i,k)}$ is formed by replacing the most significant collision bit by 0 followed by trailing 1's. The broadcast request for the k^{th} micro-zone is then used for the subsequent interrogation cycle. The most significant collision bit is also replaced by 1, followed by trailing 1's, and is queued on $Queue_k$ (line 17) which is de-queued under two scenarios. First, when no response from the tags was received for the last request (line 21) and second, after a successful tag singulation (line 25).

Reader and Fielder Communication: The tag replies to a reader request if and only if the requested serial number is greater than its own. Due to broadcasting nature, the tag listens and in some cases may respond to an irrelevant request, i.e., is not intended for its micro-zone. For instance, consider two micro-zone a and b with their respective request as $REQA_{(i,k)}$ and $REQA_{(i,j)}$. If $REQA_{(i,k)} \leq REQA_{(i,j)}$ then a subset of tags from the cluster a may response even if their serial number is greater than $REQA_{(i,j)}$. Such a situation potentially inhibits the micro-zones singulation tree with unwanted tree nodes and, hence, an unpredictable outcome. To alleviate such a data structure corruption, the fielders are kept informed, by the reader, of their successive interrogation requests. This facilitates in effective filtering (listed in lines 28-36) of the irrelevant tags' replies.



(a) Redundant cycle

(b) Filtering

(c) No tag data

Figure 4.8: Timeout scenarios in parallel singulation.

Timeout: Various scenarios trigger timeouts and retransmissions and are outlined in Fig. 4.8. The $REQA_{timeout}$ time (line 11) is the duration of an interrogation cycle, i.e., the maximum time the reader waits for a tag response. The timeout can be non-legitimate or legitimate. The non-legitimate case is when the reader, upon time expiration, broadcasts the queued request (line 21). However, shortly after that, it receives the delayed tag response (Fig. 4.8-a). In such a case, the reader cancels the current interrogation cycle, queues the transmitted request and continues with the singulation process based on the delayed responses. The handling of the delayed transmission is critical as, by neglecting such cases, we may potentially overlook some tags. The legitimate case happens when either the fielder filters out all of the tags' responses (Fig. 4.8-b) or when an empty request exists, i.e., no tag matches with the request (Fig. 4.8-c). Both scenarios lead to a graceful timeout followed by broadcasting of the successive interrogation request.

4.5.3 The Probabilistic Algorithm

The EPC Q-algorithm [40], i.e., the probabilistic class of anti-collision algorithm, uses the Q parameter which determine the number of slots in the Query Round. When a tag receives a Query, it chooses a random number in the range $(0, 2^Q - 1)$, where 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 transmit a 16 bit random number (RN16). In case of collision, the reader will adjust the Q parameter and will resent the query.

The main objective of the probabilistic parallel algorithm is to increase the singulation rate by reducing the tags' collisions. This is achieved by determining the value for Q parameter that will results into best performance, in terms of idle, collision and successful slots, over all the micro-zones. Pseudocode for the probabilistic parallel singulation algorithm is shown in Algorithm 5. The parallel singulation algorithm is composed of two logical components: initialization and updating the value of Q parameter.

Initialization: The algorithm begins with housekeeping tasks (lines 2-10). These tasks start off with setting the initial value of Q (4.0) and C (0.2), broadcasting the RESET to all tags and estimating the tags cardinality. The tags estimation is use to terminate the algorithm (line 38), however, in case of conventional Q-algorithm is also used to optimally set the Q value [72]. The tags reflectivity index is then adjusted

Algorithm 5: Probabilistic (Q-algorithm) parallel singulation algorithm.

Q-algorithm Parallel Reading ($\mathcal{F}$)
Input: $\mathcal{F}$: set of fielder.
Output: Singulated tags.
Q=4.0;
C=0.2;
Send (broadcast, RESET);
$E_t \leftarrow$ Tags estimation within the reader.
Adjust the tags reflectivity index using Algorithm 3;
foreach *fielder* f_k *in* $\mathcal{F}$ **do**
    $E_t[k] \leftarrow$ Determine tag estimation for each micro-zone of f_k;
end
Send (broadcast, Q);

repeat
    wait for response
    Q^*=1.0;
    Idx=0;
    while $Q^* \leq 15.0$ **do**
        P=-1;
        foreach *fielders* f_k *in* $\mathcal{F}$ **do**
            $S[k] \leftarrow \frac{E_t[k]}{2^{Q^*} * (1-1/2^{Q^*})^{E_t[k]}}$;
            if $S[k] > P$ **then**
                $P \leftarrow S[k]$;
            end
        end
        $P[Idx] \leftarrow P$;
        $Q^* \leftarrow Q^* + C$;
        $Idx \leftarrow Idx + 1$;
    end
    Q^*=15.0;
    while $Idx \geq 0$ **do**
        if $P[Idx-1] < P[Idx]$ ***and*** $P[Idx] \geq 1$ **then**
            break;
        end
        $Idx \leftarrow Idx - 1$;
        $Q^* \leftarrow Q^* - C$;
    end
    $Q \leftarrow Q^*$;
    Send (broadcast, $\lfloor Q \rfloor$);
until *all tags are read* ;

using the Algorithm 3. Afterwards, a rough estimate of tags cardinality, using similar method as is used in line 5, however, one a time for each fielder. Finally, the initial query request is sent using $Q = 4.0$.

Updating Q: In the conventional Q-algorithm, the Q value is either incremented and decremented, by a constant C, in case of collision and idle slot, respectively. The flow chart of the Q value updates is illustrated in Fig. 2.11. Generally speaking, if number of tags is small with large Q value, it will result into idle slots. Similarly, if the number of tags are large but with small Q value, it will results into collision slots. Henceforth, to avoid the oscillations between large and small value of Q, and directly to minimize the idle and collision slots, it is important to quickly reach the optimal value, which has been observed to be equal to number of tags [72]. However, such an update approach can not be applied directly in the context of micro-zone. Due to the non-uniform nature of tags distribution, it is possible that some micro-zone significantly will have more tags than others. Adjusting the Q value for a micro-zone may have negative effect on the rest of micro-zones hence, might overshadow the benefits of parallel singulation. To fix this, the proposed algorithm iterates over all the Q values, between 1 and 15 (line 16), incrementing each iteration by C (line 25), calculating the ratio of successful slots for each micro-zone (line 19). The Q with maximum ratio of successful slots, amongst all micro-zone, (lines $28 - 36$)is used for next query (line 37). Due to the nature of Q algorithm, unlike the deterministic algorithm (Algorithm 4), only single query is broadcast for all micro-zones. Due to the nature of micro-zones, only intra-zone collisions are now possible therefore, increasing the reading rates.

4.5.4 Delay Analysis of Deterministic Algorithm

In this section, we analyze the running complexity, i.e., average, best and worst singulation delay, of the proposed deterministic parallel singulation algorithm. Let $f(k)$ be the number of cycles required to read a set of k tags. For the binary tree protocol [1], in general

$$f(n) = c\,n - 1, \tag{4.11}$$

where c is a constant and n is total number of tags.

In the parallel singulation algorithm, the reader interrogates the micro-zones' tags in parallel. Let $E[t_1]$,...,$E[t_k]$ be the estimated number of tags within the micro-zones f_1,...,f_k, respectively. Overall number of cycles is then the maximum number of cycles, amongst all micro-zones, the singulation process takes, i.e.

$$f(n) = Max\,[f(E[t_1]), f(E[t_2]), ..., f(E[t_k])] \tag{4.12}$$

To determine the best, average and worst case scenarios, based on (4.12), it suffices to find an estimate of minimum, maximum and average of the number of tags in the micro-zones.

Best Case: The best case scenario is when all the tags are evenly distributed amongst the micro-zones

$$E[t_i] = \frac{A_i * k}{A_R}; for\ any\ given\ micro-zone\ i. \tag{4.13}$$

[1]The scheme in reference [95] is utilized in this chapter with $f(n) = 2\,n - 1$

Worst Case: The worst case scenario is when all the tags are within a single micro-zone i

$$E[t_i] = k \ \ and \ \ t_j = 0, \ (\forall i | i \neq j) \tag{4.14}$$

This corresponds to the case of the existing approaches, i.e., sequential singulation algorithms. Hence, the parallel singulation algorithm cannot perform any worse than existing algorithms.

Average Case: The micro-zone, in an attempt to cover the reader's interrogation zone, may overlap. In other words, there is a possibility that a tag may belong to multiple micro-zones and hence, is counted by than one micro-zone. The area covered by an overlapping region of the two micro-zones $A_{overlap}$, each with equal radius, i.e., $R_{c1} = R_{c2} = R_c$, is formulated using simple geometry as

$$A_{overlap} = 2R_c^2 \cos^{-1}\left[\frac{d}{2R_c}\right] - \frac{1}{2}d\sqrt{4R_c^2 - d^2} \tag{4.15}$$

and therefore, an estimate of the number of tags is

$$E[t_i] = \frac{N}{A_R}\left[1 - \frac{A_{overlap}}{O}\right] P_i \tag{4.16}$$

Here O is the count of the micro-zone overlapping regions and P_i is the probability with which the micro-zone f_i singulate the overlapping tags. A common value of P_i, assuming two overlapping micro-zones, is 0.5 as each micro-zone has equal probability of tags' singulations within the overlapping regions. That is, each micro-zone has equal probability to singulate the overlapping tags. In a typical grid-based deployment (Fig. 4.9), since each entity has at-most four neighbors, the fielder's zone is at-most overlapped by four other zones, i.e., $O = 4$.

4.5.5 Delay Analysis of Probabilistic Algorithm

In this section, we analyze the running complexity of the proposed probabilistic parallel singulation algorithm. For the Q-algorithm, the running complexity can be defined in terms of collision slots probability, successful slots probability and idle slots probability. Lets assume the number of tags is n and the frame size, for the Q algorithm, is 2^Q, then the probability of idle (P_i), probability of successful (P_s) and probability of collision (P_c) is [22]

$$P_i = \left(1 - \frac{1}{2^Q}\right)^n \tag{4.17}$$

$$P_c = 1 - P_i - P_s \tag{4.18}$$

$$P_s = \frac{n}{2^Q}\left(1 - \frac{1}{2^Q}\right)^{n-1} \tag{4.19}$$

In case of the parallel variation of Q-algorithm, the worst case reading rate is defined by the micro-zone which have the largest ratio of collision slots, amongst others. However, as the accumulative number of tags can not be smaller than even the largest tags residing micro-zone, therefore, the computational complexity of the parallel variation cannot be worst than the original Q-algorithm.

4.6 Simulation Setup and Results

In this section, we analyze and compare the performance of the proposed DR-RFID system as opposed to conventional RFID systems. We use reading range, reading rate, reading reliability and mobility as performance metrics. We also compare the performance of the proposed DR-RFID system with a multi-reader configuration.

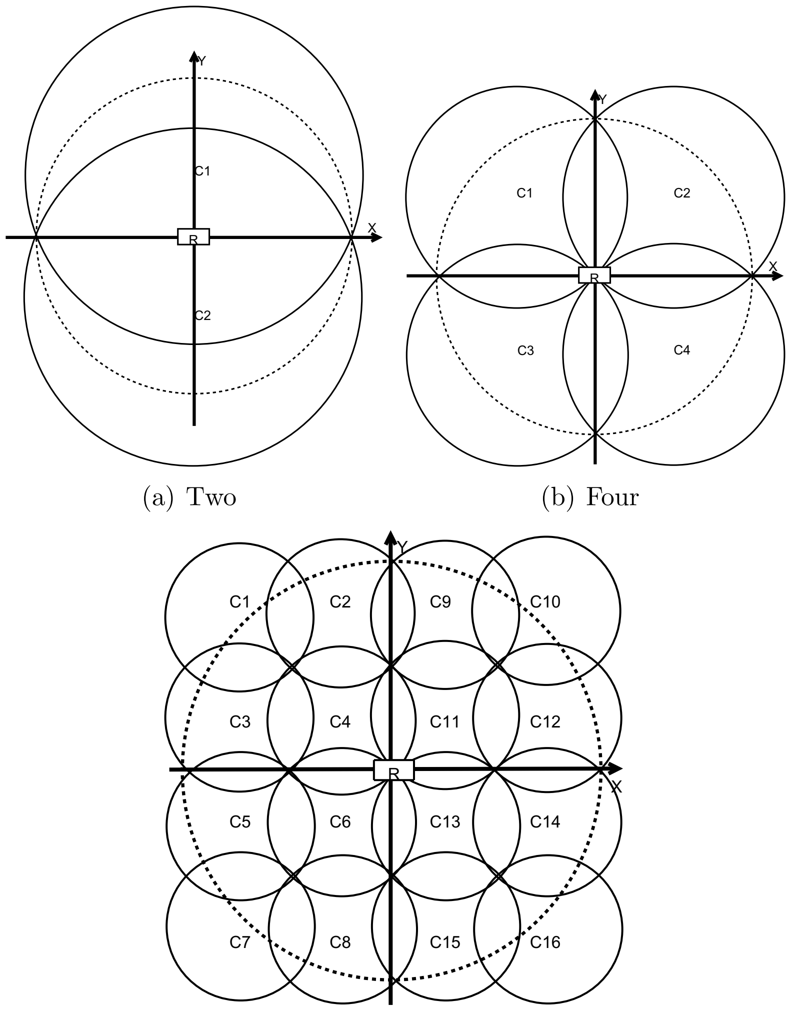
Table 4.1: Simulation parameters

Parameter	Value
Grid size	$20m^2$
Max. interrogation range	$15m$
Reader power level	$4W$
Tag1 min. IC power	$1.0\mu W$
Tag2 min. IC power [34]	$2.5\mu W$

4.6.1 Simulation Setup

We have extended the ns-2 network simulator to support both existing RFID and the proposed DR-RFID system. The major extension involves modification of the underlying simulator architecture to support the basic RFID functionality, the EPC Class1 Gen2 MAC protocol, multi-channel interfaces (RFID and IEEE 802.15.4) and non-EPC singulation protocols from the literature. Minor changes to the simulator include inheriting of the network node to serve as an RFID tag, reader, and fielder, single-hop communication model (backscattering modulation) between the tag and the reader, the reader's power control, etc. Unless otherwise specified, the simulations are performed using the following setting and parameters as shown in Table 4.1.

In the setup, tags are uniformly distributed in with single reader located at the center of the grid. The fielders are deployed in grid fashion, as configurations of 2, 4 and 16, covering the reader's interrogation zone with minimum possible overlapping. Simulations are made to run until all the tags are successfully identified. The performance metrics are averaged over twenty different experiments of different topologies. We evaluate the system for its reading range, reading rate, reading reliability and impact of tags mobility. We also compare the system with multiple readers, mimicking the DR-RFID approach.



(a) Two (b) Four

(c) Sixteen

Figure 4.9: Grid-based fielders' deployment scheme.

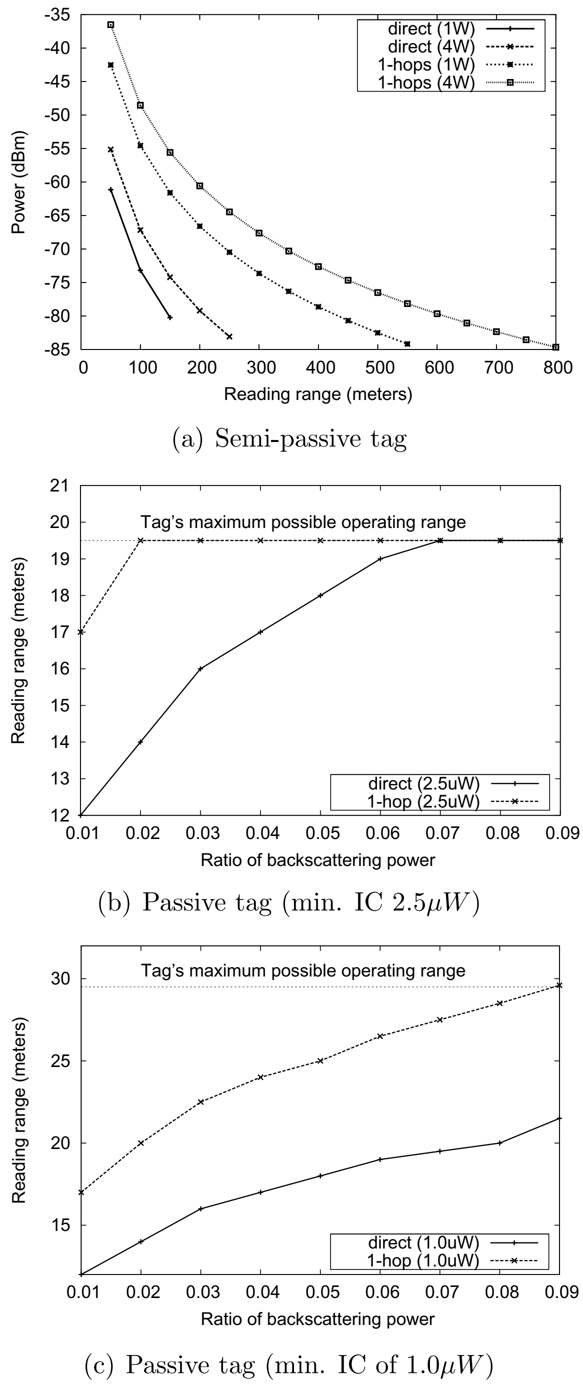
4.6.2 Simulation Results

Reading Range

Existing RFID systems use direct communication link between the tag and reader. This limits the reading range for both passive and semi-passive tags. A longer reading range means fewer readers to cover an area and longer tagged object visibility thus lower equipments manageability and monetary costs.

In the DR-RFID system, the multi-hop, i.e., relaying of data through fielders, between the reader and tags, significantly increases the operating range of the semi-passive tags. The multi-hop link involves one or more wireless-hops, i.e., fielders, to transmit the data between the tag and the reader. Fig. 4.10-a shows the reading range of a semi-passive for the reader's power level of 1W and 4W, for the direct (existing approach) and 1-hop (1-fielder per micro-zone configuration) system. The emitting power of 4W and 1W is the maximum allowable power that a reader may transmit according to the North American and European regulations, respectively. As expected, by using the DR-RFID system, the reading range for the semi-passive tag can be increased by an order of magnitude. For instance, for the 4W case, using 1-hop increases the reading range by a factor of 5. Using more than 1-hop can potentially increase the reading range of the semi-passive tags.

The reading range of passive tags depends on several factors including minimum circuitry power requirement, efficiency of the rectifying unit and strength of backscattering signal. The reading range of the two passive tags ($tag1$ and $tag2$), see Table 4.1, is shown in Fig. 4.10-b and Fig. 4.10-c, respectively. The horizontal dashed line in the graph shows the maximum possible reading range when using a rectifying module with an efficiency of 35%. The proposed system increases the passive tag's reading



(a) Semi-passive tag

(b) Passive tag (min. IC $2.5\mu W$)

(c) Passive tag (min. IC of $1.0\mu W$)

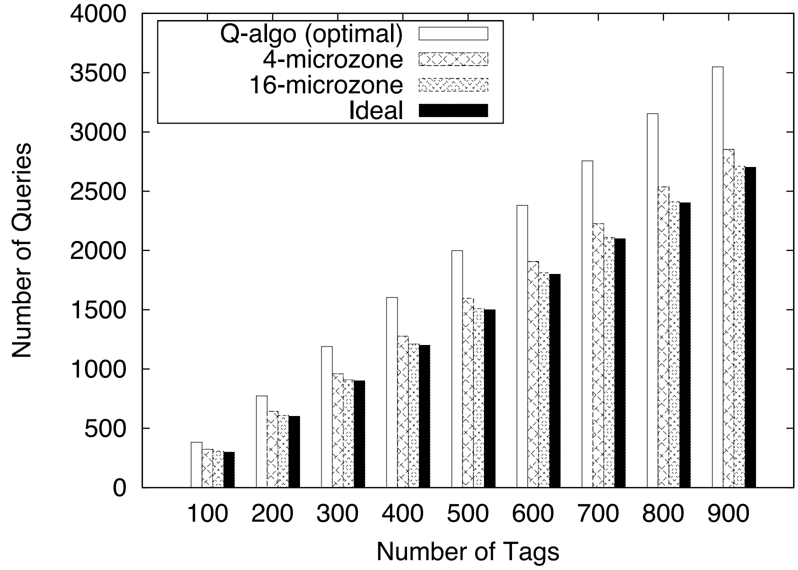
Figure 4.10: Improvement in the reading range of the semi-passive and the passive tags for the DR-RFID system.

range under two scenarios. First, low-power circuitry and second, setting of the significant available power portion for the circuitry. For instance, in the case of $tag2$, the maximum possible operating range, in the proposed system, is achievable by using a very small ratio, 1% of the available power, for backscattering. On the contrary, to maintain similar range in existing systems, 7% of the available power must be available for backscattering. Using a lower ratio adversely affects integrity of the reflected signal.

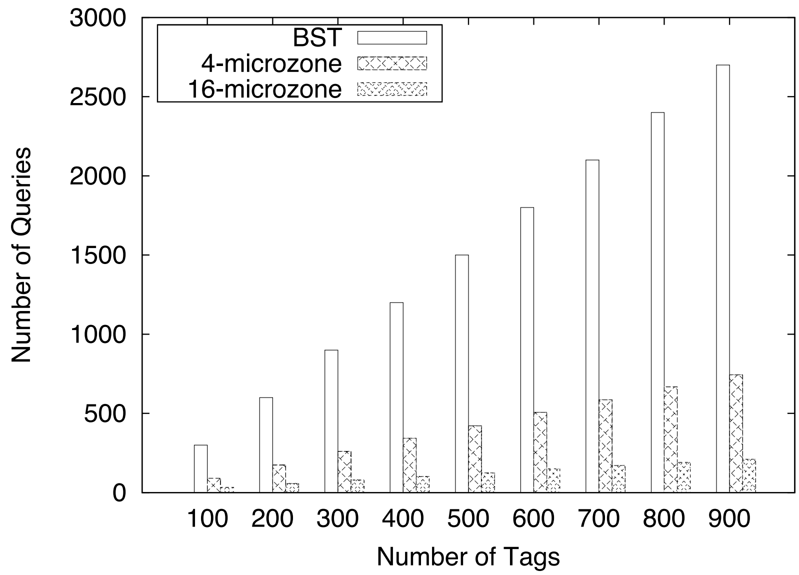
For low-power circuits, the passive tag evolves into being a backward-link constraint. For instance, $tag1$ has a maximum theoretical range of $29.5m$. Existing systems, using up to 9% of available power available for backscattering, cannot go beyond the $21m$ mark. Diverting more power for backscattering, at the cost of lesser power for circuitry, is not helpful either as the tag, in such a situation, will not have enough power to operate. On the other hand, the proposed DR-RFID system achieves the maximal operating range.

Reading Rate

The tag singulation rate is a product of the total number of interrogation queries and the individual query interval. High reading rates imply that more tags can be singulated by a reader thus supporting item-level tagging. The total number of queries for BST and Q-algorithm, using the conventional, four micro-zones and sixteen micro-zones version is shown in Fig. 4.11. The Ideal scheme, in case of BST, represents ideal number of queries, hence, no collisions, that would be required to interrogate a given number of tags. Ideal scheme is not devised for the Q-algorithm as it is a probabilistic approach. As is evident, the DR-RFID parallel singulation approach,



(a) Q-Algorithm



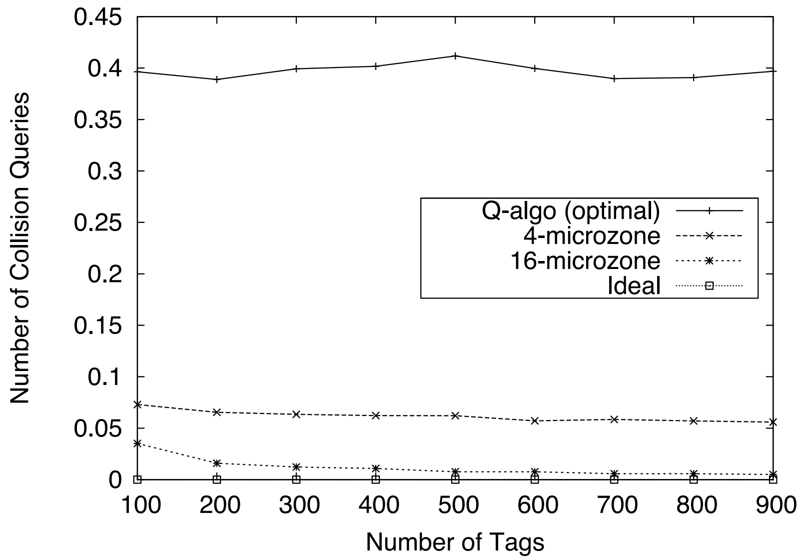
(b) BST

Figure 4.11: Comparison of number of queries for BST and Q-algorithm, using conventional RFID and DR-RFID systems.

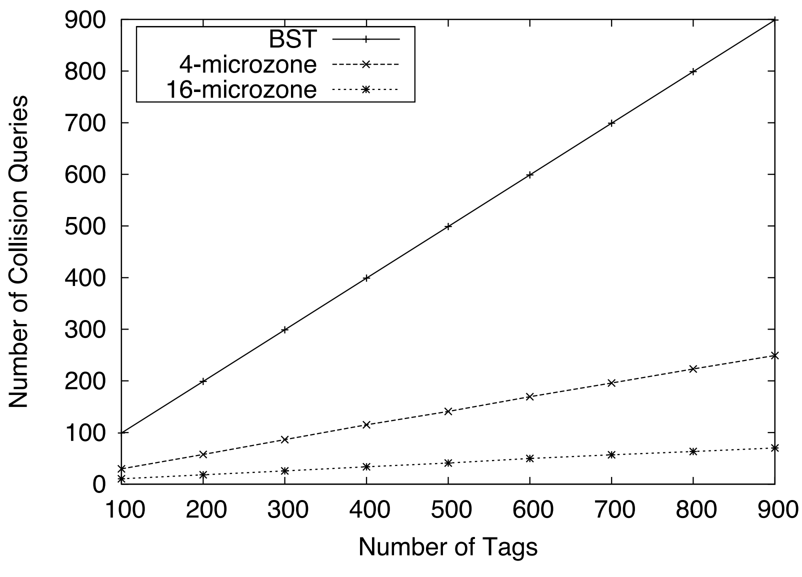
for both deterministic and probabilistic algorithm, outclass the conventional RFID by many folds. Furthermore, the proposed approach is scalable as the number of queries increases gracefully with an increase in number of tags. This is because the number of collision queries, for the DR-RFID system, does not increase significantly with an increase in tags. The number of collision queries, for both BST and Q-algorithm, is shown in Fig. 4.12. For instance, the collision queries for 100 tags for the conventional BST and DR-RFID variation of the BST are 99 and 10.3, respectively, whereas for 800 tags are 799 and 63.2, respectively. This significant performance improvements is achieved as each micro-zone has very limited number of tags, relative to overall interrogation area. The performance of DR-RFID will get effected once the number of tags within each micro-zone exceed significantly large, e.g., 500 and beyond.

Reading Reliability

Reading reliability is the probability a tag is readable regardless of the reader and tag antennas' orientations. The readability ratio of a tag, in the conventional (direct-hop) and the proposed (1-hop) system, using single antenna configuration, at various distance from the reader is shown in Fig. 4.13. Each point in the graph is an average of successful tag read, using orientations between 10° and 180°. The readability of the DR-RFID system, at long distances, is almost three times higher than the conventional system. Note that 100% readability is achievable at short distances. Such significant improvements are partly due to tag setting considerable portion of the available power for its circuitry. Therefore, even under non-friendly surroundings, e.g., a tag mounted on a steel item, the majority of available power can be used for tag operations. As well, the integrity of the backscattered signal is to be valid only



(a) Q-Algorithm



(b) BST

Figure 4.12: Comparison of number of collision queries for BST and Q-algorithm, using conventional RFID and DR-RFID systems.

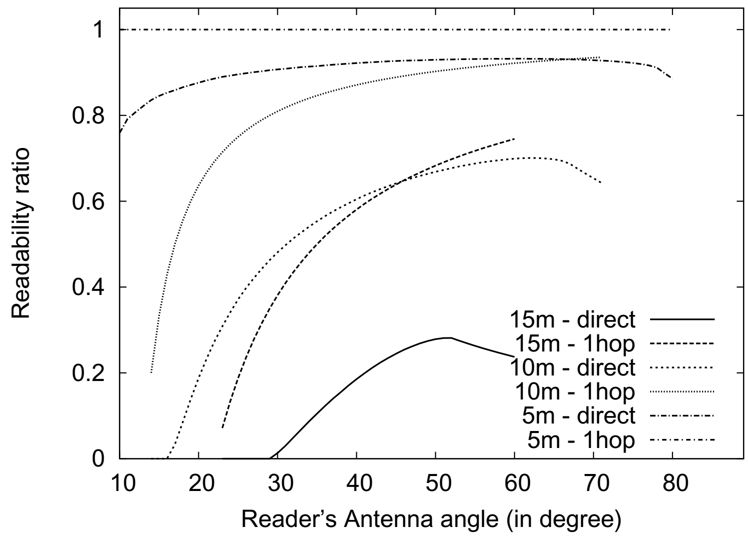


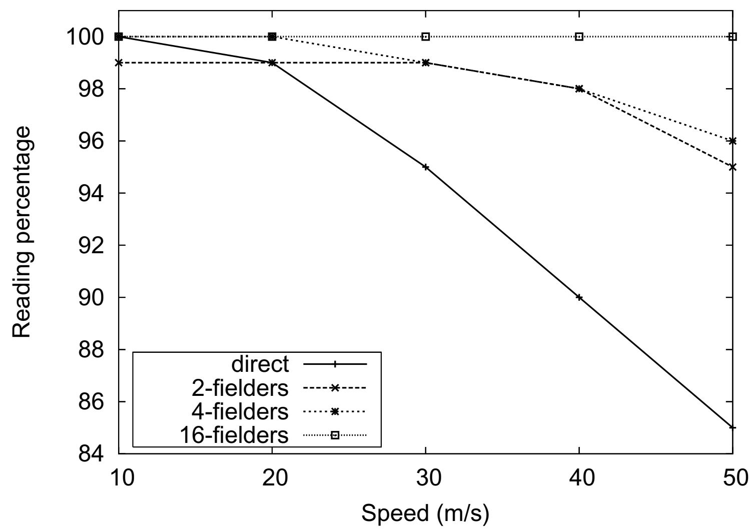
Figure 4.13: Reading reliability comparison.

inside its micro-zone. In other words, the tags in the DR-RFID system are capable of operating under diverse antenna's orientations, i.e., diverse range of power, thus meeting the challenges of futuristic applications, e.g., item level tagging.

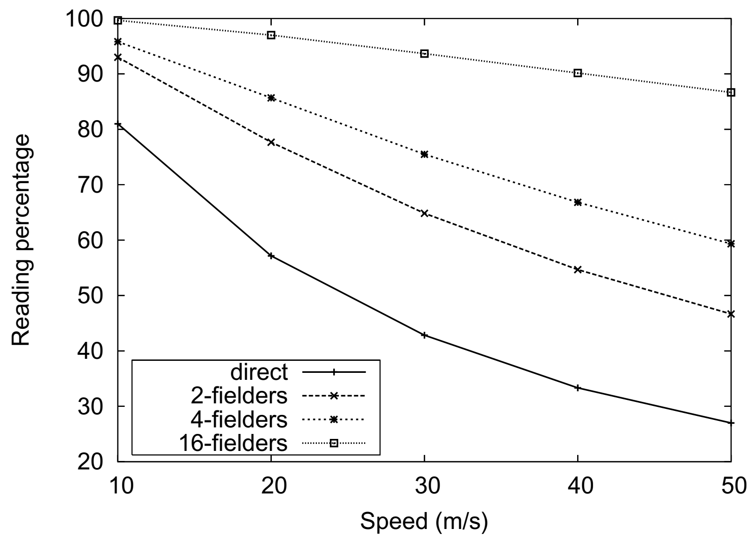
Mobility

In existing RFID systems, a mobile tag may be miss-read in two scenarios. First, if it moves out of the reader's zone before being interrogated. Second, being interrogated, in a dense environment and thus immense collisions, prevent it from being singulated in time. Both scenarios lead to miss-read tags. The effect of mobility on tag reading, using single reader configuration for the conventional and proposed system, for 100 and 600 tags is respectively shown in Fig. 4.14-a and Fig. 4.14-b. To be fair in comparison, we have not entertained the long reading range and the multipoint paradigm of the proposed system, for this experiment.

The reading rate of mobile tags in the conventional RFID system, both at high



(a) 100 mobile tags



(b) 600 mobile tags

Figure 4.14: Effect of mobility on the tag reading rate.

speeds and dense setting, falls well under 30%. The DR-RFID system, on the other hand, can handle high-speed and dense-tag environments. The micro-zones facilitate potentially fewer collisions, whereas parallel singulation algorithm support fast reading rates. Fewer collisions and fast reading rates assists in mobile tags singulation even at high speed and in dense environments. Furthermore, higher the number of micro-zone, the better system's ability is to tackle high speed mobility. For instance, using 16-fielders, the reading percentage is an order of magnitude higher than when using of 2-fielders. Reading rates of over 90% is maintainable, regardless of tags speed and density.

Multi-reader Configuration

Micro-zones may be mimicked by using a set of readers, equal in number and interrogation area, deployed at the same locations as the fielders. The motive behind such an experiment is to compare the performance of multiple readers to the distributed receiving system with multiple fielders. The total number of reading cycles, with multiple standalone readers and the fielders, is shown in Fig. 4.15. Interestingly, the total cycles for the multi-standalone system are only marginally lower than the proposed system. For instance, the difference between two and four multi-standalone readers to that of a single distributed reader aided by 2-fielders and 4-fielders is at most 4% and 11%, respectively.

The minor performance difference between the two configurations is because of the micro-zones' overlapping effect. In the case of multiple standalone readers, the tags within the overlapping region are singulated as many times as there are the overlapping readers. However, in the DR-RFID system, each tag in the overlapping

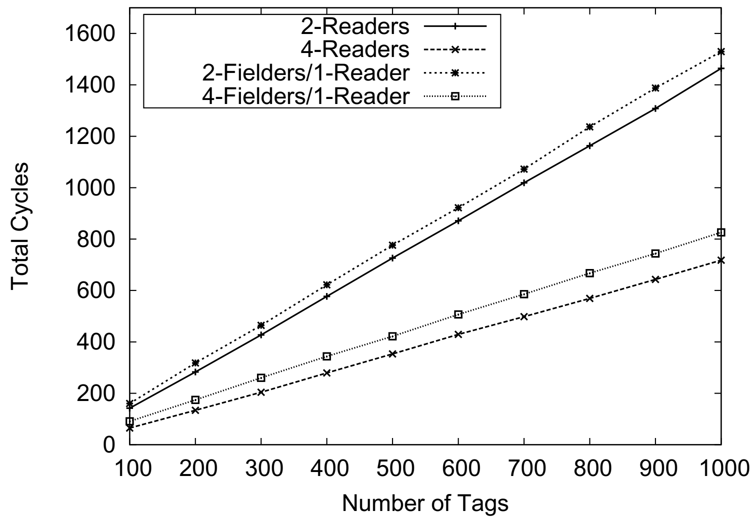


Figure 4.15: Reading cycles comparison for the multi-readers and DR-RFID.

zone is singulated only once, hence causing idle cycles for other zones' singulation trees. These overlapping micro-zones, and hence their potential negative effects, can be alleviated using an optimal placement scheme for the fielders. Nevertheless, the DR-RFID system seems an attractive and low-cost solution over the high monetary costs associated with using multiple readers, for minimal performance gains.

4.7 Work in Progress

To proof the working concept of the proposed DR-RFID, we have implemented its newly introduced components namely, fielder and reflectivity adjusting semi-passive tags. The fielder schematic, using Eagle CADsoft, is shown in Fig. 4.16. The schematic highlights various functional components of the fielder. These components include micro-controller, transceiver, power, dual antenna interfaces and RFID signal de-modulator.

The fielder uses Texas Instrument MSP430F2274 [6] for the micro-controller and

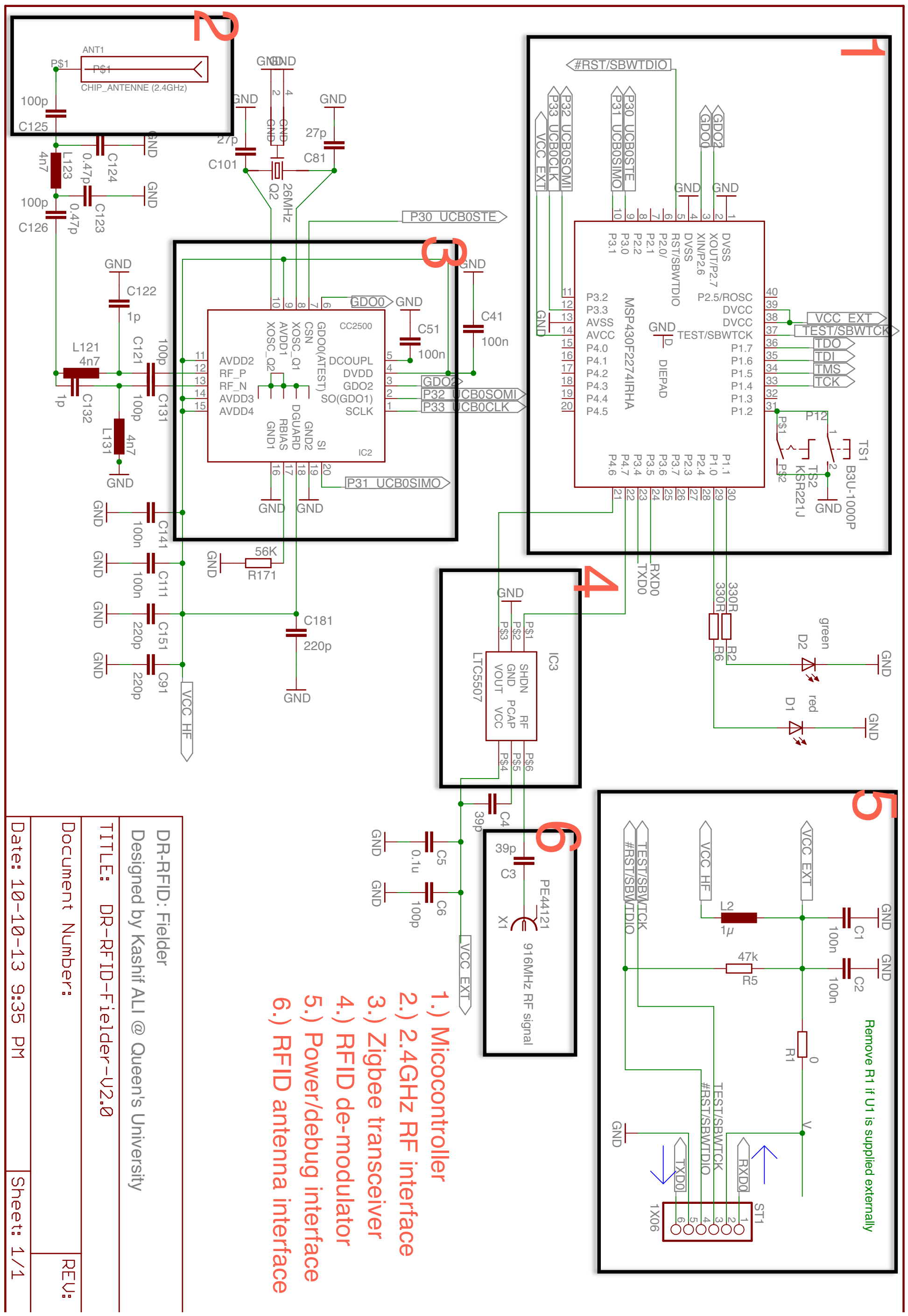
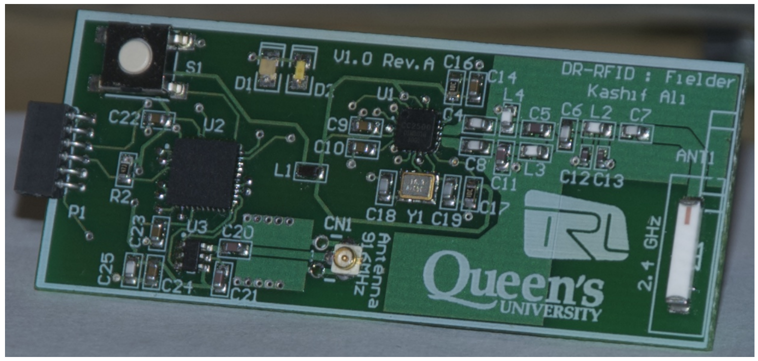
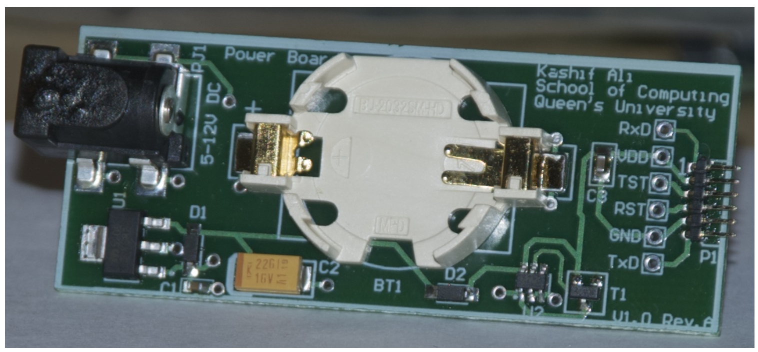


Figure 4.16: Fielder schematic for the DR-RFID system.

Zigbee based CC2500 transceiver [4] for the outgoing wireless communication with reader(s) and other IP-based network devices. The micro-controller and transceiver are extremely low-power, for instance, the MSP430F2274 controller utilizes only $0.7\mu A$ in the standby mode. The micro-controller and transceiver can be put into deep sleep modes, when idle and can be woken up due to their on-chip remote wakeup capability, To detect and de-modulate the incoming RFID signal, the fielder make use of an extremely low power RF detector LTC5507 IC, from Linear Technology [1]. The LTC5507 consumes $550\mu A$ and $2\mu A$ during active and shutdown mode. As is evident from the schematic, the fielder has two RF interfaces. First interface is the 916MHz patch antenna which is used to receive the reflected signals from the nearby tags. Second interface is the 2.4GHz chip antenna which is used by the CC2500 to transmit any IP packet to an IP-enabled device on the network or Internet. A prototype implementation of the fielder is shown in Fig. 4.17-a. The fielder, for power and debug, use the 6-pins (with 1.127Mil) spy-bi-wire JTAG interface. Using standard interface facilitate, the choice of off-shelf power board, e.g., Texas Instrument's EZ430-rf2500 kit and Cymbet's solar energy harvesting kit [5] becomes available. A custom power board with dual power source, i.e., a coin battery and the 6V adapter is also designed for the fielder. The prototype implementation of the power board is shown in Fig. 4.17-b. Depending upon the anticipated tag cardinality and interrogation rate the appropriate power source can be selected during deployment phase. For instance, in a low density environment, wherein the number of tags and readers are low, the fielder can be powered using on-board battery therefore, allowing complete wireless solution. On the other hand, the dense scenarios demands larger processing and data communication volumes therefore requires higher availability, i.e., the 6V adapter.



(a) Fielder



(b) battery board

Figure 4.17: Fielder and power board prototype.

For software, we have enhanced Contiki OS [38] to support RFID de-modulation using LTC5507. Contiki is an open source, highly portable, multi-tasking operating system designed for low memory micro-controllers. The choice of Contiki, over other OS e.g., TinyOS, is due to following reasons. First, it require low memory, i.e., fits within the available 2KB RAM and 40KB ROM of MSP430F2274 micro-controller. Second, it is IP enabled and its readily available Zigbee communication stack which is required to transfer tags information to other networked devices. We have tested the operational capability of the Fielder using the Skyetek's M9 RFID reader and Alien's RFID tags wherein, the fielder was able to successfully decode the received tag signal and transfer it via IP to the host machine.

The tag schematic, using Eagle CADsoft, is shown in Fig. 4.18. The schematic highlights various functional components of the tag. These components include micro-controller, power interface, RF antenna interface, backscattering and RF attenuation. Similar to fielder, the tag use Texas Instrument's MSP430F2274 and Linear Technology LTC5507 as its micro-controller and RFID de-modulator, respectively. The RFID de-modulator is use to detect incoming signal, from the reader, to wake up the micro-controller and to decode requests. The tag attenuates the backscatter signal using the Skywork's SKY12329 IC [3]. The SKY12329 is a GaAs digital attenuator with attenuation range of 31 dB and utilizes less than $100\mu A$. Attenuation enable the formation of non-interfering micro-zones which significantly enhances the reading rates. The tag modulate and backscatter the signal using Analog Device's ADG902 IC [2]. The tag powers up using the fielder's battery board, shown in Fig. 4.17-b. Currently, we are modifying Contiki OS to enable RFID de-modulation, backscattering and RF attenuation.

4.8 Summary

Current RFID systems suffer many shortcomings; inherently so from adopting the centralized architecture. They impose a detrimental effect on performance, scalability and usability. In this chapter, we introduce the Distributed Receiving paradigm in RFID systems, namely DR-RFID, as a foundation for a more dynamic RFID architecture. This new paradigm utilizes spatially dispersed entities, named *fielders*, to collect the modulated signals backscattered from tags. Fielders are, by design, low cost and low power devices that are deployed within the reader's interrogation zone.

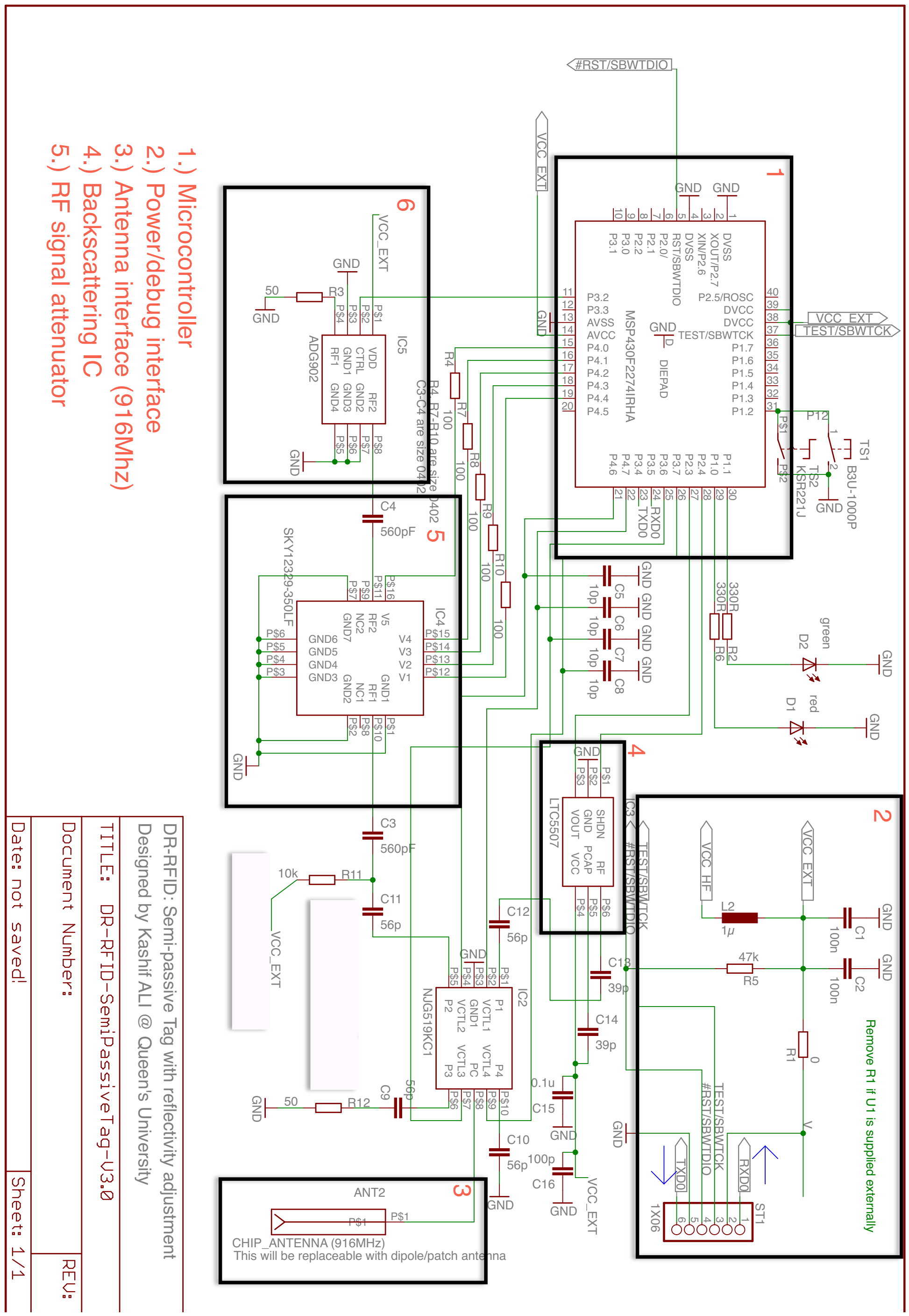


Figure 4.18: Semi-passive tag schematic for the DR-RFID system.

As such, each fielder would create *micro-interrogation zones*, in which tags with adjusted reflectivity coefficients would fall under its region, conceptually excluding them from micro-zones of other fielders. A *parallel singulation* algorithm, exploiting the localization and distributed nature of these micro-zones, autonomously interrogates each zone in parallel. Accordingly, adopting DR-RFID yields significant performance improvements in achieving high reading rates, low collisions, longer reading range for semi-passive tags and higher bandwidth.

Chapter 5

Coverage in RFID

5.1 Introduction

Coverage is crucial for large scale RFID applications. For an item-level object tagging application, in a self-checkout counter at a department store, for instance, missing a tag is simply a loss of revenue. Several factors influence coverage in RFID networks; some of these factors are density of tags, size of the interrogation area, number of deployed readers, and overlapping among readers [42]. The complexity and monetary cost associated with an RFID system strongly depend on the number of readers being deployed to interrogate tags. Similar to the wireless sensor networks, coverage in RFID systems is a deployment problem which can be formulated as a deterministic deployment and a random deployment problem.

In the case of deterministic deployment, the location and number of the readers are determined in a pre-deployment manner. A typical deployment scenario of a warehouse application is shown in Fig. 5.1. While deploying too many readers may guarantee full coverage, it has the side effect of significant interference among readers, which results in more reader-to-reader collisions and, hence, a lower performance for the whole system. Furthermore, the number of tags within each reader's interrogation zone determines the interrogation delay of that reader, and the overall interrogation delay of the whole system is determined by the longest delay associated with a single reader. Therefore, reducing overlapping and balancing the load of readers are essential to any coverage scheme in RFID systems. Several maximal RFID coverage schemes have been proposed in the literature, wherein the readers are deployed in a grid [83, 92, 93], honey grid [110] or at a predetermined set of locations [104]. While these schemes are able to achieve maximal coverage, that comes at the cost of a large pool of RFID readers and, hence, results in the previously mentioned problems of having too many readers.

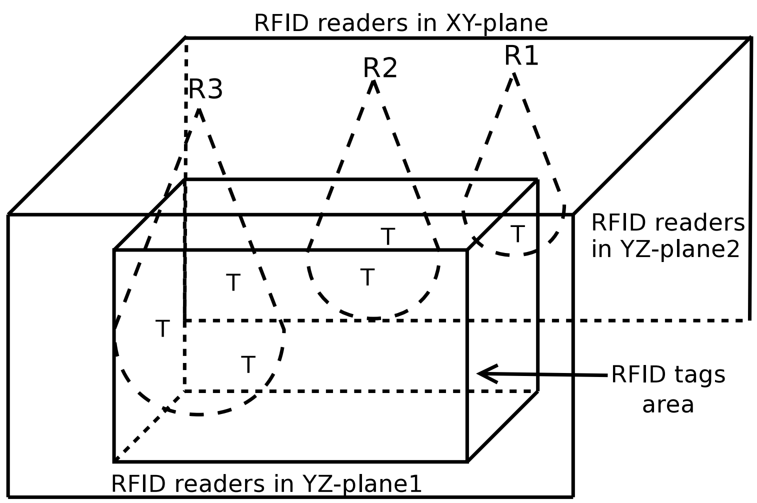


Figure 5.1: 3D Coverage in RFID Networks.

In the case of random deployment, the readers are deployed in an random manner. Typical random RFID deployment includes RFID enabled wireless sensor networks and RFID enabled mobile phones. The nature of random deployment yields overlapped interrogation zones among RFID readers. This causes significant wireless interference in terms of reader and tag collisions without improving coverage. Furthermore, the overlapping readers may also simultaneously interrogate the same set of tags, resulting into data corruption. These readers collisions severely affects the performance of the overall system [110]. Furthermore, dense deployment may result in having redundant readers; a redundant reader is one whose interrogation area is fully covered by neighboring readers. An example of such a scenario is shown in Fig. 5.2 wherein the readers $R2$ and $R3$ are redundant. That is because all tags covered by $R2$ or $R3$ (i.e., $T2$ and $T3$) are also covered either by $R1$ or by $R4$. However, tag $T1$ is exclusively covered by $R1$ and tag $T4$ is exclusively covered by $R4$. A redundant reader is one that does not exclusively cover any tag.

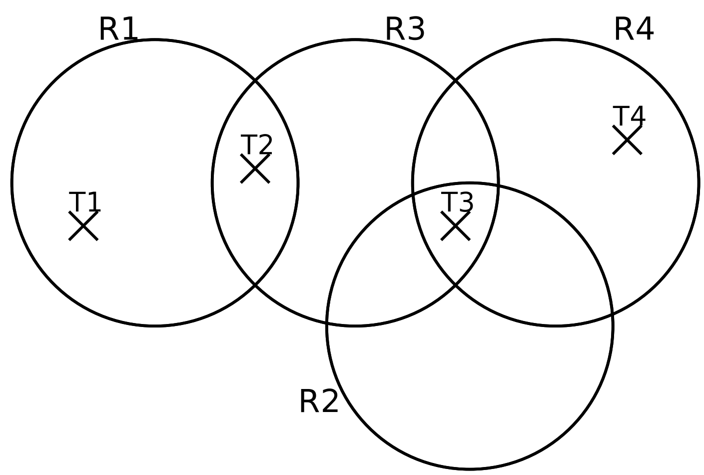


Figure 5.2: An RFID network with redundant readers.

Redundant readers translate into unnecessary energy consumptions due to duplicate interrogations. Moreover, it results into extra processing and communication overheads and does not necessarily bring an enhancement to the tags coverage. Thereby, in order to extend the lifetime of the network and to improve its performance, there is a significant need for light-weight methods that efficiently detect and eliminate redundant readers. Many schemes exist in the literature for redundant readers elimination in RFID networks. Elimination of readers is mainly based on different markings, made by covering readers, into the tags memory. These markings include tags count of the covering readers [16], identity of the first interrogating reader [52], identity of the first singulating reader [109,111], count of the neighboring readers [55] and others. Based on these markings, an algorithm decides on the redundancy of an RFID reader. These schemes, however, are not light-weight as they require considerable states to be maintained by the tags and involve frequent interrogations and singulations.

Our main contributions in this chapter are as follows. We address the deterministic deployment through the set-cover approximation approach. We present an algorithm that gives the approximate minimum number readers and their locations to cover a set of tags. By reducing the number of readers, not only is the overall network cost reduced, but the overall system performance is improved also by reducing interference and overlapping among readers coverage regions and, hence, having less collisions among readers. Furthermore, we also enhance the overall system reading rates by achieving a near-optimal load balancing amongst the deployed readers; by minimizing the maximum delay encountered by a single reader we minimize the overall delay of the system. In this work, we first minimize the number of readers than balance the load amongst readers (the opposite order can be applied depending on the application scenario). Note that overlapping readers result into readers-to-tag collisions which may cause tags being undetectable. On the other hand, load imbalance amongst readers can cause tags reading delay.

We address the random deployment using a light-weight greedy algorithm to detect and eliminate redundant readers in RFID networks. The algorithm estimates the number of tags each reader covers and finds the number of neighboring readers it has. The motivation is that a reader covering less tags and one that has more neighboring readers have a higher chance of being redundant. Based on this observation, our algorithm finds the ratio of the number of tags a particular reader covers to the number of neighboring readers it has, and uses that ratio to predict whether that reader is redundant or not. We evaluate the proposed algorithms via comprehensive simulations and we compare them with other schemes available currently in the literatures.

The remainder of this chapter is organized as follows. Section 5.2 outline the adopted model. Section 5.3 outlines the underlying assumptions and explains the proposed deterministic readers placement algorithm. Section 5.4 formulates and explains the random deployment as redundant reader elimination algorithm. Section 5.5 presents simulated experiments, evaluation metrics and analyze the obtained results using multiple scenarios. Section 5.6 summarizes our work.

5.2 System Model

We consider an RFID system of n passive tags and multiple readers. The transmission range of a passive tag t_i is modeled as a sphere of radius r_i, i.e., tag t_i can be interrogated by an RFID reader if and only if the distance between the tag and the reader is at most r_i. A reader can communicate with its neighboring readers and also some central middleware. We assume the existence of a central middleware as depicted by the EPC Gen2 standard [40], where our algorithm is to be executed.

5.3 RFID Readers Deployment (Deterministic Deployment)

In this section we present our algorithm for RFID readers deployment in rectangular cuboid. We first outlines the adopted model and its underlying assumptions. Next, we first describe an algorithm that provides full coverage, we then show how to modify the algorithm for the purpose of reducing overlapping among readers. And finally we give a scheme that uses our algorithm to give load-balancing deployment strategies.

5.3.1 Assumptions and Definitions

Tags are assumed to be placed in a 3D space modeled as a rectangular cuboid, and readers are to be placed on particular sides of the rectangular cuboid. Figure 5.1 illustrates this environment. The problem can be defined as follows. Given the number of tags and their 3D locations, find a minimum number of RFID readers and their exact locations such that all tags are covered. While the location of tags is assumed to be known [92,93], we show later how to accommodate fluctuations in tags locations.

In the presentation of our algorithms, we use the following notations:

- $T = \{t_1, t_2, \ldots, t_n\}$ is the set of tags.
- p_i is a point representing the location of tag t_i; $p_i.x$, $p_i.y$, and $p_i.z$ are the $x-$, $y-$, and $z-$ coordinates, respectively.
- r_i is the transmission range of tag t_i.
- $|S|$ is the cardinality of a set S.
- $|p, q|$ is the Euclidean distance between two points p and q.

- For any point q in the 3D space, $Cover(q)$ is the set of all tags that have q within their transmission ranges (i.e., $Cover(q) = \{t_i : |p_i, q| \leq r_i\}$).

Our algorithms are based on an approximation algorithm for the set covering problem which is known to be NP-hard [33]. For the sake of completeness, we give a formal definition for the set covering problem as follows:

An instance of the set covering problem consists of a set $\mathcal{C}$ of a finite number of elements and a set $\mathcal{F}$ whose elements are subsets of $\mathcal{C}$ with the condition that each element $c \in \mathcal{C}$ belongs to at least one subset $f \in \mathcal{F}$; when $c \in f$, f is said to cover c. The problem is to find a minimum size set $\mathcal{G} \subseteq \mathcal{F}$ such that each element in $\mathcal{C}$ is covered by at least one element in $\mathcal{G}$ [33].

5.3.2 Providing Coverage

In order to provide full coverage, each tag must have at least one RFID reader placed within its transmission range. And since RFID readers are to be placed only on the sides of the rectangular cuboid, see Fig. 5.1 we need to find the intersection of the transmission spheres of tags and the planes representing the sides of the rectangular cuboid. If a sphere intersects with a plane, their intersection will be a circle on that plane. For example, the intersection of a sphere centred at the point (a, b, c) with a radius of r and the plane $z = 0$ is a circle centred at the point $(a, b, 0)$ with a radius of $\sqrt{r^2 - c^2}$, if $r^2 - c^2 \geq 0$. Let us call those circles *side circles*. Each tag will have at most one side circle on each side, and in order to cover a particular tag t_i, at least one reader must be placed within one of the side circles that belong to that tag.

To minimize the number of readers needed to cover all tags, readers should be placed in areas where several side circles, belonging to several tags, overlap. Instead of looking for regions where side circles overlap, it suffices to focus on *intersection points*, which are the points where the boundaries of side circles intersect. These intersection points can be considered as representatives to all possible overlapping regions (for more details on this, see our earlier work in [11]). Thereby, locations of RFID readers will be limited to intersection points and, hence, the problem becomes a discrete optimization problem. Moreover, an instance of the RFID reader deployment problem can be reduced to an instance of the set covering problem in which $\mathcal{C} = T$ (i.e., the set of tags) and $\mathcal{F} = \{Cover(q) : q \text{ is an intersection point}\}$.

Therefore, the greedy approximation algorithm for the set covering problem can be used to solve the RFID readers deployment problem; and for the sake of completeness, the greedy approximation algorithm is shown in Algorithm 6 [33].

Algorithm 6: The greedy set covering algorithm.

Set Cover($\mathcal{C}$,$\mathcal{F}$)
Input: $\mathcal{C}$: set of tags.
$\mathcal{F}$: coverage set.
Output: V: set of readers.
$U = \mathcal{C}$;
$V = \phi$;
while $U \neq \phi$ **do**
  Find a set $S \in \mathcal{F}$ that maximizes $U \cap S$;
  $U = U - S$;
  $V = V \cup \{S\}$;
end
return V;

This greedy algorithm is known to have an approximation ratio of $\ln |C| + 1$ and can be implemented in $O(|C||\mathcal{F}| \text{ MIN}(|C|, |\mathcal{F}|))$ time.

5.3.3 Reducing Overlap Among Readers

Overlapping among RFID readers causes reader-to-reader interference which result in collisions at the readers and, hence, an additional delay to the interrogation process. The general set covering problem does not take overlapping among subsets into account; the sole objective therein is to minimize the number of subsets covering all elements. For example, let $\mathcal{C} = \{1, 2, 3, 4, 5\}$ and $\mathcal{F} = \{\{1, 2, 3\}, \{2, 3, 4\}, \{1, 2, 5\}, \{4\}, \{5\}\}$. The greedy algorithm may pick the set $\{\{1, 2, 3\}, \{2, 3, 4\}, \{1, 2, 5\}\}$ to cover all elements with a minimum number of subsets, which is an optimal solution for this instance of the set covering problem. However, another optimal solution with no overlapping is $\{\{1, 2, 3\}, \{4\}, \{5\}\}$, which is much more suitable for readers deployment in RFID networks. In this subsection, we modify the earlier described greedy set covering algorithm (Algorithm 6) to make solutions with less overlapping preferred.

The greedy set covering algorithm constructs the set of covering subsets incrementally; at each stage, it picks the subset that covers the maximum number of uncovered elements until all elements are covered. That can be viewed as giving each remaining subset a *weight* equal to the number of uncovered elements it covers, and picking the one with the maximum weight. We can calculate the weight of subsets in a different way that gives credit to those subsets that do not cover many covered elements. Let U be the set of uncovered elements and $weight(S)$ be the weight of a subset S. According to the general greedy algorithm, $weight(S) = |U \cap S|$. We can modify the general algorithm so that among subsets covering the maximum number of uncovered elements, it picks the one that covers the minimum number of already covered elements. This can be done using the following weight formula: $weight(S) = |U \cap S| - \alpha(|S| - |U \cap S|)$, $0 < \alpha \leq 1/n$. The greedy algorithm for set covering with less overlapping is shown in Algorithm 7.

Algorithm 7: Weighted set covering algorithm to minimize overlapping amongst subsets.

```
Weighted Set Covering(C,F,α)
Input: C: set of tags.
       F: coverage set.
       α: weight ratio.
Output: V: set of readers.
Z = F;
U = C;
V = φ;
while U ≠ φ do
    foreach subset S ∈ Z do
        Weight(S) = |U ∩ S| − α(|S| − |U ∩ S|);
    end
    Find a set S ∈ Z that maximizes Weight(S);
    if Weight(S) ≤ 0 then
        /* This means that the set C can not be covered by subsets
           in F                                                   */
        return φ and exit;
    end
    U = U − S;
    Z = Z − {S};
    V = V ∪ {S};
end
return V;
```

It is obvious that when $0 \leq \alpha \leq 1/n$, the approximation ratio of $\ln \mathcal{C} + 1$ holds for the weighted set covering algorithm. This is because both the weighted set covering algorithm and the general set covering algorithm picks the same subset at each stage except when there is a tie (i.e., several subsets covers the same maximum number of uncovered elements). When there is such a tie, the weighted set cover algorithm picks a subset that covers the minimum number of already covered elements. However, the approximation ratio of the general greedy algorithm holds regardless of how ties are dealt with.

5.3.4 Load Balancing

The algorithms we have discussed so far aim at reducing the total number of RFID readers and reducing overlapping among different readers. However, the issue of load balancing is not considered. Therefore, we may get solutions in which readers have significant variations in their workloads (i.e., the number of tags they cover), which lowers the performance[1] of the whole system. This is because each RFID reader is associated with a subset of tags and readers interrogate their tags in parallel. Thus, the reader with the maximum workload determines the overall performance because it will be the last to finish. For example, a system with two RFID readers each covers 50 tags is much better than a system with two readers one covers 90 tags and one covers 10 tags.

In this subsection we present a method that distributes the load evenly among RFID readers for the sake of improving the overall performance of the system. The main idea is to put a constraint on the maximum number of tags β, which are covered by a single reader. However, the objective of minimizing the number of readers and that of minimizing β conflict with each other; the minimum possible value of β is 1, which means that each reader covers a single tag; and the minimum number of readers may be one reader covering all tags, which results in the maximum value for β. This can be dealt with either by putting a constraint on β and finding the minimum number of readers meeting that constraint, or putting a constraint on the maximum number of readers R and finding the minimum value of β meeting that constraint. The former option is straight forward and can be done by excluding intersection points

[1] The performance herein is defined as the time needed to interrogate all tags.

Algorithm 8: RFID readers deployment algorithm with load balancing.

Readers Deployment(T,α, R)
Input: $\mathcal{T}$: set of tags.
$\mathcal{F}$: set of readers.
α: weight.
Output: V: set of readers.
$C = T$;
$Q =$ the set of all intersection points;
$\mathcal{F} = \{Cover(q) : q \in Q\}$;
$\beta_{max} = \text{MAX}_{S \in \mathcal{F}} |S|$;
$\beta_{min} = 1$;
while $\beta_{max} > \beta_{min}$ **do**
  $\beta = \lfloor \frac{\beta_{max} + \beta_{min}}{2} \rfloor$;
  $Z = \{S : S \in \mathcal{F} \wedge |S| \leq \beta\}$;
  $V =$Set Cover($\mathcal{C}$,Z,α);
  if $0 < |V| \leq R$ **then**
    $\beta_{max} = \beta$;
  else
    $\beta_{min} = \beta + 1$;
  end
end
$Z = \{S : S \in \mathcal{F} \wedge |S| \leq \beta_{max}\}$;
$V =$Set Cover($\mathcal{C}$,Z,α);
if $0 < |V| \leq R$ **then**
  return V;
else
  return ϕ;
end

whose coverage exceeds β (i.e., when $|Cover(q)| > \beta$, $Cover(q)$ is excluded from $\mathcal{F}$). The latter option is less trivial. In fact, one may need to try all possible values of β and take the minimum value that meets the constraint of having at most R readers. That can be done more efficiently by doing a binary search over all possible values of β (i.e., $[1..\text{MAX}_{S \in \mathcal{F}}|S|]$). This method is illustrated in Algorithm 8. The overall computational complexity of this algorithm is $O(\log(\text{MAX}_{S \in \mathcal{F}}|S|)|C||\mathcal{F}| \text{ MIN}(|C|, |\mathcal{F}|))$.

5.3.5 Displaced tags

While we assume that exact locations of tags are known, it is expected in practice to have some tags being displaced from their planned locations. However, this can be easily accommodated in our scheme; if we reduce the actual transmission ranges of tags by a value of r units, our scheme becomes resilient to any displacement of at most r units from the planned locations.

5.4 RFID Redundant Readers Elimination (Random Deployment)

In this section, we present our redundant reader elimination algorithm. We start with some assumptions and definitions we use in this work and that is followed by a detailed description of the algorithm we propose. We then show further details of the algorithm using an illustrative example. Finally, we discuss the algorithm's computational and communication complexity.

5.4.1 Problem Definition

Formally, the redundant reader problem is defined as follow. Given a set of RFID tags and a set of RFID readers covering all tags, find the minimum cardinality subset of RFID readers that cover all the tags [16]. To this extent we propose the Neighbor and Tag Estimation (NTE) algorithm.

5.4.2 Neighbors and Tags Estimation (NTE) based algorithm

The redundant reader elimination problem is known to be NP-hard [16]. Therefore, we propose the NTE algorithm, which is a heuristic greedy algorithm, to find near optimal solutions in a reasonable time. The main idea is that when a reader R_i has a large number of neighboring readers, tags covered by R_i have a high probability of being also covered by other readers in the neighborhood of R_i. The algorithm uses this observation to identify redundant readers. For each active reader R_i, the algorithm assigns a weight based on the ratio of the number of active tags covered by R_i to the number of active neighboring readers of R_i. Initially, all tags are active and all readers are active. At the beginning of the each iteration, weights of active readers are calculated and then a reader with the maximum weight is deactivated and all tags covered by that reader are deactivated, too. Any reader with a weight of 0 is considered to be redundant and deactivated. This process continues until all tags are inactive, at which point all remaining active readers are considered to be redundant. The pseudocode for the NTE algorithm is shown in Algorithm 9.

In the presentation of our algorithm, we use the following notations:

- $\mathcal{R} = \{R_1, R_2, \ldots, R_n\}$ is the set of active readers.
- $R^a = \{R^a_1, R^a_2, \ldots, R^a_m\}$ is the set of non-redundant readers.
- $R^r = \{R^r_1, R^r_2, \ldots, R^r_l\}$ is the set of redundant readers.
- $E(R_i)$ is the estimated number of active tags within the interrogation range of reader R_i.
- $N(R_i)$ is the number of active neighboring (interfering) readers of reader R_i.

The algorithm begins with basic housekeeping (lines 3 and 4). At the beginning of each iteration, each active reader R_i estimates the number of tags it covers (i.e., $E(R_i)$) and determines the number of active neighboring readers it has (i.e., $N(R_i)$) (lines 8 and 9). To estimate the number of tags, the scheme presented in [62] can

Algorithm 9: The greedy NTE redundant reader elimination algorithm.

```
NTE-Reader($\mathcal{R}$):
Input: $\mathcal{R}$: set of all readers.
Output: $\mathcal{R}^r$: set of redundant readers.
// Initially all tags are active;
$\mathcal{R}^a = \phi$;
$\mathcal{R}^r = \phi$;
while $\mathcal{R} \neq \phi$ do
    $max \leftarrow 0$ ;
    foreach $R_i \in \mathcal{R}$ do
        $E(R_i)$= An estimate to the number of active tags covered by $R_i$;
        $N(R_i)$ = The number of active neighboring readers for $R_i$;
        if $E(R_i) = 0$ then
            $\mathcal{R}^r \leftarrow \mathcal{R}^r \cup \{R_i\}$;
            $\mathcal{R} \leftarrow \mathcal{R} - \{R_i\}$;
        end
        else
            if $N(R_i) > 0$ then
                $Ratio[i] \leftarrow E(R_i)/N(R_i)$;
            end
            else
                $Ratio[i] = \infty$;
            end
            if $max < Ratio[i]$ then
                $max \leftarrow Ratio[i]$;
                $idx \leftarrow i$;
            end
        end
    end
    $\mathcal{R}^a \leftarrow \mathcal{R}^a \cup \{R_{idx}\}$;
    $\mathcal{R} \leftarrow \{\mathcal{R}\} - \{R_{idx}\}$;
    All tags covered by $R_{idx}$ are deactivated;
    // using a broadcasted request.
end
return $\mathcal{R}^r$;
```

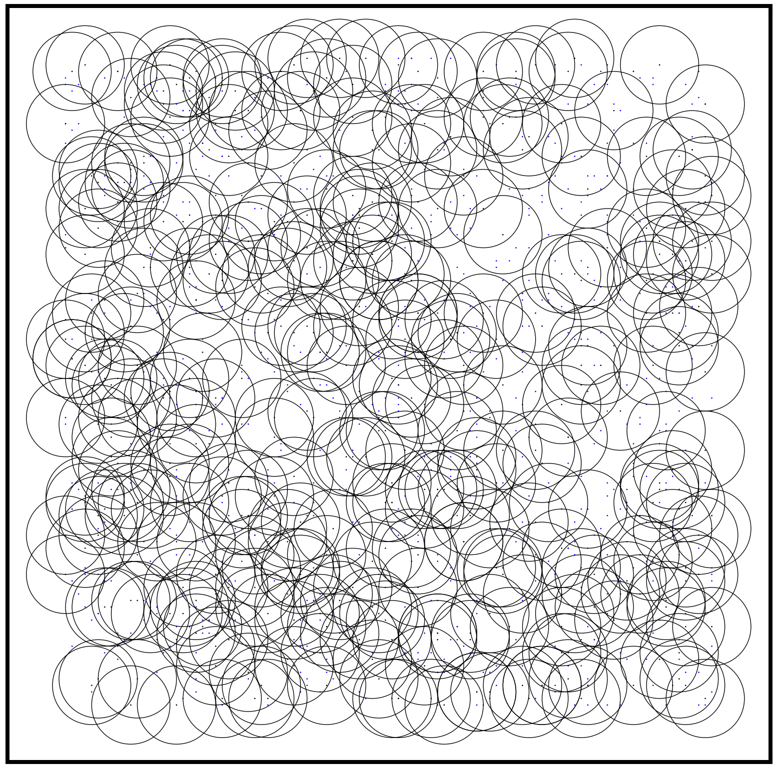
be used as it can estimate the number of tags within 99% accuracy ratio. The active neighboring readers of a reader R_i are those readers which are within the communication range of R_i and, hence, can be easily counted. Readers that do not cover any active tags (i.e., $E(R_i) = 0$) are considered to be redundant (lines 10-13). Amongst active readers that still cover at least one active tag, the one with the maximum weight (i.e., $Ratio[i]$) is selected and excluded from the redundancy list (lines 27 and 28), and active tags covered by that reader are deactivated (line 29). Any tie is broken arbitrarily. This can be done by a single message broadcasted by the selected reader. The selected reader itself is deactivated and not counted in the number of neighboring readers during subsequent iterations. The algorithm terminates when the set of readers R is empty (i.e., all readers have been classified as redundant or not).

A snapshot of an example of an RFID network before and after applying the NTE algorithm is shown in Fig. 5.3, shows how effective the NTE algorithm is in eliminating a significant number of redundant readers.

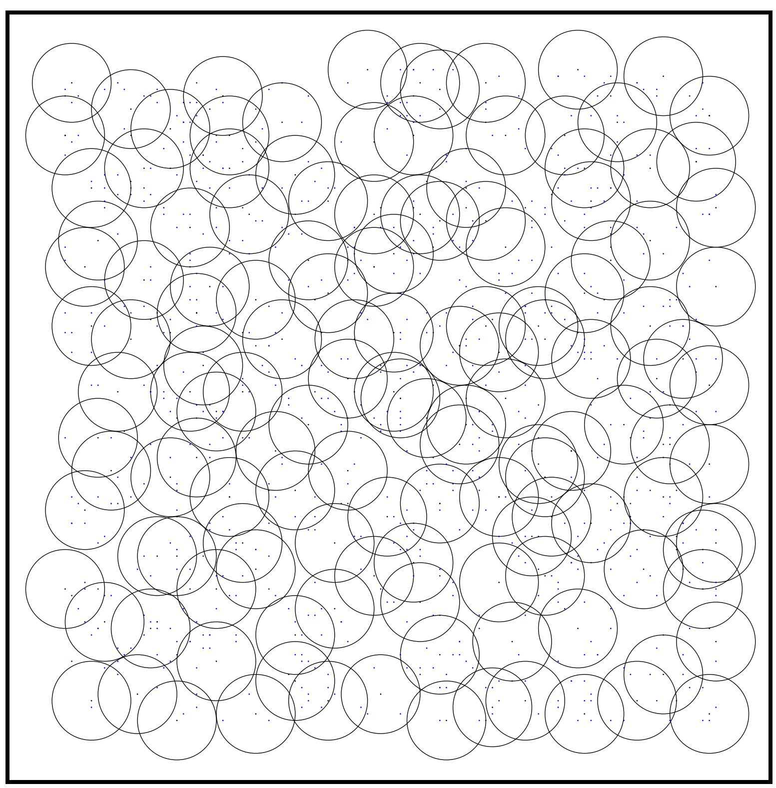
5.4.3 Exemplary Scenario

We show in this subsection how our algorithm finds the redundant readers in the scenario shown in Fig. 5.2. The set of readers $\mathcal{R} = \{R_1, R_2, R_3, R_4\}$ is given, as input, to the NTE algorithm. Tracing the NTE algorithm on this instance is shown in Table 5.1.

In the first step, all readers in $\mathcal{R}$ estimate the number of active tags they cover and the number of active neighboring readers they have. Readers R_1, R_2, R_3 and R_4 have 2 tags, 1 tag, 2 tags and 2 tags, respectively. The numbers of active neighboring



(a) Network before the execution of NTE algorithm



(b) Network after the execution of NTE algorithm

Figure 5.3: Snapshot of random RFID network from the simulator.

readers R_1, R_2, R_3 and R_4 have are 1, 2, 3 and 2, respectively. Accordingly, reader R_1 will have the maximum weight and, hence, will be excluded from the list of redundant readers and deactivated be removing it from the set $\mathcal{R}$. Active tags covered by R_1 (i.e., T_1 and T_2) are deactivated.

In the second step, active readers (i.e., the set $\mathcal{R}$) estimate the number of active tags they cover and the number of active neighboring readers they have. At this stage, reader R_1 and tags T_1 and T_2 are not counted. Therefore, readers R_2, R_3 and R_4 cover 1 tag, 1 tag and 2 tags, respectively. The numbers of active neighboring readers they have are 2, 2 and 2, respectively. R_4 is picked as it has the maximum weight.

In the last step, readers R_2 and R_3 will be added to the list of redundant readers as they do not cover any active tag. As a result, the readers R_1 and R_4 can be used to interrogate all tags and readers R_2 and R_3 will be turned off as they are redundant.

5.4.4 Computational Complexity

Estimating the number of tags covered by a reader can be done in a constant time [62]. Deactivating tags covered by a particular reader can be also done in a constant time, as it just requires a single broadcasted message. When a reader is deactivated, it can broadcast a message to its neighboring readers telling them that it is going into an inactive mode; upon receiving such a message, reader decrements its number of active neighboring readers. Thereby, readers manipulate the number of tags they cover and the number of neighboring readers they have in a constant time. Now, we are left with the *while loop* that have, in the worst case, $O(N)$ iterations, where N is the number of readers. The time complexity of each iteration is dominated by the process of

Table 5.1: Tracing the NTE algorithm for the scenario of Fig. 5.2.

(a) Step-I

Input:	$\mathcal{R} = \{R_1, R_2, R_3, R_4\}$	$\mathcal{R}^a = \phi$
Reader	$E(R_i)$	$N(R_i)$
$\underline{R_1}$	2	1
R_2	1	2
R_3	2	3
R_4	2	2
Output:	$\mathcal{R} = \{R_2, R_3, R_4\}$	$\mathcal{R}^a = \{R_1\}$

(b) Step-II

Input:	$\mathcal{R} = \{R_2, R_3, R_4\}$	$\mathcal{R}^a = \{R_1\}$
Reader	$E(R_i)$	$N(R_i)$
R_1	-	-
R_2	1	2
R_3	1	2
$\underline{R_4}$	2	2
Output:	$\mathcal{R} = \{R_2, R_3\}$	$\mathcal{R}^a = \{R_1, R_4\}$

(c) Step-III

Input:	$\mathcal{R} = \{R_2, R_3\}$	$\mathcal{R}^a = \{R_1, R_4\}$
Reader	$E(R_i)$	$N(R_i)$
R_1	-	-
R_2	0	0
R_3	0	0
R_4	-	-
Output:	$\mathcal{R}^r = \{R_2, R_3\}$	$\mathcal{R}^a = \{R_1, R_4\}$

finding the reader with the maximum weight which is done in a centralized fashion and, hence, takes $O(M)$ time, where M is the number of active readers. Therefore, the overall time complexity of the algorithm is $O(N^2)$.

5.5 Simulation Setup and Results

In this section, we evaluate the performance of the proposed algorithms and that of other recently proposed schemes for the readers deployment and redundant readers elimination in RFID. We use the number of readers, maximum load amongst the readers and the number of redundant readers as our evaluation criteria.

5.5.1 Simulation Setup

We have implemented the RFID system using an in-house simulator, for both deterministic deployment and random deployment.

Deterministic deployment: In the case of deterministic deployment, for comparison, we use two recent readers deployment schemes, namely the optimal grid coverage [83, 92] and the honey grid coverage [110]. Both schemes were selected based on their relative performance with other schemes, from the literature. For rest of the section, the two proposed schemes, i.e., Algorithm 7 and Algorithm 8 are termed as Approximate Set Cover (ASC) and Approximate Set Cover with Load Balancing (ASC-LB), respectively. For evaluation, we use the number of readers and the maximum load, i.e., the maximum number of tags a single reader may cover. Lower number of readers imply less overlapping and, hence, less reader collisions. And lower values for the maximum load amongst readers implies a higher overall reading rates. We also evaluated the schemes for various tags load (sparse and dense) and various interrogation areas. Unless otherwise mentioned, simulations for the deterministic deployment are performed using the following parameters. The RFID reader has an interrogation range of $4-5m$ and an interrogation area of 5x5x100m^3. Tags are assumed to be placed in a 3D space modelled as a rectangular cuboid, and readers are to be placed on particular sides of the rectangular cuboid, as is illustrated in Figure 5.1. Locations of tags are generated using pseudo-random number generator. The performance metrics are averaged over twenty different runs generated using distinct random seeds.

Random deployment: In the case of random deployment, or comparison, we use recently proposed algorithms such as RRE [16], LEO+RRE [52] and TREE [109]. These schemes were selected based on the their relative performance improvements over other schemes in the literature. For comparative analysis, our evaluation metrics are the number of redundant readers, the number of tag reads and the number of tag writes. A high number of redundant readers imply the scheme is effective in detecting and eliminating redundant readers. A low number of tag reads and writes implies that the scheme is light-weight and does not require state maintenance on the tags. Furthermore, we evaluated the NTE scheme in terms of resilience to the reader's range. Unless otherwise mentioned, simulations for the random deployment are performed using the following parameters. The RFID reader has an interrogation range of 5m and an interrogation area of 250x250m^2. Both tags and readers are assumed to be randomly place within the interrogation area. The results are averaged over twenty different runs generated using distinct random seeds.

5.5.2 Simulation Results for Deterministic Deployment

Number of Readers: Minimal number of readers with maximal required coverage is an important evaluation metric as it translates into minimal communication overheads, minimal communication interferences and is economically sound. Fig. 5.7 shows the number of readers required to cover the same interrogation area for various

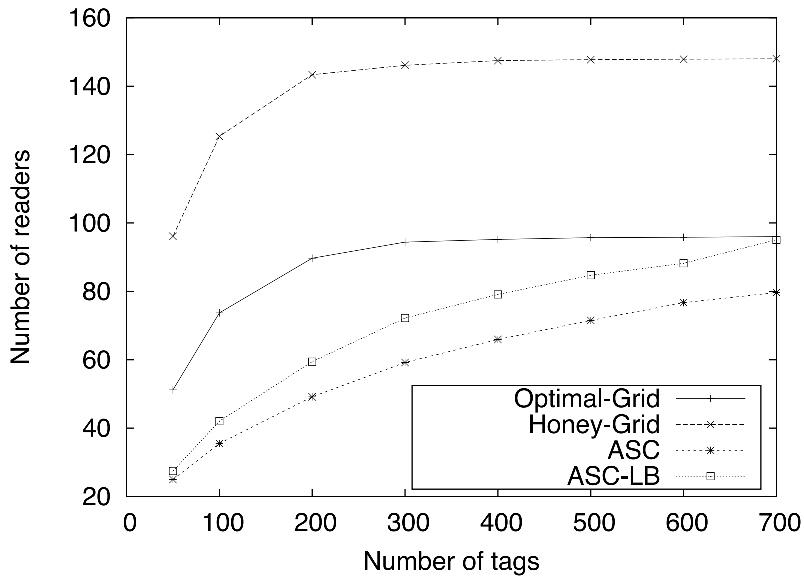


Figure 5.4: Number of readers required for various tag density.

algorithms. Our proposed ASC algorithm is the most prominent as it significantly reduces the required readers, an average two times reduction compared with Honey-Grid is obtained. Both Optimal-Grid and Honey-Grid quickly reaches its maximum allowable readers as the tags density exceed certain limits. Whereas, for the proposed algorithms, ASC and ASC-LB, such a saturation point comes much later hence, translating into lesser readers while still covering the same tags set. In highly dense environment, in terms of readers, the two proposed schemes and optimal-grid would perform same, as after certain number of tags, either scheme requires certain number of reader to achieve 100% coverage.

Load Balancing: The ASC algorithm guarantees minimum number of readers however, maybe results in imbalance number of tags between the readers. Fig. 5.5 shows the maximum number of tags, amongst all the readers interrogation range for various algorithms. As anticipated, having reader deployment scheme, without any

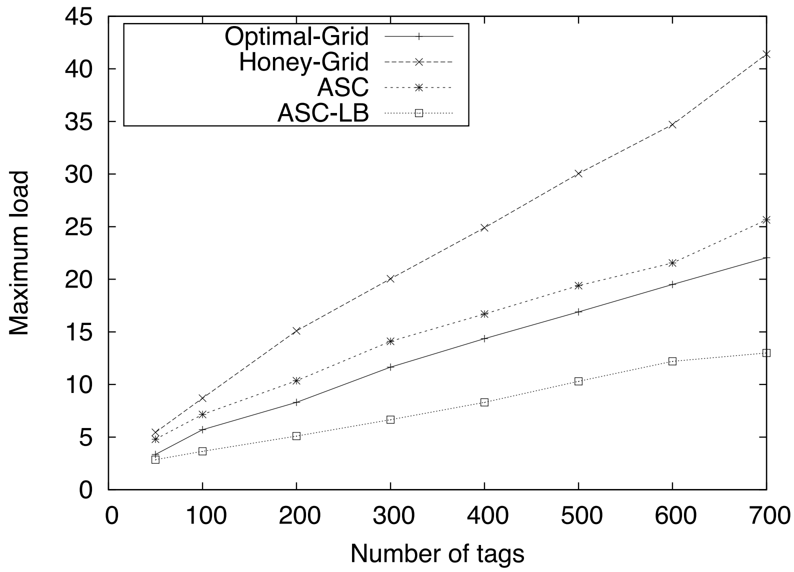
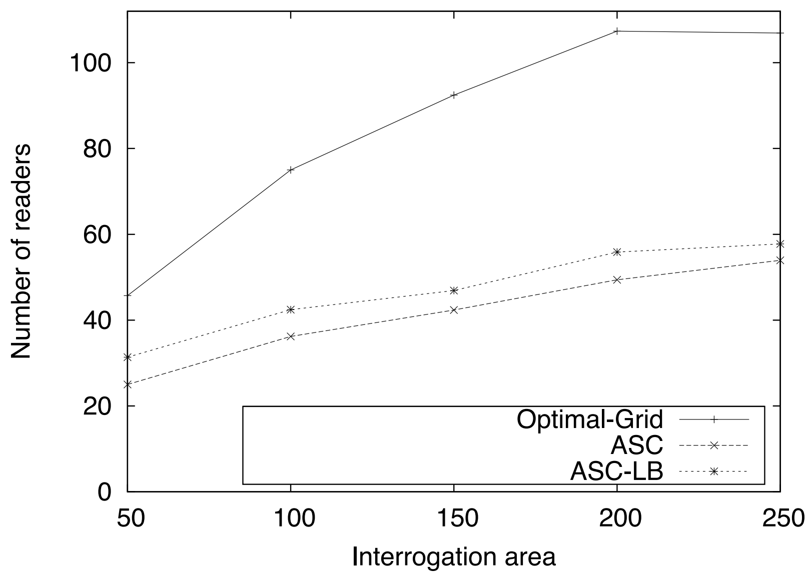
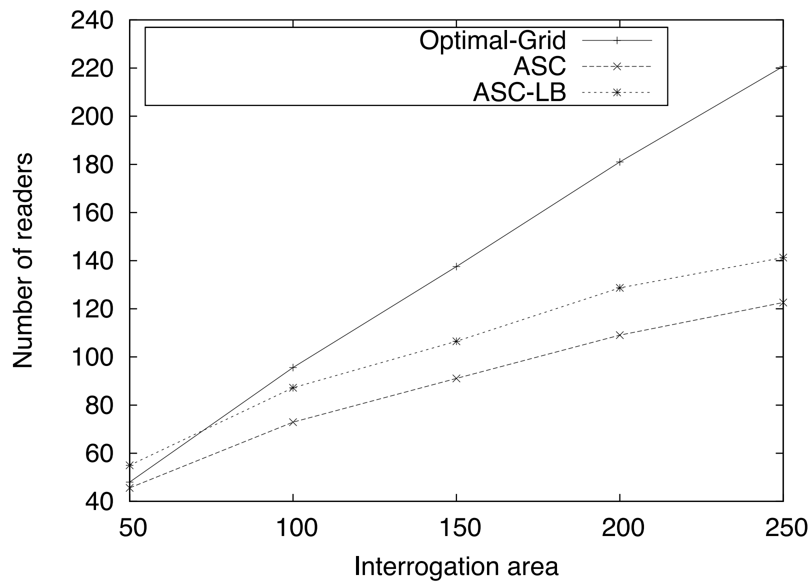


Figure 5.5: Maximum load (tags) for various tag density.

load balance, will yield reader(s) having much larger set of tags to interrogate, compared with others. For instance, as the number of tags increases, the loads for all the schemes increase. Therefore, we may get solutions in which readers have significant variations in their workloads (i.e., the number of tags they cover), which lower the performance of overall system. As expected, the proposed load-aware placement scheme, i.e., ASC-LB performs the best, as it is distribute the load many-folds efficient compared with others. The effect of increasing the interrogation area, in sparse (100tags) and dense (500tags) settings, are shown in Fig. 5.6. With an increase in the interrogation areas and tags cardinality, our proposed algorithms are more scalable i.e., can handle diverse tag deployments. However, trade-off exists between minimal readers and load balancing as the later would require more readers in order to maintain the balance amongst them.



(a) 100 tags



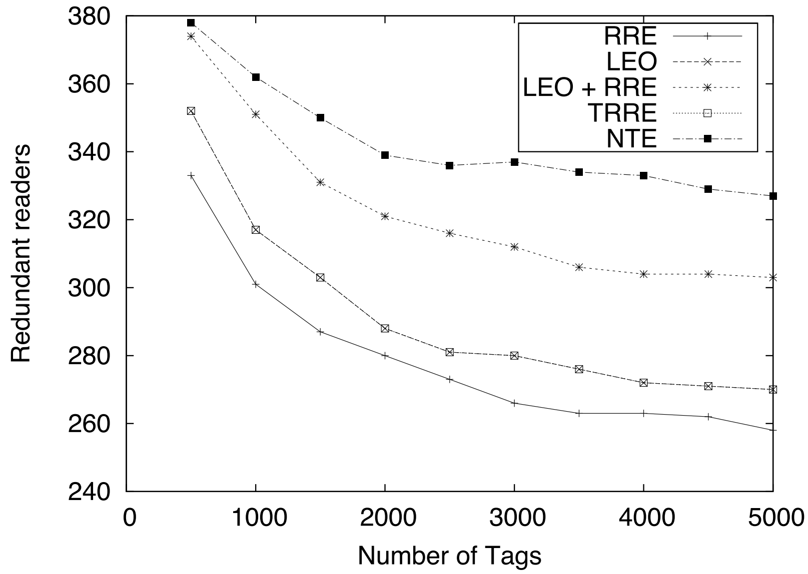
(b) 500 tags

Figure 5.6: Effect of tag density and interrogation area on the readers deployment algorithms.

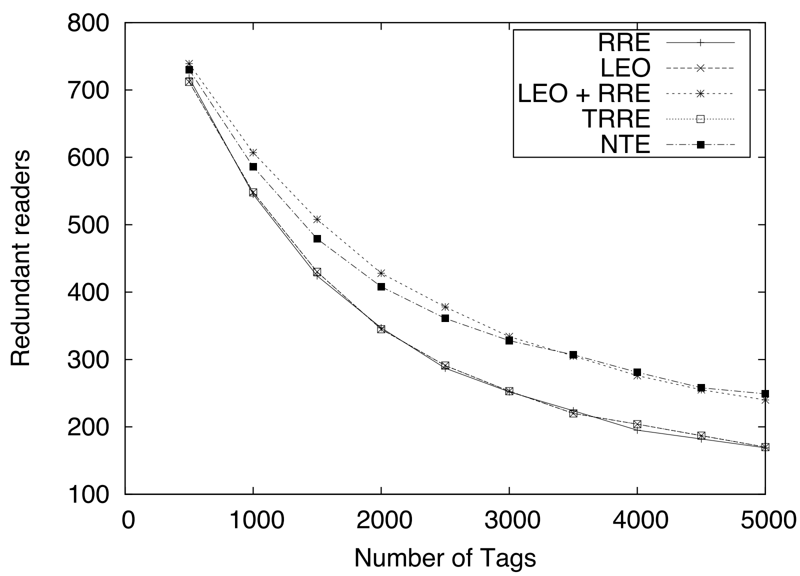
5.5.3 Simulation Results for Random Deployment

Redundant Readers: The overall network performance, mainly in terms of energy consumption and reading delay, is influenced by interference among readers [42]. Hence, an effective scheme is one that detects more redundant readers. Comparisons of different schemes based on the number of redundant readers they detect for both dense (50x50m^2) and sparse (250x250m^2) networks are depicted in Fig. 5.7. In dense environments, the NTE algorithm detects redundant readers far beyond other schemes whereas in a sparse environment the improvement obtained is not significant. For instance, in dense environments, the NTE schemes can detect 15% more redundant readers than the best of the other schemes, i.e., LEO+RRE. However, in sparse environments only 2% improvement is observed over LEO+RRE. There are two reasons behind this behavior. First, in a dense environment a reader has a good chance of having a large number of neighbors and picking a reader with the maximum tags to neighbors ratio as a non-redundant reader has the potential to render many neighboring readers redundant, which is not the case in a sparse environment. Second, in a sparse environment, readers are expected to have a limited variation in the tags to neighbors ratio they have, and accordingly this ratio is not as effective as it is in a dense environment.

Tags Reads and Writes: Most of the existing schemes, e.g., RRE and LEO, in the literature have high communication complexities associated with them. Communication complexity is defined as the number of reads and writes operation made from and to tags. Tag singulation is required in order to read-from a tag. Tag singulation is an expensive process as it is determined by the number of tags within a reader's interrogation range and the overlapping among readers. Fig. 5.8 and Fig. 5.9 show

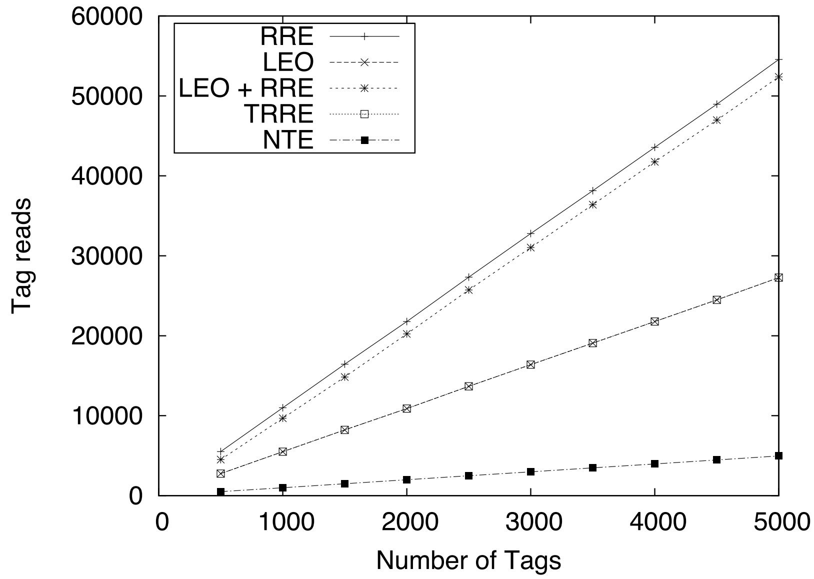


(a) Simulation area of 50x50m^2

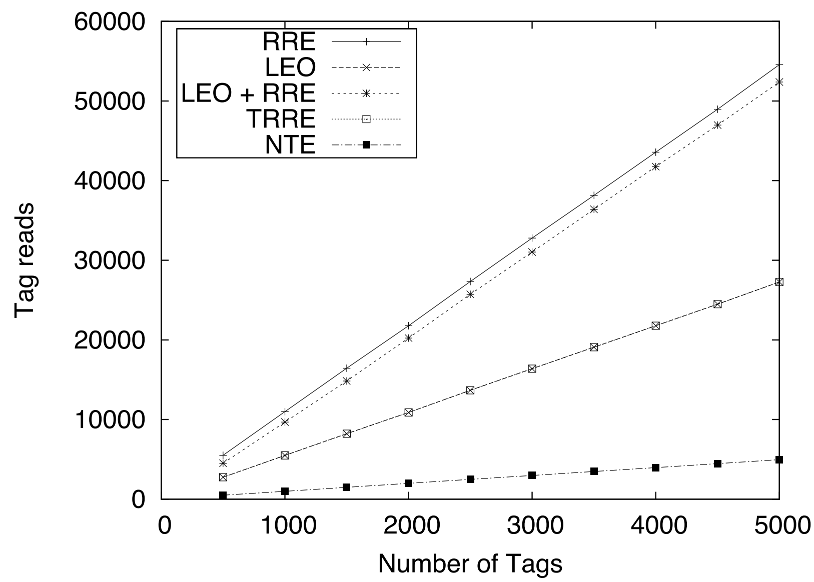


(b) Simulation area of 250x250m^2

Figure 5.7: Redundant reader detected in sparse and dense network.



(a) Simulation area of 50x50m^2



(b) Simulation area of 250x250m^2

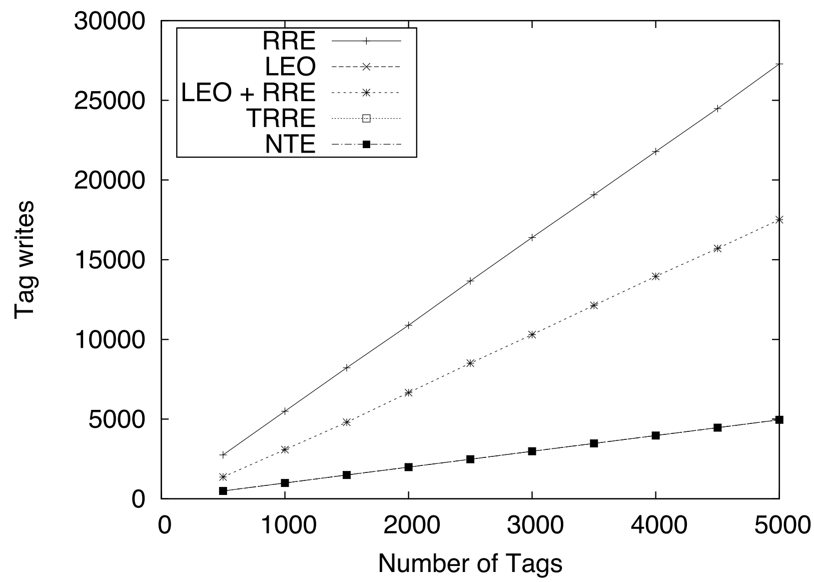
Figure 5.8: Number of tag reads in sparse and dense environments.

comparisons between different schemes in terms of the number of read and write operations they incur. The number of reads and writes is obviously lower in sparse environments than it is in dense environments for all schemes. However, the number of reads and writes in the NTE scheme is many folds less than those in other schemes. This is because the reader, in the NTE scheme, writes only once to the tags within its range. Furthermore, each tag receives a single write operation.

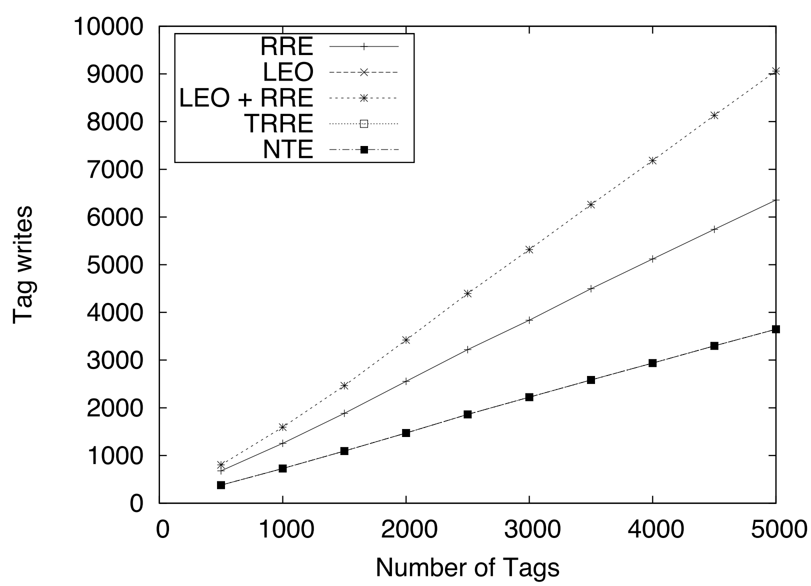
Operations in the tags count estimation are not counted as read operations. This is because the estimation scheme does not require tags singulation. Read operations that make a difference are ones that require singulation and no such an operation is needed in the NTE scheme. Therefore, although the number of redundant readers detected by the LEO+RRE scheme is similar to that in the NTE scheme, in the sparse environment, the NTE scheme is much more efficient in terms of energy consumption and delay. In fact the NTE algorithm is at least six times more efficient in accessing the tags memory.

5.6 Summary

Coverage is crucial for large scale RFID applications wherein large number of readers can be deployed in deterministic and random manners. In deterministic approach, minimum readers must be deployed to maintain certain coverage. In random approach, once the readers are deployed, redundant readers must be detected to avoid unnecessary interference caused by them. Several schemes have been proposed in the literature, however, issues such as interrogation zone overlap among readers, load balancing amongst reader and light-weight redundant readers detection schemes have received little attention. In this chapter, for deterministic approach, we propose an



(a) Simulation area of 50x50m^2



(b) Simulation area of 250x250m^2

Figure 5.9: Number of tags write in sparse and dense environments.

algorithm that approximately determines the minimal number of readers and the location of each reader in a 3D space, and guarantees less overlapping among readers and a balanced distribution of load among them. Also, for random approach, light-weight greedy algorithm to detect and eliminate redundant readers in RFID networks. By reducing the number of readers, either to-be deployed or to-be active at one time, not only is the overall network cost reduced, but the overall system performance is improved also by reducing interference and overlapping among readers coverage regions and, hence, having less collisions among readers.

Chapter 6

Conclusion

The last decade has witnessed a growing interest in RFID due to their unique potential in a wide range of applications. RFID systems provide low cost and low power object identification and tracking mechanisms. While being the key requirement for anticipated ultra large scale applications, e.g., Internet of Things, RFID brings several design challenges that need to be overcome. One of these challenges is tag anti-collision and hence, the reading rates of RFID tags. The tags, especially passive RFID tags, with functional constraints due to limited power cannot adopt conventional medium access control approaches. Another challenge is scaling to large scale application (a typical scenario in Internet of Things) which involve a large number of tags within the interrogation zone of single or multiple readers. This scenario results in a large number of tag collisions and therefore, lowers overall system reading rate. Furthermore, power requirements and signal attenuation limit the reading range. A promising solution to overcome these limitation exists at the protocol and system architecture levels. At protocol level, an optimal power level algorithm which clusters and isolates tags according to their physical distance can reduce tag collisions. At the system architecture level, reducing collisions can be achieved by distributing the signal receiving task amongst spatially dispersed devices. These devices then selectively collect and relay them to the reader; forming micro-interrogation zones which are interrogated in parallel and autonomously.

6.1 Summary

Schemes presented in Chapter 3, Chapter 4 and Chapter 5 aim at enabling RFID systems for ultra large scale of the anticipated applications, such as the Internet of Things and item-level tagging. These schemes achieve higher reading rates and range, using sophisticated medium access control and architecture design, and to provide load-aware and energy-efficient reader deployment to prolong overall network lifetime.

In Chapter 3, we introduce the use of reader's power control to mitigate tag collisions. By interrogating a subset of tags, one at a time, collisions are reduced and hence higher reading rates can be achieved. To this end, two optimal power stepping algorithms are proposed. The first scheme targets an ideal setting in which the transmission power, and hence, the transmission range of an RFID reader can be tuned with high precision. The second scheme relaxes this assumption and considers an RFID reader with a finite and discrete transmission range. For each optimization problem, we present mathematical delay analysis and devise an efficient method to find the optimal clustering.

In Chapter 4, we introduce a new paradigm in RFID systems, namely Distributed Receiving RFID. The objective is to lessen the limitations and alleviate bottlenecks imposed by centralized architectures; with the goal of boosting the operational performance of RFID systems. In the proposed paradigm, the task of collecting the modulated backscattered signals is dispersed to spatially distributed entities (devices) within a reader's interrogation zone. This model supports multipoint communication and hence eliminates redundant interrogation of the same set of tags, by overlapping RFID readers. To this end, we propose two schemes. In the first scheme, using the spatial devices and by adjusting the tags reflectivity co-efficient, micro-interrogation zones are formed. Micro-zones spatially isolate tags within the readers interrogation zone therefore facilitate higher bandwidth communication link and data rates. In the second scheme, exploiting micro-zones, the tags are interrogated in parallel; namely parallel singulation. We propose both a deterministic and a probabilistic model of this parallel singulation mechanism. Parallel singulation assists in achieving a higher reading rate under both dense and mobile tag environments.

In Chapter 5, we introduce RFID coverage as deterministic and random deployment problems. The complexity and monetary cost associated with ultra large scale RFID systems strongly depends on the number of readers being deployed to interrogate tags. To this end, three RFID deployment schemes are proposed. The first scheme, targeting deterministic deployment, proposes a set-cover approximation algorithm to determine the minimal number of RFID readers required to maintain the requested coverage while having minimal interrogation overlapping among the readers. The second scheme then extends the algorithm to facilitate load-balancing deployment strategies. The third scheme, targeting random and post deployment coverage, proposes the use of neighbouring readers ratio and covering tags to heuristically turn off redundant readers to achieve the maximal coverage with the least possible readers and overlapping interrogation zones.

6.2 Future Outlook

Several future research problems stem from our work thus far. In this section, we point out some of them.

1. Current proposals for RFID systems assume near-ideal interrogation environment. A more challenging problem is evaluating the performance of an RFID system and the proposed algorithms in a testbed setting.

2. The parallel singulation algorithm makes use of the binary search tree and the query tree algorithm. An efficient and tailored algorithm, aware of the underlying distributed receiving reader-tag communication architecture, will yield optimal data rates.

3. In Chapter 4, the fielders are deployed in a grid, thus have problematic overlapping regions. These regions result in idle queries. Optimized fielder deployment techniques, and formation of micro-zones with minimal overlapping, is an interesting problem as it would to further boost system performance. Novel MAC protocols, for both fielders and reader, need to be developed in a distributed context.

4. In Chapter 5, reader deployment algorithms assume that RFID readers have a fixed transmission range. An interesting problem is optimizing and/or dynamically controlling the transmission range of each reader to minimize reader overlap and balance workload among readers.

Bibliography

[1] LTC5507: 100kHz to 1GHz RF power detector.

[2] ADG901/ADG902: Wideband, 40 db isolation at 1 GHz, CMOS 1.65 v to 2.75 v, SPST switches, rev. b, 2005.

[3] SKY12329-350LF: GaAs digital attenuator 5-bit, 1 db LSB 400 MHz4 GHz, Sep 2007.

[4] CC2500 single chip low cost low power RF transceiver, May 2008.

[5] eZ430-RF2500-SEH solar energy harvesting development tool, May 2010.

[6] MSP430x22x2, MSP430x22x4 mixed signal microcontroller, March 2010.

[7] The network simulator ns-2, available at http://www.isi.edu/nsnam/ns/, 2011.

[8] www.skyetek.com, 2011.

[9] K. Ali and H. Hassanein. Passive RFID for intelligent transportation systems. In *Proceedings of the 6th Annual IEEE Consumer Communications & Networking Conference (CCNC)*, pages 1–2, 2009.

[10] K. Ali, H. Hassanein, and A. M. Taha. RFID anti-collision protocol for dense passive tag environments. In *LCN '07: Proceedings of the 32nd IEEE Conference on Local Computer Networks*, pages 819–824, 2007.

[11] W. Alsalih, S. Akl, and H. Hassanein. Placement of multiple mobile data collectors in underwater acoustic sensor networks. In *Proceedings of the IEEE International Conference on Communications (ICC)*, pages 2113–2118, 2008.

[12] W. Alsalih, K. Ali, and H. Hassanein. Optimal distance-based clustering for tag anti-collision in RFID systems. In *Proceedings of the 33rd IEEE Conference on Local Computer Networks (LCN)*, pages 266–273, 2008.

[13] N. Amin, Ng Wen Jye, and M. Othman. A BPSK backscatter modulator design for RFID passive tags. In *Proceedings of the IEEE International Workshop on Radio-Frequency Integration Technology*, pages 262–265, 2007.

[14] R. Angeles. RFID technologies: Supply-chain applications and implementation issues. *Information Systems Management*, 22(1):51–65, 2005.

[15] S.M. Birari and S. Iyer. Mitigating the reader collision problem in RFID networks with mobile readers. In *Proceedings of the 13th IEEE International Conference on Networks*, pages 463–468, 2005,.

[16] C. Bogdan, K. R. Murali, K. Mehmet, H. Christoph, and G. Ananth. Redundant-reader elimination in RFID systems. In *Proceedings of the Second Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks (SECON)*, pages 176–184, 2005.

[17] L. Bolotnyy and Robins G. Randomized pseudo-random function tree walking algorithm for secure radio-frequency identification. In *Proceedings of the Fourth IEEE Workshop on Automatic Identification Advanced Technologies*, pages 43–48, 2005.

[18] J. Capetanakis. Tree algorithms for packet broadcast channels. *IEEE Transactions on Information Theory*, 25(5):505–515, 1979.

[19] B. Carbunar, M. K. Ramanathan, M. Koyuturk, C. Hoffmann, and A. Grama. Redundant reader elimination in RFID systems. In *Proceedings of the Second Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks (SECON)*, pages 176–184, 2005.

[20] M. Cardei and D-Z. Du. Improving wireless sensor network lifetime through power aware organization. *Wireless Networking*, 11:333–340, May 2005.

[21] J. Cha and J. Kim. Novel anti-collision algorithms for fast object identification in RFID system. In *Proceedings of the 11th International Conference on Parallel and Distributed Systems*, pages 63–67, 2005.

[22] J. Cha and J. Kim. Novel anti-collision algorithms for fast object identification in RFID system. In *Proceedings 11th International Conference on Parallel and Distributed Systems*, pages 63–67, 2005.

[23] J. Cha and J. Kim. Dynamic framed slotted aloha algorithms using fast tag estimation method for RFID system. In *Proceedings of the 3rd IEEE Consumer Communications and Networking Conference (CCNC)*, pages 768–772, 2006.

[24] H. S. Chae, J. G. Park, J. F. Cui, and J. S. Lee. An adaptive load balancing management technique for RFID middleware systems. *Software Practice and Experience*, 40(6):485–506, 2010.

[25] H. Chen, Y. Zhu, and K. Hu. Multi-colony bacteria foraging optimization with cell-to-cell communication for RFID network planning. *Applied Software Computing*, 10(2):539–547, 2010.

[26] W. Chen, S. Horng, and P. Fan. An enhanced anti-collision algorithm in RFID based on counter and stack. In *Proceedings of the Second International Conference on Systems and Networks Communications (ICSNC)*, pages 21–24, 2007.

[27] C. H. Cheng and R. D. Murch. Asymmetric RFID tag antenna. In *Proceedings of the IEEE International Symposium of Antennas and Propagation Society*, pages 1363–1366, 2006.

[28] K. W. Chiang, C. Hua, and T. P. Yum. Prefix-randomized query-tree protocol for RFID systems. In *Proceedings of the IEEE International Conference on Communications (ICC)*, pages 1653–1657, 2006.

[29] K.W. Chiang, C. Hua, and P. Yum. Prefix-length adaptation for PRQT protocol in RFID systems. In *Proceedings of the IEEE Global Telecommunications Conference (Globecom)*, pages 1–5, 2006.

[30] J. Choi, D. Lee, and H. Lee. Bi-slotted tree based anti-collision protocols for fast tag identification in RFID systems. *IEEE Communications Letters*, 10(12):861–863, 2006.

[31] J. Choi, D. Lee, and H. Lee. Query tree-based reservation for efficient RFID tag anti-collision. *IEEE Communications Letters*, 11(1):2007, 85–87.

[32] J.H. Choi, D. Lee, H. Jeon, J. Cha, and H. Lee. Enhanced binary search with time-divided responses for efficient RFID tag anti-collision. In *Proceedings of the IEEE International Conference on Communications (ICC)*, pages 3853–3858, 2007.

[33] T. Cormen, C. Leiserson, R. Rivest, and C. Stein. *Introduction To Algorithms (2nd Edition)*. McGraw-Hill, 2001.

[34] J. Curty, N. Joehl, C. Dehollain, and M.J. Declercq. Remotely powered addressable UHF RFID integrated system. *IEEE Journal of Solid-State Circuits*, 40(11):2193–2202, Nov. 2005.

[35] K. Dasgupta, M. Kukreja, and K. Kalpakis. Topology-aware placement and role assignment for energy-efficient information gathering in sensor networks. In *Proceedings of the 8th IEEE Symposium on Computers and Communication (ISCC)*, pages 341–348, 2003.

[36] D. M. Dobkin. *The RF in RFID: Passive UHF RFID in Practice*. Newnes, 2005.

[37] Q. Dong, A. Shukla, V. Shrivastava, D. Agrawal, S. Banerjee, and K. Kar. Load balancing in large-scale RFID systems. In *Proceedings of the 26th IEEE International Conference on Computer Communications (INFOCOM)*, pages 2281–2285, 2007.

[38] A. Dunkels, B. Grnvall, and T. Voigt. Contiki - a lightweight and flexible operating system for tiny networked sensors. In *Proceedings of the 29th Annual IEEE International Conference on Local Computer Networks (LCN)*, pages 455–462, 2004.

[39] D.W. Engels and S. E. Sarma. The reader collision problem. In *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics*, pages 641–646, 2002.

[40] EPCglobal. EPC radio-frequency identity protocols class-1 generation-2 UHF RFID protocol for communications at 860 MHz - 960 MHz version 1.2.0. 2008.

[41] B. Feng, J. Li, J. Guo, and Z. Ding. Id-binary tree stack anticollision algorithm for RFID. In *Proceedings of the 11th IEEE Symposium on Computers and Communications*, pages 207–212, 2006.

[42] K. Finkenzeller. *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification*. John Wiley & Sons, Inc., 2003.

[43] C. Floerkemeier. Transmission control scheme for fast rfid object identification. In *Proceedings of the Fourth Annual IEEE International Conference on Pervasive Computing and Communications (PerCom) Workshops*, pages 457–462, 2006.

[44] C. Floerkemeier. Bayesian transmission strategy for framed ALOHA based RFID protocols. In *Proceedings of the IEEE International Conference on RFID 2007*, pages 228–235, 2007.

[45] P.R. Foster and R.A. Burberry. Antenna problems in RFID systems. In *Proceedings of the IEE Colloquium on RFID Technology*, pages 1–5, 1999.

[46] F. Fuschini, F. Paolazzi C. Piersanti, and G. Falciasecca. Analytical approach to the backscattering from UHF RFID transponder. *IEEE Antennas and Wireless Propagation Letters*, 7:2008, 33–35.

[47] D. W. Gage. Command control for many-robot systems. In *Proceedings of the Nineteenth Annual AUVS Technical Symposium*, pages 22–24, 1992.

[48] W. W. Gregg, W. E. Esaias, G. C. Feldman, R. Frouin, S. B. Hooker, C. R. McClain, and R. H. Woodward. Coverage opportunities for global ocean color in a multimission era. *IEEE Transactions on Geosience and Remote Sensing*, 36(5):1620–1627, 1998.

[49] J.D. Griffin and G.D. Durgin. Gains for RF tags using multiple antennas. *IEEE Transactions on Antennas and Propagation*, 56(2):563–570, 2008.

[50] Q. Guan, Y. Liu, Y. Yang, and W. Yu. Genetic approach for network planning in the rfid systems. In *Proceedings of the Sixth International Conference on Intelligent Systems Design and Applications (ISDA)*, pages 567–572, 2006.

[51] J. Ho, D. W. Engels, and S. E. Sarma. HiQ: a hierarchical Q-learning algorithm to solve the reader collision problem. In *Proceedings of the International Symposium on Applications and the Internet Workshops (SAINT-W)*, pages 88–91, 2006.

[52] C-H. Hsu, Y-M. Chen, and C-T. Yang. A layered optimization approach for redundant reader elimination in wireless RFID networks. In *Proceedings of the 2nd IEEE Asia-Pacific Service Computing Conference (APSCC)*, pages 138–145, 2007.

[53] J-W. Hung, I-H. Li, H-H. Lin, and J-A. Cai. The first search right algorithm for redundant reader elimination in RFID network. In *Proceedings of the 9th WSEAS international conference on Software engineering, parallel and distributed systems (SEPADS)*, pages 177–183, 2010.

[54] T. Hwang, B. Lee, Y. S. Kim, D. Y. Suh, and J. S. Kim. Improved anti-collision scheme for high speed identification in RFID system. In *Proceedings of the First International Conference on Innovative Computing, Information and Control (ICICIC)*, pages 449–452, 2006.

[55] N. Irfan and M.C.E. Yagoub. Efficient algorithm for redundant reader elimination in wireless RFID networks. *International journal of computer science issues*, 3(11):1–8, May 2010.

[56] K. Kar and S. Banerjee. Node placement for connected coverage in sensor networks. In *Proceedings of the Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt)*, 2003.

[57] U. Karthaus and M. Fischer. Fully integrated passive UHF RFID transponder IC with 16.7-μw minimum rf input power. *IEEE Journal of Solid-State Circuits*, 38(10):1602–1608, 2003.

[58] G. Khandelwal, A. Yener, and M. Chen. OPT: Optimal protocol tree for efficient tag identification in dense RFID systems. In *Proceedings of the IEEE International Conference on Communications (ICC)*, pages 128–133, 2006.

[59] G. Khandelwal, A. Yener, K. Lee, and S. Serbetli. ASAP : A MAC protocol for dense and time constrained RFID systems. In *Proceedings of the IEEE International Conference on Communications (ICC)*, pages 4028–4033, 2006.

[60] J. Kim, W. Lee, E. Kim, D. Kim, and K. Suh. Optimized transmission power control of interrogators for collision arbitration in uhf rfid systems. *IEEE Communications Letters*, 11(1):22–24, 2007.

[61] J. Kim, J. Yu, J. Myung, and E. Kim. Effect of localized optimal clustering for reader anti-collision in RFID networks: fairness aspects to the readers. In *Proceedings of the 14th International Conference on Computer Communications and Networks (ICCCN)*, pages 497–502, 2005.

[62] Murali Kodialam and Thyaga Nandagopal. Fast and reliable estimation schemes in RFID systems. In *Proceedings of the 12th Annual International Conference on Mobile Computing and Networking (MobiCom)*, pages 322–333, 2006.

[63] C. Law, K. Lee, and K. Siu. Efficient memoryless protocol for tag identification. In *Proceedings of the 4th international workshop on Discrete algorithms and methods for mobile computing and communications (DIALM)*, pages 75–84, 2000.

[64] Ching Law, Kayi Lee, and Kai-Yeung Siu. Efficient memoryless protocol for tag identification. In *Proceedings of the 4th International Workshop on Discrete Algorithms and Methods for Mobile Computing and Communications (DIALM)*, pages 75–84, 2000.

[65] Jeongkeun Lee, Taekyoung Kwon, Yanghee Choi, Sajal K. Das, and Kyung ah Kim. Analysis of RFID anti-collision algorithms using smart antennas. In *Proceedings of the 2nd international conference on Embedded networked sensor systems (SenSys)*, pages 265–266, 2004.

[66] S. Lee, S. Joo, and C. Lee. An enhanced dynamic framed slotted ALOHA algorithm for RFID tag identification. In *Proceedings of the Second Annual International Conference on Mobile and Ubiquitous Systems: Networking and Services (MobiQuitous)*, pages 166–172, 2005.

[67] Y-D. Lee, K-K. Nae, E-J. Lee, H-H. Ron, J-W. Jung, Y-K. Han, J-W. Jung, S-C. Baek, M-S. Jung, H-G. Cho, H-R. Oh, Y-R. Seong, and J-S. Park. ASK modulator for RFID system using a novel variable DGS resonator. In *Proceedings of the 2007 European Microwave Conference*, pages 1660–1663, 2007.

[68] K. S. Leong, M. L. Ng, and P. H. Cole. The reader collision problem in RFID systems. In *Proceedings of the IEEE International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications (MAPE)*, pages 658–661, 2005.

[69] C. Lin and F. Lin. A simulated annealing algorithm for RFID reader networks. In *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC)*, pages 1669–1672, 2007.

[70] H. Liu, M. Bolic, A. Nayak, and I. Stojmenovic. Taxonomy and challenges of the integration of RFID and wireless sensor networks. *IEEE Network*, 22(6):26–35, November-December 2008.

[71] L. Liu, Z. Xie, J. Xi, and S. Lai. An improved anti-collision algorithm in RFID system. In *Proceedings of the 2nd International Conference on Mobile Technology, Applications and Systems*, pages 137–142, 2005.

[72] Y. Maguire and R. Pappu. An optimal Q-algorithm for the ISO 18000-6C RFID protocol. *IEEE Transactions on Automation Science and Engineering*, 6(1):16–24, 2009.

[73] M. Marengoni, B. A. Draper, A. Hanson, and R. Sitaraman. A system to place observers on a polyhedral terrain in polynomial time. *Image and Vision Computing*, 18(10):773–780, 2000.

[74] S. Meguerdichian, F. Koushanfar, G. Qu, and M. Potkonjak. Exposure in wireless ad-hoc sensor networks. In *Proceedings of the 7th annual international conference on Mobile computing and networking (MobiCom)*, pages 139–150, 2001.

[75] C. Mutti and C. Floerkemeier. CDMA-based RFID systems in dense scenarios: Concepts and challenges. In *Proceedings of the IEEE International Conference on RFID*, pages 215–222, 2008.

[76] J. Myung and W. Lee. Adaptive binary splitting: a RFID tag collision arbitration protocol for tag identification. *Mobile Network Applications*, 11(5):711–722, 2006.

[77] J. Myung, W. Lee, J. Srivastava, and T. K. Shih. Tag-splitting: Adaptive collision arbitration protocols for RFID tag identification. *IEEE Transaction on Parallel and Distributed System*, 18(6):763–775, 2007.

[78] V. Namboodiri and L. Gao. Energy-aware tag anti-collision protocols for RFID systems. In *Proceedings of the Fifth Annual IEEE International Conference on Pervasive Computing and Communications (PerCom)*, pages 23–36, 2007.

[79] V. Namboodiri and L. Gao. Energy-aware tag anti-collision protocols for RFID systems. In *Proceedings of the Fifth Annual IEEE International Conference on Pervasive Computing and Communications (PerCom)*, pages 23–36, March 2007.

[80] M. Nanjundaiah and V. Chaudhary. Improvement to the anticollision protocol specification for 900MHz class 0 radio frequency identification tag. In *Proceedings of the 19th International Conference on Advanced Information Networking and Applications (AINA)*, pages 616–620, 2005.

[81] P.V. Nikitin and K.V.S. Rao. Theory and measurement of backscattering from RFID tags. *IEEE Antennas and Propagation Magazine*, 48(6):212–218, 2006.

[82] P.V. Nikitin, K.V.S. Rao, and R.D. Martinez. Differential RCS of RFID tag. *Electronics Letters*, 43(8):431–432, 2007.

[83] A. Oztekin, F. Mahdavi, K. Erande, Z. Kong, L. K. Swim, and S. T. S. Bukkapatnam. Criticality index analysis based optimal RFID reader placement models for asset tracking. *International Journal of Production Research*, 48(9):2679–2698, 2010.

[84] J. ORourke. *Art Gallery Theorems and Algorithms*. Oxford University Press, 1987.

[85] J. Park, M. Y. Chung, and T. Lee. Identification of rfid tags in framed-slotted ALOHA with tag estimation and binary splitting. In *Proceedings of the First International Conference on Communications and Electronics (ICCE)*, pages 368–372, 2006.

[86] J. Park, M. Y. Chung, and T. Lee. Identification of RFID tags in framed-slotted ALOHA with robust estimation and binary selection. *IEEE Communications Letters*, 11(5):452–454, 2007.

[87] N. Pastos and R. Viswanathan. A modified grouped-tag tdma access protocol for radio frequency identification networks. In *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC)*, pages 512–516, 2000.

[88] N. Pastos and R. Viswanathan. A modified grouped-tag TDMA access protocol for radio frequency identification networks. In *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC)*, pages 512–516, 2000.

[89] V. Raghunathan, C. Schurgers, S. Park, and M. B. Srivastava. Energy-aware wireless microsensor networks. *IEEE Signal Processing Magazine*, 19:40–50, 2002.

[90] D.C. Ranasinghe, D. W. Engels, and p. H. Cole. Security and privacy solutions for low-cost RFID systems. In *Proceedings of the 2004 Intelligent Sensors, Sensor Networks and Information Processing Conference*, pages 337–342, 2004.

[91] K.V.S. Rao, P. V. Nikitin, and S. F. Lam. Antenna design for UHF RFID tags: a review and a practical application. *IEEE Transactions on Antennas and Propagation*, 53(12):3870–3876, 2005.

[92] A. Reza, T. K. Geok, and K. Dimyati. Tracking via square grid of RFID reader positioning and diffusion algorithm. *Wireless Personal Communications*, pages 1–24, 2010.

[93] A. W. Reza and T. K. Geok. Investigation of indoor location sensing via rfid reader network utilizing grid covering algorithm. *Wireless Personal Communications*, 49(1):67–80, 2009.

[94] J. Ryu, H. Lee, Y. Seok, T. Kwon, and Y. Choi. A hybrid query tree protocol for tag collision arbitration in RFID systems. In *Proceedings of the IEEE International Conference on Communications (ICC)*, pages 5981–5986, 2007.

[95] X.-L. Shi, X.-W. Shi, Q.-L. Huang, and F. Wei. An enhanced binary anti-collision algorithm of backtracking in RFID system. *Progress In Electromagnetic Research*, 4:263–271, 2008.

[96] D. Shih, P. L. Sun, D. C.Yen, and S. M. Huang. Taxonomy and survey of RFID anti-collision protocols. *Computer and communication*, 29(11):2150–2166, 2006.

[97] W. J. Shin and J. G. Kim. Partitioning of tags for near-optimum rfid anti-collision performance. In *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC)*, pages 1673–1678, 2007.

[98] C-S. Son, J-S. Park, H-G. Cho, and J-B. Lim. A novel variable-impedance microstrip circuit and its application to direct antenna modulation. In *Proceedings of the European conference on Wireless Technology*, pages 403–406, 2005.

[99] P. Vandenameele. *Space division multiple access for wireless local area networks.* Kluwer Academic Publishers, 2001.

[100] G. De. Vita, F. Bellatalla, and G. Iannaccone. Ultra-low power PSK backscatter modulator for UHF and microwave RFID transponders. *Microelectronics Journal*, 37(7):627–629, 2006.

[101] G. De Vita and G. Iannaccone. Design criteria for the RF section of UHF and microwave passive RFID transponders. *IEEE Transactions on Microwave Theory and Techniques*, 53(9):2978–2990, 2005.

[102] H. Vogt. Efficient object identification with passive RFID tags. In *Proceedings of the First International Conference on Pervasive Computing (Pervasive)*, pages 98–113, 2002.

[103] J. Waldrop, D. W. Engles, and S. E. Sarma. Colorwave: an anti-collision algorithm for the reader collision problem. In *Proceedings of the IEEE International Conference on Communications (ICC)*, pages 1206–1210, 2003.

[104] L. Wang, B. A. Norman, and J. Ragopal. Placement of multiple RFID reader antennas to maximize portal read accuracy. *International journal of Radio Frequency Identification Technology and Applications*, 1(3):260–277, 2007.

[105] T. Wang. Enhanced binary search with cut-through operation for anti-collision in RFID systems. *IEEE Communications Letters*, 10(4):236–238, 2006.

[106] S. Weis, S. E. Sarma, R. L. Rivest, and D. W. Engels. Security and privacy aspects of low-cost radio frequency identification systems. *Security in Pervasive Computing*, 28(2):201–212, 2004.

[107] C. P. Wong. Grouping based bit-slot aloha protocol for tag anti-collision in RFID systems. *IEEE Communications Letters*, 11(12):946–948, 2007.

[108] Q. Xianming and Y. Ning. A folded dipole antenna for RFID. In *IEEE International Symposium on Antennas and Propagation Society*, pages 97–100, 2004.

[109] Z-Y. Yang and J-L. Chen. The simulation and analysis of algorithms for redundant reader elimination in rfid system. In *Proceedings of the Third UKSim European Symposium on Computer Modelling and Simulation (EMS)*, pages 494–498, 2009.

[110] W. Yoon and N. H. Vaidya. RFID reader collision problem: performance analysis and medium access. *Wireless Communications and Mobile Computing*, pages 1–24, 2010.

[111] K-M. Yu, C. W. Yu, and Z-Y. Lin. A density-based algorithm for redundant reader elimination in a RFID network. In *Proceedings of Second International Conference on Future Generation Communication and Networking*, pages 89–92, 2008.

[112] L. Zhang and Z. Wang. Integration of RFID into wireless sensor networks: Architectures, opportunities and challenging problems. In *Proceedings of the Fifth International Conference on Grid and Cooperative Computing Workshops*, pages 463–469, 2006.

[113] N. Zhang and B. Vojcic. Binary search algorithms with interference cancellation RFID systems. In *Proceedings of the IEEE Military Communications Conference (MILCOM)*, pages 950–955, 2005.

[114] X. Zhang and S. B. Wicker. How to distribute sensors in a random field? In *Proceedings of the 3rd International Symposium on Information Processing in Sensor Networks (IPSN)*, pages 243–250, 2004.

[115] F. Zhou, C. Chen, D. Jin, C. Huang, and H. Min. Evaluating and optimizing power consumption of anti-collision protocols for applications in RFID systems. In *Proceedings of the 2004 International Symposium on Low Power Electronics and Design (ISLPED)*, pages 357–362, 2004.

[116] F. Zhou, D. Jin, C. Huang, and M. Hao. Optimize the power consumption of passive electronic tags for anti-collision schemes. In *Proceedings of the 5th International Conference on ASIC*, pages 1213–1217, 2003.