RELIABLE MIDDLEWARE FRAMEWORK FOR RFID SYSTEM

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RELIABLE MIDDLEWARE FRAMEWORK FOR RFID SYSTEM

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To

My inspiration, my maa,

Gultekin Khan,

My love, my whole world,

Anuva and Arisha,

My strength and hope,

Arshad Chowdhury.

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GLOSSARY

α Per message CPU cost (%), p. 54.

$A_{(Path,k)}$ Path level accuracy as a proportion of items correctly detected along a path and total items, p. 85.

$A_{(PR,i)}$ PR level accuracy as a proportion of items correctly detected by PR and total items, p. 85.

A_{sys} System performance as a ratio of observed item by the system compared to actual number of items, p. 85.

$A_{(th)}$ Threshold accuracy is the desired accuracy level of the system, p. 86.

$A_{(VR,j)}$ VR level accuracy as a proportion of items correctly detected in a VR and total items, p. 85.

$ComputationalCapacity(C)$ Computational capacity of a VR that corresponds to communication and computation involved in a particular VR, p. 88.

$conn_{in}$ Maximum number of incoming messages handled per unit time, p. 53.

$conn_{out}$ Maximum number of outgoing messages handled per unit time, p. 53.

dB Decibel, p. 61.

$delta$ sensitivity parameter for space based load shedding, p. 89.

D_i RFID data with ID i corresponds to timestamp and identification, p. 84.

$D_{(proc)}$ Data items to be processed in a VR under heavy load, p. 86.

$D_{(shed)}$ Data items to shed in a VR under heavy load, p. 86.

D_{total} Total amount of RFID data in system, p. 85.

$D_{(total)}$ Total Data items in the system, p. 86.

$expectedTagList_{(p,i)}$ Information from neighbor $VR_{p(i-1)}$ along the path, p. 53.

$FalseNegative$ RFID item missed that are within the reading range of the RFID reader, p. 119.

$FalsePositive$ RFID item read that are beyond the reading range of the RFID reader, p. 118.

GPS Global Positioning System, p. 109.

$GuidanceServer(GS)$ Server that makes decision to guide mobile objects in the environment in a fine grain manner, p. 110.

$Instantaneousload(L)$ Computational Load of a VR that corresponds to communication and computation involved in a particular VR, p. 88.

$L_{(t)}$ Upper limit for instantaneous load, p. 88.

$MAX_{(tags)}$ Maximum number of tags flowing through a path per time, p. 89.

$Message_{in}(source)$ Incoming messages from source, p. 53.

$Message_{out}(destination)$ Outgoing messages to destination, p. 53.

MHz MegaHertz, p. 61.

$missingTagList_{(p,i)}$ Tags expected from $VR_{p(i-1)}$ but not received by PRs, p. 53.

$MobileObject(MO)$ Mobile entity carrying RFID reader and computational device, p. 110.

$Monitoringserver(MS)$ Server that is in charge of coarse grain guidance and monitoring of mobile objects, p. 110.

MPI Message Passing Interface, p. 60.

NS Name Server, p. 50.

$observedTagList_{(p,i)}$ tag information detected by corresponding PRs, p. 53.

PE Pervasive Environment, p. 110.

$PR_{(p,i,j)}$ Set of PRs corresponding to $VR_{(p,i)}$ as $PR_{(p,i,1)}$, $PR_{(p,i,2)}$, .., $PR_{(p,i,m)}$, p. 53.

PS Path Server, p. 50.

QoS Quality of Service, p. 49.

$receivedTagList_{(p,i)}$ Filtered tag information comparing PR inputs, p. 53.

RF^2ID Reliable Framework for Radio Frequency Identification, p. 49.

$RFID$ Radio Frequency Identification, p. 50.

$spuriousTagList_{(p,i)}$ Tags received but not expected from $VR_{p(i-1)}$, p. 53.

tao Sensitivity parameter for time based load shedding, p. 91.

$T_(cycle)$ Time a particular item takes to traverse from source to destination, p. 90.

$T_{(interval)}$ Time interval between read times of VRs, p. 90.

$Total\_Path$ Total number of paths associated with a given VR, p. 53.

$Total\_PR$ Total number of PRs Associated with a given VR, p. 53.

$T_{(read)}$ Time a VR accepts data read by PR, p. 90.

$T_{(window)}$ Window of time considered for load shedding mechanism, p. 88.

$VPath$ Virtual Path, p. 49.

VR Virtual Reader, p. 49.

VR_gCount_{PathID} Final count of number of VRs in new path, p. 54.

$VR\_localCount_{PathID}$ Local copy of final count in each VR, p. 54.

$VR_{(num)}$ Number of VRs along a particular path, p. 88.

$VR_{(p,i)}$ Set of VRs corresponding to a Vpath P as $VR_{(p,1)}$, $VR_{(p,2)}$, .., $VR_{(p,n)}$, p. 53.

$VR_{(p,i)num}$ Number of participating VRs in path P_i, p. 53.

VR_{tr} Minimum number of VRs needed for a new path P, p. 54.

VS Virtual Station, p. 111.

w_{cpu} Average per path CPU load on a VR (%), p. 53.

w_{curr} Current CPU load on a VR (%), p. 54.

w_{est} Estimated load due to a new path P (%), p. 54.

w_{tr} Threshold maximum permissible CPU load on a VR (%), p. 54.

SUMMARY

The reliability of RFID systems depends on a number of factors including: RF interference, deployment environment, configuration of the readers, and placement of readers and tags. While RFID technology is improving rapidly, a reliable deployment of this technology is still a significant challenge impeding wide-spread adoption. This research investigates system software solutions for achieving a highly reliable deployment that mitigates inherent unreliability in RFID technology.

We have considered two different problem domains for large scale RFID deployment. One is item tracking and the other is guidance-monitoring. Item tracking considers applications that have statically placed RFID readers to observe the RFID tagged objects in motion. An airport scenario to observe the tagged baggage or warehouse scenarios to track the tagged goods are examples of item tracking applications. A self guided tour, search and rescue scenario or a visually impaired person looking for direction and guidance in a tagged environment are examples of item location applications. It is observed that there is a notion of path that follows the direction and flow of the mobile items in the item tracking applications and a path gets created along the direction and flow of the mobile object in item location applications. A system level knowledge of the data flow can benefit the system in different aspects such as improved reliability, resource management and real time response. We have designed and implemented an RFID middleware for item tracking: RF^2ID (Reliable Framework for Radio Frequency Identification) to organize and support queries over data streams in an efficient manner. We have developed (1) a virtual reader abstraction to improve the potentially error-prone nature of reader generated data (2) a

novel path abstraction to capture the logical flow of information among virtual readers. Prototype implementation using both RFID readers and emulated readers using an empirical model of RFID readers show that RF^2ID is able to provide high reliability, support path-based object detection and offer efficient resource management. We propose a middleware solution that takes into account the data flow information for item location applications that requires real time response.

The guidance-monitoring scenario considers mobile RFID readers that traverse in a tagged environment. We consider the scenario of an Assisted Living Center for elderly residents as a motivating guidance-monitoring application. The solution for guidance-monitoring system is called *GuardianAngel*. The application scenario considers a tagged indoor environment with residents having their own RFID readers to provide them with adequate information about the surroundings. The guidance and monitoring requirement can be conflicting. The guidance information requires very fine grain information about the environment to make proper decisions. On the other hand, the monitoring system must not have a fine grain knowledge of the residents to protect their privacy concerns. We consider this aspect during the design and implementation. The system is a two layered infrastructure that has the upper layer which is the monitoring layer. This layer is in charge of monitoring of the actors in the environment. The monitoring layer is physically a set of distributed virtual stations that have the knowledge about the environment. The environment itself is equipped with RFID tags. The residents of the environment have a mobile object that has a sensing element and a computing element (e.g., handhold device with a portable RFID reader) - the guidance server runs on this mobile object. The guidance server is in charge of making local decisions for the users. It is resource limited and asks for new information from the virtual stations as needed. The guidance server also provides the monitoring server with the information regarding the status of the mobile object. But the status information is not fine grained - the guidance server wraps up the information over a period of time and over a larger region to obfuscate space and time at the discretion of the user.The system uses the logical path based abstraction to guide the users. We have implemented a real testbed using grid structured RFID devices along with scalability study using emulated RFID readers.

The basic contribution of our work is providing novel middleware solution that is able to serve the application taking into account the inherent unreliability of RFID technology. Our path abstraction that uses the physical flow of data as an ally to generate a logical system level flow enhances the performance in many ways. The contributions of this dissertation are summarized below:

- *Defining novel system architecture for item tracking applications:* We have defined a system architecture referred to as Reliable Framework for RFID (RF^2ID) that takes into account the unreliability of RFID devices and provides a scalable, reliable system architecture for item tracking applications. It uses a distributed system abstraction named Virtual Reader (VR) that handles RFID data in different geographic locations. Virtual Path (VPath) is the abstraction that creates channels among the VRs and facilitates a data flow oriented data management in the system.

- *Implementation of* RF^2ID*:* We have implemented RF^2ID that is able to incorporate physical RFID devices as well as emulated devices for scalability study taking into account various real world challenges of large scale RFID deployment.

- *Load Shedding Based Resource Management:* RF^2ID requires a mechanism to handle unexpected system load in the presence of asynchronous arrival of data items. Space based load shedding and time based load shedding techniques are used in RF^2ID. The basic idea is to exploit the VR and Vpath abstraction to intelligently share the load among the VRs in the presence of high system load, and yet provide some guaranteed Quality of Service (QoS).

- *Architecture for GuardianAngel:* We define an architecture for an indoor pervasive environment which provides novel system abstraction and communication framework. The layered architecture has distributed computational elements known as the virtual station (VS) that are in charge of serving different regions of the environment. The Mobile Objects (MO) are the physical and logical entities that use sensing device and traverse the environment. The environment itself is tagged with RFID. The MO uses its sensing device to make guidance decisions locally. The VS keeps status information of MOs and keeps coarse grained information of the MO over time and space providing a virtual location for each MO.

- *Implementation of GuardianAngel:* We have implemented the GuardianAngle system as defined by the architecture. We have used a testbed that uses real RFID readers and tags in the pervasive environment in a limited laboratory setup. We have also developed a distributed system setup using emulated tags for a scalability study of the proposed architecture. We have also *implemented a prototype application*, to test its feasibility in the real world.

- *Evaluation of the system:* We have conducted extensive evaluation using the real RFID testbed as well as scalability study using emulated readers and tags. The evaluation using the real RFID tags and readers gives us the credibility of the system under various environmental considerations. The large scale experimentations provide us with scalability and feasibility study to strengthen our limited resource study using real RFID testbed.

CHAPTER I

INTRODUCTION

In recent years, there is widespread adoption of RFID technology in various applications. For example, RFID technology is rapidly becoming part of today's life through a variety of applications in smart homes, airports, and supply chain management. With the ubiquity of RFID deployments, there exists a growing amount of data being generated from multiple sources that needs to be processed in order to support user queries. However, handling large volumes of sensor generated data streams stresses even high performance computing resources and broadband network bandwidth. It presents several challenges, especially when these streams are distributed across multiple geographic locations. First, the amount of data from different sources that needs to be organized properly is very large [65], [51], [59]. A retail strategy consulting company estimates Wal-Mart could generate as much as 7.7 million terabytes of data per day if all its items are tagged [105], [60]. Second, because of the nature of RFID applications, the streamed data and possibly legacy data must be fused together in a time-sensitive manner (e.g., using timestamps). Finally, the overall system has to be able to manage complexities in a scalable manner to answer queries efficiently. These problems become more severe in RFID systems where data is generated from error prone devices like RFID readers [38], [47],[57], [72], [61].

RFID readers use radio waves to communicate with electronic tags that vary in type, capability and size. Passive tags, in particular, are gaining considerable amount of attention as a low cost solution for automating a wide range of applications. However, one of the major drawbacks of the readers using passive tags is their unreliable behavior. Typical readers accurately detect tags 80-90% of the time, whereas readers with improved performance have a detection rate of 95-99%. Unfortunately, this rate is adversely affected by different environmental factors such as the presence of metal objects, objects containing liquids, interference from multiple readers, or the presence of multiple tags within close proximity of one another. For example, the detection rate drops to 70% when a reader attempts to detect more than five tags [38], [47]. The RFID reader's inability to read an item within its reading range is referred to as *false negative* reads and the reader's ability to read an item beyond its reading range is called *false positive* read. The existing technology suffers from these false negative and false positive readings.

We take a close look at the possible application scenarios and application specific requirements and try to provide a middleware framework to handle the existing challenges. The broad category of large scale RFID deployment is divided into *item tracking* applications and *item guidance-and-monitoring* applications. Item tracking applications consider a vast application environment where the RFID readers are statically placed at various points in the environment and the mobile items are tagged with RFID tags. The objective is to get adequate information about these RFID tagged items as they flow through the system in real time with high reliability. Example of such an application scenario is an airport baggage handling system where the baggage are tagged with RFID tags and are destined to various routes through conveyor belts. Other application scenarios include supply chain systems where goods are equipped with RFID tags and their flow is observed using RFID readers placed at strategic points. It is observed that there is a notion of *path* as the tagged items traverse from a specific source towards a destination.

The item guidance-and-monitoring considers a different scenario in terms of RFID tags and reader deployment. In this case, we consider an environment that is equipped with the RFID tags and the residents have their own RFID reader to get guidance as well as monitoring support from the system. The environment under consideration can be an assisted living center where the residents require close guidance and monitoring through their daily activities. The level of guidance can be different in a search and rescue scenario where a robot may be equipped with an RFID reader along with a chemical sensor to guide the search and rescue personnel through a safe way in the environment dynamically; monitoring is required for the overall organization among the personnel and information sharing. We observe a *path* as the mobile users equipped with RFID readers explore the environment. The goal is to seek a solution for item tracking applications and item guidance-monitoring applications where large scale RFID deployment is considered.

1.1 Thesis Statement

We use the concept of *path* at system level that is based on the data flow and status of the mobile objects as shown in Figure 1. The thesis statement of this dissertation is as follows:

We can significantly improve system reliability using a data flow oriented path based distributed middleware for item tracking and location applications that employ inherently error-prone sensing technologies, such as RFID.

1.2 Solution Approach

The broader scope of the solution space explored in this dissertation is shown in Figure 1. The RFID infrastructure is at the lowest layer serving both item tracking applications and item guidance-monitoring applications. There are various types of RFID readers and tags such as active tags and readers, passive RFID tags and readers, or environment where a combination of active and passive RFID technology may co-exist. At the top level are applications that can benefit from the RFID deployment. There are tracking applications where various RFID tagged goods are tracked as the items are followed as they flow through a designated source to destination route by statically placed RFID readers. Similarly, there are guidance-monitoring applications where the environment is tagged with RFID tags and the mobile users use their RFID readers to get local guidance information while at the same time the users are monitored at a coarser grain for their safety (in a hospital or an assisted living center). Our contribution is in the middle layer that connects the application layer with RFID infrastructure. We take a close look at the application requirements and figure out the proper system support for such applications. The block diagram illustrates our middleware solutions for item tracking as we have done in the system named RF^2ID and and item guidance-and-monitoring system named *GuardianAngel* that facilitates various large scale RFID deployment. We discuss each of the scenarios (item tracking and item guidance-and-monitoring) separately as the application requirements vary significantly in these two cases.

1.3 Item Tracking

We first concentrate our focus on item tracking applications. We look at application specific requirements, existing solution approaches and our solution scheme in the following subsections.

1.3.1 Requirements

A middleware for RFID deployment requires careful design considerations taking into account the inherent vulnerabilities of these devices. We have designed a novel system architecture that addresses different aspects of such a middleware design. In designing this architecture, we have considered various application requirements that are specific for item tracking applications.

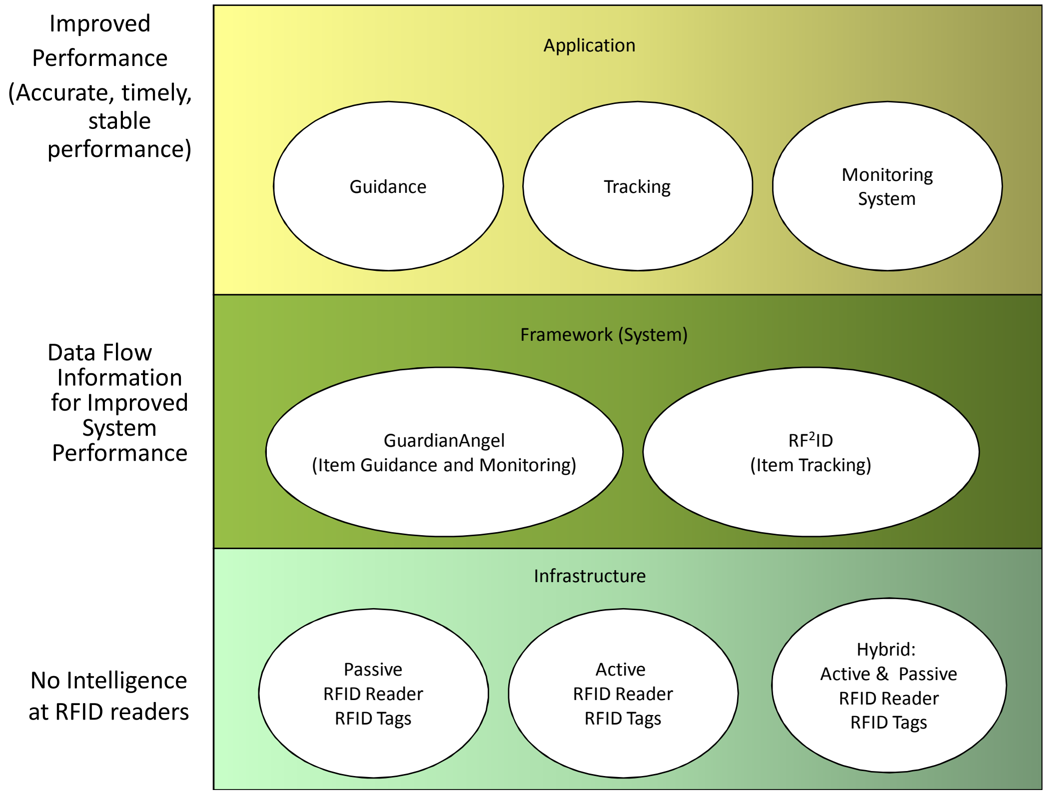


Figure 1: A Block Diagram of the Solution Space Provided as a Framework

1.3.1.1 Reliability

Our primary challenge is to provide system level reliability for inherently unreliable components. The system should be able to provide a certain Quality of Service (QoS) as required by application queries. For example, in the item tracking scenario using passive RFID technology, the RFID data contains many false negative and false positive reads. The system must be able to deliver a level of data accuracy in terms of number of actual items flowing through the system.

1.3.1.2 Load Balancing

System load should be balanced across the computational elements when handling a large amount of data. In real application scenarios in a supply chain environment or in an airport baggage handling system, there are period of times when there is a sudden increase in the amount of items (tagged goods in a warehouse or tagged baggage in the airport). The system must be able to dynamically adjust to unexpected amount of incoming data without hampering the basic operations.

1.3.1.3 High Throughput

The system is expected to provide extremely high update rates from the readers and therefore requires high throughput to handle the sheer numbers of items. The throughput is important for most of the tracking applications that require the systems ability to operate within a bounded time.

1.3.1.4 Scalability:

The system should be capable of handling the addition of new readers or to dynamically ignore malfunctioning readers without significantly impacting performance. Also the system should not contain a dependency on a single point of failure which occurs in centralized set ups.

1.3.1.5 Data Organization

The data organization process requires cleaning up of large amount of RFID reader generated data (e.g., removing duplicate reads), timestamping the data in a consistent manner (consistent in spatial and temporal relationship of the data items), sorting the data with respect to its destination and type (e.g., observed items and missing items) and finally being able to deliver the data according to application requirements. In summary, for large amounts of data there is a need to properly sort and organize data for efficient query responses.

1.3.1.6 Real Time Responses

The system must process appropriate feedback to the application within a predefined window of time. In many of the item tracking applications, there are requirements for real time observational data. For example, real time inventory in supply chain systems asks for the real time information regarding the tagged goods. The system must be able to provide tracking information within a predefined window of time that is acceptable for that particular application.

1.3.2 Existing Solution Approaches

There have been several recent proposals involving middleware systems for RFID deployment. The Savant architecture presented by the MIT Auto ID Lab presents a framework for management of RFID generated data through data capturing, monitoring and transmission [91]. A Pervasive environment is built on the savant architecture [41] that tracks mobile RFID tagged objects. A middleware solution for RFID devices is proposed in RFIDStack [46] which uses aggregation and filtering mechanism on RFID data for efficient data management. The High Fan-in System [47] takes into account the volume of data produced at different level of a sensor deployment and proposes a specific topology for data management. WinRFID [81] presents a middleware solution for RFID devices that takes care of the details of network communication and data management for a distributed environment.

The focus of our work is complementary to these systems. In our work, we focus on the inherent unreliability of RFID systems, and ask whether the reliability can be improved using a middleware system. We use the nature of the data flow as our ally to improve reliability. Further, the data flow can help in data organization as well, which has been the focus of earlier systems. For example, consider a typical RFID deployment scenario in a warehouse. RFID readers are placed at appropriate locations, and they continuously read tags associated with the moving items, e.g., palettes. Often, palettes of a particular item type follow the same physical path from an entry point to the designated destination in the warehouse. Therefore, for many applications, generated tag data can be categorized based on their physical flow. Recent studies have addressed the resource management problem in large scale RFID systems as well. The heuristic based solution [44] provides near optimal reader to tag assignment for statically placed reader and tags rather than considering tags in motion for item guidance-monitoring applications. Load migration based approach is used in various research works for RFID data. Examples include a mobile agent [39] to re-adjust imbalance of load, and the connection pool based method [80] where load is re-adjusted from heavily loaded nodes to lightly loaded nodes. Load migration based techniques are not very suitable for streaming data to meet real time constraints [98], [64].

1.3.3 RF^2ID for Item Tracking

We make the following *contributions* to address the item tracking problem and provide an effective solution approach:

1.3.3.1 Study of the unreliable behavior of RFID devices

A middleware for RFID devices needs to take into account the inherent unreliable nature of these devices. To have a better understanding of the RFID readers and tags, we have done an extensive study of these devices to identify the variety of parameters that affect RFID reader performance.

1.3.3.2 Design and Implementation of a path based system architecture

In item tracking applications, items follow a path from source to destination. The key idea is to allow collaboration among resources along a particular data flow path. A system that has an understanding of the data flow at system level has been developed as RF^2ID (Reliable Framework for Radio Frequency Identification) to combat the error prone nature of the RFID technology[16]. By using redundancy and exploiting the relative flow of RFID tagged objects with respect to the readers, RF^2ID increases the reliability of an RFID deployment. RF^2ID provides two system level abstractions for increasing the reliability: *Virtual Reader (VR)* and *Virtual Path (VPath)*. Each VR is assigned to a distinct geographical region and by collecting data from physical readers in its vicinity, it locally increases the reliability of the deployment. Further, the VRs in the direction of flow of the items form a logical path (VPath). By exchanging data with one another along the VPath, the VRs further increase the global reliability of the deployment. The net result of this middleware is to increase the reliability of the entire deployment (by reducing the number of *false negatives*, i.e., the number of tags that are missed by the system) in spite of the error prone nature of the physical readers.

1.3.3.3 Incorporating load shedding based resource management in RF²ID

We deal with the large volume of data and the time sensitive nature of both tag and query processing, by incorporating *cooperative load shedding* into the RF²ID middleware. The key insight is once again to leverage the notion of *path* for dynamic load distribution among the VRs under heavy load for item tracking applications. We propose intelligent load shedding mechanisms that avoid or minimizes data loss - when one VR sheds load, another VR along the same path most likely covers for the data loss by the first one. Two different load shedding approaches are presented here: *space based* load shedding mechanism and *time based* load shedding mechanism. In the space based approach, each VR dynamically decides to read a subset of the tags on the path that it is participating, based on their physical ordering in space. In time based load shedding, each VR dynamically decides to read tags for a chosen time interval.

1.3.3.4 Evaluation of RF²ID

We have evaluated the system using a real testbed using passive RFID readers (ALR-9800 readers) and tags (Gen2 tags) as well as emulated readers in a large distributed setup for scalability study. We have done detailed evaluation of the system to validate the scalable solution and resource management techniques using the load shedding mechanisms.

1.4 Item Guidance-and-Monitoring

The focus of the item guidance-monitoring problem is different as it considers monitoring and guidance support in an indoor environment. It is interesting to note the limited incorporation of pervasive technology in our daily lives. For example, consider the following hypothetical scenarios in an assisted living center for elderly residents: Grandma Ayesha is not able to locate her medicine box with her impaired vision. She requires assistance as she moves along the center. On the other hand, uncle Joe, a quiet person who spends a large amount of time isolated in his room, falls and is injured in the bathroom, but due to his solitary nature his caretakers do not notice his situation.

These hypothetical scenarios are meant to draw attention to situations where non-intrusive monitoring and guidance can enhance the quality of life as well as ensure the well-being of residents in such environments. The problem is challenging since neither Grandma Ayesha nor Uncle Joe would feel comfortable with an intrusive monitoring system (such as video cameras or wearing an ID badge) that would reveal the details of their daily lives to all and sundry. We define this problem in the pervasive environment as a *monitoring and guidance requirement*, where individuals seek guidance information in a complex indoor environment at a desired level chosen by them without compromising privacy.

The monitoring and guidance facility introduces challenges in the requirements. A robust guidance system requires positioning information, which enhances the monitoring capabilities. However, monitoring individuals at a fine grain level is not desirable for reasons already mentioned. So we ask the questions: (1) What are the requirements of a simple pervasive environment? (2) What are the challenges in existing solutions? (3) What is the system level support required to bridge the gap between existing technology and the requirements? We present the answers to these questions in this work.

1.4.1 Application Scenario and Requirement Analysis

The applications we consider are best suited for environments that are statically tagged with an RFID location grid. This would be especially useful for a visually impaired person to be self-reliant within a large office complex, hospital, etc. Equipped with a gadget that combines an RFID reader and an audio system that gives verbal instructions, such an individual would be able to chart out a route unassisted through an unfamiliar large indoor environment. Essentially, the fixed RFID tags enable the dynamic creation of a *path* from source to destination. A second use case for such a static deployment of RFID tags is in *search and rescue* operations following either a man-made or a natural disaster. A robot or a swat team may use this infrastructure to dynamically chart out paths that are reachable within the indoor environment following the disaster, as well as locate assets (humans and articles of value) within the affected environment.

While the details of each specific application may be different, they all pose some common requirements. We investigate such common requirements to design a middleware system solution. The premise in this discussion is that the application comprises mobile agents that use the RFID-tagged environment for making forward progress.

From an application perspective, the middleware should provide the following types of information to the mobile agents in the application:

1.4.1.1 Current location

The mobile agent may need this information to make some local decisions (e.g., have we arrived at the destination yet?). This information is best presented in some familiar form such as GPS coordinates.

1.4.1.2 Routing information

The mobile agent would benefit if the middleware could provide a route given the current location and the desired destination.

1.4.1.3 Assets in the neighborhood

This would be particularly useful in asset location applications as well as self-guided tours in museums and the like. Based on the current location information, the middleware provides a map of assets in the neighborhood.

1.4.1.4 Terrain

The kind of information envisaged here includes obstacles (e.g., doors, stairwell, etc.) as well as landmarks (e.g., information desk, copier room, etc.). This information serves the mobile agent to make local routing decisions to destinations when there are multiple paths available as well as seek help if needed.

1.4.1.5 Message board

This allows a mobile agent to share information with other agents if so desired. Essentially, this allows the mobile agent to leave electronic *bread crumbs* (either signed or anonymous) that may be useful for other applications or agents that use the same infrastructure.

1.4.2 Existing Solution Approaches

The GPS based guidance systems do not cover the indoor scenario. The low cost of sensor devices such as passive RFID technology opens up many new possibilities. RFID readers use radio waves to communicate with electronic tags. There has been previous research investigating indoor positioning systems, including the Active Badge location system [89], Radar [23], Cricket [93], LotTrack [101], and Landmarc [76]. The goals of these systems are to figure out the precise location information.

There are two major differences of our work related to these existing systems. First, we do not present a positioning system to identify the exact position of a mobile person; rather, we want to give them a sense about where they are in a more coarse grain level at low cost. Second, we differ due to the fact that we do not expect the user to wear a sensor badge or tag. Instead, we assume the user to possess a mobile sensor device that they can carry around that allows them to be in control of when they want the environment to know about their whereabouts. The environment itself is equipped with low cost passive RFID tags. The Sixth Sense [83] system considers a tagged environment covered by readers and incorporates privacy concerns as the entire environment is being sensed constantly. Similarly the MAX system [112] considers a hierarchy of tagged environment that is observable by the base stations containing reader elements. Fundamentally, our approach is different in that the intent is to enable the user to sense the environment and update the environment at their will rather than the other way around. This circumvents privacy and security concerns that would require the user to trust the environment for such information sharing.

For those cases in which information sharing is desired, security can be improved by the use of available protocols for two-way authentication [26]. Such techniques can be plugged into our guidance and monitoring framework, but are outside of the purview of this research, so they will not be further discussed. There have also been research efforts in guidance systems for various outdoor scenarios, but these differ from our own in that we focus on an indoor environment. Context aware frameworks [14], [28], [15], [62] would serve to enhance the robustness of the solution approach.

1.4.3 GuardianAngel for Guidance-Monitoring

We have developed a two layer middleware solution named *GuardianAngel* that provides system support in such a pervasive environment. The lower layer, named as the *Guidance Layer*, provides the locality information to the user to make guidance decisions. The upper layer, known as the *Monitoring Layer*, has the global knowledge of the environment. The environment is equipped with low cost RFID tags. The guidance layer is supported by a hand held device that has an RFID reader attached to it. The guidance layer is thus able to provide information regarding the resident's current location and immediate objects by sensing the environment. The monitoring layer has the information about the entire environment. The guidance layer under user control periodically updates coarse grain information defined as the *virtual location* about the resident to the monitoring layer. The guidance layer with its limited capability only keeps partial map information that is acquired on demand from the monitoring layer. If we go back to our previous example: Grandma Ayesha can use her hand held device through the guidance layer to figure out where she is and where her medicine is. Uncle Joe is periodically sending information about his coarse grain location information to the monitoring layer. It detects an unusual amount of time spent in the restroom and sends out an alert signal to the application layer.

The novelty of our approach lies in its uniqueness along three dimensions: first, by virtualizing the user position information; second, by providing a more natural way of gathering environmental information using RFID tags in an unobtrusive manner under user control; and third, by enabling the deployment of large scale indoor environment using low cost passive RFID tags and mobile readers. Specifically, our contributions are summarized in the following subsections.

1.4.3.1 Defining an architecture

We define an architecture for an indoor pervasive environment that provides a novel system abstraction and a communication framework. The layered architecture comprises distributed computational elements known as the virtual station (VS) that are in charge of serving different regions of the environment; the Mobile Objects (MO) are the physical and logical entities that use the sensing device and traverse the environment; the environment itself is tagged with RFID tags. The MO uses its sensing device to make guidance decisions locally. The VS keeps status information of MOs and keeps coarse grained information of each MO over time and space (providing a virtual location) that hides the fine grain positioning information of each MO.

1.4.3.2 Implementation of the middleware system

We have implemented the GuardianAngle system as defined by the architecture. We have used a testbed that uses real RFID readers and tags in the pervasive environment in a limited laboratory setup. We have also developed a distributed system setup using emulated tags for a scalability study of the proposed architecture along with an *implementation of a prototype application*, to test its feasibility in the real world.

1.4.3.3 Evaluation of the system

We have conducted extensive evaluation using the real RFID testbed as well as scalability study using emulated readers and tags. The evaluation using the real RFID tags and readers gives us the credibility of the system under various environmental considerations. The large scale experimentations using emulated readers and tags strengthens our limited resource study that uses a real RFID testbed.

1.5 Item Tracking Applications and Item Guidance-Monitoring Applications

Our experience on working with RFID technology has given us the opportunity to deal with the limitations of the current technology and has guided us to come up with simple but powerful solution approaches to use in various scenarios. There are common goals to achieve in item tracking applications and item guidance-monitoring applications which ask for a scalable solution having knowledge of data flow through the system. The flow of data is different for two different application requirements as the item tracking aims to share the tagged object through a path while the guidance-monitoring application asks for status information to be shared across a designated path. The way the information is shared is very unique in each individual application scenario. For example, the goal of the item tracking application is transparency of information, being able to determine the object's placement in a particular window of time. On the other hand, the item guidance-monitoring applications bring in challenges as information transparency conflicts with the privacy requirements of the indoor residents. We present two distinct solution approaches that are very specific for the individual problems in RF^2ID and GuardianAngel.

1.6 Major Contributions

We describe the major contributions in the following subsections.

1.6.1 Path Based System

We present a data flow oriented approach in designing the middleware using the system abstraction called *path*. A path allows interesting ways to improve the system performance. The generic concept of data flow oriented path is used to increase the system accuracy for item tracking applications in RF^2ID. The path is further used to dynamically balance the system load in the presence of unexpected system load for item tracking applications. For item location applications as presented in GuardianAngel, the concept of path is used to support guidance and monitoring.

1.6.2 A system for Unreliable Devices

Large scale deployment of sensor devices can be error prone as most of the scenarios have some level of physical inaccuracy. The RFID devices are error prone and are very sensitive to the environment they are deployed in. The environmental factors like presence of metal objects or liquid can increase the level of inaccuracy of the RFID readers. The incorporation of motion, large number of items also play a role in the reading of the RFID devices. Our system takes into account the basic unreliable nature of these RFID devices and uses a redundancy and data flow centric design to improve the system accuracy.

1.6.3 Human Centric Design

The consideration of the users in the item guidance and monitoring system introduces interesting design considerations. We used an architecture that provides unobtrusive system solution for the users. The user is able to control the amount of data being shared among the users and monitoring servers. The consideration of the user's preference for an unobtrusive system is a way to bridge the gap between a system designer and the user centric choices.

1.7 Outline of the Dissertation

We organize the dissertation in the following manner: the detailed background of the system is presented in Chapter 2 that covers the two major application scenarios and the basic working principles of different types of RFID technology. We then focus our study on the properties of RFID technology which asks the following questions: How unreliable are these RFID readers and tags? What are the factors that affect the performance of these RFID readers and tags? The answers to these questions are presented in Chapter 3. The unreliable property of the RFID readers creates the motivation for a reliable, scalable solution approach. We discuss the solution for item tracking named RF^2ID in Chapter 4. The resource management requirements and a suitable solution using the data flow centric concepts are discussed in Chapter 5. It discusses how the system incorporates load shedding based resource management techniques using a time based load shedding mechanism and a space based load shedding mechanism. We leverage the data flow information used in RF^2ID to intelligently shed load dynamically in the presence of unexpected overflow of data.. The item guidance-monitoring solution GuardianAngel is presented in Chapter 6.

The unique challenges and lessons learned developing the two solution approaches are discussed in Chapter 7. The conclusions and future work are presented in Chapter 8.

CHAPTER II

BACKGROUND

This section presents the background information that enables us to understand the existing applications that use RFID technology along with the very basic information on how the technology operates. There are a wide range of applications that use the basic RFID technology. We focus on mainly applications concerning large scale deployment of the technology. We categorize them into two general classes of large scale RFID deployment as *item tracking applications* and *item guidance-monitoring applications*. We discuss each type of applications in the first subsection. We then explore the RFID technology itself based on various kinds of existing RFID tags and readers and their operating principles. We also discuss various factors that impact the decision on which particular RFID technology to choose for a particular application scenario. We use this chapter to set the stage for the research presented in the subsequent chapters.

2.1 Applications using RFID Technology

RFID technology is rapidly gaining attention in various applications. There are reference based applications such as collection tolls without stopping the vehicle, gaining access in the building, automated parking etc.; there are monitoring based applications in automobile stores and merchandise stores; there are tracking applications in libraries, airport and retail industries; there are location based applications in search and rescue scenarios [71]. There are set of medical applications that links patients with drugs, personnel with patients and links equipment access to the hospital personnel. The RFID technology has been successfully used in sports event to track the athletes and their race time in recent days [74],[94], [1]. We address the application scenario that considers large scale deployment of RFID devices. There are a set of applications called *item tracking* applications and *item guidance-monitoring* applications that we are going to mainly focus on for our research work. We discuss these two applications in detail.

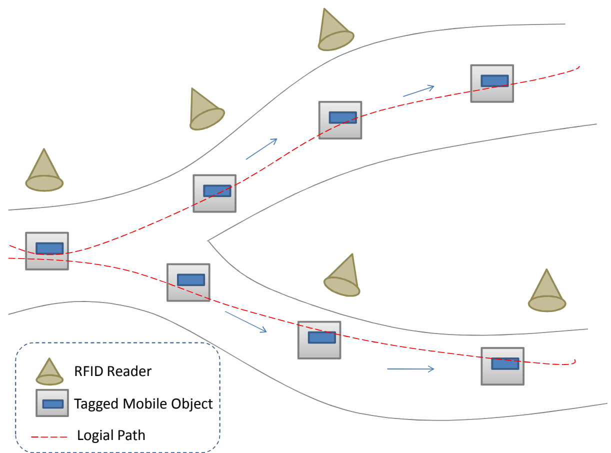


Figure 2: Basic Concept of Item Tracking

2.1.1 Item Tracking Applications

The item tracking applications consider taking notes on the RFID tagged items using static RFID readers. In the item tracking applications, statically placed readers are in charge of tracking tagged items in motion as shown in Figure 2. The warehouse scenario where objects are tracked as the items arrive and leave and the airport baggage claim system where tagged baggages are tracked through the conveyor belts are examples of tracking applications. It is observed that there is a flow of data that creates a path as the tagged items traverse through the system. The main challenges faced by large scale deployment of item tracking applications are the unreliable RFID readers as they provide false negative and false positive readings. False negative readings refers to the reader's inability to read an existing item and false positive is the reader's reading of an item that is beyond its reading range. Then there is the challenge that a large amount of data is produced as the items traverse through the system in item tracking applications. The system must be able to provide adequate support for large scale expected and unexpected (sudden) data arrival.

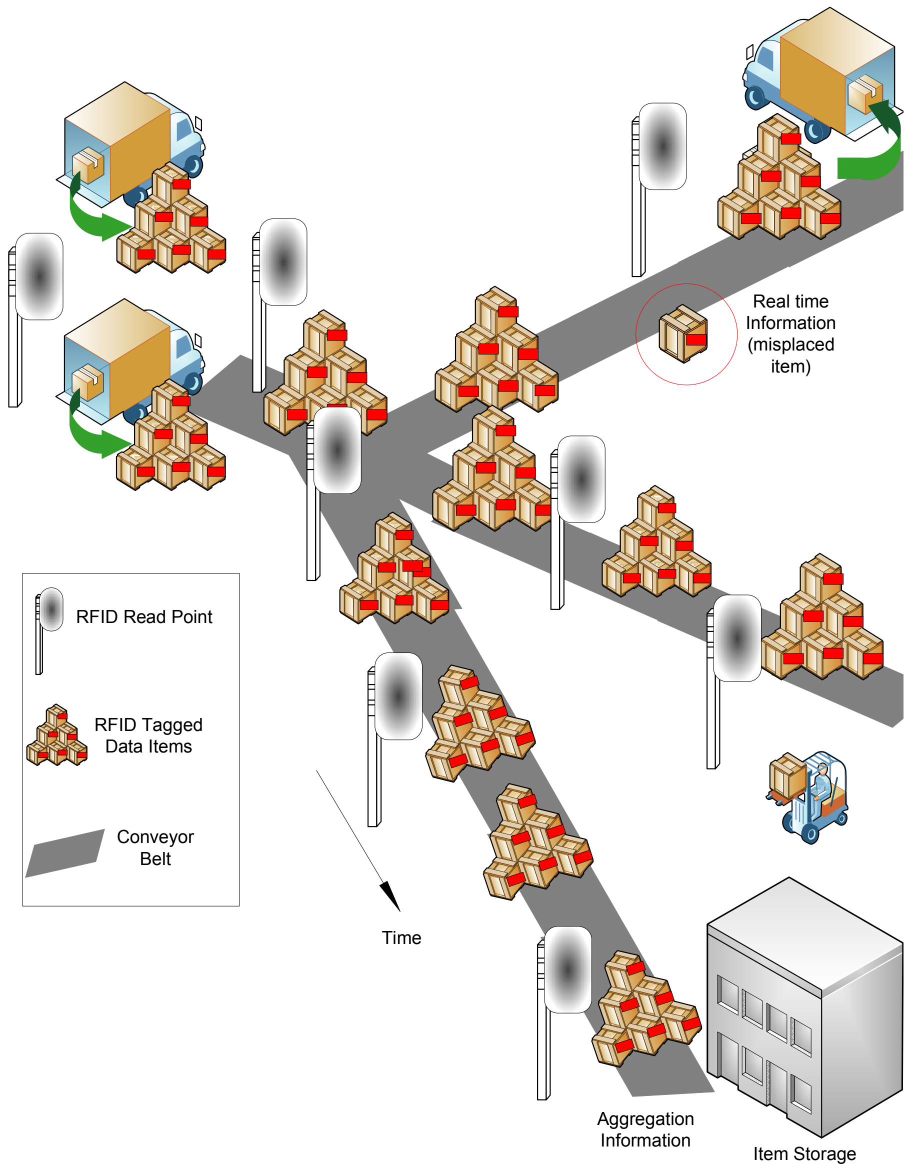


Figure 3: Item Tracking Application Scenario

There are many large scale item tracking applications using current RFID technology. A warehouse scenario which uses RFID tags to monitor and note real time information as shown in Figure 3 is a classic example of item tracking using RFID technology. There are many interesting item tracking deployment mentioned in the literature [74],[94],[10],[4],[5], [88] and shown in Figure 4:

Figure 4: Example of Item Tracking Applications [10],[4],[5] (a) RFID technology enabled toll booth (b) The RFID tag used in toll booth (c) RFID enabled fast tracking in FedEx

- *Logistics and Supply Chain:* In this case, the RFID tagged containers and items are tracked as items enter, traverse through the system and leave.
- *Baggage Entry:* Airport baggage system uses RFID technology for easier tracking of baggage and proper management of baggage destinations.
- *Livestock or Pet Tracking:* RFID tagged items are tracked as they live in the environment and appropriate actions are taken if they are lost.
- *Traffic Tracking:* Speed pass and E-pass pay tolls around USA uses wireless RFID tags to track vehicles to pay tolls, other fees.

- *Express Parcel Tracking:* It is used in fast tracking of package delivery in many companies (e.g., FedEx) using RFID technology.
- *Library Systems:* RFID tagged library books are managed using passive RFID technology to keep track of checked in and checked out books.

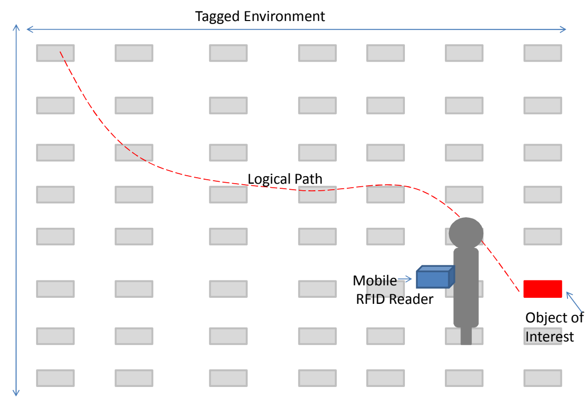


Figure 5: Basic Concept of Item guidance-monitoring

2.1.2 Item guidance-monitoring Applications

The problem of *item guidance-monitoring* considers a complimentary scenario of tracking applications as shown in Figure 5. It assumes a tagged environment that is relatively static and mobile readers are used to locate objects of interest. A search and rescue scenario where rescue personnel are equipped with RFID readers is an example of item guidance-monitoring. It is observed that a path gets created as the rescue personnel traverse the environment. The main challenge in this scenario is to provide adequate guidance to a user without hampering the individual's comfort level.

There are many interesting proposals and approaches towards item guidance-monitoring applications. The real implementation of RFID technology requires various considerations such as interference with the environment and privacy concerns of the users. There are many proposals for such application scenario (such as [74],[94],[8], [9]). Figure 6 shows an example.

Figure 6: Examples of Item guidance-monitoring Applications [8], RFID Reader on a patient

- *Healthcare Industry:* RFID technology can be used in the hospitals, nursing cares where the residents can achieve improved care using the technology in an RFID enabled care unit.
- *Search and Rescue Scenario:* Search and rescue becomes very challenging for complex indoor environment. An RFID enabled building can be searched using robots and rescue personnel equipped with RFID readers to make real time decisions.

2.2 RFID Technology

We discuss the various components of the RFID technology in this section. We initiate our discussion with RFID tags.

The RFID tag is a device that is attached to other items for identification. It consists of a micro chip and an antenna. RFID tags can be categorized in many different ways. The tags can be divided by their operational methodology or data acquisition techniques. We discuss different types of tags in the subsequent sections.

2.2.1 Tag Types by Operational Methods

The basic operational methodology divides the tags in certain types. RFID tags can be categorized as active, passive and semi-passive (semi-active) [11]. EPC global classification divides them according to four categories: class 1 tags are passive tags, class 2 are passive tags with additional memory and commands, class 3 are semi passive tags. As the name suggests, the active tags are always active, semi-passive tags are sometimes active and passive tags are not active unless activated externally. We describe each type of tags in the following subsection.

2.2.1.1 Active Tags

Active RFID tags are often known as beacons. The active tags have their own power source to power the IC and generate an outgoing signal. The active tags consist of an on board power supply, an active transmitter and an active receiver. The specification defined by ISO 18000-7, the active tags are not allowed to have tag to tag communication - the communication takes place through the reader. The active transmitter of the tags allows longer transmission of signal and active receiver enables receiving of signal from a longer distance compared to ones in passive tags. Many of the active tags send out signals in a fixed interval to minimize the power consumption. There are existing active RFID tags that have ranges as far as tens of meters and limited battery life that can be as long as 10 years. The lifetime of active tags depend on the power supply entirely as it is not able to harvest energy from the environment.

2.2.1.2 Passive Tags

Passive RFID tags do not have an internal power supply. The incoming electrical current induces the antenna to power up the CMOS Integrated Circuit (IC) and to transmit a response. The reader antenna has to be specially designed to collect power from the incoming signal as well as transmit outgoing response. The absence of on board power supply reduces the size of such tags. The life time of the passive tag is unlimited. The reading distance can range from 2 mm to few meters. The passive tags are the cheapest among all the types of tags. The passive tags are divided into three categories based on their operational process: near field tags, far field tags and SAW tags.

Near Field RFID: The near field tags require physical proximity between the reader and tag. Near field tags use magnetic coupling. It is illustrated in Figure 7. Here the reader generates the magnetic field which excites the tag coil (antenna). This works within the reading distance of 1 meter. The boundary of near filed is inversely proportional to frequency and approximately equal to $c/2 * \Pi * f$ where c is the speed of light, f is the frequency. Thus only low carrier frequencies are used which requires a large antenna coil. Another limitation is its low bandwidth causing low data rate in near field RFIDs. But the near field RFID uses long wave lengths for communication which makes them very efficient regardless of what is attached to them. The signal is able to travel through many non-metallic substances and non-penetrable substances such as water and metal. The most common operating band is 13.56 Hz band for commercial use.

Far Field RFID: Far field RFID are different from near filed ones and use traveling waves to transmit and receive information as shown in Figure 8. An antenna requires to satisfy the distance $d > max(\lambda, D^2/\lambda)$ to be in the far field where D is the largest dimension of reader antenna. Antenna can be small compared to near filed RFID. Far field tags have many applications such as toll collection, automated assembly line

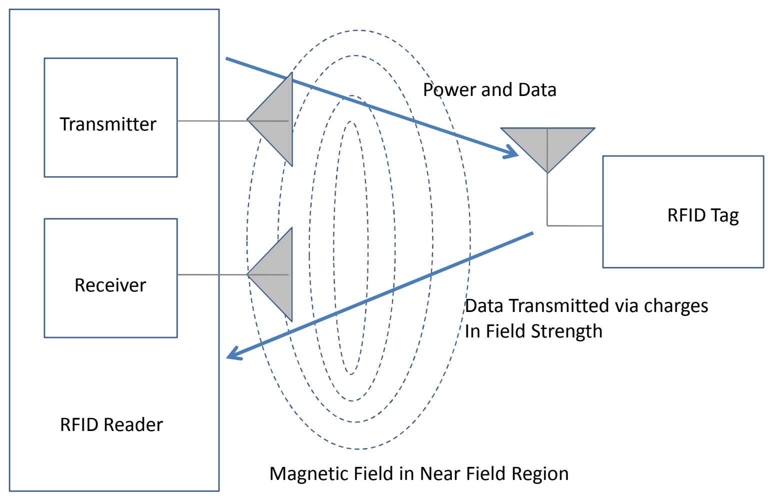


Figure 7: Near field RFID

etc. where the tag does not need to be physically close to the reader. The far field antennas are implemented using higher frequency signal as the low frequency signal would require an extremely large antenna size. Most of the far field tags use UHF and microwave bands. The commonly used bands are 915MHz, 2.4 G Hz and 5.4 G Hz. One limitation of far field tags is the vulnerability to the material attached to it (e.g., metal or water). The advantage of these tags are the small antenna size which requires low fabrication and assembly cost. The improvement in silicon technology has allowed tag designs that consume very low power.

SAW Tags: The SAW tags work on a different principle compared to near field and far field tags. It uses the surface acoustic wave (SAW) technology. The tags were bulky in size when first introduced but with improved technology of having smaller sizes these tags are gaining attention in recent days. It has the built in capability of measuring the temperature of an object and estimate real time location of the object. It has higher reliability in presence of water and metal. Although the SAW tags have

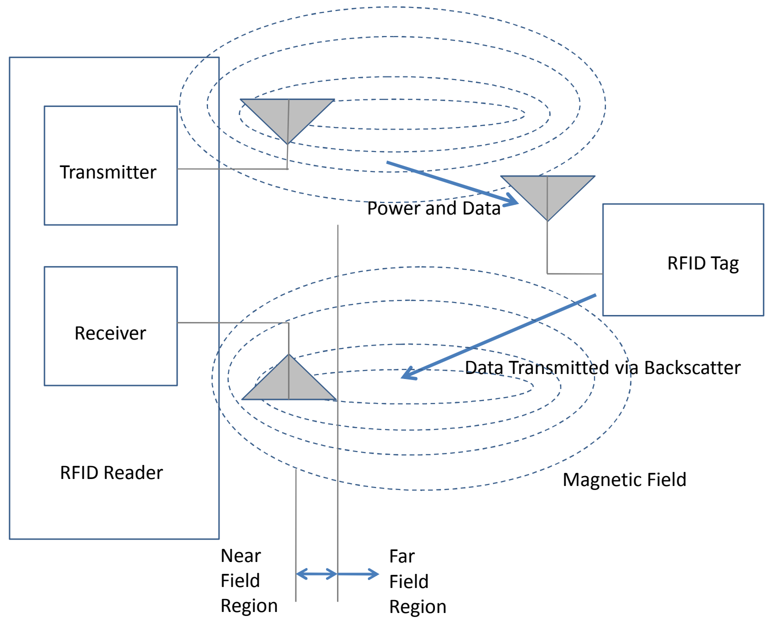


Figure 8: Far field RFID

many advantages over silicon based tags, it has not gained the commercial acceptance for widespread adoption.

2.2.1.3 Semi-Passive Tags

Semi-passive tags have an internal battery attached to it. It works in similar way as the passive tags do except for the fact that the internal battery allows the tag IC to be constantly powered. This removes the necessity of the antenna to be collecting power from incoming signal. These types of tags are faster in response and have a stronger reading ratio compared to passive tags.

2.2.2 Tag Types by Operational Methods

RFID tags can be again classified based on the data acquisition techniques. The data in a tag are acquired in various methods where each method has its own advantages and limitations. The tags are classified by data acquisition techniques into five major categories: pre-encoded tags, Write-Once-Read-Many (WORM), Erasable tags (EEPROM), Read-Write tags and Database on a tag. The following definition is used to define the data acquisition process:

Commissioning: The initial data entry technique to the tag is known as commissioning.

We describe the different tag categories here.

2.2.2.1 Pre-Encoded Tags

The pre-encoded tags are commissioned at the manufacturing time. Users request to encode specific information can be applied to the tag only it is placed before the actual manufacturing process. The users do not have control to change the tag information. These tags are used in small scale applications like pilot projects of RFID where the user wants to explore how the RFID enabled environment performs.

2.2.2.2 Write-Once-Read-Many

This class of tags are commissioned by the user unlike the pre-encoded tags. The encoded information is permanent once it is written to the tag. These tags are also known as field programmable tags. These tags are used in many smart labels.

2.2.2.3 Erasable Tags

The Erasable tags, as the name suggests allow information to be erased after it is commissioned to the tag, adding more flexibility to the previously mentioned categories. This type of tags can be rewritten multiple times. It uses electronically erasable programmable read only memory (EEPROM). Typically these tags can preserve information as long as the oxide layer of the EEPROM is available which is close to ten years for many tags.

2.2.2.4 Read Write Tags

The read-write tags are programmed using a reader at any point of time. Data can be added to the tag as the tag traverses through the system. This capability enables these set of tags to be used in many different application scenarios. These tags can be attached to other sensors for rich set of environmental information. The capability of embedding important information in the tag opens up security concerns. There are active and passive read write tags available commercially.

2.2.2.5 Database on a Tag

These tags use a compression mechanism to hold a large set of data in the tag. The large set of data can comprise of an entire database. Automated entry of items in a system that has numerous individual items is an example application of such tags.

2.2.3 Considerations for Choosing Particular Type of Tag

The large variety of available tags make it very important to make a decision on which type of tag to consider for a particular application scenario. There are many different factors that are considered that we present in the subsection.

- *Physical Size of Tag:* The physical tag size is important when tags are attached to various items. For example in merchandise scenario, the attached label must be readable and prominent in some cases (e.g., where tags are used to show the item's lifetime for a perishable item), or can be as small as possible for some cases e.g., clothes to describe the item itself.

- *Durability of Tag:* The tag selection must consider the environment into account. For example there are environments that require special considerations for the tag like extreme cold temperature or environment containing moisture. The tag durability depends on many of these environmental factors.

- *Reusability of Tag:* If the application requires multiple write operations, tag selection should be based on them.

- *Sensitivity of Tag:* The tag sensitivity in many cases depend on the parameters like tag to reader orientation or reader to tag distance. The application must take into account various factors to make sure the system is performing in the desired manner.

The RFID antenna is discussed in the next section.

2.2.4 RFID Antennas

The basic function of an RFID antenna is to convert electronic signals and broadcast them into radio waves. Antennas are present in RFID tags as well as RFID readers. The high frequency antennas require very careful design as they cannot tolerate much error. On the other hand, the low frequency antennas are tolerant of minor deviations [29].

We discuss some of the basic properties of the RFID antennas that impact the performance.

2.2.4.1 Impedance

The resistance of an electronic component to alternating current is called impedance, the unit measurement of impedance is in ohms. The performance of an RFID antenna depends on the matching impedance of the antenna and device circuit. The power is able to flow through the reader to antenna if the impedance is matched. Otherwise, if the impedance of the reader does not match that of the tag, some power is returned to the reader and this can decrease the reader performance and in many cases even damage the reader. The antenna impedance is affected by various environmental factors such as the materials around the environment.

2.2.4.2 Polarization

The polarization of the radio wave is perpendicular to the direction the wave travels. There are linear polarization antennas where the polarization is constant as the wave travels. The linear polarization antennas can be horizontal or vertical. There are also circular polarized antennas which rotates in a place that is perpendicular to the direction of the wave. The polarization also affects the reader to antenna performance heavily - the best performance is achieved when the reader and tag antenna have aligned polarization. Thus the best performance is achieved when the reader and tag are placed in parallel for linear polarization antennas. For circular polarization antennas the performance is constant and it is useful when the reader to tag orientation can be variable.

2.2.4.3 Gain

Gain is the measurement of antenna performance - it is measured as the proportion of the output in a given direction against a standard. It is measured in decibels (dB). A higher power antenna radiating in a given direction requires the other antenna to radiate in a different direction.

2.2.5 Basic RFID Operational Technology

The basic Radio Frequency Identification system has three major parts. It consists of a scanning antenna, a transceiver with a decoder to interpret data and a transponder also known as the tag which contains the information.

The scanning antenna is responsible for delivering Radio frequency signals in a relatively short range. The RF frequency enables the communication with the transponder and provides energy for the transponder to respond for the passive RFID tags [12]

2.2.5.1 Passive RFID Operation using Backscatter communication

The passive tag contains an antenna which serves two purposes. First, the antenna stores energy from incoming signal. Second, the antenna also communicates back to the interrogator. The amount of energy a tag can preserve is affected by several major factors such as antenna to tag distance, the transmission power of interrogator

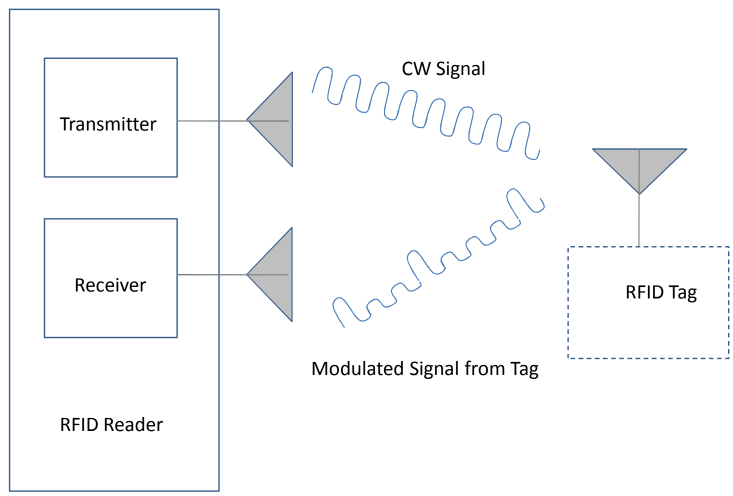


Figure 9: RFID Operation using backscatter method

and efficiency of tag antenna.

The backscatter modulation works in the following steps as shown in Figure 9. First, the reader sends out a continuous wave signal to the tag known as a CW signal. Second, the tag uses the electromagnetic energy to do two things: (a) power up and (b) operate. Third, the tag modulates into pre programmed code and sends out a modulated reflection of CW signal.

2.2.5.2 Active Tag Operation

Active RFID tags contain their own power supply, an active transmitter and active receiver. The active receiver is able to decode even very weak signals. And the active transmitters have a longer range compared to backscatter communication. The active tag can transmit a signal at a specific power level regardless of the power it received from the interrogator. The lifetime of the active tags are limited by the power supply.

2.3 Summary

In this section we concentrate on the basics of RFID technology and its various applications. We focus on item tracking and item guidance-monitoring applications for large scale RFID deployment. The item tracking applications consider statically placed RFID readers to track mobile tagged items. The item guidance-monitoring applications, on the other hand, assume a tagged environment where mobile RFID readers locate objects of interest. We have discussed the different types of RFID tags which varies in operating principles and reading strengths.

CHAPTER III

STUDY ON RFID READERS

The goal of this chapter is to understand the physical behavior of RFID devices under various environmental conditions. This exploratory evaluation gives us insight about the problems large scale RFID deployments would face and thus provide us a motivation for a reliable solution. The effect of physical conditions like item speed or presence of multiple tags in the environment are studied as these conditions are present in large scale item tracking applications. We study the passive RFID reader-tag behavior and active reader-tag behavior in this section. Our study points out the limitations and strengths of different types of RFID technology.

3.1 Basic Properties of Passive RFID Devices

An RFID reader from Alien technology ALR-9800 [45] is used with two circular antennas along with 2x2 Omni directional passive tags for the study. The experiments show the key factors that affect the number of detected tags by a reader: varying the reader to tag distance, reader to tag angle and RF attenuation level. Lastly, it is studied how the tag reading varies over time when the above parameters remain unchanged.

3.1.1 Effect on Reader to Tag Distance

Figure 21 shows the impact of reader to tag distance when varying quantity and proximity of tags from the antenna. For example, using six tags, 3 tags are detected at a distance of 40 inches; whereas for 2 tags all the tags are detected up to 40 inches away.

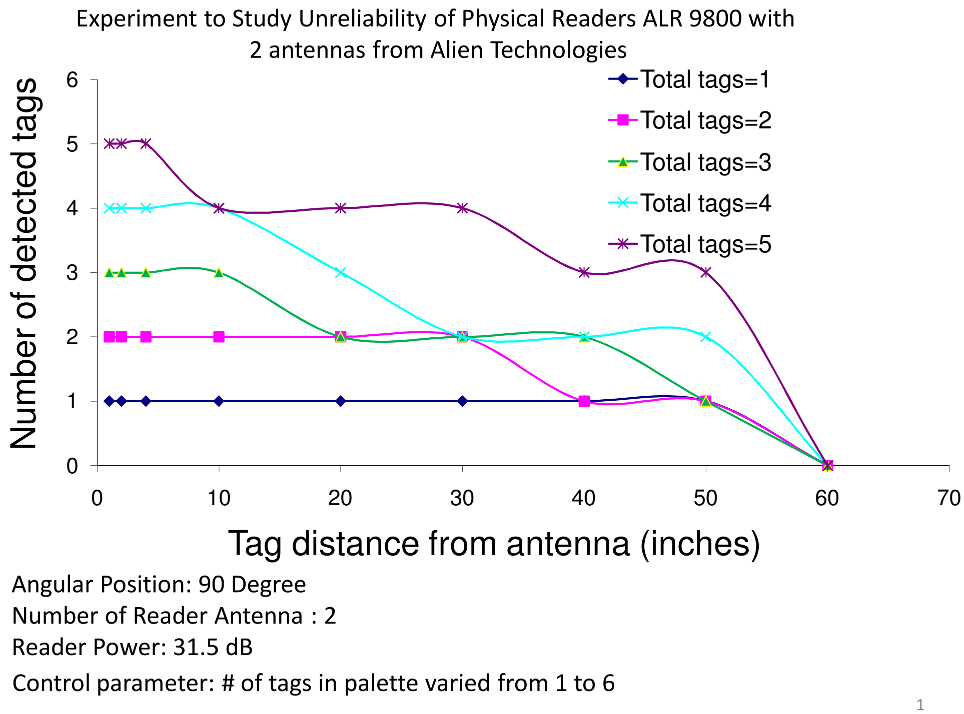


Figure 10: Physical properties of Passive RFID Devices VaryingTag distance from antenna

3.1.2 Effect on Reader to Angular Position

Similarly, Figure 11 exhibits how the angle of the antenna affects accuracy while varying the total number of tags. For a fixed reader to tag distance of 15 inches- it is observed that, when the palette is placed +30 from perpendicular to the antenna, most of the tags are detected; otherwise, the number of tags detected begins to degrade.

3.1.3 Effect of Reader Attenuation

Reader attenuation level also has an impact on the number of detected items, which is shown in Figure 12. Considering a group of 6 tags placed 15 inches from the reader at an angle of 90 , only 3 items can be detected with a reader attenuation of 9 dB.

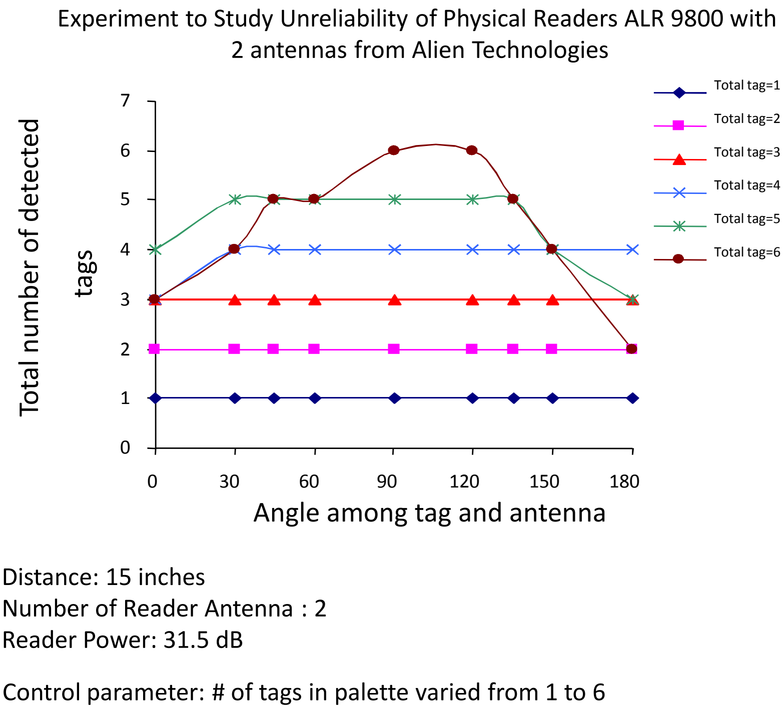


Figure 11: Physical properties of Passive RFID Devices VaryingTag distance from antenna

However, if the attenuation is decreased to 0 dB, the number of tags identified by the reader is increased to 6.

3.1.4 Effect on Reader to Angular Position

In Figure 13 RFID reader behavior is observed over a period of 100 seconds when a palette of six tags is placed 15 inches from the antenna. Our study shows that tags are often missed by the reader, with the specific missing tags varying randomly over time. This behavior can be due to the fact that experiments were not done in a totally interference-free environment.

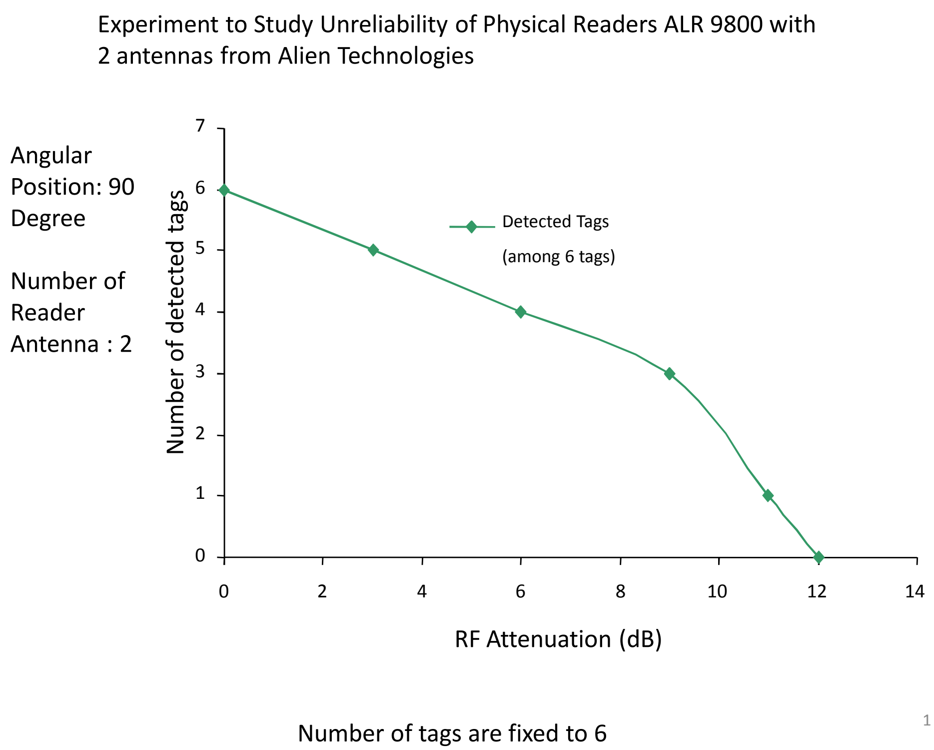


Figure 12: Physical properties of Passive RFID Devices VaryingTag Reader Attenation

3.1.5 Passive RFID Devices for Item Tracking Applications

The RFID devices are studied for item tracking applications where RFID readers are stationary and the tags are in motion. These experiments consider the bulk size (number of items traversed through the system in a time window) and the item speed.

3.1.5.1 Effect of Bulk Size

The bulk size has a significant impact on the reader's ability to detect items. Alien ALR 9800 reader is studied using the tag speed of 9cm/sec to achieve the best PR level accuracy varying the bulk size. The number of detected items decreases as the bulk size increases. Figure 14-(e) indicates 98% detected items for a bulk size of 5 tags which decrease as the bulk size increases; it lowers to 16% when the bulk size

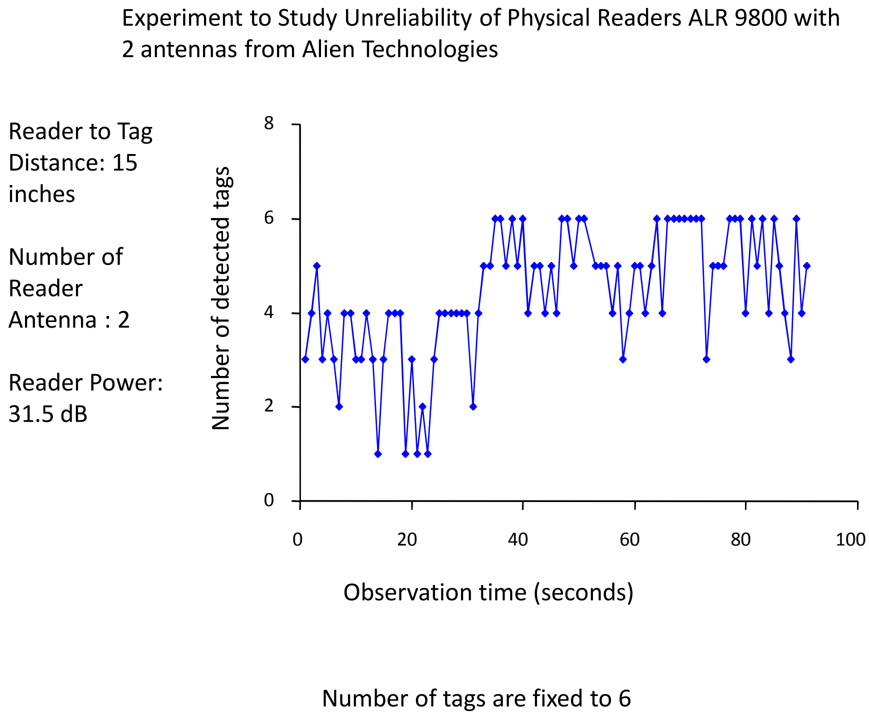


Figure 13: Physical properties of Passive RFID Devices VaryingTag Observation Time

reaches 98.

3.1.5.2 Effect of Item Speed

The speed of the tagged items plays a role in the system performance in terms of detected items at the physical reader level. Alien ALR 9800 RFID reader is studied using 7 tagged items varying the item speed. Figure fig:speed illustrates the reader performance with various tag speed. The number of detected tags decrease as the tag speed is increased. For example, the number of detected item decreases to 62% to 42% when the tag speed increases from 9 cm/sec to 36 cm/sec. The effective time to detect a tag decreases when the tag speed is increased and thus affects the system accuracy.

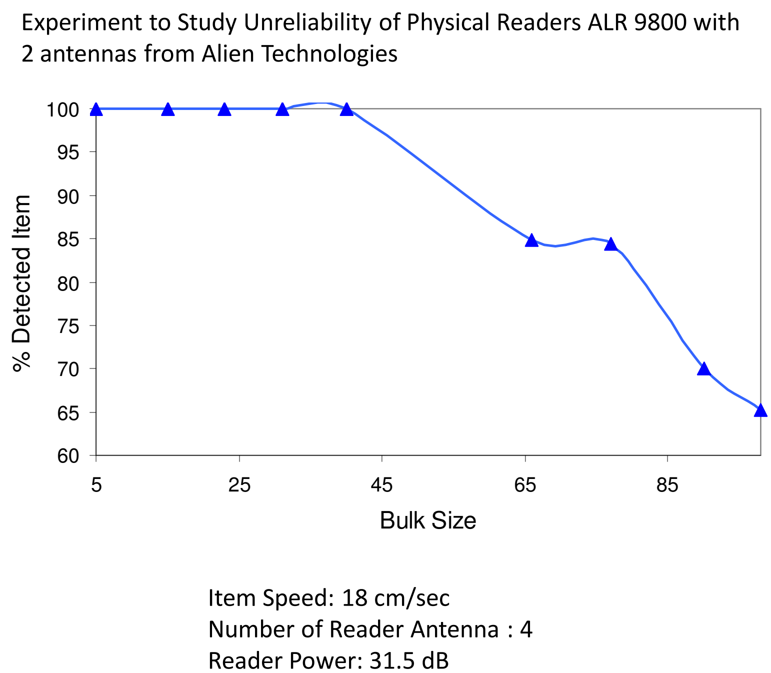


Figure 14: Physical properties of Passive RFID Devices Varying bulk size

Our experiment with the readers gives insight into their unreliable nature. Environmental factors that hamper the reading as well as the inherent unreliability in the reader behavior are elaborated upon here.

3.2 Basic Properties of Active RFID Devices

In this section we explore RFID technology for the pervasive environment. We have considered active RFID tags and readers instead of the passive RFID readers and tags as the passive technology is very vulnerable to its environment.

We have used a setup that uses a single VS that interacts with a mobile RFID reader (M220 reader from RFCode) using blue tooth connection. The pervasive environment is the laboratory setup with 25 active RFID tags (M100-i IR Asset Tags).

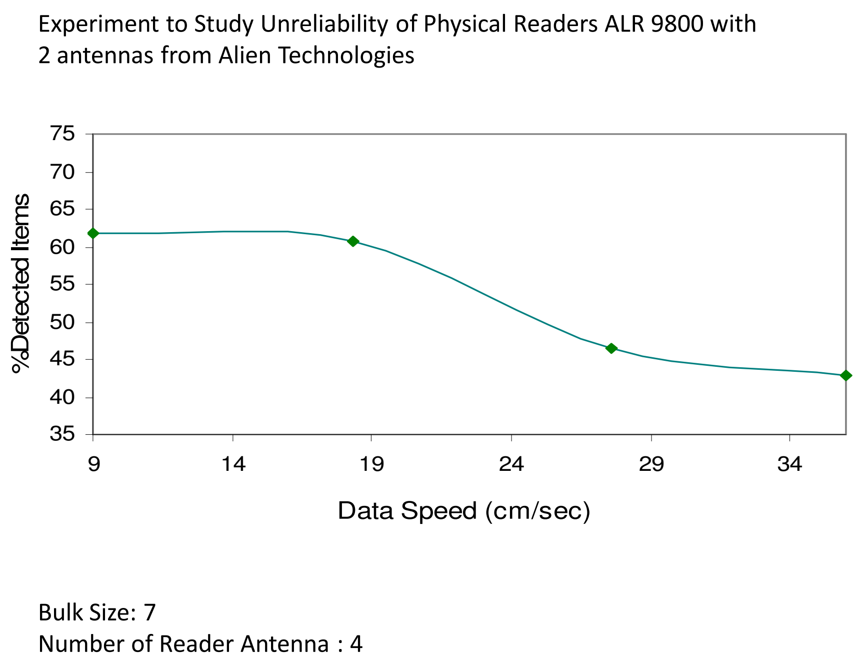


Figure 15: Physical properties of Passive RFID Devices Varying Item Speed

The RFID reader sensitivity ranges from -58 dB to 108 dB and has eight factory programmable ranges each with a 5 dB increment in power level.

3.2.1 Stable Reader to Tag Positioning

In these studies the reader to tag placement (distance, angular position) are stable during the experiment. We have used two different reader to tag distance - 50 cm and 100 cm under power level 2 and the angular positions are considered to be 30 degrees apart starting from 0 degree.

3.2.1.1 Reading stability over time

We have conducted study on the reader performance over time in 16. It is observed that items are observed within a range of signal strength for a certain reader to tag relative position (distance, angular position). For example, the reader is able to read the items at power level 56 when an item is placed 50 cm away while the same item is observed using signal strength 64 when the reader to item distance is 100 cm. We have observed that the active tags are detected with various signal strengths without having any false negative reads at power level 2. A higher power level setting (power level ≥ 3) stabilizes the item reads. We have conducted the experiments to define the behavior at minimal power level. We have not used any statistical methods to represent the data here, we have collected the data over a 280 seconds interval.

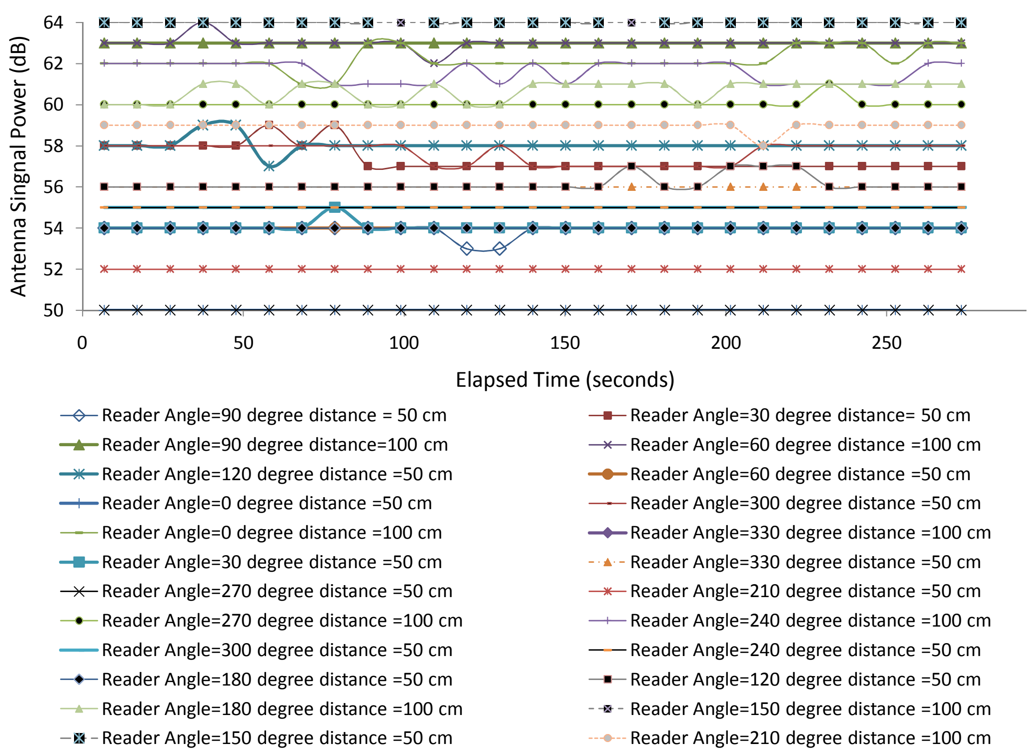


Figure 16: Active RFID Reader properties over time

3.2.1.2 Distance and Angular Position

The reading performance under various reader to tag distance and relative angular position are observed in this study. Figure 21 indicates how the reader power level various in various reader to tad distances and angular positions. There are angular positions that have lower reader signal strength compared to other angular positions. For example, the reader signal strength is higher for 150, 20 degrees angular positions for both 50 c and 100 cm reader to tag distance.

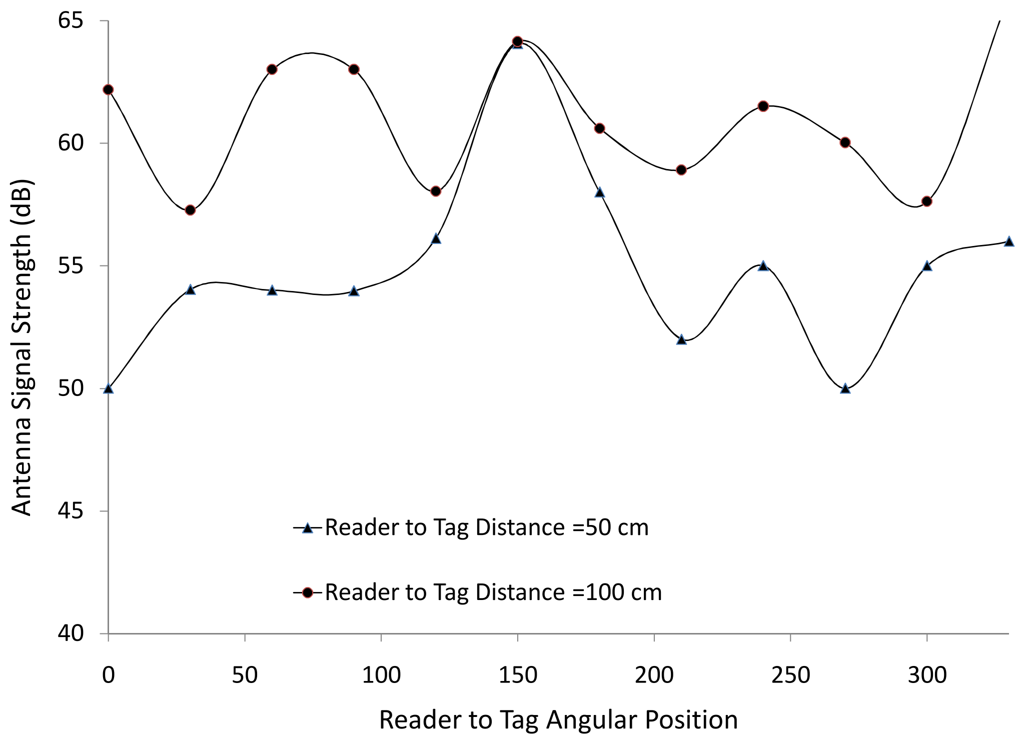


Figure 17: Active RFID Reader Properties based on distance and angular position

The stability of the readings over time varying the distance and angular position is observed in Figure 18 where the standard deviation is measured over the 280 seconds time period. It shows that the readings are more stable with closer reader to tag distances.

3.2.2 Mobile Reader and Stable Tags

The effect of user speed in tag detection is studied using a toy train setup where the train carries the mobile reader to mimic the effect of a mobile user carrying a reader.

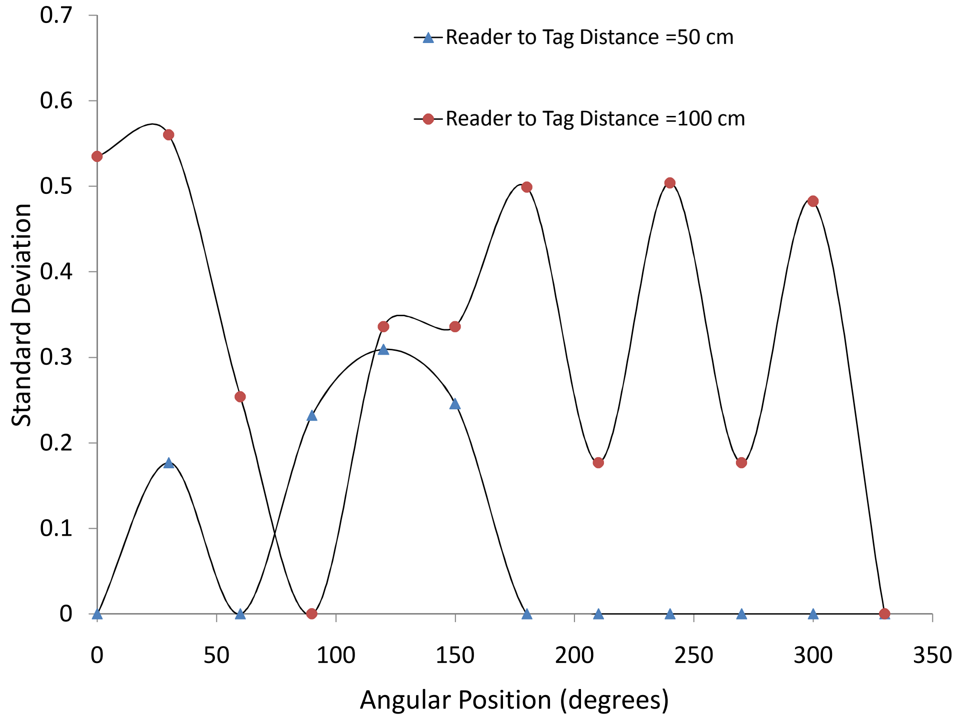


Figure 18: Active RFID Reader Properties based on distance and angular position (standard deviation of readings to define the stability of readings)

The reader to tag distance remains less than 10 cm in this study. It is observed that the signal strength increases as the reader speed increases. For example, the signal strength is increased from 28 to 30.2 when the train speed increases from 9 cm/sec to 30 cm/sec as can be seen in Figure 19.

3.2.3 Positioning Performance

We have used the 4 x 4 grid spaced setup presented to determine the mobile objects approximate location information as a positioning system. The inter tag distance is varied from 20 cm x 20 cm to 50 cm x 50 cm in a laboratory setup. The intent of this experiment is to figure out a radius in where the user belongs approximately. But unfortunately, the results had many false positive readings at low power level

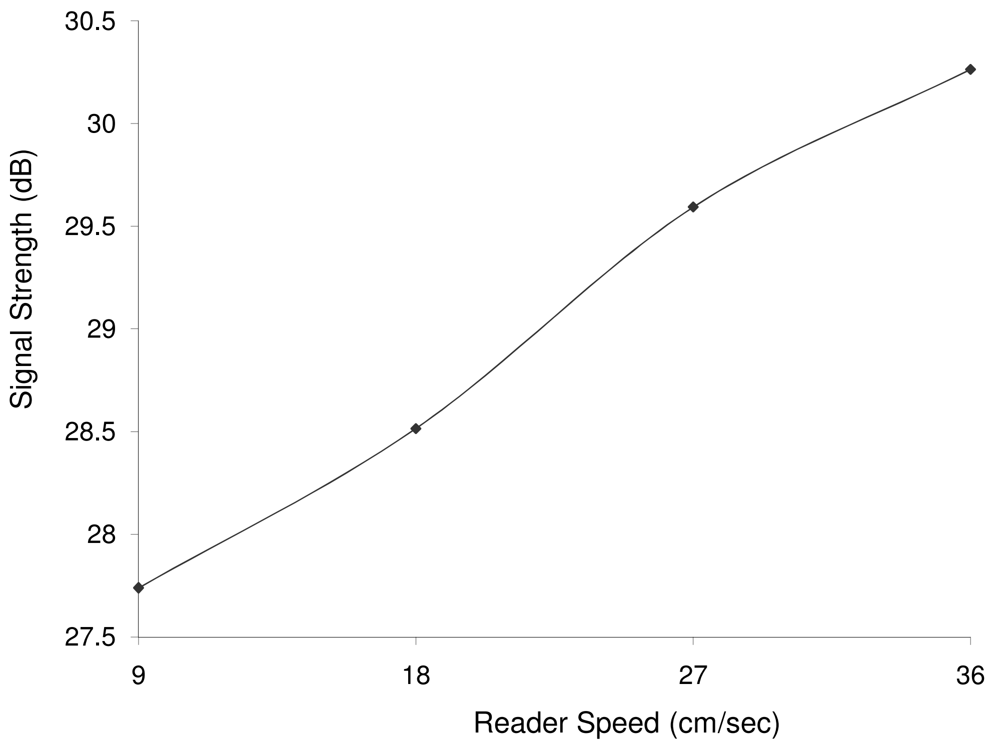


Figure 19: Effect of Speed in RFID Read Performance

and increasing the power level includes the various tags in a larger range making it difficult to determine a small radius of user's current position.

The reader is able to detect all the tags irrespective of its power level when the tags are placed within the range of 10 cm. That is why we started the inter tag spacing starting at 20 cm. The reader starts with its minimum power level to detect the surrounding reference tags. Ideally, the reader should detect the tags surrounding the reader at the minimum power level. But the reader receives many false positive readings. False positive readings refer to the reader's ability to detect surrounding tags that are theoretically out of range of the reader. Figure 20 presents the mean square error along with the actual deviation of reading using a setup where the tags are placed 20 cm apart from each other. The average reading incorporates error although some individual samples may contain error free reading. The sampling has been conducted with the same setup but varied with time.

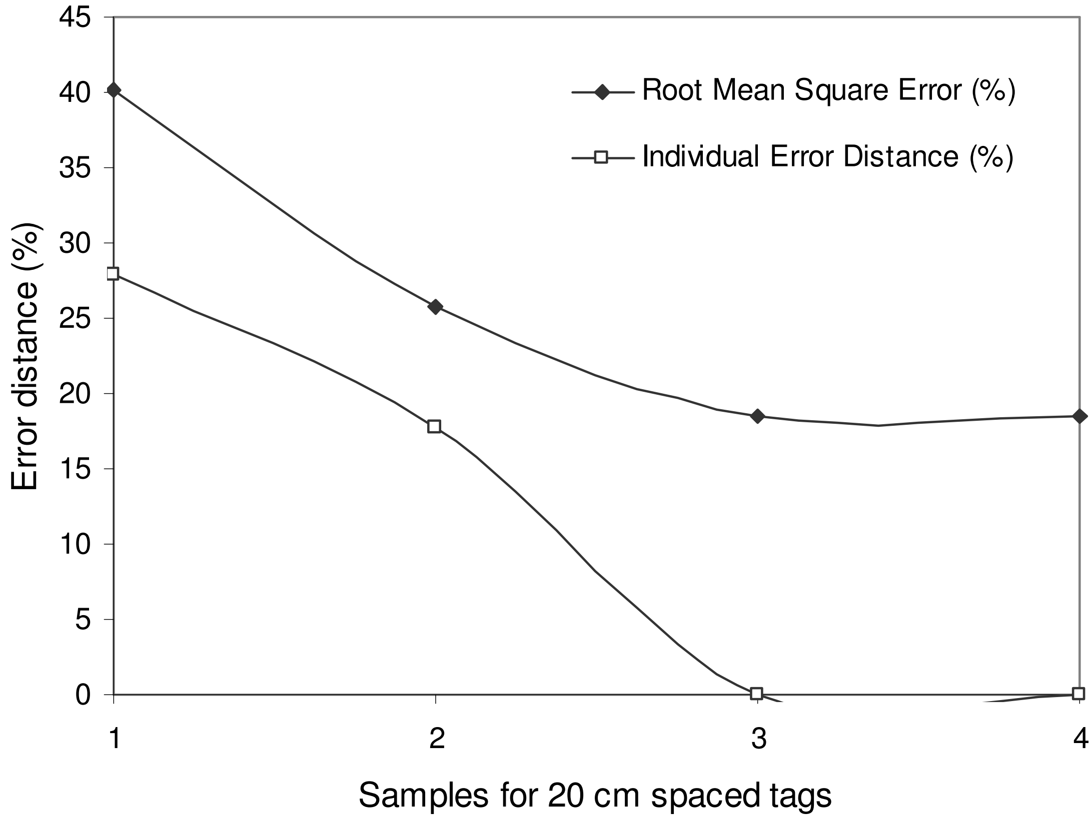


Figure 20: Error in Tag Detection for 20 cm Inter Tag Spacing

3.2.4 Guidance Performance

We have studied RFID tag placement for coarse grain guidance information rather than accurate positioning information. For this particular experiment, the system had the pre-installed information of the tag placement and a define source to destination route to guide the mobile user. The mobile user equipped with the RFID reader, provides the system its status information that contains the current observed tags. The system has been able to successfully guide the user when the reader is placed at power level 2: the reader is able to detect all the tags in its vicinity and get proper guidance. At the minimum power level (power level =1), the reader is not able to detect tags placed far apart and could not gain adequate guidance information shown in Figure 21. This experiment is a proof of concept study that shows how the system is able to guide the mobile user if the reader power level is matched to the inter tag distance in the environment.

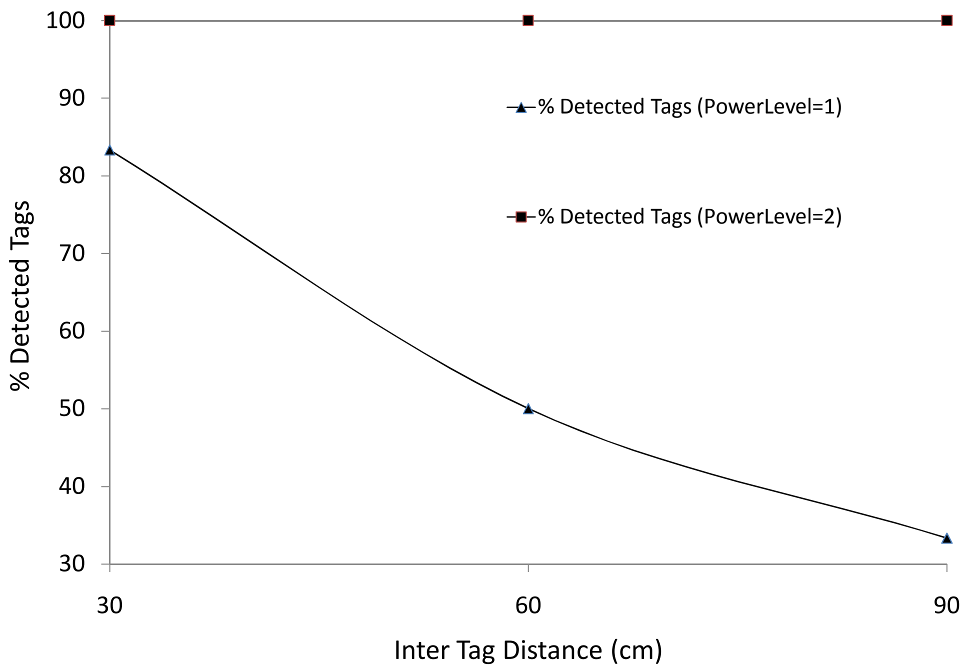


Figure 21: The effect of inter tag distance on reading accuracy

3.3 Summary

We have studied the RFID technology under various reader to tag relationship. The passive RFID technology is getting wide spread adoption in many large scale tracking systems such as supply chain management and airport baggage claim systems. But this technology has its limitations as the reader performance is heavily influenced by various environmental conditions. It is interesting to find out that the passive reader provides unstable readings under constant environmental conditions when multiple samples are taken. The reader performance further decreases as mobility of tagged items and presence of multiple tags are considered. Thus a middleware solution to handle RFID generated data must take into account the inherent unreliable nature of this data. The active RFID technology has a more stable reading performance under varying environmental factors. It can be used to complement the unreliable passive RFID behavior in many different scenarios. A search and rescue scenario or an indoor assistive living center scenario requires stable place holders for exploratory purpose. Our study using the active RFID technology confirms such possible applications.

CHAPTER IV

RF^2ID:RELIABLE FRAMEWORK FOR RADIO FREQUENCY IDENTIFICATION

The study on the inherent unreliability of passive RFID readers validate the requirement of a solution that is able to improve the system performance in terms of reading accuracy. The solution approach must be scalable that is able to perform in real time to deal with large amount of RFID generated data. The system requirements can be further evaluated from analyzing the basic application requirements in the context of the item tracking applications. The item tracking application refers to the set of applications that use RFID tags to track the mobile items while the RFID readers are placed at static locations around the environment. Airport baggage tracking and tracking of goods in a warehouse are examples of such applications.

A middleware that has inherent support for this flow of data considered as a path can be very useful for organizing, filtering and thus responding faster to queries. Using the intuition of data flow, we have designed a path based distributed system architecture for RFID middleware called RF^2ID *(Reliable Framework for Radio Frequency Identification).* Our proposed scheme consists of (1) a *virtual reader(VR)* abstraction to capture the static and potentially error-prone nature of the physical readers and antennas in a scalable manner; and (2) a novel path abstraction, called *VPath (Virtual Path)* to capture the logical flow of information among the virtual readers as RFID-tagged objects move throughout the environment. Using a notion of path at the system level gives us several advantages. First, the system load can be distributed among multiple virtual readers that constitute a specific virtual path. Second, different *QoS* attributes can be defined for a path, such as accuracy and priority levels that the virtual readers use to operate on data flowing through the corresponding path. Finally, as there is an internal representation of data based on path attributes, it becomes trivial to support path-related operations on the data, e.g., searching for query results, or making a future projection of data behavior based on history.

We present the system architecture, the implementation of the system and its evaluation in the light of two motivating application scenarios: a warehouse scenario and an airport scenario. The evaluation considers a testbed that consists of real RFID readers to serve as a proof-of-concept system solution. The system is further evaluated using emulation based RFID readers and tags in a large scale distributed system setup to study the scalability aspects. The related work and summary of the chapter is presented followed by the system evaluation.

4.1 System Architecture

The inherent unreliable nature of RFID devices requires a system architecture that is able to improve the system reliability as well as being scalable. Our proposed solution, RF^2ID consists of a name server, a path server, virtual reader and the $RFID$ readers [14]. The name server and path server keep system wide information to improve system performance. Virtual readers (VR) are distributed computational elements placed in a particular geographic location that are in charge of physical RFID readers (PR) in that vicinity. Virtual readers communicate to each other using a logical communication channel called virtual path (Vpath).

The system architecture is shown in Figure 22. The novelty of the system lies in the notion of logical communication channels among the VRs called *Virtual Paths* (Vpaths), creating a scalable and robust solution for RFID middleware. The *name server (NS)* and *path server (PS)* are components that keep systemwide information to improve the system efficiency. We discuss the overall system in the following

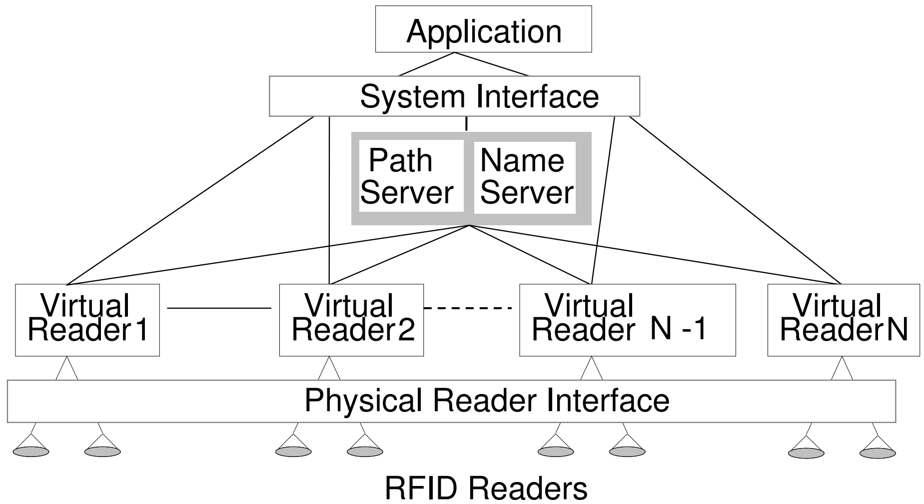


Figure 22: System architecture of RF^2ID

subsections briefly.

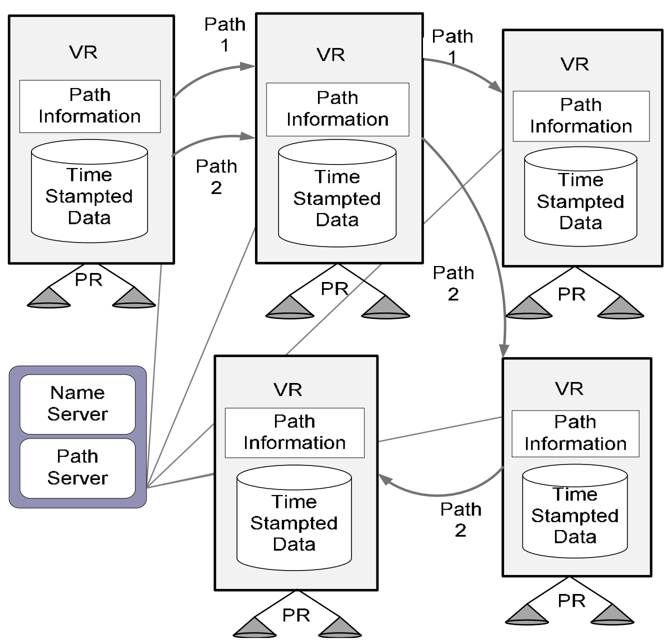


Figure 23: VR to VR Communication using logical Path

The VRs and Vpaths can be considered as a graph G=(V,E) where V represents the VRs as nodes and E is the logical connection among VRs as edges of the graph. Each VR V is responsible for processing E (Data) along edges incident to it - the node value at V is defined in terms of $Data_{accuracy}$. A Vpath P is a sequence of edges starting from node s and ending at node t defined as P(s,t) where $s, t \in V$ and $s \neq t$. Every Vpath in the system should provide a QoS value Q in terms of $Data_{accuracy}$, all the VRs in a path should provide an overall QoS as a group. This can be defined by a function $f(V, Data_{accuracy}) \leq Q$ where f is the function that represents the operations on data sets to provide system accuracy.

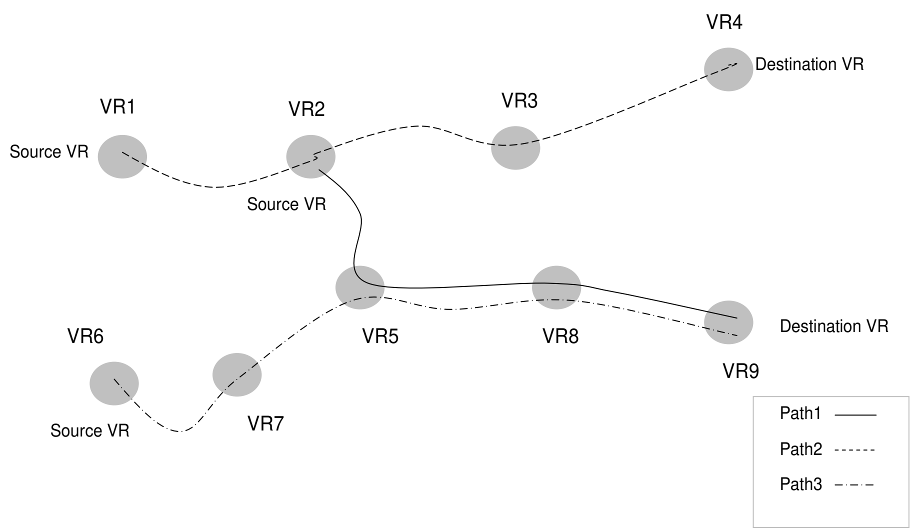


Figure 24: Graph representation of the System

4.2 Virtual Reader

To achieve reliability in a scalable and distributed manner, we have designed a novel abstraction called virtual reader (VR). Virtual Paths (Vpaths) are logical channels across a set of VRs. A Vpath is created dynamically taking into account various VR specific parameters described in later subsections. Each VR is responsible for a set of physical readers (PR) within its vicinity. For applications such as a warehouse wherein the topology does not change very often, the PR to VR mapping takes place during initialization (described in next subsection). A VR is responsible for data management, virtual path management, and query management. VRs use local variables and data structures to make individual local decisions that impact global system behavior. We use the following notations in describing these functions carried out by a VR:

- Set of VRs named as $VR_{(p,i)}$ corresponding to a Vpath P as $VR_{(p,1)}$, $VR_{(p,2)}$, .., $VR_{(p,n)}$
- Set of PRs named as $PR_{(p,i,j)}$ corresponding to $VR_{(p,i)}$ as $PR_{(p,i,1)}$, $PR_{(p,i,2)}$, .., $PR_{(p,i,m)}$
- A VR maintains five lists and a variable for each path P_i
  - $observedTagList_{(p,i)}$: tag information detected by corresponding PRs
  - $receivedTagList_{(p,i)}$: filtered tag information comparing PR inputs
  - $expectedTagList_{(p,i)}$: information from neighbor $VR_{p(i-1)}$ along the path
  - $missingTagList_{(p,i)}$: tags expected from $VR_{p(i-1)}$ but not received by PRs
  - $spuriousTagList_{(p,i)}$: tags received but not expected from $VR_{p(i-1)}$
  - $VR_{(p,i)num}$: number of participating VRs in path P_i
- A set of control parameters in a VR to make path creation decisions
  - $conn_{in}$: maximum number of incoming messages handled per unit time
  - $conn_{out}$: maximum number of outgoing messages handled per unit time
  - $Total\_Path$: Total number of paths associated with a given VR
  - $Total\_PR$: Total number of VRs in the system
  - $Total\_PR$: Total number of PRs Associated with a given VR
  - $Message_{in}(source)$: Incoming messages from source
  - $Message_{out}(destination)$: Outgoing messages to destination
  - w_{cpu}: Average per path CPU load on a VR (%)

- w_{curr}: Current CPU load on a VR (%)
- w_{est}: Estimated load due to a new path P (%)
- w_{tr}: Threshold maximum permissible CPU load on a VR (%)
- VR_{tr}: Minimum number of VRs needed for a new path P
- VR_gCount_{PathID}: Final count of number of VRs in new path
- $VR\_localCount_{PathID}$: Local copy of final count in each VR
- α: Per message CPU cost (%)

Input: w_{cpu}, $c_{i,i+x}$, $c-i, p$, w_{est}, $c_{i,i+x_est}$, $c_{i,p-est}$

Output: Creates a Vpath among VRs

foreach *($VR-i$ for i=1 to total_VR)* **do**

w_{curr} =

$\sum_{j=1}^{total\_PR}((w_{curr}+\alpha(Message_{in}(VR_{i-1})+Message_{out}(VR_{i+1})))+\sum_{k=1}^{total\_PR}(\alpha * Message_{in}$

w_{est} =

$w_{CPU}+\alpha(estimatedMessage_{in}(VR_{i-1})+estimatedMessage_{out}(VR_{i+1}))$

if *($w_{curr}+w_{est} \leq w_{tr}$)* **then**

Send participatedPathCreation(PathID, VRID) to VR_{dest}

end

else

Send notparticipatedPathCreation(PathID, VRID) to VR_{dest}

end

if *(VRID==VR_{dest})* **then**

VR_gCount_{PathID}= Total number of participate messages received

end

if *($VR\_gCount_{PathID} \geq VR_{tr}$)* **then**

Register (PathID, VR_gCount_{PathID}) in Path Server

$VR\_localCount_{PathID}$=VR_gCount_{PathID} Send pathCreation(PathID,

VR_gCount_{PathID}) to VR_{i-1}

end

else

Throw pathNotCreated exception to the Application

end

else

Receive pathCreation (PathID, VR_gCount_{PathID}) from VR_{i+1}

$VR\_localCount_{PathID}$ =VR_gCount_{PathID} Send pathCreation(PathID,

VR_gCount_{PathID}) to VR_{i-1}

end

end

Algorithm 1: Distributed Load Estimation and Path Creation Algorithm

4.2.1 Initialization

In a physical topology of a warehouse, there are separate sets of PRs associated with different conveyor belts. A VR creates a complete list of PRs within its own geographic region; including path associations related to each PR. Figure 25 shows an RFID deployment in a warehouse. The figure shows a 2-dimensional (plan) view of the physical space where the system is deployed. The physical space is divided into regions (dashed rectangles) and a VR is assigned to each geographical region. The tracks show the belts along which items will flow physically from source to destination. Each VR is initially assigned to a disjoint set of PRs that are in the geographical region covered by that VR. A set of 6 PRs are assigned initially to VR1 since they are in the geographical coverage area of VR1. However, the set of PRs used by a VR during system operation is path specific. In Figure 25, VR1 uses the readings from the top PR group for the path created between Source A and Destination D; similarly, it uses the readings from the bottom PR group for the path created from Source B to Destination E.

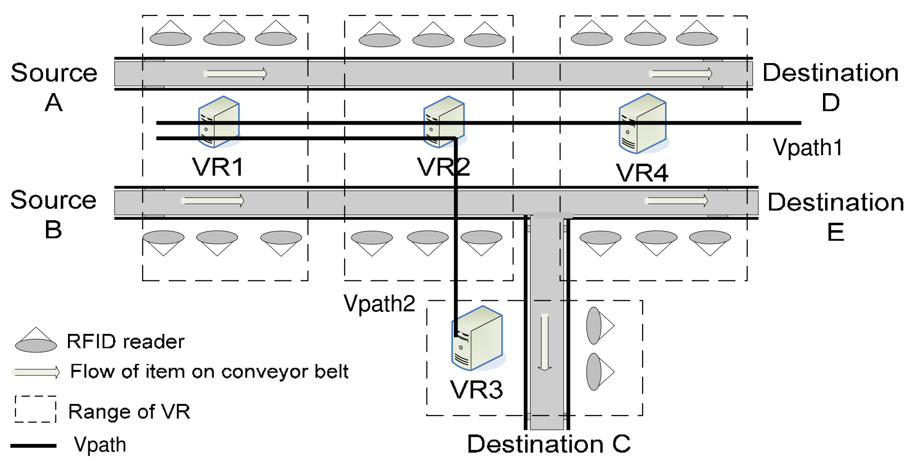


Figure 25: A Warehouse scenario showing RFID deployment

4.2.2 Data Management

The data management consists of two major tasks-filtering the data (from the PRs associated with this VR, and from neighboring VRs), and timestamping the data in a consistent manner. We assume that $VR_{(p,i)}$ is able to send the data to neighboring $VR_{(p,i+1)}$ in path P, before the item physically reaches the neighbor. The data acquisition and processing phase by $VR_{(p,i)}$ is the process of accumulating scan data from all PRs $PR_{(p,i,1)}$, $PR_{(p,i,2)}$, ..,$PR_{(p,i,m)}$ contained in path P. A corresponding $observedTagList_{(p,i)}$ is generated for each PR in order to compare them with each other. The result of these comparisons is a concrete list of tags in $receivedTagList_{(p,i)}$ that is timestamped with the current system time. In the data comparison phase, every $VR_{(p,i)}$ (except the source VR), receives a list of expected items from $VR_{(p,i-1)}$ along path P and stores it in $expectedTagList_{(p,i)}$. The timestamps in $expectedTagList_{(p,i)}$ and $receivedTagList_{(p,i)}$ are then compared to guarantee a consistent temporal ordering amongst these VR-generated lists. The items of $expectedTagList_{(p,i)}$ and $receivedTagList_{(p,i)}$ are also compared to create a list of items expected but not acquired in $missingTagList_{(p,i)}$ and received items that are not expected in $spuriousTagList_{(p,i)}$.

4.2.3 Path Management

Path management includes a load estimation and path creation phase and an overloaded path management phase. The load estimation and path creation phase works as follows shown in Algorithm 1. A VR receiving a path creation request first contacts the path server to check if any existing path satisfies the request; otherwise, it contacts the name server for possible set of VRs that can potentially belong to that path. Each $VR_{(p,i)}$ in path P estimates its current load wcurr from the number of existing paths (n) that it is currently serving. The load estimation takes into account the current CPU load wcpu; incoming and outgoing messages $c_{i,j}$ from VR_i to VR_j; and messages from the associated PRs. The numbers of incoming and outgoing messages to $VR_{(p,i)}$ are bound, respectively, to connin and connout to restrict the total number of messages handled by a VR in a given time period. Messages beyond this bound is likely to overload the system and would lead to random message drops above this number. Then $VR_{(p,i)}$ estimates the additional load west for the new path using history data from previous paths. If the combined workload of wcurr and west does not exceed a predefined threshold wtr then the VR sends a participateNewPath message; otherwise it sends a notparticipateNewPath message to $VR_{(p,i+1)}$ along the path until the message reaches the destination $VR_{(p,n)}$. $VR_{(p,n)}$ sends a pathCreation message containing the number of participating VRs as $VR_{(p,num)}$ to all the member VRs in the path if and only if this number is not below a predefined system threshold VR_{tr}. Otherwise a pathNotCreated exception is sent out to the application. Each VRpi then updates its local variable $VR_{(p,i)-num}$ with the number of participating VRs in the path.

The overloaded path management phase works as follows: although each VR makes an assumption of its future load, at a particular point of time, one or more member VRs can become overloaded. An overload is detected through comparing current system load wcurr with the load estimation threshold value w_{tr}. The overloaded $VR_{(p,i)}$ will update VRpinum and send messages to member VRs to reduce their local value $VR_{(p,i)-num}$. Any $VR_{(p,i)}$ receiving the overloaded message updates its local variable $VR_{(p,i)-num}$ and checks if the updated value is below VR_{tr}. The application is notified about the path overload whenever the number of participating VRs falls below the threshold VR_{tr}.

4.2.4 Query Management

Any VR can respond to queries from an application. Vpaths allow a VR to either answer the query itself or route the query to the VR best able to answer the query. The set of queries include aggregation operation such as:

- Information on all items
- Information on items along a specific path (source to destination)
- Information on items of a specific type or number of items over a period of time

The real power of the path abstraction lies in its ability to handle item location queries and troubleshooting queries such as:

- Locate a missing item
- Locate an item last recorded by a specific VR or a specific PR in a VR
- Information about a malfunctioning reader (e.g., a reader that is consistently missing items)
- Information about a specific conveyor belt (e.g., a Vpath that is missing items below a threshold)

It is well known that the time to respond to a real time query has to be very precise [25, 26]. The system is well positioned to handle time specific queries since the readers timestamp the information they gather as well as disseminate. Thus for example, if a VR receives a query that is in its immediate past, it will forward it to the appropriate VR that is ahead of it in the Vpath.

4.3 Name Server and Path Server

The name server is responsible for keeping the mapping between the topology of the warehouse and the VRs assigned to different regions. It knows the physical location of the PRs in the warehouse as well as the physical routes via conveyor belts that exist in the warehouse. In a scenario where the deployment is reasonably stable such as a warehouse, all the information in the name server are defined at initialization.

A lookup request to the nameserver for a physical route between a source, destination pair (Source(x, y), Destination(x, y)), yields the set of VRs VR_{source}, VR_1, VR_2,..VR_n, VR_{dest} that are along that route. The path server carries dynamic information about the paths that exist in the system at any point of time. A path is registered with the path server upon creation by the destination VRdest, and contains the path id, participating VRs in that path and a lifetime associated with the path. The path entry is deleted when the lifetime expires allowing an automated garbage collection scheme. A new request to use an existing path or a subpath increments the path's lifetime

4.4 Implementation

We have implemented a proof of concept prototype of the system architecture. The prototype allows us to perform controlled experiments to quantify the reliability properties of the proposed architecture. It embodies all the same distributed computing elements as described in Section 4.1, albeit in a stripped down form. The main difference is in the decision making components. The implementation uses a *centralized path controller* which works with a *static route map* instead of the path server and name server, described in the previous section. This structural difference does not affect our study on system performance or reliability. On the other hand, our prototype includes physical readers as well as emulated physical readers. This feature of the implementation allows us to perform controlled experiments far beyond the limited scale of the real hardware at our disposal using the same distributed architecture. In the next few subsections, we describe the features of the prototype system.

4.4.1 Virtual Readers

In a real deployment, a VR may be mapped to any PC class machine (or even one of the PRs in a given region). Our implementation of the VR is in C, and fully implements the functionalities outlined in Section 4.2. *MPI* is used for inter-VR communication. In the VR implementation, the path management and creation mechanisms are considerably simplified to get a prototype system up and running for experimentation. Using a static route map, each VR knows its neighbors for any desired source-destination pair. So, upon receiving a path request, a source VR knows the neighbor to contact to create a path. The path creation request is transmitted in a chain-like fashion along the static route by the VRs until it reaches the destination VR. When the message reaches the destination VR, it broadcasts the successful path creation message to all the VRs. This is clearly inefficient when there is a large number of VRs in a Vpath. Further, this can be a source of bottleneck if a specific destination VR is hot. Since the primary purpose of the prototype implementation is to study reliability, we decided to use this simple minded path creation and management. However, a full-fledged deployment will use the detailed algorithms (shown in Algorithm 1) using parameters such as computational and communication load on each VR.

4.4.2 Physical Readers

The physical reader used in our implementation is ALR-9800 [2] from Alien Technology. We have done extensive study of this reader with two antennas supporting point to multipoint and multi static architectures, operating at frequency range of 902.75 MHz to 927.25 MHz, and including 50 hopping channels with channel spacing of 500 KHz. We studied tag behaviors using 6 passive RFID tags with reader power set to its maximum level (31.5 dB). Alien reader provides a rich set of APIs to access a variety of reader and tag parameters. Reader discovery methods such as setDiscoveryListener() and startService() are used for network component discovery within the same subnet. For a large system consisting of thousands of readers, this auto discovery is very efficient. Various reader methods are used to get and set different reader parameters and observed tag information such as getReaderType(), getAcquireMode(), getTagList(), setRFAttenuation(), and setRFLevel(). A PR talks to its associated VR using Unix sockets. The tags are placed by a PR in a queue abstraction implemented using sockets. Thus the PR-VR communication follows a producer-consumer model.

4.4.3 Emulated Physical Readers

We have implemented a emulated physical reader that is designed to have the same interface and behavior as the Alien readers. Thus a VR treats a emulated PR no different from a true PR. These emulated physical readers offer a powerful and transparent mechanism to study system scalability. Different parameters that affect the reader accuracy such as reader to tag distance, reader to tag angular position, reader power level, etc. are defined as input parameters to the emulated PRs. They can be set to be different for different emulated PRs to study a heterogeneous deployment, or all the same for a homogeneous deployment. In the experiments conducted that involved varying accuracy levels of readers, we maintained the optimal positions among reader and tags. For example, we placed the reader to tag distance to be within 5 inches, angular positions as perpendicular from tag to reader, highest reader power level and limited the number of items in a palette to six, thereby demonstrating optimal tag detection properties. Therefore, it differs from other simulators concerned with tuning device level components such as the work in [28]; instead, our focus is on efficient and distributed computations on reader generated data in order to support scalability studies of the system.

4.4.4 Path Controller and Static Path Map

As we mentioned earlier, the path server and name server are non-existent in our prototype implementation. Instead, the system maintains a static route map (in lieu of a name server) that contains for each potential source-destination pairs the list of VRs. Upon a request to create a new path, this static route map is consulted to determine the set of VRs that could be participants for the new Vpath. The VRs initiate the path creation as we detailed in section 4.2.3. The VRs that are potential participants may elect to be part of the Vpath or not depending on their current CPU load and memory utilization. Once a path is created, the centralized path controller creates an entry in its table with a unique ID for the new Vpath and the set of participating VRs for that path.

4.5 Evaluation

The system is studied using emulated and real RFID readers. We have considered two different item tracking application scenarios: a warehouse scenario that tracks the tagged items in motion where the RFID readers are statically placed in the environment. The main objective of this scenario is to track the items of interest in real time and be able to query about specific items (e.g., missing or misplaced items). The airport scenario is also considered where it is assumed that every passenger gets an RFID tagged boarding pass along with a baggage that is tagged with the RFID tag that has the exact same ID as the passenger to match the baggage with corresponding passenger. The goal of this system is to make sure that a passenger is matched with their corresponding baggage for convenience and security of the environment.

4.5.1 Improved System Reliability and Scalability using RF^2ID

The reliability improvement is investigated here where reliability is defined as the number of detected items in the presence of false negative readings. False negative readings indicate a reader not being able to detect an existing item. The impact on increasing accuracy level in a single VR over the system reliability is studied here. Multiple emulated PRs are attached to a single VR. Figure 26 illustrates that the presence of more than one physical reader for each VR improves the system accuracy significantly. For example, when the VR consists of four PRs, with accuracy varying form 50% to 100%, the aggregated (VR) accuracy level of the system is obtained as

97%.

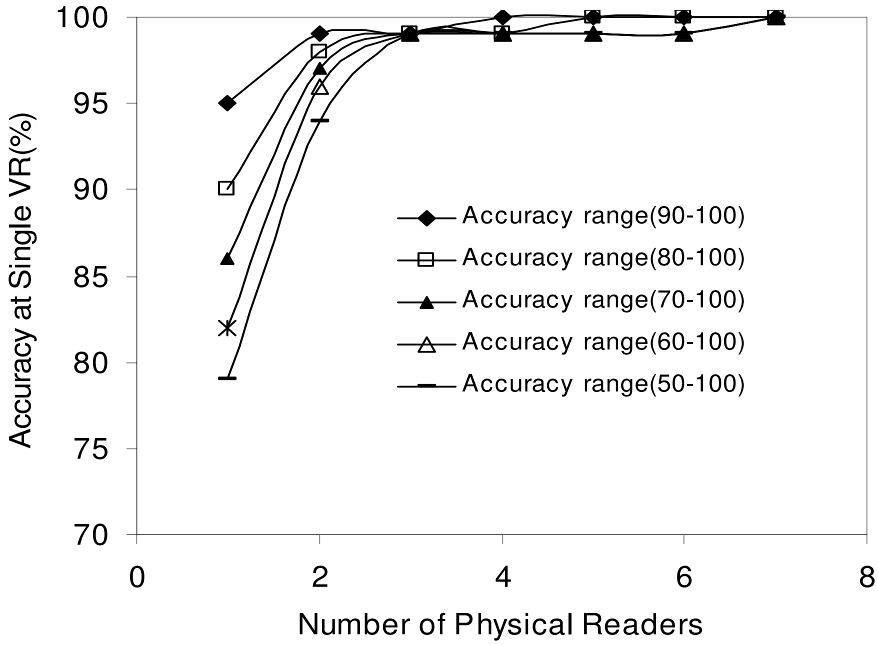


Figure 26: Accuracy as percentage of found items at virtual reader level varying number of readers

Figure 27 demonstrates improved performance when two actual physical RFID readers are used with varying number of tags. Individual PRs show false negative readings from 55% to 60% of the time. But using our notion of Vpath false negatives are reduced significantly. A reading over 120 tags show 52% and 55% false negative readings in PR1 and PR2 where a Path reduces this to 39%. Due to the limited number of physical RFID readers and tags, we have used emulated physical readers to examine reliability as well as scalability in the presence of larger numbers of VRs. A one to one mapping of PR to VR effectively simulates the unreliability of PRs. In Figure 26, it is observed that the increasing number of VRs reduces the number false negatives. For example, 10 VRs with 50% reader accuracy achieves less than 10% false negatives.

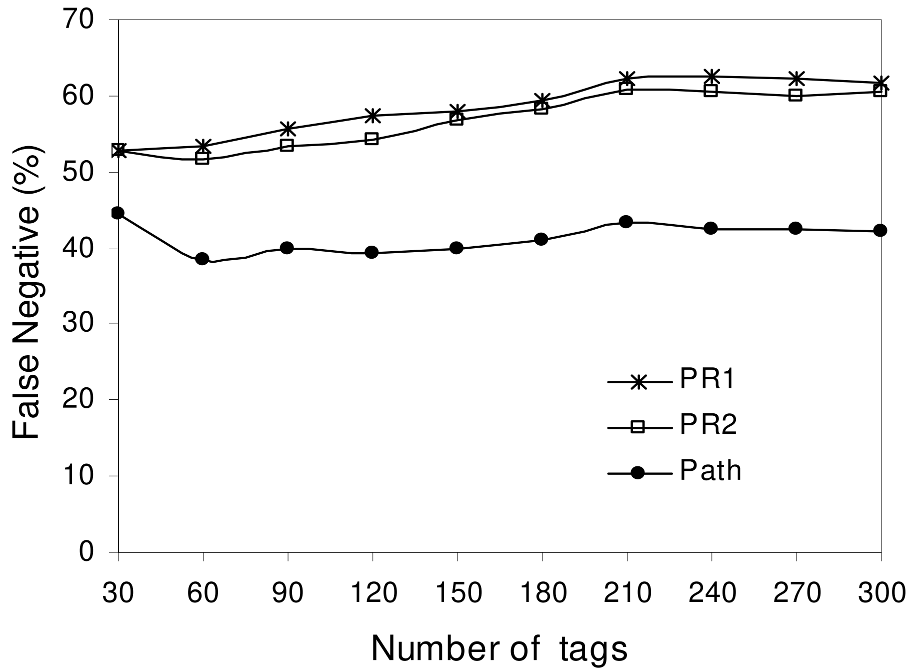


Figure 27: False Negative Reading of the System using single PR (PR1, PR2) and Path among PRs

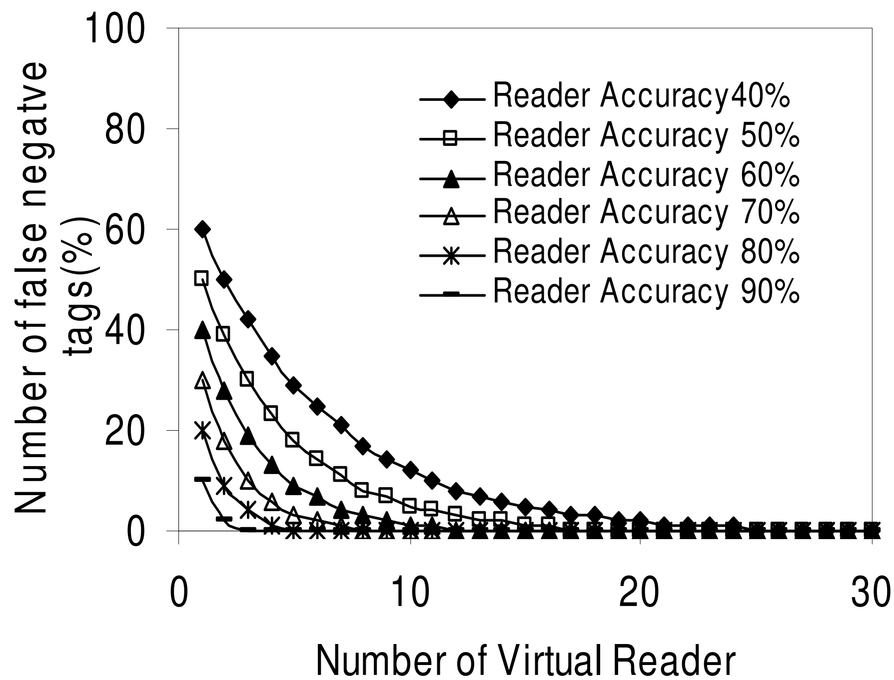


Figure 28: False negative readings varying number of VRs

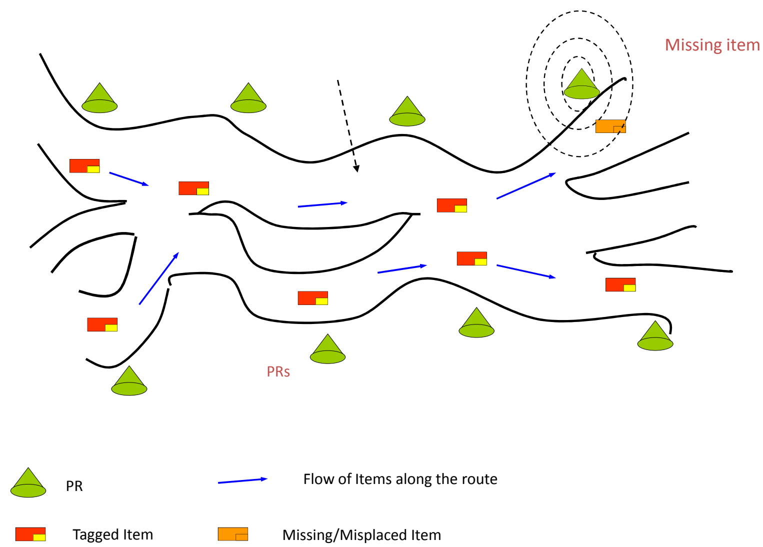


Figure 29: Missing or misplaced item detection

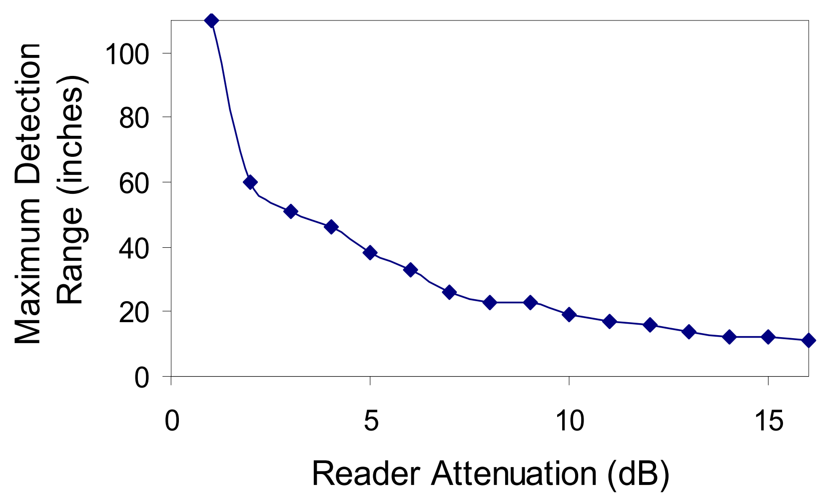


Figure 30: Attetuation and Reading Range

4.5.2 Missing and Misplaced Item Location

Our Vpath abstraction plays in important role in item location. We have examined the maximum tag detection range of readers in perpendicular position gradually decreasing antenna attenuation level from 31.5 dB. This study allows us to define a radius around the reader, of possible tag location as can be seen in Figure 29. Figure 30 shows the relationship between reader attenuation and maximum item detection range. In an item tracking scenario, a particular item or group of items may be misplaced along its physical route (e.g., conveyor belt). After deciding that an item is lost, the system identifies which PR last observed this item and initiates item location operations. Antenna attenuation can be used to locate, within a certain radius, the last physical location of a lost item. To this end, we have placed a tag 28 inches apart from the reader at an angle of 90 degrees relative to the antenna. Here the item is detected by the reader at attenuation set to 7dB indicating a 30 inches radius.

The results from the mentioned studies indicate how the system is able to improve the system reliability in a scalable manner using the built in system redundancy considered in the system architecture. The key idea is to take into account the data flow along the Vpaths using redundant VRs and PRs for higher system accuracy in terms of detected tags (lower false negative readings).

4.5.3 RF^2ID Deployed in a Real Testbed System

The effectiveness of RF^2ID is studied in a real testbed setup for itopretion while the proposed study uses a testbed of 2 RFID readers and 500 tags. Moreover the motion of items and various bulk sizes are considered in the current setup. Bulk size refers to the number of items flowing through the conveyor belt at the same time. Two different application scenarios are considered for the study - a warehouse setup and an airport setup.

Figure 31: Laboratory Testbed

4.5.3.1 Laboratory Setup

Two EPC Class 1 Gen 2 compliant RFID readers from Alien technology have been used with eight 915 MHZ linear antenna attached to it. Gen 2 (2 x 2) tags from Alien technology are used for the experimentations. Toy trains with railroad tracks are used to take into account tag motion in the experiments. The toy trains carries the RFID tags while the RFID readers observe the tags from their static locations. Figure 31 shows four RFID readers in our laboratory setup where the train cars are carrying RFID tags.

We have adjusted the antennas so that moving train cars carrying the tags are positioned perpendicular with respect to the antenna. It has been studied how false negative reading tends to increase with speed of the tagged items. We have set the train speed to 18 cm/second for the rest of the experiments based on this study as the tags are read most consistently by all the antennas. Every antenna is considered as separate PRs in the system that communicates to different VRs. The antenna to tag distance has been chosen such that multiple tags can be detected effectively by the readers. The antenna orientation also plays a role in tag detection. It has been observed that tags are best detected within the range of 50 cm and when the tags are placed perpendicular with respect to the antenna. The term bulk size is used to indicate the number of items moving through the system at a time. The system parameters considered for the experiment are presented in Table 1.

Table 1: System Parameters

Description	**System Parameters**
Number of VRs	Varies from 1 to 8
Number of PRs	Varies from 1 to 8
PR/VR	1
PR Type	ALR 9800 model RFID reader
PR Attenuation	0 dB
Total Number of Tags	500
Bulk size	Varies from 1 to 98 dB
Tag to Antenna Distance	Within 50 cm
Tag to Antenna Orientation	90 degrees perpendicular
Tag Speed	18 cm/sec

4.5.3.2 Environmental Factors in Real Testbed

The mobility and bulk size are the two factors that affect the readings in a real RFID system deployment. A careful study has been done that aims to figure out an optimal setup in which the RFID readers are able to read items consistently and accurately. The environmental factors ask for a solution that is able to show improved performance taking into account the physical limitations of PRs.

Object Tracking with Various Tag Speed: The speed of the tagged items plays a vital role in the PR level accuracy. Figure 32 indicates how the system accuracy is affected by the speed of tagged items. In this particular study twenty RFID tags have been attached to the train cars and the train speed is varied among four different speed levels. It is observed in out study that objects are tracked with higher accuracy when the objects are moving in a slower speed and the number of detected items decreases with increased speed level. For example, 62% items are detected when the tags travel at 9cm/sec which decreases to 41% when the speed level is increased to 36cm/sec.

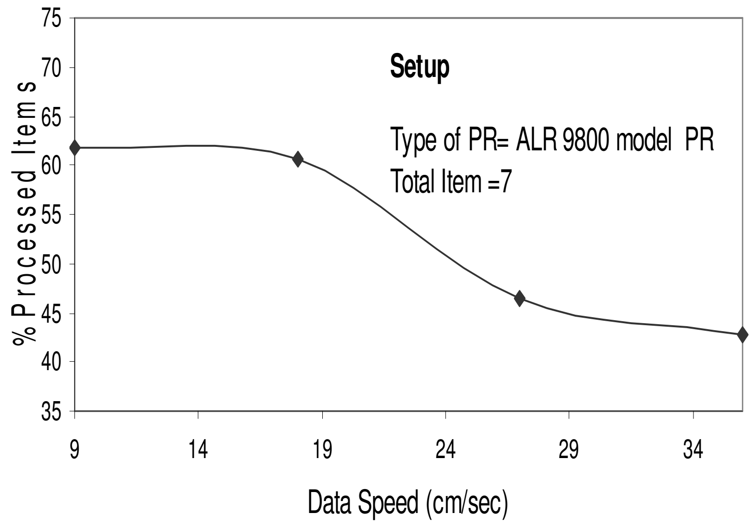


Figure 32: Impact of detected items with various data speed

Object Tracking with Various Bulk Size: The bulk size impacts the reader accuracy level as we have studied in section two and it worsens when the items are in motion. Figure 33 shows how the number of detected items decreases when the bulk size is increased. The study considers 8 PRs each attached to a single VR and varies the number of tags in motion. The system is able to detect all the tagged items until the bulk size remains smaller than 60. When the bulk size is further increased, the accuracy level starts to drop as we can see it reaches 65% for a bulk size 97.

The decreased system performance in terms of detected items validate the need for a solution that is able to provide improved performance taking into account the physical limitations of physical RFID devices (PRs).

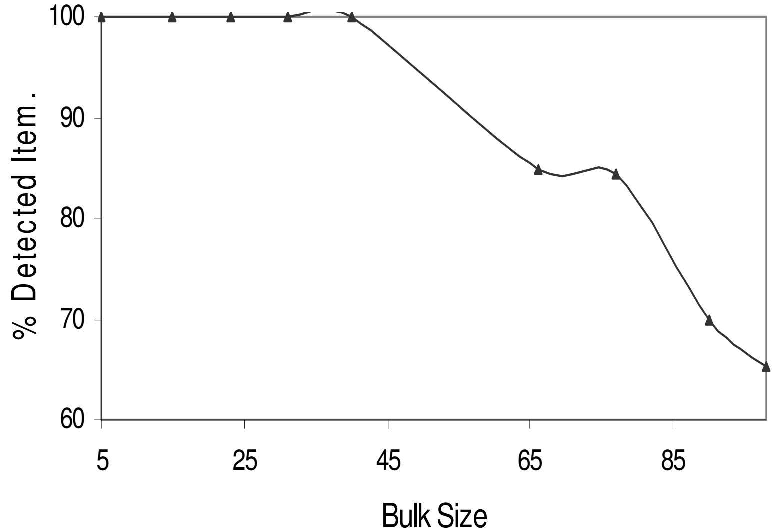


Figure 33: Percentage of detected items with varying bulk size

4.5.3.3 Experiments for a Warehouse Scenario

The warehouse like scenario is considered for tracking multiple items where number of items passes through the RFID readers on a conveyor belt. This section illustrates how the redundancy in RF^2ID system helps to achieve higher accuracy level in the system.

Evaluation Setup: The testbed experiments vary from the previously mentioned experiments as real RFID readers and tags are used and the tagged items are in motion as opposed to statically placed items. Studies have been conducted varying the speed of tagged items and number of items.

A logical view of the warehouse setup is shown in Figure 34. Here the train cars carry various numbers of tags along a route guarded by eight different RFID reader antennas (PRs). Every PR is attached to a single VR in this setup. The train cars attached with RFID tags in motion resemble the warehouse conveyor belts carrying tagged items. We have conducted some basic experiments to figure out the

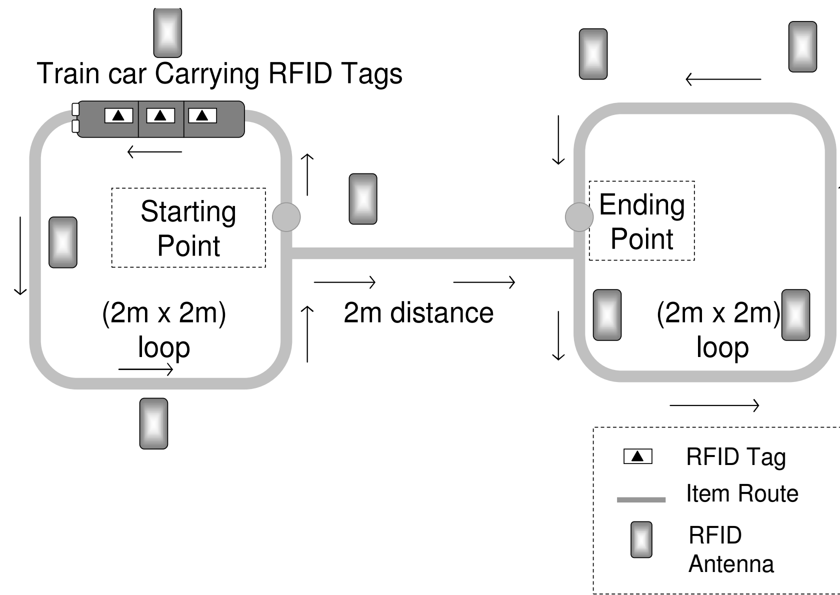


Figure 34: Experimental Layout to mimic a Warehouse

Table 2: Comparison of a Real Supply Chain Deployment with Experimental Testbed

Parameters	**Real Supply Chain Deployment**	**Experimental Testbed**
Area	22 meter x12 meter	2 meter x 2 meter
Read Points	9	8
PR/Read Point	order of 10	1
Number of tags	order of thousands	500
Conveyor Speed	$\geq$ 18 meter/min	15meter/min

parameters further affecting the reader accuracy while the objects are in motion and then conducted evaluation to study the reliability as well as scalability of the system.

Testbed Compared to a Real Warehouse: Table 2 compares the experimental testbed to an actual warehouse deployment. The magnitude of the experimental setup is much smaller compared to a real deployment and we have limited resources for the experiments.

Evaluation Results: Finally we have studied the impact of increasing number of VRs to improve the system accuracy in a real deployment as shown in Figure 35.

We have used 8 VRs each attached to a single PR, used two different bulk sizes of 25 and 50 to conduct this study. The study shows improvement in item detection, for example 22% items are detected with a single VR where 100% items are detected when 8 VRs are used. The improvement raises sharp when the 7th and 8th VR are introduced. The PRs attached to these two VRs outperforms others in terms of item detection.

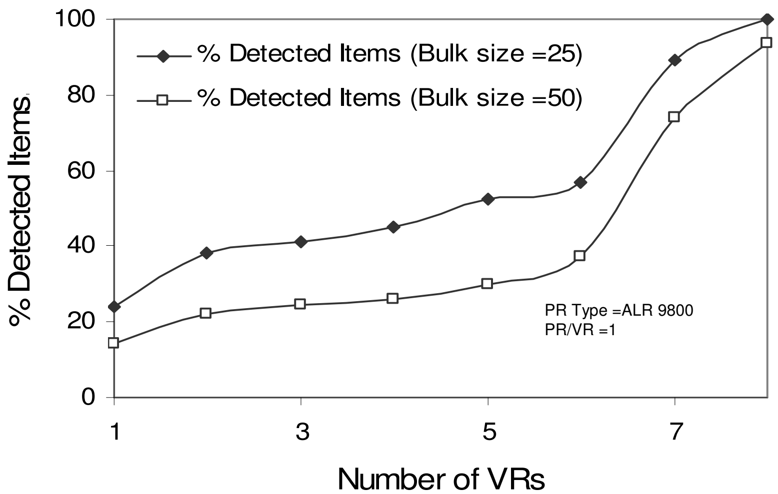


Figure 35: Increased System accuracy with increasing number of VRs

The evaluation result confirms improved system performance in tracking multiple items under various bulk sizes. There is a requirement to study the system to figure out its tracking capability for missing, misplaced and high priority items. The study conducted in the theme of an airport scenario considers such cases.

4.5.3.4 Experiments for an Airport Scenario

In this section we evaluate the item tracking capability of RF2ID in an airport scenario. Tracking of multiple items, high priority items and individual item of interest

Table 3: Comparison of a Real Airport Deployment with Experimental Testbed

Parameters	**Real Airport**	**Testbed**
Conveyor Length	18 Km	2 meter x 2 meter
Number of Baggage	1500/flight, daily 5 flights	500
Tag Type	Gen2 RFID Tag	Gen2 RFID Tag

(missing, misplaced items) are considered for this study.

Evaluation Setup: Figure 36 shows the logical setup for the testbed to mimic an airport scenario. In this scenario, two separate routes are used - one for the baggage and the other for the passenger wishing to board a particular aircraft. Every person is given a unique RFID tag on his or her boarding pass and one on the baggage the person is carrying. The system matches the arrival of matching tags before either the person or the baggage enters the aircraft.

We have established a testbed that consists of criss-crossing toy train tracks to simulate a mock-up of baggage belts and passenger movement in an airport. One train track represents the path used for moving baggage and a second train track represents the path taken by passengers as they wander through the airport. The baggage themselves are emulated by moving train cars carrying RFID tags corresponding to the ones that will be on the baggage. Similarly, the passengers are emulated by train cars carrying tags corresponding to them. We have a total of 8 antennas so we can devote 4 antennas for each of the tracks (baggage and passengers). In other words, with our experimental testbed we can have at most 4 matched pairs of VRs.

Testbed Compared to a Real Airport: Our testbed is compared against an RFID enabled airport to illustrate the scaling factors of the systems. Heathrow airport has deployed RFID technology in terminal 5 recently [50],[33],[32]. The actual numbers of RFID reader and read points are not available but from the length of the conveyor belt, it is evident that the number of items, PRs and VRs will be much larger than our experimental testbed.

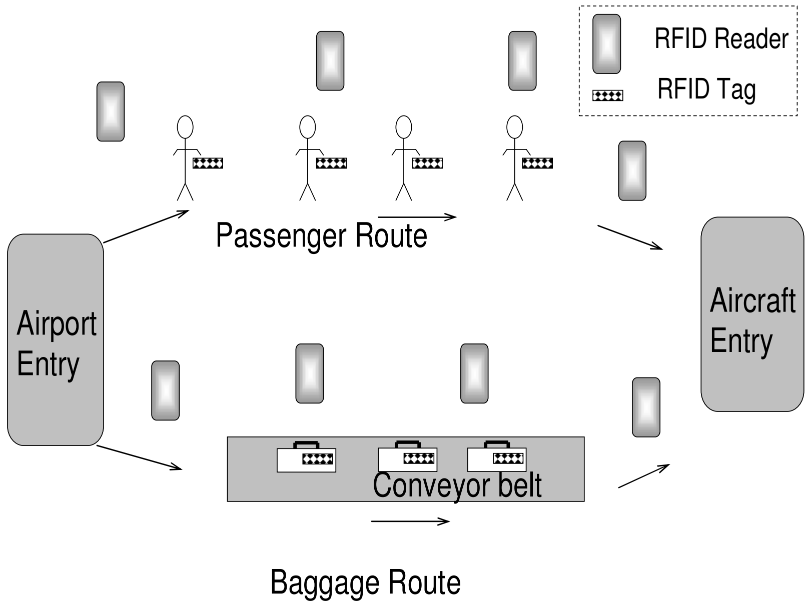


Figure 36: Testbed Setup

Evaluation Results: The evaluation phase observes the airport based experimental scenario to figure out how the system performs in the context of tracking multiple objects, tracking a particular object and finding out about a missing object from the environment.

Multiple Object Tracking: This study uses four VRs each associated with a single PR. The toy trains carry various numbers of tags along the physical route guarded by PRs. For this study two set of items pass the PRs along its route - one set corresponds to people and the second set is their associated baggage. The PRs are very sensitive to various bulk sizes - the PR accuracy drastically decreases with larger bulk size. The study shown in Figure 37, shows the number of detected people with their baggage when the bulk size is varied. It is seen that the system is able to achieve 100% accuracy level with a bulk size as small as 50 and is able to gain above 35% and 55% for a bulk size of 99 using four VRs and two VRs respectively. The base system accuracy consisting a single PR shows lower accuracy level for all the bulk compared to RF2ID using multiple VRs.

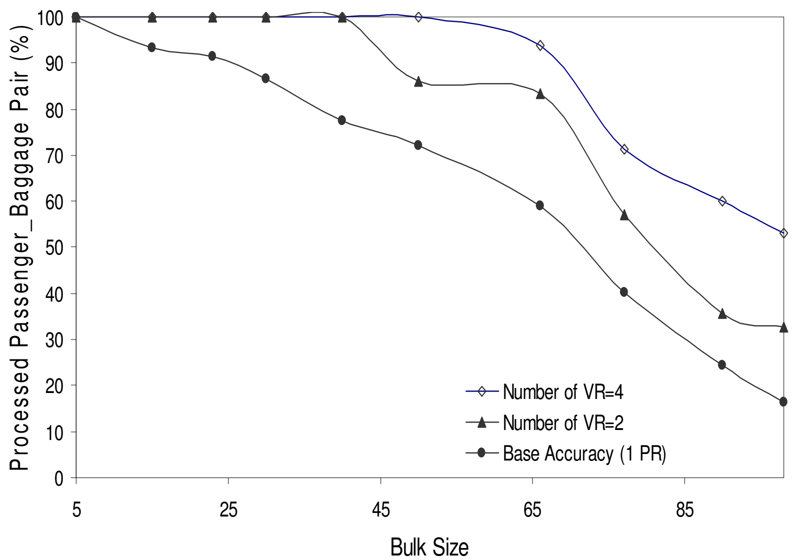


Figure 37: Effect of Variable Bulk Size on Detected Baggage corresponding to People

Tracking Missing Item: The system is able to track missing item when it is tracking multiple items. The study tries to match the baggage with its owner (people) here. A baggage which does not have a corresponding person is a possible threat to the environment. This experiment allows set of baggage to flow through the physical route without any changes while some of the items are removed from the set of person. This study uses four VRs, each using one PR attached to it shown in Figure 38. The number of mission person is varied to one and five to figure out how the system performs while objects are removed from the system. The system is efficiently able to detect 100% mismatch for a bulk size lower than 55 but decreases in its ability to detect all missing item with larger bulk size.

Tracking High Priority Items: Application level information concerning the priority of different objects can be used to detect high priority items using a priority aware method. In an airport scenario, particular baggage of interest can be assumed to have

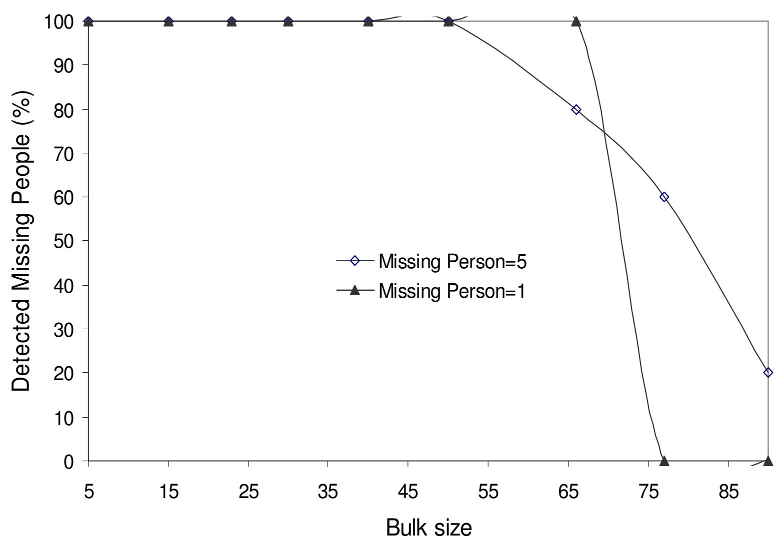


Figure 38: Detected missing people with various bulk size

higher priority over others. When individual VRs have limited processing capability, there is a need to select high priority objects over lower priority ones. Figure 39 shows the number of tracked objects using a priority aware and non-priority aware policy using different bulk sizes using the experimental testbed. The priority aware methods are able to track 100% high priority items using 4 VRs where the scheme which is not priority aware tracks 50% and 81% of high priority items using bulk size of 25 and 50, respectively.

4.6 Related Work

The various aspects of related work are discussed here. We consider different middleware systems aimed at RFID based data for item tracking applications. There are also other works that have similarities to ours considering the path based flow of data through the system. The two subcategories are discussed in detail.

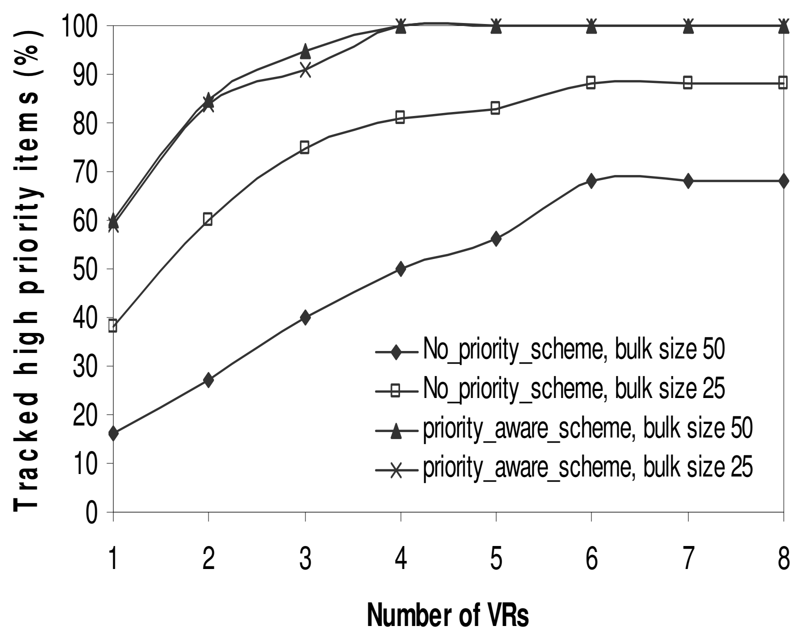


Figure 39: : Number of VRs vs Tracking of High Priority Objects

4.6.1 RFID Based Systems

It is important to compare other middleware that have been proposed for RFID based systems. The Savant architecture proposed by the MIT Auto-ID Center involves a hierarchy of software components called Savants [91]. The RFID middleware design of RFIDStack [46] focuses on reducing data flooding with built-in aggregation and filter types. The architecture of High Fan-in Systems [47] utilizes a tree structure with large numbers of sensors at the edges. De et al. [41] propose a system for object tracking that builds on the Savant architecture. Similarly, MAX [111] uses a tree-like structure for object location. WinRFID [81] uses a hierarchical tree-like architecture that uses web services for deployment of information. SCOUT [69] uses two different approaches depending on the application to ensure scalability of object tracking for mobile devices. None of these systems exploit the data flow that is inherent in the movement of items typical of RFID deployments. Jiang [107] defines a Virtual Route Tracking algorithm to form a virtual route among readers that are in close proximity to one another. The idea of virtual route is similar in spirit to Vpath of RF^2ID, with the exception that Vpath spans geographically distributed elements.

4.6.2 Path Abstraction

The concept of path is used in many different contexts including fault tolerance [37], compiler optimization [19], profiling distributed systems [24], [53], and resource allocation [108], [85]. Our proposed architecture is inspired by the use of paths in these various contexts.

4.7 Summary

We have presented the design and implementation of RF^2ID, a reliable middleware framework for RFID deployment. We have discussed two novel abstractions that RF^2ID uses; *virtual reader* and *virtual path*, and we have presented experimental results to validate the usefulness of these abstractions. We have shown that a path-based architecture improves system accuracy and enables the support of queries over partially located items, i.e., items whose tags are lost at some intermediate location along the physical route from source to destination. We consider two specific application scenarios for item tracking applications: a warehouse scenario where tagged items flow through a conveyor belt and an airport scenario where tagged boarding pass holders are matched with their tagged baggage. We have evaluated the system using real RFID readers as well as emulation based scalability framework.

CHAPTER V

LOAD SHEDDING BASED RESOURCE MANAGEMENT

The RF^2ID system uses the inherent flow of data to increase the system wide reliability in a scalable fashion. The system suffers from unexpected burst of load which requires real time processing and query support in many applications (e.g., real time inventory). Here we use the data flow in the system as an ally to make load distribution decisions. In item tracking applications, items follow a path from a source to destination. The key idea is to allow collaboration among resources along a particular data flow path.

The detailed architecture of RF^{2}ID (Reliable Framework for Radio Frequency Identification) is presented in Chapter 4 [16]. By using redundancy and exploiting the relative flow of RFID tagged objects with respect to the readers, RF^{2}ID increases the reliability of an RFID deployment. RF^{2}ID provides two system level abstractions for increasing the reliability: *Virtual Reader (VR)* and *Virtual Path (VPath)*. Each VR is assigned to a distinct geographical region and by collecting data from physical readers in its vicinity, it locally increases the reliability of the deployment. Further, the VRs in the direction of flow of the items form a logical path (VPath). By exchanging data with one another along the VPath, the VRs further increase the global reliability of the deployment. The net result of this middleware is to increase the reliability of the entire deployment (by reducing the rate of *false negatives*, i.e., the number of tags that are missed by the system) in spite of the error prone nature of the physical readers.

To deal with the volume of data and the time sensitive nature of both tag and query processing, we incorporate *cooperative load shedding* into the RF^{2}ID middleware. The key insight is once again to leverage the notion of *path* for dynamic load distribution among the VRs under heavy load. The inherent redundancy in the system allows the system to do effective load shedding with desirable performance in the context of item tracking applications. Two different load shedding approaches are proposed in this paper: *space based* load shedding mechanism and *time based* load shedding mechanism. In the space based approach, each VR dynamically decides to read a subset of the tags on the path that it is participating, based on their physical ordering in space. In time based load shedding, each VR dynamically decides to read tags for a chosen time interval. We show by experimentation that our load shedding schemes achieve the desired performance results without significantly sacrificing reliability.

The evaluation testbed considers real world constraints such as tag mobility, presence of multiple RFID readers and multiple paths using real PRs as well as emulated PRs for item tracking applications. The workload is different for various application scenarios. For example, in an airport baggage claim scenario, there is asynchronous arrival of large batches of tagged items, that is, the arrival of items can be bursty. On the other hand, in supply chain systems items can arrive any time from different sources, and the flow of items into the system is more consistent. The application requirements also play a major role in the selection of a suitable load management strategy. The time based strategy achieves improved performance for synchronous data arrival, while minimizing the power consumption, as it allows readers to operate in dormant mode in different time intervals. The space based method is the simplest strategy that sheds load and achieves improved performance taking into account the built in redundancy in our system.

The motivation for resource management is presented first, then we discuss the notations to clarify the resource management problem, followed by the load shedding techniques and the evaluation of the resource aware RF^2ID system. The related work and summary of the resource aware system is presented afterwards.

5.1 Motivation

RF^{2}ID[16] focused on the error prone nature of RFID readers and how using middleware techniques we can increase the reliability of an RFID deployment. For example, using physical readers with 60% read accuracy, and 10 virtual readers (each associated with a single PR) the system achieved 100% accuracy. The experimental set up for this result uses emulated PRs that process 100,000 tags using variable tag arrival rate.

The volume of data produced in typical RFID deployments have been increasing by leaps and bounds. This is going to have a significant effect on both the tag processing and query processing times in any RFID deployment. An example presented in [98] considers 10,000 items in a warehouse using 96-bit RFID tags where the system takes inventory every 2 minutes. Roughly 1000 items are added and 1000 items are removed from the warehouse every day. The approximate amount of data generated every two minutes is 117 kilobytes which is almost 3.5 megabytes of data every hour and 85 megabytes of data per day. A more ambitious example presented in [64] considers a larger dataset of 1 billion items generating 720 Gbytes of data per day. A study mentioned in [55] estimates the current inventory database of Wal-Mart at 460 Terabytes. The database grows roughly at a rate of half a Gigabyte being populated by reading 1 million items from nine disjoint access points with each item represented by a 65-byte record daily. Although the amount of data can be reduced by different filtering mechanisms, the system should be able to capture this amount of data in the first place for further processing. If the arrival rate of items is fixed and uniform then it is fairly straightforward to provision the storage and processing resources for data capture. However, the challenge is in the bursty and often unpredictable nature of item arrival in many RFID deployments [90]. This could lead to overloading the infrastructure and potential loss of data and contributing to the unreliability of RFID deployments.

To illustrate this problem, we have conducted some simple experiments using the RF^{2}ID middleware. Each VR is a dual core Pentium-4 Xeon processor, which represents one node of a 56-node Linux cluster. The experiment studies the CPU load experienced by a VR as a function of the tag arrival rate. The CPU load indicates the load in a single VR. Figure 40 shows the impact on a VRs CPU load as the tag arrival rate is increased. As can be seen, the CPU load is close to 100% when the tag arrival rate is 50000 data per minute (y-axis of left hand side). Figure 40 also shows decrease in the accuracy in item detection as a result of increased tag arrival rate. The study on system accuracy uses 9 VRs, each attached to 5 PRs. It shows that we are able to achieve 100% accuracy for tag reading with a tag arrival rate of up to 20000 tags/minute (y-axis of right hand side). However, as we increase the tag arrival rate the accuracy of the system starts deteriorating. It can be seen that the system accuracy drops to 50% when the tag arrival rate is around 35000 tags/min. Basically, the VRs are overloaded and cannot cope with the arrival rate for tag processing. The interesting point to note is that due to the built-in redundancy of the RF^{2}ID middleware, the VRs may be spending time processing the same set of tags. We have observed the overlap in the set of tags read by distinct VRs to be between 40% and 80% in this experimental set up. Clearly, the VR CPU bandwidth used in processing this overlapping set of tags represents wasted resources. If we could harness this wasted CPU bandwidth for processing disjoint sets of tags then obviously we could achieve higher accuracy even at higher tag arrival rates. This is the intuition behind the cooperative load shedding approach presented in this work. We present some notations and terminologies to define the problem and our proposed solution strategy to solve the problem. It should be noted that each of the term is defined in consideration of operation within a time window t_{window}.

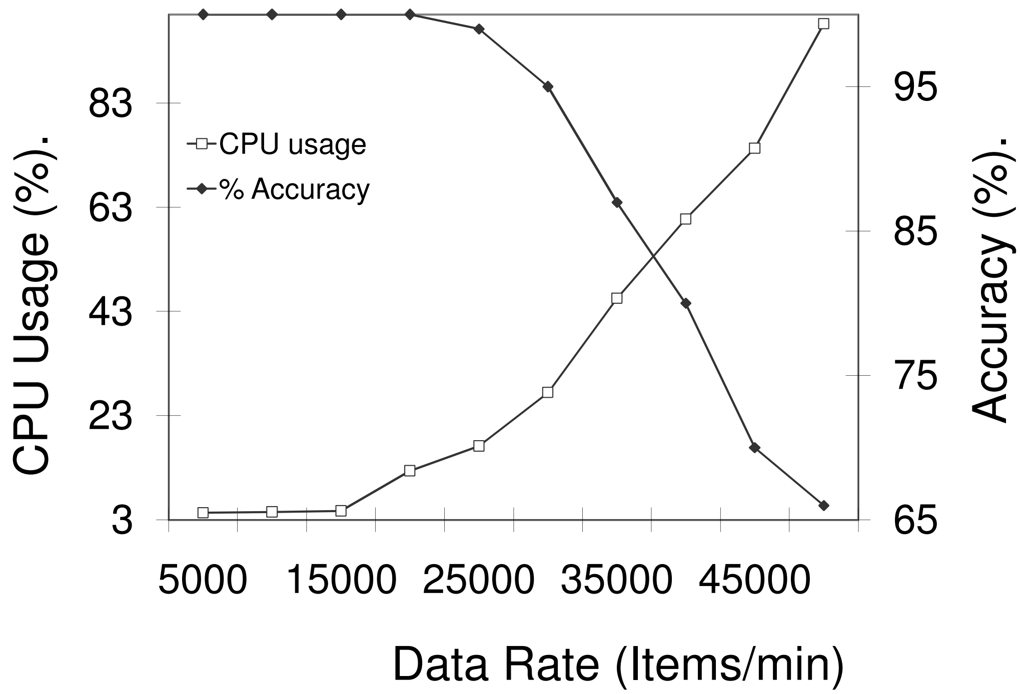


Figure 40: CPU usage and data accuracy with respect to variable tag arrival

5.2 Notation and Terminologies

- *VRs and PRs:* The RF^{2}ID system comprises of multiple VRs denoted as $\{VR_1, VR_2, \ldots, VR_n\}$. Each VR_i is associated with number of PRs as $\{PR_1, PR_2, \ldots, PR_m\}$. Each PR has a physical accuracy level that is an average detection level of items considering various environmental factors (presence of metal, liquid, multiple tags, high data speed ect.) that impact the reader accuracy.

- *Data Items:* The set of data items D in the system is defined as $\{D_1, D_2, \ldots, D_l\}$. Each data item $D_i \in D$ is represented by a unique id and timestamp D_i(ID, time). We present the data item as D_i in the rest of the paper for simplicity. The data items are directed to various paths in the system and the total data along a path is defined as $D_{(path,ptotal)}$ where path is the pathID and ptotal is the total number of items intended along that path. For a total of p paths in the system, the total amount of data in the system D_{total} is defined as:

$$D_{total} = \sum_{i=0}^{p} D_{(p,ptotal)} \tag{1}$$

- *System Performance:* The system performance is measured by the system accuracy level A_{sys} which can be in the range of [0,1] and is defined as a fraction of correctly processed items D_{proc} and total items D_{total}:

$$A_{sys} = \frac{D_{proc}}{D_{total}} \tag{2}$$

The overall system accuracy level depends on the VR accuracy level which is determined by the accuracy level of PRs.

- *PR Level Accuracy:* The PR accuracy level $A_{(PR,i)}$ is defined as the proportion of items correctly detected by PR_i ($D_{PR,i}$) and the total data for path p ($D_{(p,ptotal)}$):

$$A_{(PR,i)} = \frac{D_{(PR,i)}}{D_{(p,ptotal)}} \tag{3}$$

- *VR Level Accuracy:* The VR level accuracy $A_{(VR,j)}$ is determined by m PRs attached to a particular VR and a VR's ability to process the data. The accuracy level is defined as a proportion of processed data of VR_j ($D_{(VR,j)}$) and the total data along path p ($D_{(p,ptotal)}$):

$$A_{(VR,j)} = \frac{D_{(VR,j)}}{D_{total}} = \frac{(\bigcup_{j=0}^{m} D_{PR,j})}{D_{(p,ptotal)}} \tag{4}$$

- *Path Level Accuracy:* The path level accuracy $A_{(Path,k)}$ for a $path_k$ is determined by n VRs that participate in a path. The accuracy ($A_{(p,k)}$) level is defined as a proportion of processed data along a path p ($D_{(p,k)}$) and the total data along path p ($D_{(p,ptotal)}$) given as:

$$A_{(p,k)} = \frac{D_{(p,k)}}{D_{(p,ptotal)}} = \frac{(\bigcup_{k=0}^{n} D_{VR,k})}{D_{(p,ptotal)}} \tag{5}$$

- *System Level Accuracy:* The system level accuracy A_{sys} for p paths is determined by the following equation:

$$A_{sys} = \frac{D_{(sys)}}{D_{total}} = \frac{(\bigcup_{l=0}^{p} D_{path,l})}{D_{total}} \tag{6}$$

- *Problem Definition:* The goal is to achieve desirable accuracy level defined as threshold accuracy ($A_{(th)}$) even when the system is under heavy load. This can be defined as:

$$A_{sys} \geq A_{th} \tag{7}$$

- *Solution Strategy:* As the items follow a particular route, it is likely that if a particular VR gets overloaded, the successive VRs along the path will become overloaded eventually. The basic idea is to let each VR process a subset of total data ($D_{(proc)} \subset D_{(total)}$) along a path. Each VR_i makes decision on shedding a certain amount of load ($D_{(shed)}$)where

$$D_{proc} + D_{shed} = D_{total} \tag{8}$$

5.2.1 Acceptable Values for A_{VR} and A_{PR}

Given a threshold value for the overall system performance A_{th} and accuracy of individual VRs (A_{VR}) for n VRs in the system, the minimum acceptable value of A_{VR} can be computed. If we assume that each of the n VRs have the same accuracy level, the system accuracy level can be generated in the following way which must be greater than or equal to the threshold value defined by the application.

$$A_{th} \leq 1 - (1 - A_{VR})^n \tag{9}$$

Thus the desired level of VR accuracy after shedding load must be within the given range

$$A_{VR} \geq 1 - (1 - A_{th})^{1/n} \tag{10}$$

Similarly, as a single VR value is comprised of the accuracy level of m PRs (A_{PR}) attached to it, the VR level accuracy (A_{VR}) can be determined as:

$$A_{VR} = 1 - (1 - A_{PR})^m \tag{11}$$

Thus individual VR accuracy can be improved by using appropriate number of PRs with operational accuracy level. To preserve the accuracy level after load shedding, the system must ensure proper distribution of the overall data within a window of time. The proper methods to choose the amount of load to shed are determined by the load shedding strategies discussed in the next section.

5.3 Load Shedding Strategies

Operationally, the load shedding strategy can be split into two phases. The first phase, namely, *load monitoring and overload detection* is common to all the load shedding strategies.

5.3.1 Load Monitoring and Overload Detection Phase

The computational load on an individual VR has two components:

- A *communication* component that comprises receiving messages from the PRs physically associated with it and for sending/receiving messages to/from the peer VRs logically associated by the paths with this VR.

- A *computation* component that comprises a complex mixture of processing time for reading and classifying tags from PRs into the physical routes and logical paths associated with this VR; processing time for filtering the tags (elimination of false positives, etc.) based on the messages received from peer VRs; executing admission control algorithm in response to path creation requests; and processing queries for inventory control.

Each VR has to ensure that the cumulative load does not exceed its computational capacity ($ComputationalCapacity(C)$). We express the above computational load on a VR in terms of its physical and logical connectivity. Let each VR be connected to m PRs and p paths. Let PR_i be the computational load due to an individual physical connection i; let $Path_j$ be the computational load due to an individual path j. The instantaneous load $Instantaneousload(L)$ on a VR is expressed as:

$$L = \sum_{i=1}^{m} PR_i + \sum_{j=1}^{p} Path_j \tag{12}$$

The system as a whole is not overloaded so long as the following equation holds for all VRs:

$$L \leq C \tag{13}$$

Since items flow along paths, if one VR is overloaded then it is likely that other VRs on the same path are overloaded as well. Fortunately, the path abstraction gives a common basis for each VR to make a *local* determination on the load for taking load shedding decisions. To ensure that there is some performance cushion for dealing with overloads and for avoiding sudden drop in the quality of service, we preset an upper limit for the instantenous load on a VR as $L_{(t)}$ ($L_t < C$). Each VR monitors its instantenous load (L) and when it exceeds the preset threshold L_t, it enters a load shedding phase.

5.3.2 Load Shedding Strategies

Two load shedding approaches - *space based load shedding* and *time based load shedding* mechanisms are discussed here.

5.3.2.1 Space Based Approach

In this approach, each VR decides to read a *subset of the tags* flowing through a given path in a given *time quantum* $T_{(window)}$. Each VR has a finite *per path queue* of size Q for processing incoming tags. Each VR knows *a priori* the number of VRs ($VR_{(num)}$)

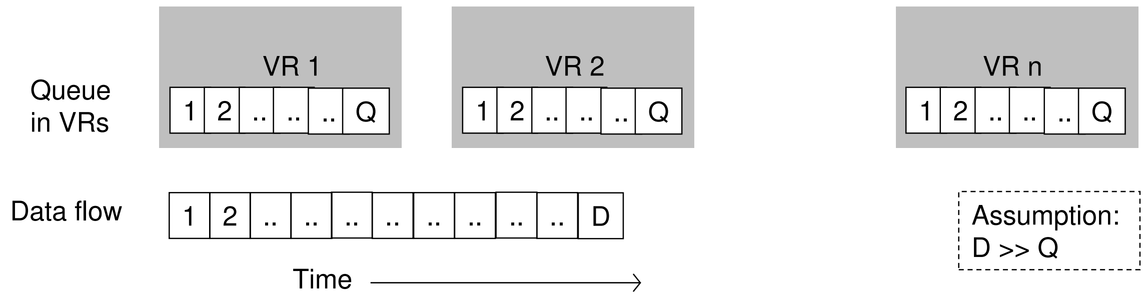


Figure 41: Space Based Load Shedding

on a particular path. Let $MAX_{(tags)}$ be the expected maximum number of tags per time quantum flowing through the path. This quantity can be readily computed knowing the item arrival rate into the system. A particular VR_i reads a number of items D_{read} in a time window which is defined by the queue length as follows:

$$D_{read} = Q = \frac{MAX_{tag}}{VR_{num}} \tag{14}$$

In an ideal situation (i.e., assuming PRs with 100% accuracy), it is sufficient if each VR reads MAX_{tags} / VR_{num} disjoint set of tags to ensure 100% accuracy of the deployment. However, there is the complication that the PRs do not have 100% accuracy. The term *delta* is used in the evaluation of space based load shedding where Δ is a sensitivity parameter for keeping the error rate within acceptable bounds.The performance impact of Δ is studied in the evaluation section. The evaluation study considering the sensitivity parameter is given by:

$$D_{read} = Q = \frac{MAX_{tag}}{VR_{num}} + \Delta \tag{15}$$

We propose two variations of space based load shedding which differ in the method of choosing the amount of data to read and process (D_{read}) based on its queue length Q.

- The *random space based load shedding strategy* provides read-autonomy to individual VRs, each VR reads a random subset of items bounded by queue size Q.

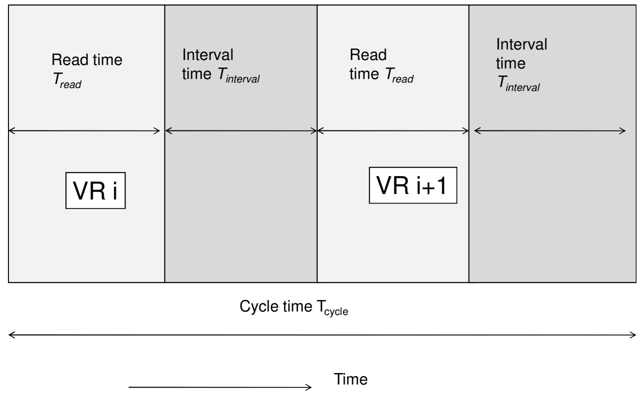


Figure 42: Time Based Load Shedding

- The *cooperative space based load shedding strategy* allows individual VRs in a path to cooperatively select a disjoint portion of the RFID data stream bounded by the queue size Q. The disjoint set is determined by choosing a data set in the same sequence as the sequence of VRs along the path in a particular window of operation. Ideally, each VR would read separate sets of tags. However, RFID readers use their internal protocol to reduce collision [86], [104] and reads tags in the reading range in a random order.

5.3.2.2 Time Based Approach

This approach can be considered as the time analog to the space-based approach. First, we introduce some terminologies:

- *Cycle Time* ($T_(cycle)$) is the time a particular item takes to traverse from source to destination along a particular physical route.

- *Read Time* ($T_{(read)}$) is the time a VR accepts data read by PRs, where, $T_{read} \ll T_{cycle}$.

- *Interval Time* ($T_{(interval)}$) is the time interval between the read times of two consecutive VRs, where, $T_{interval} \ll T_{cycle}$.

If we consider the conveyor belt speed as S m/sec, width of W and number of items in a palette as N items, then we can define the data rate (r) as:

$$r = \frac{(S \times N)}{W}(items/sec) \tag{16}$$

Each VR reads (D_{read}) items within a predefined read time:

$$D_{read} = r \times T_{read} \tag{17}$$

We use $tao \subset T_{interval}$ that serves as the sensitivity parameter to increase the reliability of the deployment. Thus the read time is defined as:

$$D_{read} = r(T_{read} + \tau) \tag{18}$$

Note that neither of the load shedding strategies require any additional intelligence in the PRs. The choice of a specific strategy depends on the application requirement. In the next section, we evaluate these strategies.

5.4 Evaluation

This section discusses the implementation, experimental setup used for the experiments and finally, the performance results using the proposed load shedding strategies. The performance results subsection evaluates the system in various phases which looks at performance bottlenecks under heavy load of the basic PRs, the baseline system which uses RF^{2}ID but no load management scheme and finally presents the system performance using the load shedding techniques.

5.4.1 Implementation of the Load Shedding Strategies

As we mentioned earlier in section 4.4, RF^{2}ID is currently implemented in Java using sockets for inter-VR communication. The implementation supports both physical

RFID readers (Alien 9800 model) as well as emulated physical readers that are indistinguishable so far as the VRs are concerned. The emulated physical readers are a faithful reproduction of the Alien 9800 readers, and allow controlled experiments to be carried out varying different sensitivity parameters of the physical readers. Each VR executes on a 3 GHz dual core Intel Xeon processor with 1 GB RAM, 512 KB L2 cache and 1 MB L3 cache. The processors are interconnected by Gigabit Ethernet and form part of a 56-node cluster.

We have extended the implementation of the base RF^{2}ID system to include the load shedding strategies discussed in the previous section. At system initialization time any particular load shedding strategy may be chosen providing the system with the parameters specific to that strategy (for e.g., queue size for space-based approach; read and interval times for time-based approach).

5.4.2 Experimental Setup for the Study

The purpose of the experimental study is to understand the effectiveness of the load shedding strategies under heavy load to increase the reliability of an RFID deployment without data loss. In our lab, we have constructed a mock up of a supply chain using toy trains (the trains move carrying the tags on stationary tracks instead of stationary tagged items moving on a conveyor belt) illustrated in Figure 43. The various parameters considered for the experimental testbed is presented as a comparison toward an actual testbed in Table 4.

Table 4: Comparison of a Real Supply Chain Deployment with Experimental Testbed

Parameters	**Real Supply Chain Deployment**	**Experimental Testbed**
Area	22 meter x12 meter	2 meter x 2 meter
Read Points	9	8
PR/Read Point	order of 10	1
Number of tags	order of thousands	500
Conveyor Speed	$\geq$ 18 meter/min	15meter/min

The laboratory setup is considered as a scaled down version of a typical distribution center as presented in [56, 55]. We have used this testbed for validating the emulated physical readers used in the RF^{2}ID middleware.

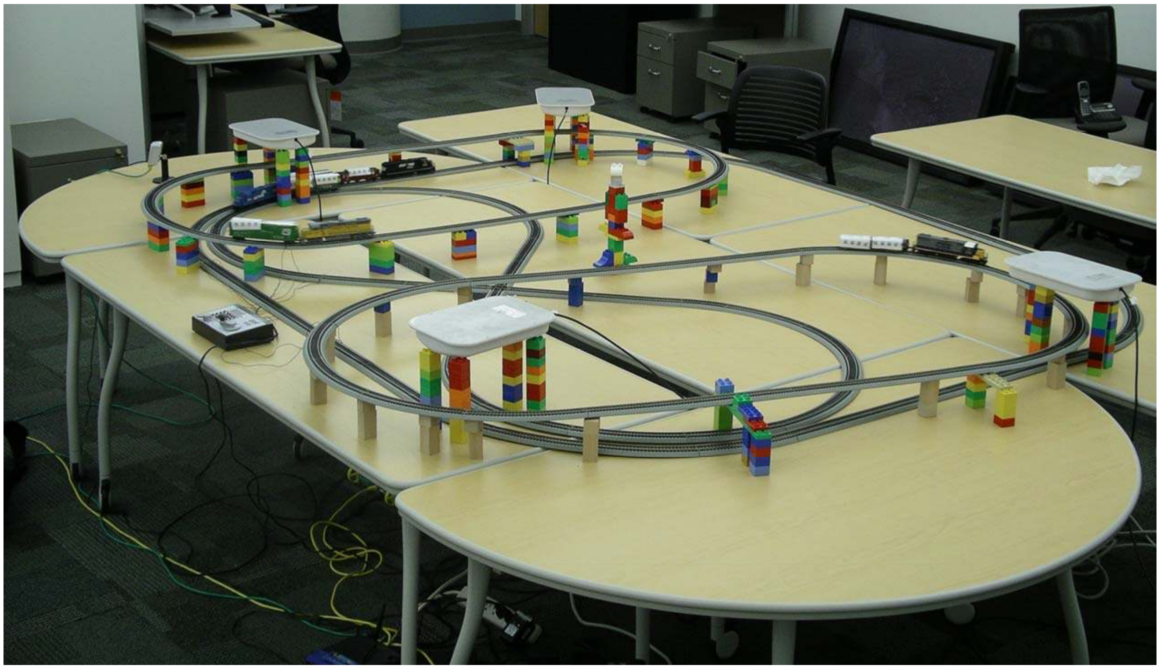


Figure 43: Experimental Setup

5.4.2.1 Validation of Emulated PRs

The scalability study to be discussed in the next section uses emulated PRs that have been designed to faithfully reproduce the behavior of the real PRs. We have designed experiments to validate the emulated PRs using the RF^{2}ID middleware and the laboratory testbed. In this experiment, we fix the tag arrival speed at 15 meter per minute (approximately, 35 ft per minute) and use 7 RFID tags in the validation study. Each VR is associated with a single PR, thus making it a one-to-one comparison of the performance of real PRs and emulated PRs. We vary the number of VRs from 1 to 4 and observe the accuracy (i.e., the number tags read compared to actual number of tags). Figure 44 shows the result comparing the false negative rate of the real PRs and emulated PRs. As can be seen, the observed results validate the accuracy of the emulated PRs in faithfully reproducing the results of the real PRs. For one PR, the readings are almost identical. However, for higher number of PRs, there is a small difference between the real and emulated results. This is due to the variance in the accuracy levels of the individual real PRs, which is not present for the emulated ones. Still the discrepancy between real and emulated PRs is less than 5%.

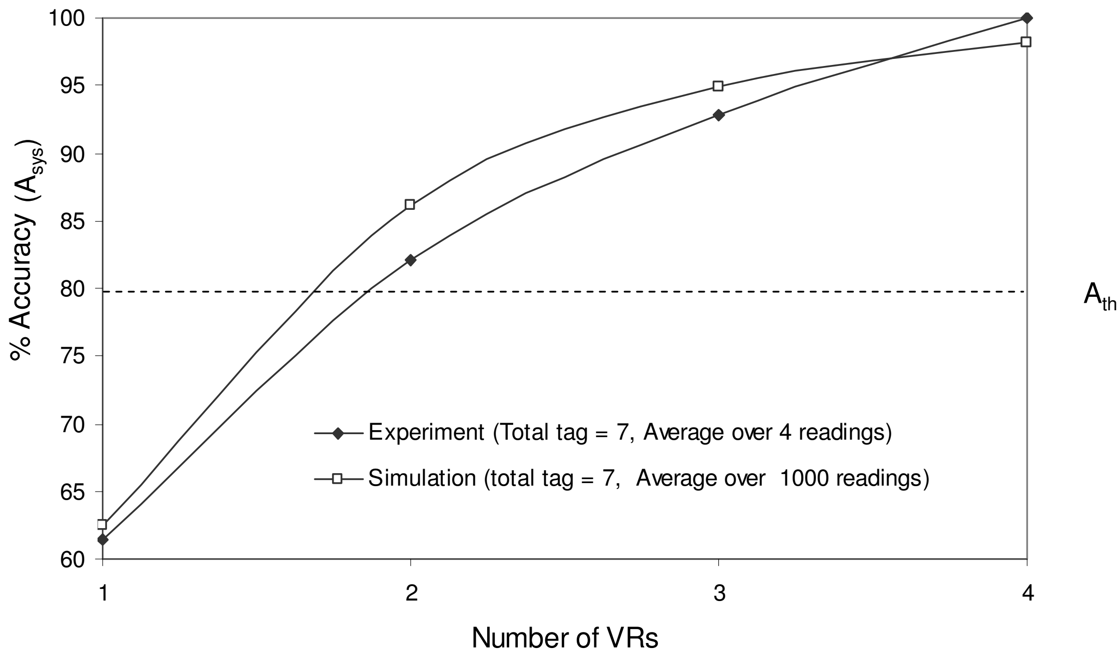


Figure 44: Emulated PR vs Real PR Performance

5.4.2.2 System Parameters

In this study, we consider a distribution center of moderate size (described in [56, 55]). The distribution center uses 9 disjoint read points which we have considered to be individual VR operating points. Each VR is attached to 5 PRs. A moderate sized center expects 1 million data items every day, which amounts to 7000 items per minute [56]. A uniform distribution of this much amount of data may not cause the system to get overloaded. However, the arrival of RFID tagged data is bursty in nature that could cause the system to overload. The various system parameters used for the experiment are discussed here.

- *System Performance (A_{sys}):* The measured quantity for evaluation is in system accuracy A_{sys}, indicating the reliability of the deployment.
- *Incoming Data Rate:* In the experiments requiring variable data rates, we have considered the data rate defined from the conveyor speed, palette width and items per palette (defined as *bulk size*) as defined in equation 16. We have fixed the belt speed and palette width and vary the bulk size to vary the data rate.
- *Data Processing:* A time window (t_{window}) for n tags is considered within which a VR performs the following tasks: processing of the tags (n $\times$ t_{tag}), processing of incoming VR messages t_{in}, processing of outgoing VR messages (t_{out}) and processing of queries (t_{query}). The VR needs to make sure $t_{process} < t_{window}$ holds before it can send its processed data to the next VR.

$$t_{process} = (n \times t_{tag} + t_{in} + t_{out} + t_{query}) \tag{19}$$

- *Time Window (t_{window}):* A real distribution center needs to update the data values every 1 to 2 minutes to meet real time application requirements [16]. Based on these requirements, we choose a time window of 1.5 minutes, since the the computation and communication at every VR has to complete within the data update rate demanded by the real time requirements.
- *System Threshold (A_{th}):* We have considered a threshold system accuracy (A_{th}) of 80%. The system evaluation using the minimum PR accuracy as low as 19%, attaching 5 PRs to a single VR and having a total of 9 VRs in the system, ideally, the system should perform at 99.994% accuracy level. But we must take into account the real time requirements that limit the system performance which is exhibitted in the next subsections.

The various workload parameters for the conducted experiments are summarized in Table 5.

Table 5: System Workload Parameters

Data rate	5000 to 55000 items/minute
Time window	1.5 minutes
Number of VR	1 to 9
Number PR assigned to VR	1 to 5
Types of PR	Emulated PRs and real PRs (ALR 9800)
Speed of Items	9 to 36 cm/sec
Accuracy (A_{th})	80%

5.4.3 Performance of Baseline System

In this section, we evaluate the baseline system. First, we study the inherent physical limitations of the PRs, and motivate the need for the RF^{2}ID middleware for improving system reliability. While RF^{2}ID scales well and meets reliability requirements (Section 5.3.2) under normal data rates, we show its limitation in meeting reliability requirements at high data rates. Finally, we show the performance of the RF^{2}ID system enhanced with the load shedding strategies proposed in this paper.

5.4.3.1 PR Level Evaluation

The PR performance depends on various environmental factors such as tag to reader distance, orientation, and angle has been reported in previous chapter.

In this study, we look at two other limiting factors, namely, belt speed and bulk size. These factors are of great importance in the context of a warehouse. We use item speed and belt speed synonymously in this paper, since in our laboratory testbed the items move on the train instead of a moving belt in a real warehouse. Figure 45 shows the sensitivity of processed items to the item speed and bulk size. We use Alien ALR 9800 RFID reader and the experiment uses 7 tagged items with our experimental set up for the speed evaluation (y-axis of left hand side). The number of detected items decreases as the item speed is increased. For example, the number of detected item decreases from 62% to 42% when the item speed increases from 9 cm/sec to

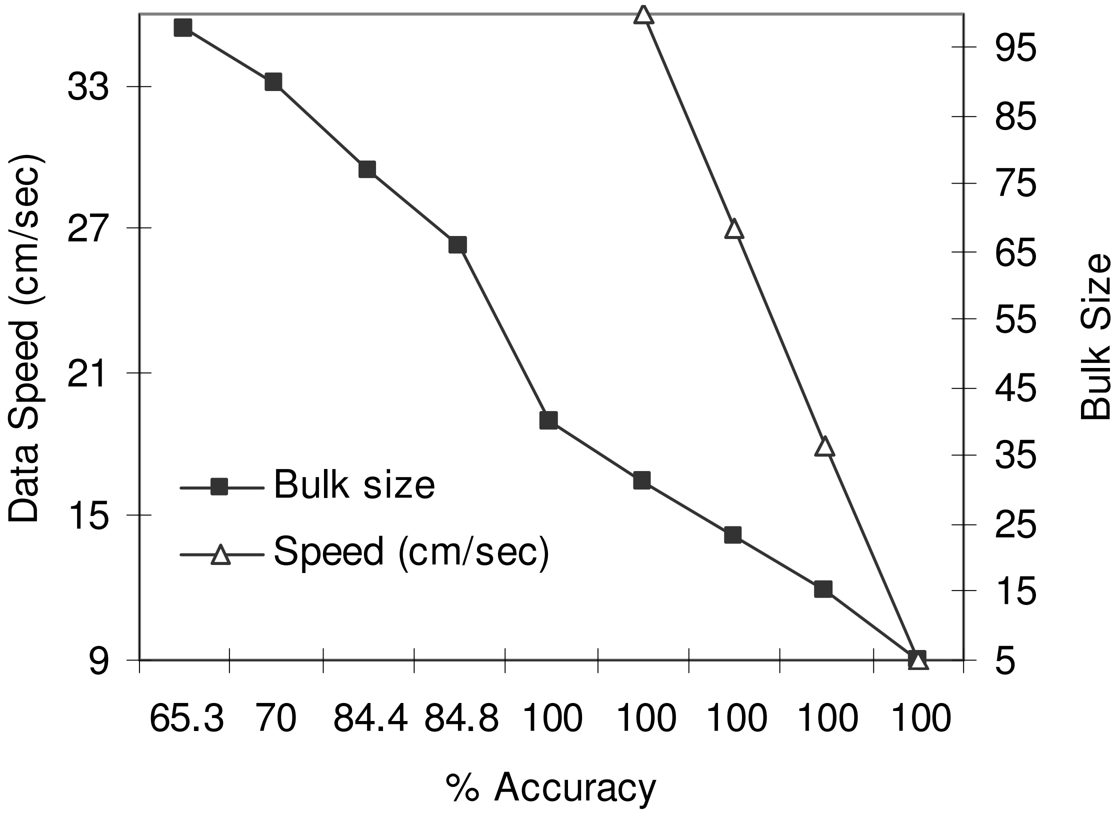


Figure 45: PR Performance with variable Speed and Bulk Size

36 cm/sec. Figure 45 also shows the sensitivity of the processed items to bulk size (y-axis of right hand side). We fix the item speed at 18 cm/sec. The number of detected items detoriates as the bulk size increases. As can be seen, 98% of the items are detected when the bulk size is 5, which drops to 16% when the bulk size reaches 98.

These results clearly show that as the data rate is increased (either due to belt speed or bulk size or both), a single PR is incapable of meeting the reliability requirements of an RFID deployment. We show in the next section how the reliability can be improved using the RF^2ID middleware.

5.4.3.2 Improved System Accuracy using RF²ID

The system performance is improved using the redundancy of PRs using RF²ID. The performance is enhanced at individual VR level using larger number of PRs and at system level increasing the number of VRs. First, we look at multiple PRs associated with a single VR.

Figure 46 shows the sensitivity of processed items as bulk size is varied assuming an item speed of 18 cm/sec and associating 4 PRs with a single VR. As can be seen, 100% processed items is achieved when the bulk size is 40, while it is only 60% with a single PR. Next, we study the scalability of the system for larger number of PRs

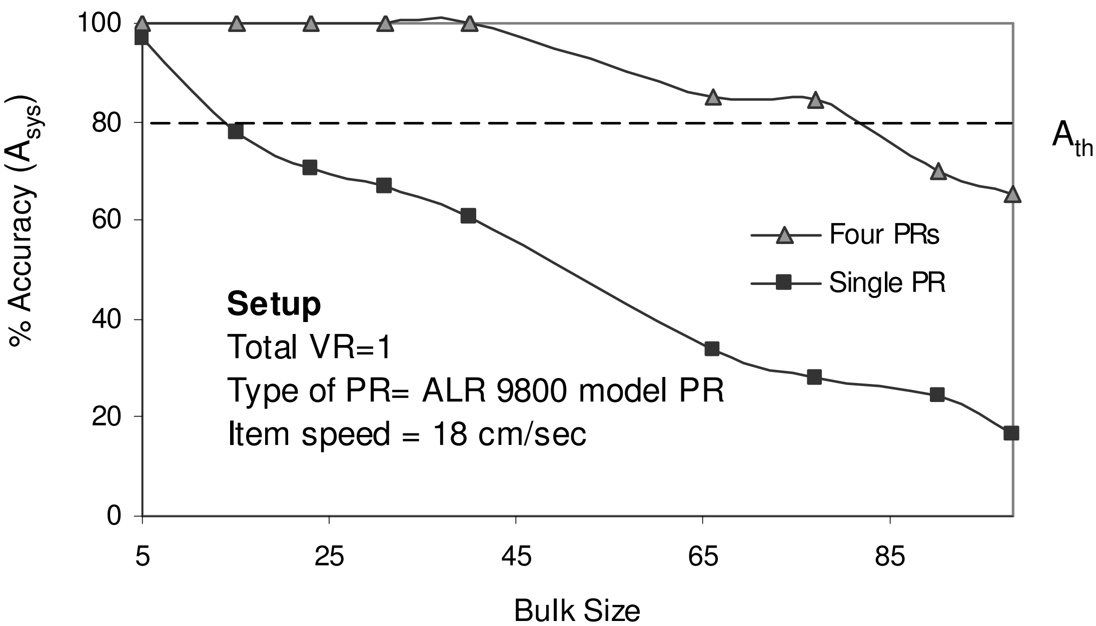


Figure 46: Improved System Performance with Increased Number of PRs with Variable Bulk Size

and larger data rates.

5.4.3.3 RF²ID Performance under Heavy Load

Figure 47 shows the scalability of the RF²D middleware. The set up uses 9 VRs with each VR associated with 5 PRs. As can be seen, the system scales well up to 25000 items/minute. However, at higher data rates the reliability drops off. This is the reason for the proposed load shedding mechanisms.

In the next section, we evaluate how the load shedding mechanisms are able to address the scalability problem at high data rates.

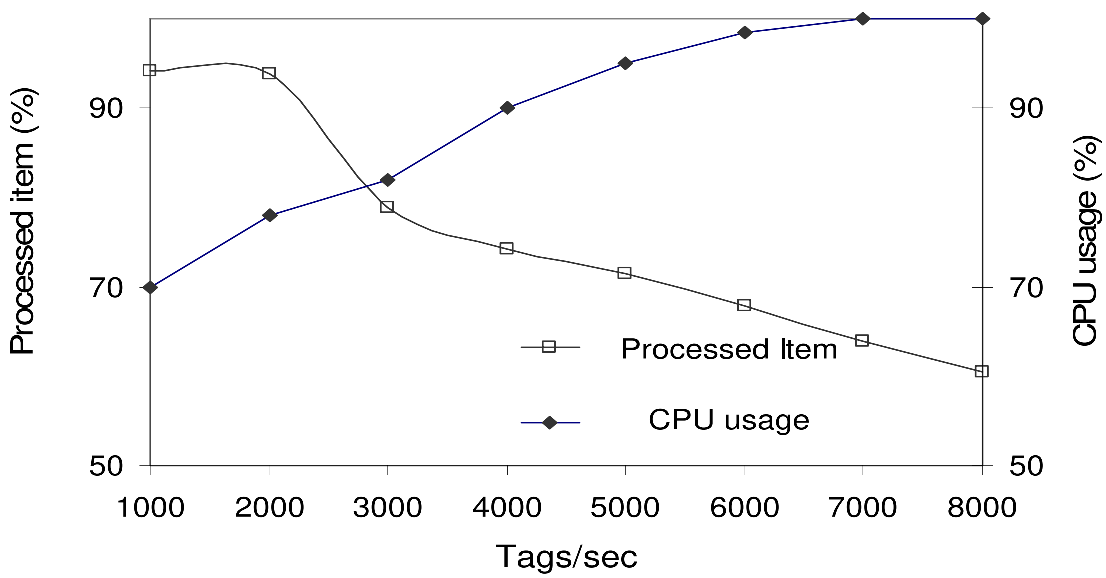


Figure 47: System Performance for Various Data Rate

5.4.4 Performance of RF^{2}ID with Load Shedding

The load shedding mechanisms are studied elaborately in this section. The space based load shedding and time based load shedding mechanisms are studied and compared against the baseline system that does not use load shedding. We also conduct sensitivity analysis on the parameters of each of the load shedding strategies.

5.4.4.1 Comparison of Baseline with the Two Load Shedding Mechanisms

The study uses 9 VRs, each associated with 5 PRs. The baseline performance detoriates when the data rate increases beyond 25000. As we discussed earlier, within the time window of 1.5 min, each VR has to do all the chores associated with processing the items and communicate the result to the VR downstream from it. As the data rate increases, the baseline has a hard time keeping up with the demands of processing all the items (see Figure 48). On the other hand, it can be seen that the space-based approaches is able to sustain good reliability with higher data rates. The cooperative space based approach performs the best among all the evaluation strategies (above A_{th}). The randomized space based load shedding performs better than the baseline method for higher data rates. The time-based approach, although has a lower reliability compared to baseline for low data rates, does better at high data rates and performs at A_{th} level.

In the next two sections, we study the sensitivity of space-based and time-based mechanisms to the parameters that define those strategies.

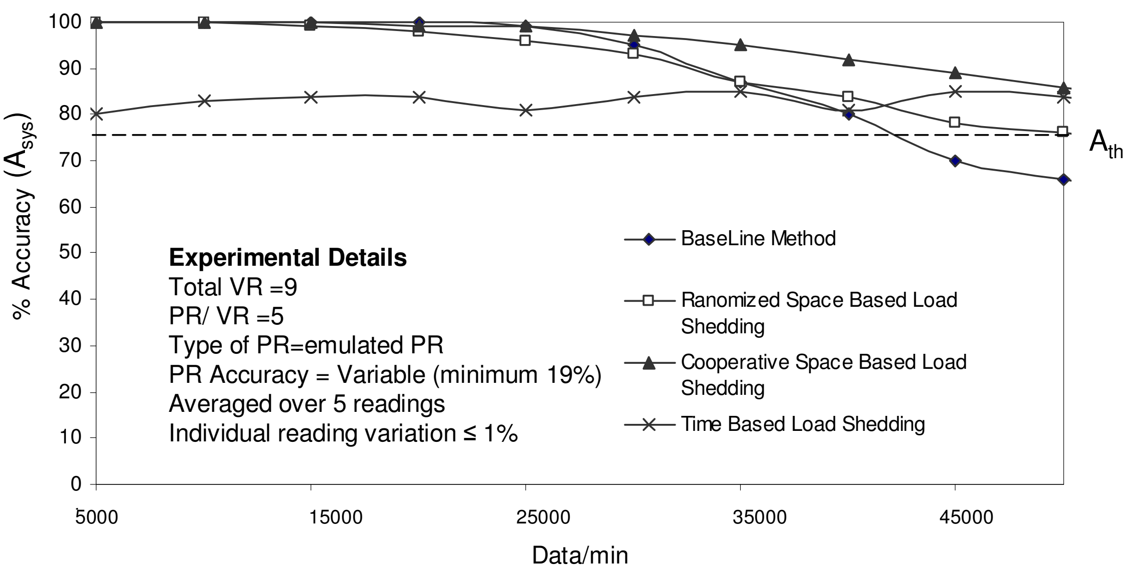


Figure 48: Baseline System Performance Compared to Space Based and Time Based Load Shedding

5.4.4.2 Space Based Load Shedding

Figure 49 shows the sensitivity of the space-based approach to the Δ parameter (the effective queue length is equal to $5000 + \Delta$). With increasing Δ values, the system reliability increases.

However, arbitrarily increasing the queue length would eventually degrade the performance. This is illustrated in Figure 50. For this experiment, the data rate is fixed at 75000 items/min, and Δ is 0 using cooperative space based load shedding. The number of processed tags detoriates for larger queue lengths as there is more data to process at each reader. This coupled with the incoming data from neighbor VRs results in degradation of performance. The accuracy level increases with increasing queue length up to 15000 and then detoriates for larger queue size. It should be noted that, the cooperative space based approach performs beyond the A_{th} level of performance.

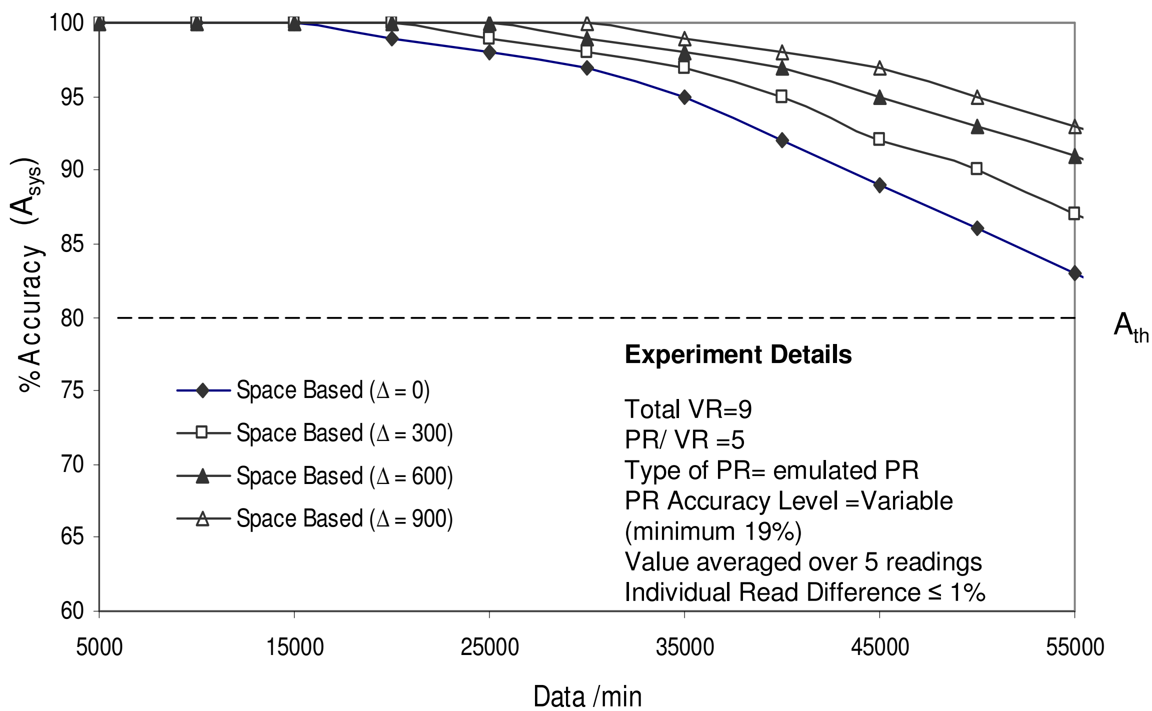


Figure 49: Space Based Load Shedding -Varying value of Δ

The study conducted using variable queue size illustrates how the queue size impacts the system accuracy under heavy load in the cooperative space based load shedding approach. The queue size is varied while the data rate is constant to 15000 items per minute using 9 VRs and 5 PRs per VR for this experiment shown in Figure 50. The number of processed tags detoriates for larger queue length as there are more data to process along with the incoming data stream from neighbor VRs and gets closer to the baseline performance as the queue length keeps increasing. The accuracy level increases with increasing queue length up to 10000 and then detoriates for larger queue size.

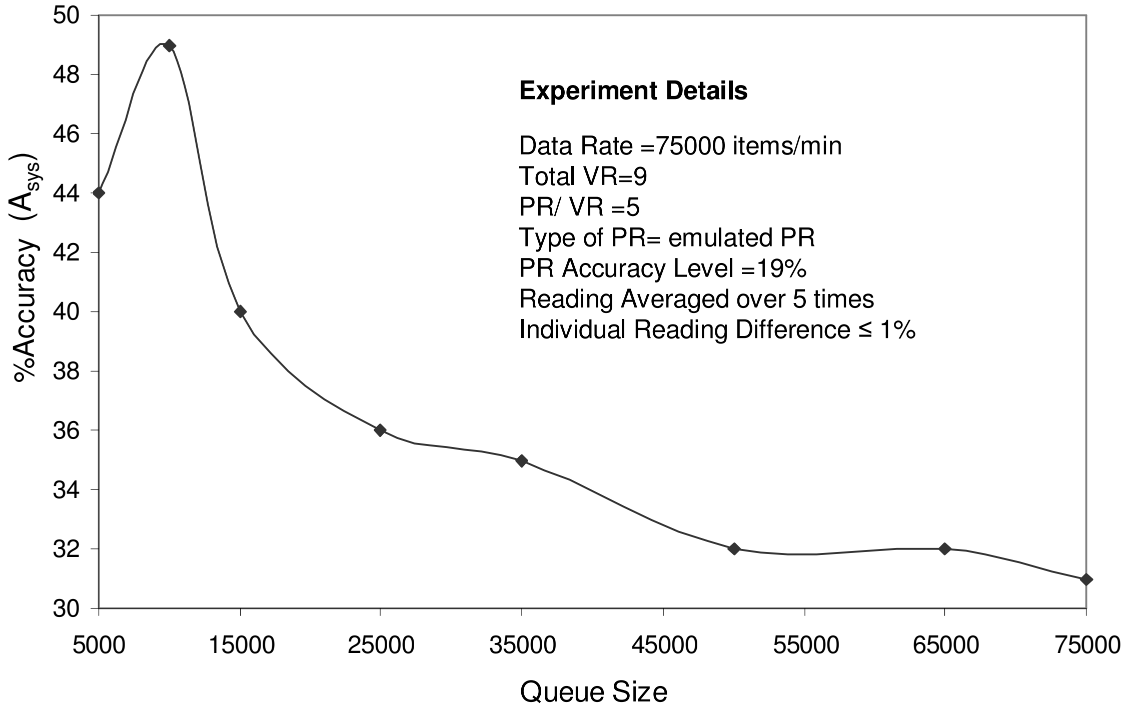


Figure 50: Space Based Load Shedding using various Queue Size

5.4.4.3 Time Based Load Shedding

The sensitivity of the time-based strategy to its parameters is shown in Figure 51. This study compares the effect of overlapping read times among the PRs. In the non overlapping case, the interval time (τ= 0) is considered to be 0. For the overlapping case, each reader reads for 200 ms more (τ=200) time along with its distinct read time. It is shown that the larger read time increases the system performance in terms of processed items.

The impact of variable interval time is shown in Figure 52. The overlapping reading (Interval time > 0) shows improved performance over non overlapping reads (Interval time = 0) in the study. However, the number of processed items decrease

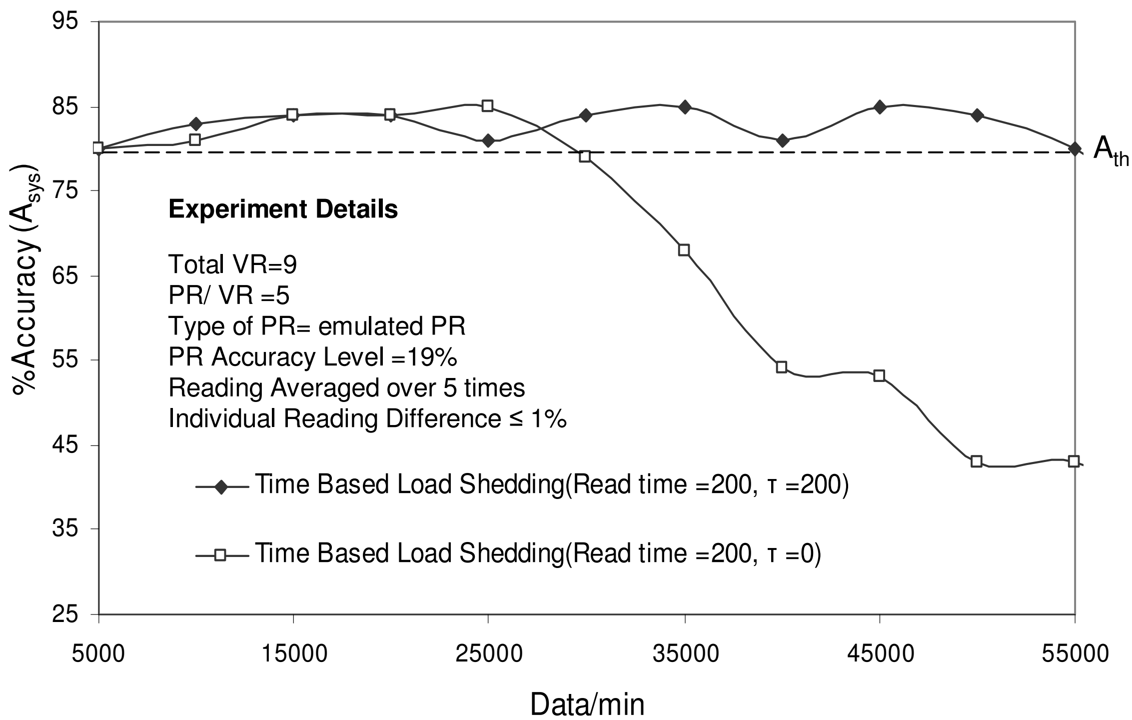


Figure 51: Time Based Load Shedding with various read time

as the interval time increases over 800ms. For example, the percentage of processed items are 30%, 62% and 44% for interval time of 0, 600 and 1000 milliseconds, respectively. Basically, increasing the overlapping times effectively increases the load on the associated VRs, and this detrimental effect eventually dominates leading to deterioration of performance. The load shedding based approach is an effective way to handle temporary overload in the VRs where the technique itself is not computation intensive. The performance study on the system shows how the inherent redundancy is used to alleviate the adverse affect of system overload. The choice of a specific load shedding strategy depends on the application scenario and the available resources. Time based load shedding mechanism requires synchronization among PRs as well as VRs in real time which is desirable in a smaller setup. It allows set of PRs to be in dormant mode while other PRs are in operation. This feature can be very useful considering resources which has power constraints. On the other hand, the space based method operates independently among VRs and is able show improved performance

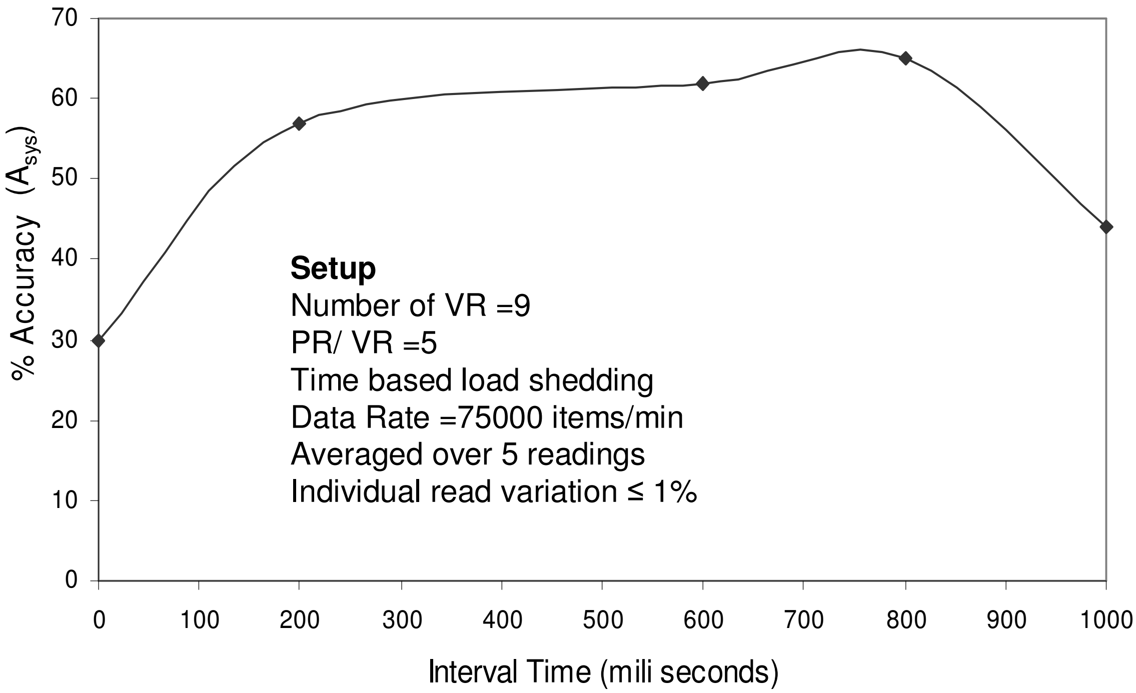


Figure 52: Time Based Load Shedding with various interval time

over the time based approach. This approach is preferable in large distributed system setup.

5.5 Related Work

It is interesting to note that work related to ours falls across fairly diverse domains. First of all, the traditional area of resource management and load balancing in distributed systems has relevance to our work. Also, there is work on streaming data that bears some resemblance to some of the issues studied in this paper. We briefly review these related areas in this section.

5.5.1 Load Balancing and Resource Migration in Distributed Systems

There is a significant amount of work on load balancing in distributed systems where the aim is to distribute the load evenly using techniques such as load migration [40, 44, 54]. However, the streaming nature and the unpredictable burstiness of the data being handled in RFID based systems calls for a different treatment of the problem.

Recently, there has been research work focusing on load management aspects of RFID based systems. The work in [42] provides a heuristic based solution for near optimal reader to tag assignment to deal with the load in the system. However, the solution only addresses statically placed readers and tags. Producing a system that accounts for tags in motion adds another layer of complexity. The mobile agent based load management system in [39] uses a mobile agent to re-adjust imbalance of load in the system using load migration. The connection pool based load balancing presented in [80] also readjusts load among different nodes from heavily loaded one with a lighter load. Load migration is not very suitable for streaming data that needs to meet real time constraints [98, 64]. There is a need for load management that deals with a large amount of error prone data while simultaneously meeting the challenge of real time query processing requests, which is the focus of our paper. Traditional resource migration techniques may not be applicable for RFID based systems since such techniques require additional processing to make such decisions when the system is already under stress to meet the real time query processing requests and data overload. *Load shedding* based load management has been incorporated as an effective stream handling mechanism systems such as Aurora [38, 22, 96], that are designed to meet real time application constraints. Our work is similar in that we adopt a cooperative load shedding strategy among the system components.

5.5.2 Streaming Applications

The Aurora system [38, 22, 96] uses the notion of load. MobiQual [48] uses load shedding based techniques to make decision based on freshness of data. Our system is also based on load shedding but it uses the built-in redundancy of the RF^{2}ID middleware to cope with the load with minimal data loss. TelegraphCQ [34] is aimed to support streaming data but differs from our work in system structure. It uses stream partitioning for load balancing compared to load shedding techniques. The pipelined framework [61] processes correlated data locally which has similarity to the VR abstraction of our work; however, the power of our work is in having the VRs operate in concert via the Vpath abstraction.

5.6 Summary

RFID based deployments for large-scale supply chain environments are becoming widespread. These deployments face the fundamental challenge in RFID based systems that the devices are error prone. The demands placed on the deployments from the applications in the form of increased data rates and requests for real time query processing are compounding these challenges even more. We have designed cooperative load shedding mechanisms for dealing with the increased data rates and query processing requests in large-scale RFID deployments. The mechanisms are piggybacked on a middleware called RF^2ID that deals with the error-prone nature of the physical RFID readers. The middleware uses the spatial notion of path along which the items flow in a supply chain to cumulatively aggregate the tags collected by the virtual readers to increase the overall reliability. The load shedding algorithms leverage the built-in redundancy in this middleware to cooperatively shed the load among the virtual readers with minimal data loss thus increasing the overall reliability of the deployment. Our implementation and performance results confirm the utility of these load shedding mechanisms.

CHAPTER VI

GUARDIANANGEL: AN RFID-BASED INDOOR GUIDANCE AND MONITORING SYSTEM

We have focused on item tracking problem in the previous two chapters using RFID technology. We focus on item location in this chapter. Specifically we consider an indoor guidance and monitoring system in an RFID enabled environment.

The monitoring and guidance facility introduces challenges in the requirements. A robust guidance system requires positioning information, which enhances the monitoring capabilities. However, monitoring individuals at fine grain level is not desirable for privacy concerns as mentioned in Chapter 1.

We have developed a two layer middleware solution named *GuardianAngel* that provides system support in such a pervasive environment. The lower layer, named as the *Guidance Layer*, provides the locality information to the user to make guidance decisions. The upper layer, known as the *Monitoring Layer*, has the global knowledge of the environment. The environment is equipped with low cost RFID tags. The guidance layer is supported by a hand held device that has an RFID reader attached to it. The guidance layer is thus able to provide information regarding the resident's current location and immediate objects by sensing the environment. The monitoring layer has the information about the entire environment. The guidance layer under user control periodically updates coarse grain information defined as the *virtual location* about the resident to the monitoring layer. The guidance layer with its limited capability only keeps partial map information that is acquired on demand from the monitoring layer.

The novelty of our approach lies in its uniqueness along three dimensions: first, by virtualizing the user position information; second, by providing a more natural way of gathering environmental information using RFID tags in an unobtrusive manner under user control; and third, by enabling the deployment of large scale indoor environment using low cost passive RFID tags and mobile readers.

We present the application scenario and requirement analysis of the system, then we discuss the system architecture followed by the evaluation of the system. The GuardianAngel system is evaluated in an RFID enabled testbed as well as in a large scale emulation based system. The related work and summary are presented to conclude the chapter.

6.1 Application Scenario and Requirement Analysis

The applications we consider are best suited for environments that are statically tagged with an RFID location grid. This would be especially useful for a visually impaired person to be self-reliant within a large office complex, hospital, etc. Equipped with a gadget that combines an RFID reader and an audio system that gives verbal instructions, such an individual would be able to chart out a route unassisted through an unfamiliar large indoor environment. Essentially, the fixed RFID tags enable the dynamic creation of a *path* from source to destination. A second use case for such a static deployment of RFID tags is in *search and rescue* operations following either a man-made or natural disaster. A robot or a SWAT team may use this infrastructure to dynamically chart out paths that are reachable within the indoor environment following the disaster, as well as locate assets (humans and articles of value) within the affected environment.

While the details of each specific application may be different, they all pose some common requirements. We investigate such common requirements to design a middleware system solution. The premise in this discussion is that the application comprises mobile agents that use the RFID-tagged environment for making forward progress.

From an application perspective, the middleware should provide the following types of information to the mobile agents in the application:

- *Current location:* The mobile agent may need this information to make some local decisions (e.g., have we arrived at the destination yet?). This information is best presented in some familiar form such as GPS coordinates.
- *Routing information:* The mobile agent would benefit if the middleware could provide a route given the current location and the desired destination.
- *Assets in the neighborhood:* This would be particularly useful in asset location applications as well as self-guided tours in museums and the like. Based on the current location information, the middleware provides a map of assets in the neighborhood.
- *Terrain:* The kind of information envisaged here include obstacles (e.g., doors, stairwell, etc.) as well as landmarks (e.g., information desk, copier room, etc.). This information serves the mobile agent to make local routing decisions to destinations when there are multiple paths available as well as seek help if needed.
- *Message board:* This allows a mobile agent to share information with other agents if so desired. Essentially, this allows the mobile agent to leave electronic *bread crumbs* (either signed or anonymous) that may be useful for other applications or agents that use the same infrastructure.

6.2 System Architecture

The overall system setup is presented in Figure 53. The physical environment is the indoor space under consideration. The physical environment has RFID tags installed

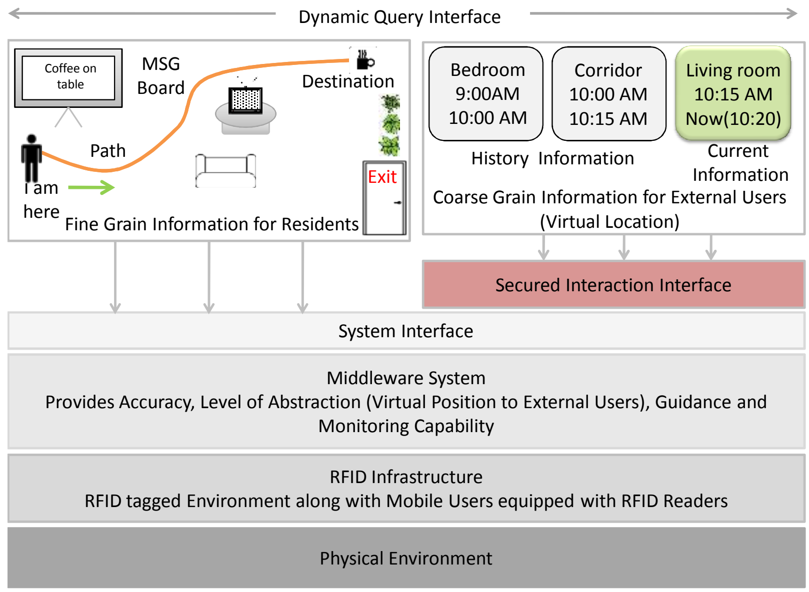


Figure 53: Overivew of the entire system.

and has the residents carrying mobile RFID readers [1]. The middleware is a data flow oriented system which is responsible for processing the environmental information, monitor the mobile residents and guide the residents as required taking care of all the low level communication and computational details. The residents of the environment (e.g., grandma in assisted living center) and the external user (family members of grandma) get different views of the envornment and can use the user interface to generate dynamic queries in real time.

The GuardianAngel system has three major components. The first of these is the *Pervasive Environment (PE)*. This is the indoor environment in which the system operates. Second is the *Mobile Object ($MobileObject(MO)$)*, which is the entire mobile system: user, computational device, and reader. The *Guidance Server ($GuidanceServer(GS)$)*, a software entity that computes position and gives directions to the destination, runs on this MO. The third component is the *Monitoring Server ($Monitoringserver(MS)$)*, a logically omnipresent server that contains information

[1]We assume that it is quite natural for a mobile user to carry a handheld device that incorporates such RFID reader capability. Nokia has developed a cellphone equipped with a passive RFID reader, and there are several mobile RFID readers available in the market today [97].

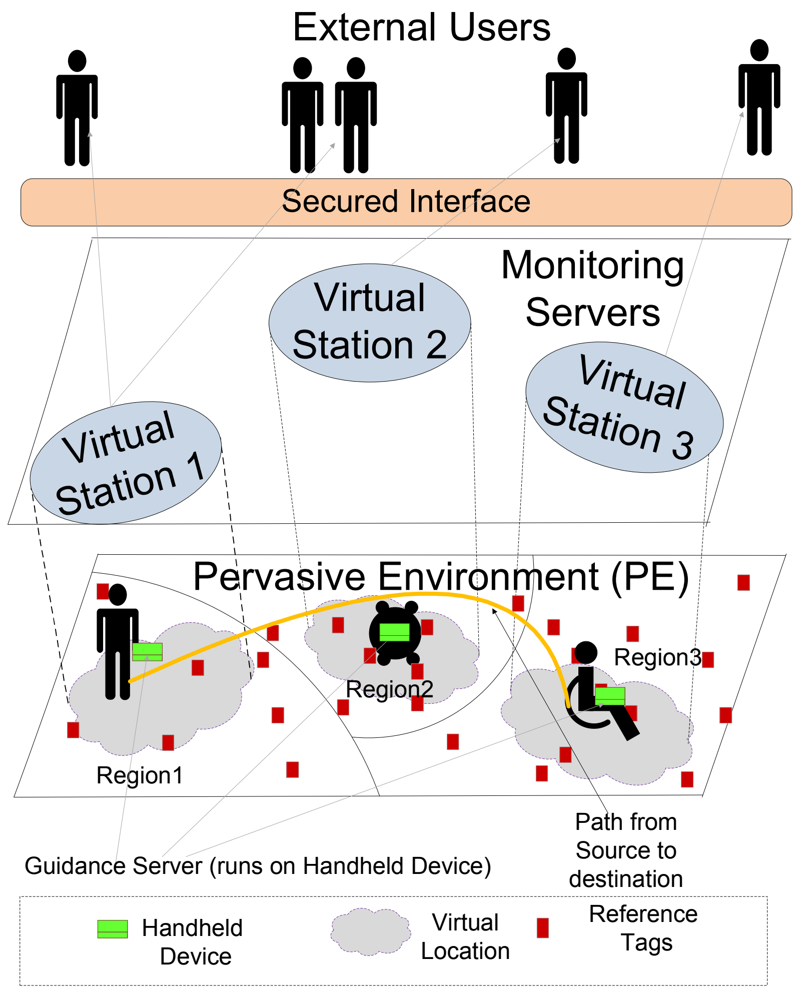


Figure 54: GuardianAngel Architecture.

about the PE. It communicates with the GS to obtain information about the status of mobile users. While a single logical entity, physically the MS is broken into a set of distributed servers, called *Virtual Servers (VS)*, that load balance and provide better feedback to the user through geographic and logical proximity. The monitoring information does not reveal the actual location information of the active users, it presents a virtual location over a period of time. The system architecture is presented in Figure 54.

6.2.1 Pervasive Environment

The pervasive environment (PE) represents the entire indoor environment under consideration. The PE is logically divided among different regions. The logical definition can be matched with physical entities (e.g., each room of a house or each floor in a building). The zones can be matched to physical spaces based on application requirements (e.g., a family space region can be subdivided into TV zone, sitting zone and empty zone).

The PE consists of a set of regions $R = \{r_1, r_2, ..., r_n\}$. Each region r_i is equipped with set of reference tags $T_{(r)} = \{t_{(1,r,T)}, t_{(2,r,T)}, ..., t_{(m,r,T)}\}$. The reference tags are logically divided among three different layers for different operations. The *location tags* $T_{(l)} \subset T_{(r)}$ are used to define the current location of an object. The *direction tags* $T_{(d)} \subset T_{(r)}$ are used to define direction information. The *object tags* $T_{(o)} \subset T_{(r)}$ are the tags containing objects of interest. We must note that $T_{(r)} = T_{(l)} + T_{(d)} + T_{(o)}$. The PE requires a *setup phase* by which the environment is installed with RFID tags. The setup phase is followed by the *location phase* that provides the system with actual or virtual position information.

6.2.1.1 Setup Phase

The setup phase requires two consecutive steps: the *installation of tags* followed by *zone definition*.

The tag installation phase can be carried out manually in a *structured format* (e.g., grid format) or a *random format*. The structured tag installation process requires manually placing the tags in a grid structure in the environment providing a convenient way to define a mobile user's current location. The random installation process is easier to install but requires a *tag discovery process*. In the tag discovery process, mobile users (e.g., human user, robot) traverse the environment in a definitive route to discover tag placement information. We have considered the grid structured tag installation in our implementation as the tag discovery process is often error prone.

The zone definitions are initialized in one of three fashions, static, dynamic, or semi-dynamic. Static definition requires that the user or application directly program each tag into its appropriate zone. This process is best for situations in which a tailored zone setup is needed, but is very time consuming. Dynamic allocation sets up the zones automatically, without user input or further input from the application. This is easiest, but can lead to imbalanced zones or zone layouts that are not appropriate for the physical environment due to the error prone reading properties of RFID readers [38], [47]. Semi-dynamic setup relies on the user to define *root nodes*, which act as anchors for each zone. The system then follows a heuristic algorithm a variant of breadth-first search in the prototype to assign proximate nodes to the same zone. We used the semi-dynamic approach in the GuardianAngel system.

6.2.1.2 Location Phase

The RFID reader equipped with the guidance server uses the environmental information to determine the location information. We use an application defined probability threshold $Pr(location) \geq Pr(Th)$ to place the MO within a *boundary location*, or the location of the MO within a predefined area of the PE. From this, the GS can compute the MO's *virtual location*, which combines historical and present position information to calculate with higher accuracy the current location of the MO. Note that the boundary and virtual locations do not have to perfectly coincide with the MO's physical position, just approximate it.

The location information depends on the tag samples read by the RFID reader and the reading accuracy of an RFID reader while the person carrying it is in motion. The reading accuracy is determined by a reader's ability to correctly read items compared to the total number of actual items: $Pr(r) = \frac{R}{T}$ where R refers to the number of items correctly read and T refers to the total number of items. The observation accuracy can be increased by increasing the number of samples where the observation accuracy is defined as: $Pr(O) \equiv 1 - (1 - Pr(r))^s$, where s is the number of samples and O is the probability over a number of samples.

The *single sample time* depends on the physical properties of the RFID readers and is defined as $t_{(sample,1)}$: time required for a single sample read. The *total sample time* ($t_{(sample,s)}$) is the time required to read s number of samples. We have, $t_{(sample,s)} = s * t_{(sample,1)}$. We must take the speed of the mobile user into consideration. If the user speed is d distance per unit time then the user traverses a distance of $d * t_{(sample,s)}$ in $t_{(sample,s)}$ time. We must make an optimal choice of choosing a reasonable sample size to limit the distance traveled during the sample time.

The actual position of a mobile object can be determined using a number of samples of tags from the environment. For s number of samples of tags, the current position is defined using a weighted average of tag positions observed over the samples. We can assume Wt_i to be the number of times a particular tag t_i is seen over the S samples and Pos_i to be the (x,y) position of that particular tag along with its history information as: $CurrentPos = f(Sample(s), History(h))$ where the sample is expressed as $\sum_{i=1}^{s} ((Wt_{i-1}) * Pos_i)$ and History is mentioned as $\sum_{j=1}^{h} ((Wt_{j-1}) * Pos_j)$ where history represents last few samples to make sure the proper area is chosen discarding outlier tags.

The system has provision for providing a boundary within which the MO stays with higher probability rather than defining an (x,y) position. As the MO advances along with time, the system is able to define the relative direction information from the history boundary information relative to current position boundary. The *virtualized position* is similar to defining the boundary of the tags except the boundary region is defined over a period of time T_{period}. If the boundary position is very definitive as MO remains temporarily stationary over the last time period, the virtual position is defined by some cushion area around the current position. The mobile user depends on its handheld computation device for this information. The user sends out its virtual position to the monitoring server.

6.2.2 Virtual Server (VS)

The VS provides services to the MO present in the designated region for that VS. The major responsibilities include communication management, information management, and status management as shown in Table 6.

6.2.2.1 Communication Management

The VS provides three major communication abstractions for effective communication among the system components. There is a *message board* interface that allows information exchange among the MOs in the same region. The message board is a *permanent communication abstraction* that remains in a region. The *path based* communication mechanism uses the route information from the MO to create a logical communication channel across the PE among the VSs. The path abstraction is a *semi-permanent communication abstraction*. It remains active as long as there is a MO traversing through the designated route. The MO to VS communication is done *on demand*, and thus is a *transient communication mechanism*.

The message board interface, as the name suggests, provides an open interface for communication among the MOs. There is a single message board in each region. The message board acts as a provision to put electronic bread crumbs in the environment by existing MOs that can be followed by incoming MOs in the same region. The message board is designed to be distributed in each region for improved scalability of the messaging mechanism. The MOs are able to post general messages for information exchange within the same region and read posted messages from the board. The MOs can post information regarding the MO status and information regarding environmental updates (e.g., missing reference or addition of new references) to the

Table 6: VS Responsibilities

Task Name	**Responsibilities**
Information Management	(1)Store physical and logicalmap of a zone (2) Provide subzone or zone map to MO based on compute capability (3) Update zone information based on inputs (4) Provide guidance information given source and destination information
Status Management	(1) Generate an automaton based status list for each participating MO which is organizedby time sequences (2) Generate a rule set for general or specific MO status (3) Update MO status information & check MO rule engine whether any rule is violated (4)Garbage Collect status information based on predefined application requirements (5)Generate appropriate alert messages
Communication Management	(1)Manage the logical message board across MO in a region (2) Communicate to neighbor MS for path generation or alert message exchange (3)Communicate from Mo to MS periodically for map update, status update and guidance queries or item queries (4)Communicate from MS to MO if MO has not contacted beyond a predefined threshold

message board. The VS creates a logical path among the VSs if guidance information is required for a particular source to destination route. The path creation request is initiated by a request from a particular MO to a VS. A VS contacts its peer VSs and generates a list of VSs that correspond to the shortest path. The cost associated with a path may be expressed using traditional metrics (such as time and distance), or may be expressed based on convenience (e. g., a path without any stairs is lower in cost and more desirable) commensurate with application requirements. The VSs agree on a path creation after assessing the current and predicted future workload in a similar way that is done in RF^2ID [16] as mentioned in Chapter 4. As the MO progresses through the regions, the MO to VS assignment changes based on the current MO location. The VSs transparently transfer status information regarding the MO along the logical path for monitoring purposes. The handoff of VS to MO takes place after the MO changes its region and which is initiated by the VS. The VS to MO messaging takes place in a sporadic fashion based on needs. The MO asks for PE information as it makes progress in the environment. The MO also needs to update the MO status information to the VS. The MO piggybacks its status information with its request for new blocks of PE information. The VS queries the MO if it does not hear from a particular MO beyond a predefined threshold time.

6.2.2.2 Information Management

The information management of a VS requires managing the physical map and logical map based on application requirements, providing region information to the MO, updating region and zone information and guidance services. It concentrates on maintaining the PE information and providing such information to the MOs present in a particular region. The *physical map and logical map* functionality allows the VS to act as a distributed repository of information regarding the PE. The information contains the three layer view of the PE consisting of the RFID tags. The VS is able to provide physical information about an object of interest as well as logical information about the environment. Logical information provides an abstraction to the MO in a more natural way. For example, a query about the *medicine with the tag ID 770* can be responded by its (x,y) coordinate position or by a logical entry such as *it is on the black table near you*. The logical setup requirements are application specific. The VS is responsible for providing *region and zone information.* The MO can ask for map based information in a block by block manner where the block size is dependent on the computational capability of MO along with the application requirements. The VS provides *guidance information* given the source and destination inputs from the MO. The VS is in charge of creating a path to guide the MO as discussed in previous subsection.

6.2.2.3 Status Management

The VS keeps the information of each individual MO in the form of a deterministic finite automata. The status information of the MO is represented as a sequence of states and important information concerning each state. The state change parameters are application dependent and can be adjusted based on requirements. The application can also specify logical rules to be checked dynamically on the MO status. The rules must be set to minimize the number of $FalsePositive$ notices. The application should also be able to determine a threshold on how much status information should be stored so that the VS can perform automatic *garbage collection* on MO status information.

6.2.3 Mobile Object (MO)

The mobile object (MO) is the mobile entity that contains an RFID reader along with a portable computation and communication device. The residents of the pervasive environment carry the MO. The MO provides the guidance service to the user. The relationship of the guidance server and the monitoring server can be compared to that of the cache and main memory. The monitoring server keeps the information regarding the entire PE. The guidance server asks for block of data about the current surroundings. The MO makes proper decisions based on that information. Thus the MO is responsible for several specific tasks. It *senses the PE* using the RFID reader attached to it. The MO has to make sure of adjusting the power level of the RFID reader to minimize the effect of $FalseNegative$ *reads* ((missing an item in its range)) and *false positive reads* (reading items beyond its range). The MO has to *acquire proper map information* for the current region it is in from the VS. The MO uses the map to make proper *guidance decisions* for the user. The MO is responsible for *answering the queries* regarding objects of interest (e.g., where is my medicine?) or objects within surroundings (e.g., what objects are around me?). It is also responsible for *updating the status as a virtual location* of itself to the VS. The MO sends out a list of encountered tags along with its virtual location information. The VS can update its environment if required. The MO is able to *post* and *read* messages from message board to communicate to other MOs in the same region.

6.2.4 Other Components

The system consists of the external users who are interested in obtaining the monitoring information about the residents (MO). To address the privacy and security concerns of the residents, we have created system hooks so that various security measures can take place while the external users gain access to monitoring information. In the current implementation, we consider a two way authentication among the MO and VS before any monitoring information can be transferred. But the system is able to incorporate other security measures such as cryptography based authentication for more secured communication - the balance of performance and security is application dependant and must be considered carefully. The application queries are supported by a user interface based approach which shows the current surrounding information in case of the MO residents and a coarse grain state information for the external residents. We have a basic implementation of the interface to communicate to the system (e.g., for path creation, finding out the objects of interest).

We have implemented the GuardianAngel system and developed a prototype application for testing purposes. We describe it in the next section.

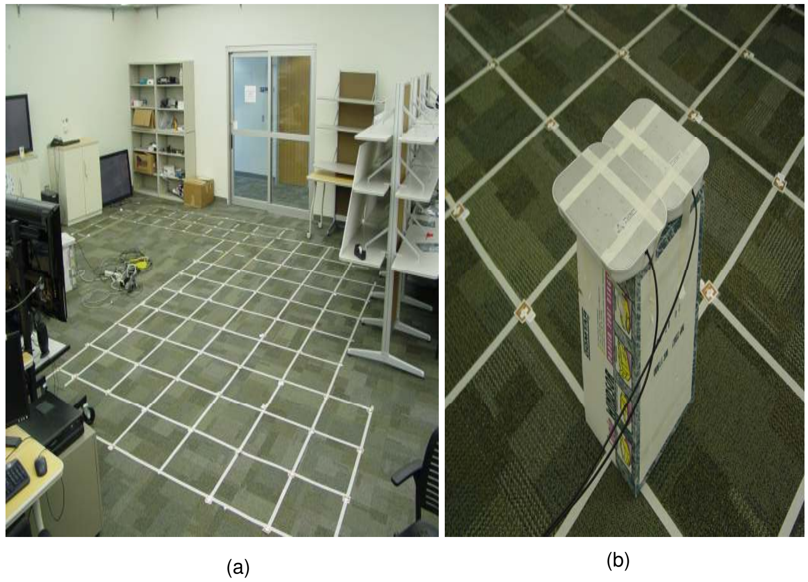


Figure 55: Experimental Setup of the (a) Pervasive Environment. (b) The antenna setup that mimics the reading performance of a mobile user.

6.3 System Prototype

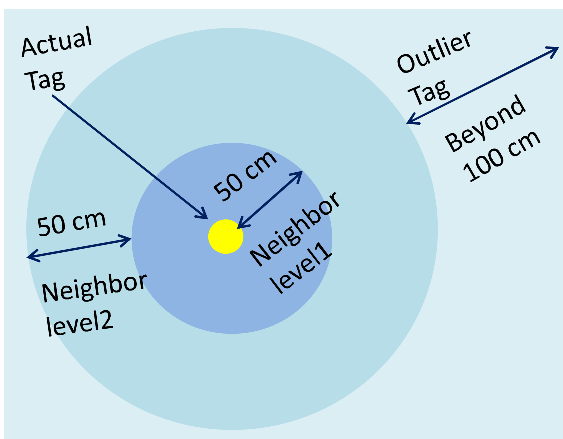
To study the feasibility of a passive RFID-based location system constructed on the GuardianAngel framework, we have developed a prototype application centered around evaluating various aspects of the system. The evaluation takes place in two phases. In the first phase we consider the feasibility of an RFID enabled pervasive environment. We use an indoor prototype system using real hardware (RFID readers and tags) for this purpose. The second phase of the evaluation considers a large scale building scenario using emulated readers. We elaborate on our study in the following subsections.

6.3.1 RFID Testbed

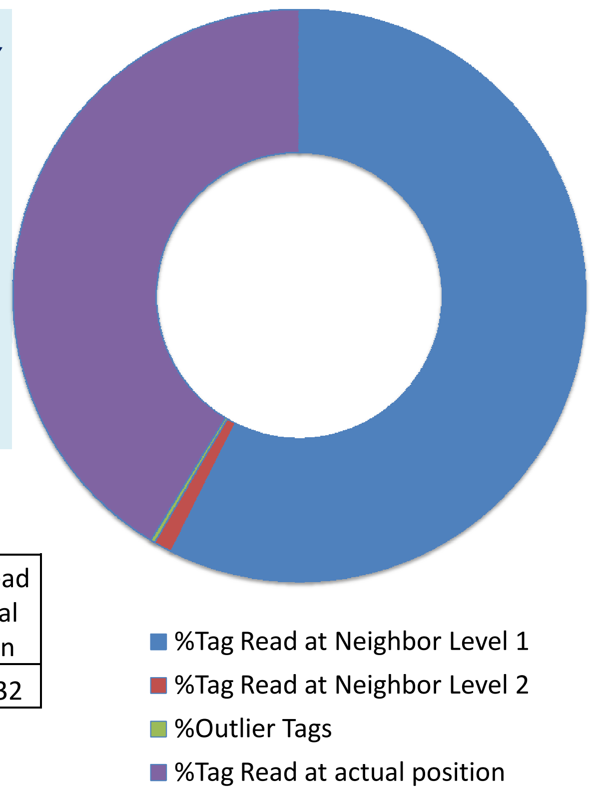
The objective of the RFID testbed using real RFID readers and tags is to determine the feasibility of an RFID enabled pervasive environment. We explore the system and its performance in the following subsections.

6.3.1.1 *Testbed Setup*

The small scale prototype testbed consists of Alien ALR 9800 model passive RFID reader and Alien Gen 2 passive RFID tags. The prototype is developed using Python, interfacing with the RFID reader using the Telnet protocol. We have placed passive RFID tags in the laboratory setup as shown in Figure 55. The area is covered by (14 x 11) tags and each tag is placed 50 cm apart from each other as shown in Figure 55-(a). There is an obstacle of (7 x 6) tag space where the reference tags are not present. We have used a *grid structured* based setup phase to create the PE. It enables a convenient way to locate objects of interest. The Mobile object of consideration uses two ALR 9800 model omnidirectional passive antennas. The redundancy at the antenna level increases the number of items read in each iteration.



(a)



(b)

%Tag Read at Neighbor Level 1	%Tag Read at Neighbor Level 2	% Outlier Tags	%Tag Read at actual position
57.39348	1.027569	0.250627	41.32832

(c)

Figure 56: RFID testbed behavior over time steps (a) Definition of actual tags, neighbor tags and outlier tags. (b) Percentage of various tag reads (c)Table quantifying the various tag reads.

6.3.1.2 The RFID Behavior in Indoor Setup

We have done extensive study on the RFID reader and tag performance in the indoor laboratory setup. We first define the relationship of the tags based on proximity from the tag of interest mentioned as actual tag. The tags within 50 cm radius are mentioned as *neighbor level 1* tags and the tags from 51 cm to 100 cm radius are *neighbor level 2* tags. The tags beyond neighbor level 2 are called *outlier* tags as shown in Figure 56-(a). Figure 56-(b) shows the comparative distribution of different tags over 300 samples where the neighbor level 1 tags are read 57.39% of the the overall reads, the actual tags are read 41.3% of the times, the neighbor level 2 and outlier tags are read 1.02% and 0.25% of the times respectively as indicated in 56-(c).

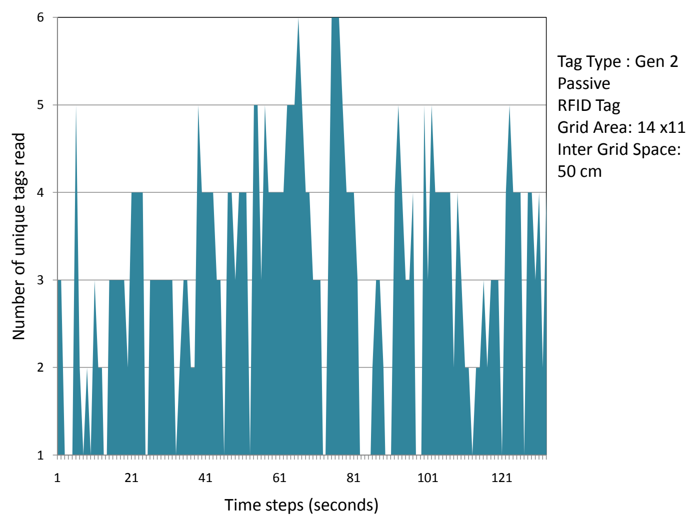


Figure 57: Number of unique tag reads.

Figure 57 indicates how the sample size varies over time when the mobile object is in motion which shows a large variation in the sample size over time with the average read being 3.33 over 300 samples.

Figure 58 shows the neighbor tags with respect to a tag of interest which assures that the majority of the tags read in the sample are mostly the close neighbors. Figure

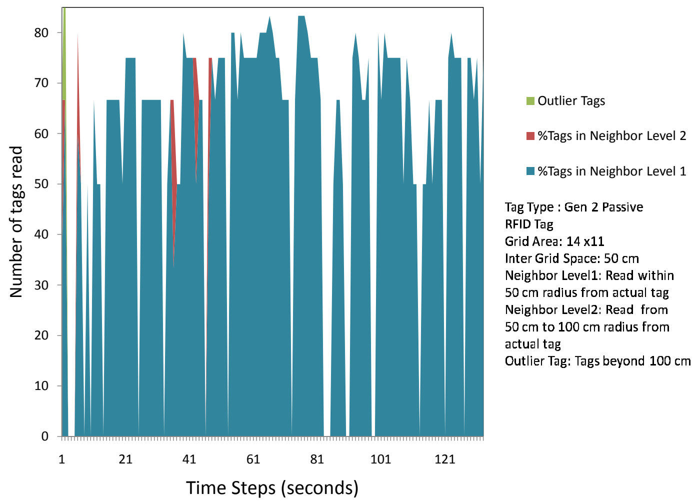


Figure 58: Number of tag neighbor and outlier tag reads.

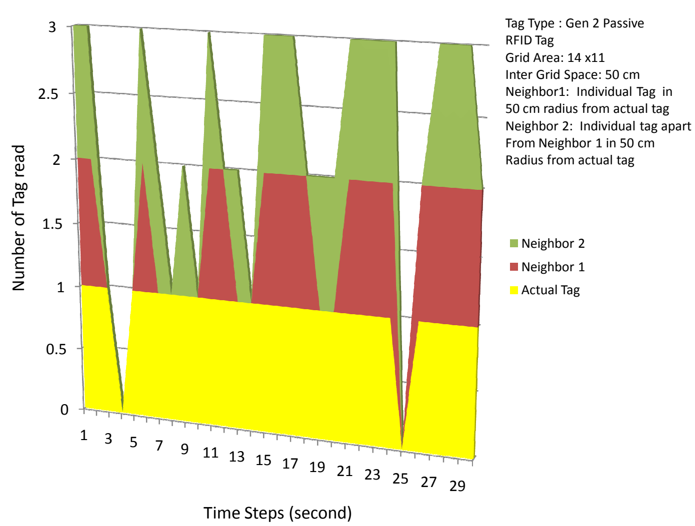


Figure 59: Number of actual and neighbor tag reads.

59 illustrates the consistency of different types of tag reads over time - it is observed that the neighbor tags are not read as consistently as the actual tag reads (which is good news).

We have used a buffer size of 5 samples to determine location information. The

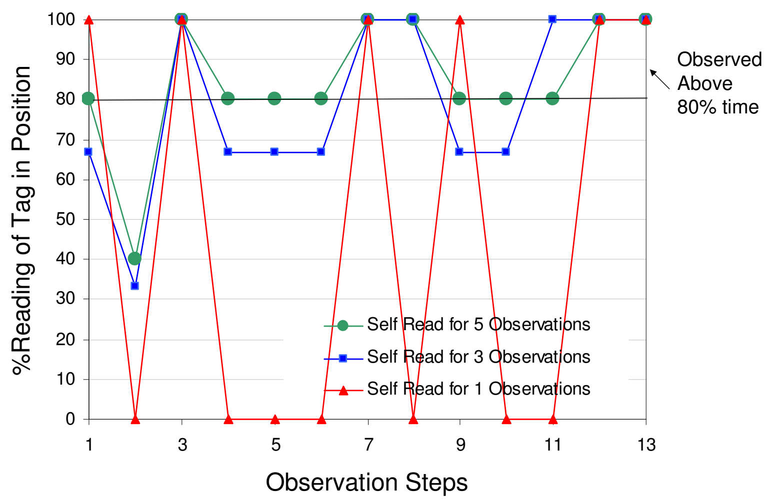


Figure 60: Reading performance with varying sample size.

sample size less than 5 shows larger variations and larger samples require larger sampling time as can be seen in Figure 60. The sample size of 5 proved to be optimal in terms of time and performance.

Figure 61 shows the variation of number of readings of individual tags over three samples where each position is visited manually. The tag placement is shown in colored circles where the brighter red circles indicate larger number of readings of a particular tag compared to a darker shade of tag.

6.3.1.3 The RFID Behavior in Indoor Setup

The accuracy of zone information is shown in Figure 62-(a) to be 100% over the readings of the tag after the data is sampled 5 times for each output. The output over multiple samples yields a perfect zone information despite the inaccurate readings of the RFID tags. The study using a larger setup using emulated RFID readers and tags are discussed in the next subsection.

The evaluation of the indoor pervasive environment depicted in Figure 62-(a)

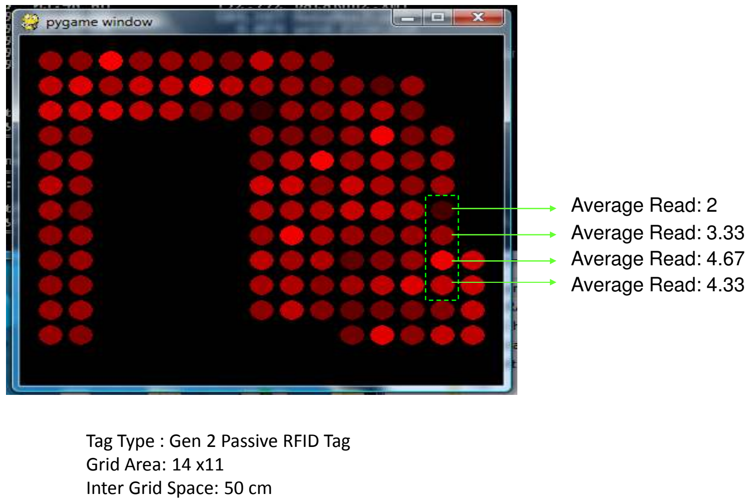


Figure 61: (a) Reading performance for individual tag read.

shows that the system comprising a simple passive RFID based infrastructure is able to provide accurate zone information that can be the basis for a guidance application. Our current implementation is feasible for many indoor scenarios where a coarse grain zone information is sufficient for various activities.

6.3.2 Emulated RFID Based System

The distributed large scale testbed considers a large scale application scenario that requires significant communication and computational capabilities. This setup is used for the scalability study of the system. The testbed uses emulated MOs, emulated RFID tagged environment [2] and a set of distributed VSs for scalability study.

[2]We faithfully emulate the behavior of the Alien RFID reader for this large-scale set up. This allows scaling up the pervasive environment since the behavior of the real and emulated readers are indistinguishable. For more details on the emulated readers please refer to [17].

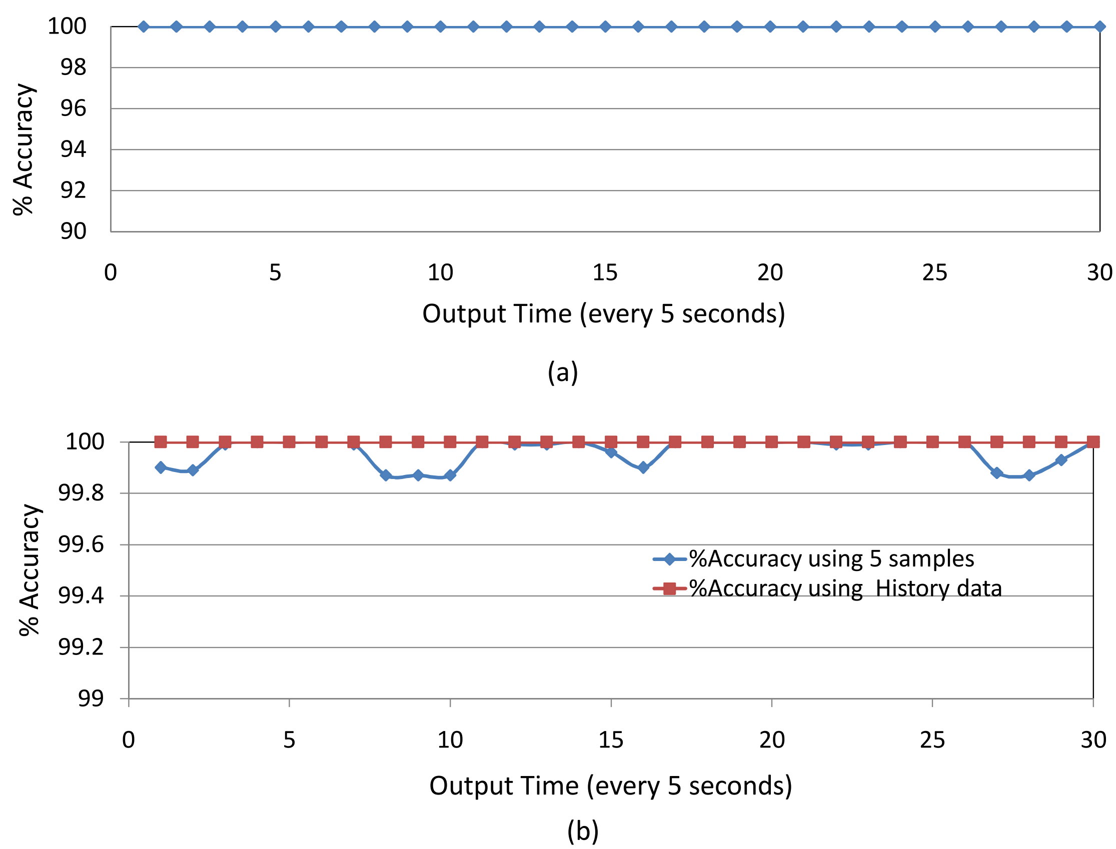


Figure 62: (a) Percent accuracy for RFID testbed. (b) Percent accuracy for emulation based study.

6.3.2.1 Setup

The system is developed in C using MPI for communication among the system components. The system runs over a 53-node, 106-core Dell PowerEdge 1850 Linux cluster with dual Pentium4 Xeon EMT 64 processors using Infiniband interconnects and Gigabit Ethernet.

6.3.2.2 Guidance in a Region Towards a Zone

The zones are defined in a *semi static* manner in the PE. We have used a GUI based interface that shows the PE tag distribution as shown in Figure 63. A set of root tags in the region are selected by the application user as shown in Figure 63.

The number of root tags defines the number of zones in the region. Once the root

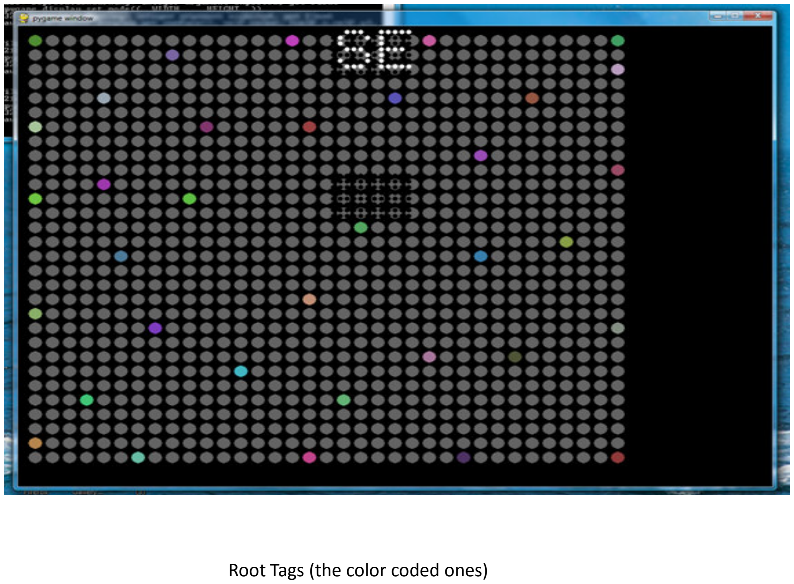


Figure 63: GUI based interface showing Root Tag information.

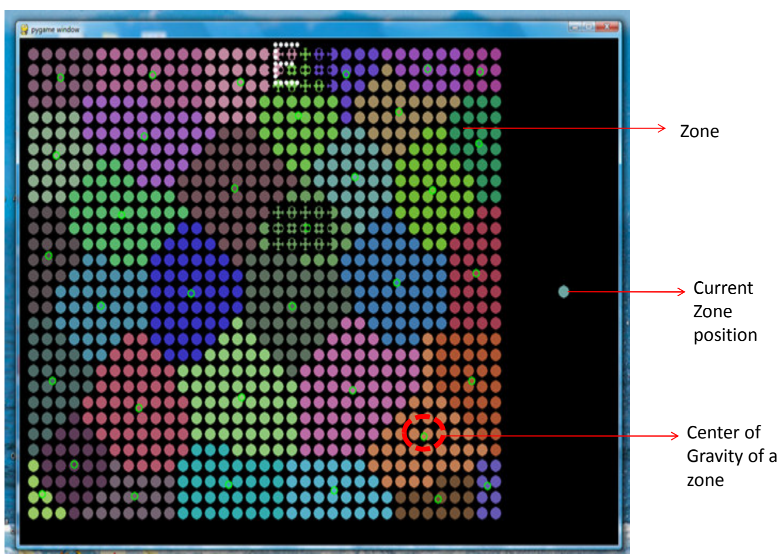


Figure 64: GUI based interface showing Zone information.

tags are defined, the VS runs a breadth first search based heuristic where each tag is assigned to its nearest root node as shown in Figure 64 where each different colored area corresponds to a unique zone within a region. The breadth first algorithm could be changed where the root nodes choose the closest tags for a faster zone assignment that would result in an uneven zone distribution. So we have used our current method as it only runs once during the initialization of the environment.

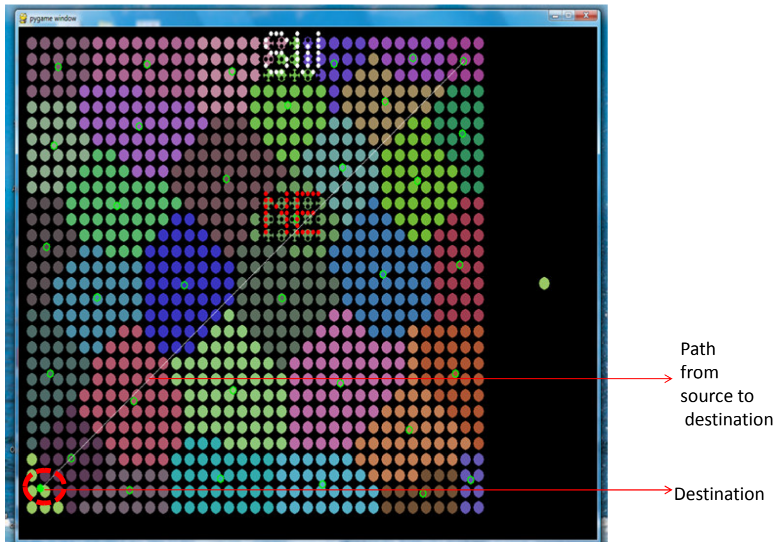


Figure 65: GUI based interface showing Source to destination Path Direction.

The VS uses the GUI based interface to define the desired destination of the user from his/her current location. The system then directs the user (using direction and flow) towards the destination as shown in Figure 65. If the user goes towards a wrong direction, the system recalculates the destination route and guides the user accordingly. We have considered a 50 x50 grid size where the grid spacing is 50 cm within the region. It mimics a large physical space within the indoor environment which can be a large room or corridor of the building under consideration.The system is able to detect the zone information with an average of 98.7% accuracy using 5 samples which reaches 100% accuracy considering the history data to determine a particular zone.

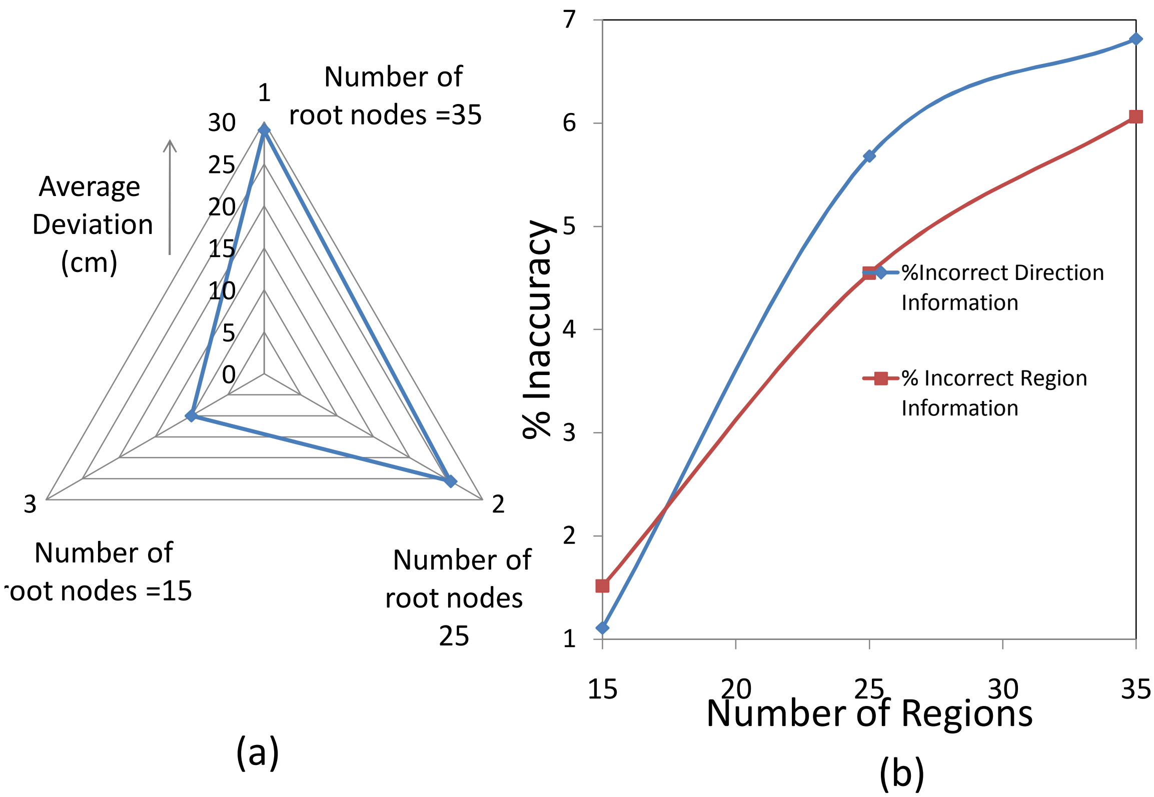


Figure 66: Measurements of a large indoor space. (a) Deviation from destination. (b) Percent inaccuracy in direction and region information.

6.3.2.3 Guidance In a Building Towards a Region

We have considered a large scale indoor space for this experiment of 3900 sq foot which approximately corresponds to a 1100 x 1100 tag placement in a grid setup where the inter tag distance is 50 cm using emulated tags and readers. The results shown in Figure 66 confirm the soundness of our design in that the reading performance and accuracy is maintained in this larger deployment. The average deviation from a source to destination position is shown in Figure 66-(a). As can be seen, the deviation from the desired destination is a function of the number of zones or regions defined by the root nodes. The deviation is 10 cm with 15 regions. It increases to 28 cm with 25 regions, and to 35 cm with 35 regions. The number of incorrect region information and direction information is shown for the same setup in Figure 66-(b). The level of inaccuracy increases with smaller zone area as we increase the number of root nodes.

The region shows 1.51%, 4.54% and 6.06% incorrect region information and 1.1%, 5.68% and 6.18% incorrect direction information due to wrong zone information for a setup using 15, 25 and 35 regions, respectively. The level of accuracy is acceptable for the guidance information towards a room as the deviation from the destination is below 35cm.

6.3.2.4 Communication

The VS acts like a repository of local information for the particular region it is in charge of. At the same time it keeps information concerning the MOs attached to it and all the message board information.

We have implemented three general APIs for message posting. The *Post-new* function call allows the MO to post the current update message concerning the current region and is posted locally in the VS message board. This message can be posted anonymously if the MO wishes to remain unnoticed. The *Post-status* message keeps the status information on an MO locally at the VS and must contain the information of the MO posting the message. The *Post-alert* message is sent to the VS which again sends the message to the name server and the name server broadcasts the message to all the participating VSs in the system. This message cannot be sent anonymously so that the system is able to figure out the MO in case there are too many alert messages generated by a particular MO. We have used the broadcast functionality provided by the MPI library to implement the broadcast messages for generating the alert messages.

The message board interface allows the MOs in the same region to share information for that specific region or residents residing within that region. Examples of shared information can be notes like *coffee in coffee pot* or *Mr. X prefers to stay alone for a while* or the opposite like *MS Y wants to speak to some one.*

Our system level evaluation of the large scale system has confirmed that the messaging schemes are scalable across the system as we have seen insignificant increase of execution time when there is communication across multiple VSs. The VS acts like a repository of local information for the particular region it is in charge of. At the same time it keeps information concerning the MOs attached to it and all the message board information.

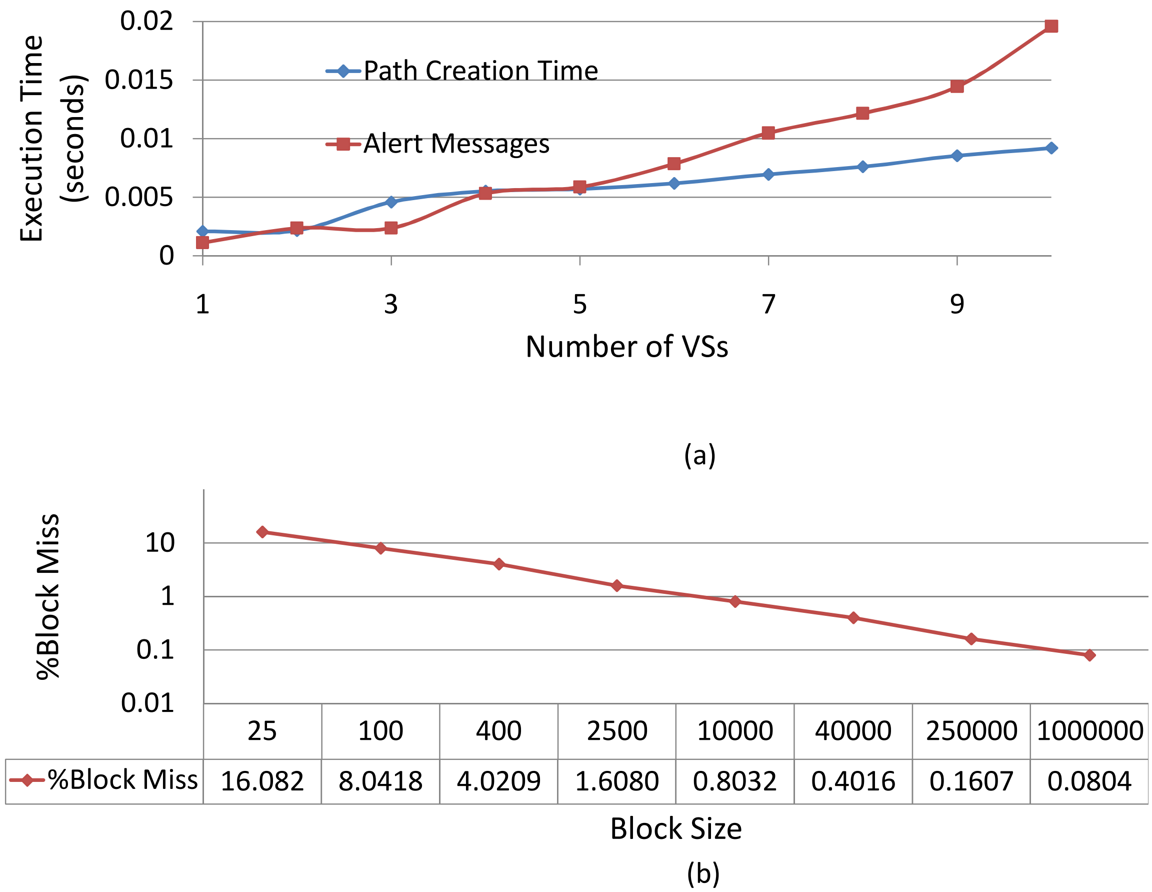


Figure 67: (a) Scalability study of VS serving multiple MOs (b) Block miss rate in an MO varying block size

Scalability for Messaging:

The study presented in 67-(a) illustrates the communication overhead as the number of VSs increase. We have used 10 VSs in the system and each VS is attached to 5 MOs. It shows that the communication time does not increase more than linearly with the number of VSs.

The alert message uses a broadcast mechanism to make sure the alert reaches every component of the system. But the generation of alert message is expected to be limited. It grows linearly with the number of VSs. As can be seen, 4 VSs require 0.005 seconds, which increases to 0.015 seconds using 9 VSs.

The path creation time increases gradually but again this is a one time system cost that occurs during initialization of the system. For example, 4 VSs require 0.005 seconds to process the path creation requests which is similar to the time for alert message generation using the same number of VSs. However, the growth is slower compared to alert message generation. For example, with 9 VSs, the system requires only 0.009 seconds.

Local Caching Effect on the MO:

We have studied the caching effect at an MO using a single MO, VS pair as shown in 67-(b). We have considered a region covering (10000 x 1000) tags. We have simulated object motion behavior taking into account the locality of reference considering that an MO is sequentially moving from source to destination. The MO asks for information regarding the environment from the VS, as it progresses to a new region (it is a lazy policy requesting a block only when it is needed). The MO keeps using its local block information to help the user until there is a location that is not available in its local block causing a block miss. It is evident from our study that the larger size of block information reduces the number of block misses in MOs. For example a (5x5) block size experiences 16% block misses compared to 4% block misses when the block size is increased to (20x20). The optimal block size would depend on the MO capacity as well as application requirements.

Our evaluation results confirm the scalability of GuardianAngel in a large scale deployment.

6.4 Related Work

It is interesting to note that work related to ours falls across fairly diverse domains. We briefly review each of these related areas in this section.

First, there is research aimed at indoor positioning systems. The active badge system [89] uses IR sensing for providing location support. IR has line of sight problem and consequently has a limited sensing range. Radar [23] uses RF signal based location information and considers the signal strength information gathered at multiple locations to triangulate user location information. The Cricket [93] system uses ultrasound signals to find out precise location information. LotTrack [101] uses RFID and Ultrasound sensors for accurate location information. Landmarc [76] uses active RFID readers and reference tags as an inexpensive solution for indoor location sensing. The positioning systems like Radar, Cricket, Landmarc, LotTrack and ActiveBadge aim to provide precise location information. Our work is complementary to these research efforts. Our proposed solution strategy considers the middleware level requirements to support guidance information to applications.

The Sherlock system [75] uses an environment that has objects of interest using RFID tags along with two RFID readers mounted on a motor along with a camera to make localization decisions where the hardware cost is close to 10,000 dollars. Although the environmental consideration is similar to our work, we focus on a low cost environment using state of the art devices for use in daily lives. The Sixth Sense [83] system considers a tagged environment covered by readers which raises privacy concerns as the entire environment is being sensed constantly. Similarly the MAX system [112] considers a hierarchy of tagged environment that is observable by the base stations containing reader elements.

There is also a rich variety of work in the field of context aware computing which focuses on a generalized solution for a diverse set of devices, interfaces, and operations. A supportive environment for individuals requiring cognitive assistance is presented in Chang et. al. [35]. This system considers using a tag enabled environment, similar to our approach, but focuses more on creating a unified interface that improves the user experience. Our work complements this approach, as we focus on the underlying system that would support such applications. The system described in Abascal et. al. [14] presents an environment for people with cognitive disability which provides context-aware information and intelligent decision making. Our work also expands on this approach, focusing specifically on RFID technology for monitoring and guidance purposes.

Also worth noting are the programming abstractions described in Acharya et.al. [15], which provide for a high level virtualization architecture that enables a layer to aggregate queries. This is more generalized than our work, which focuses on a specific sensor technology. Other research has been done with RFID-based middleware systems. The work presented by Thiem et. al. [100] discusses a framework that combines RFID infrastructure with a wireless communication interface. This allows for the expansion of existing infrastructure, increasing environment coverage at a significantly lower cost than other options.

Systems like Savant [91], RFIDStack [46], High Fan-in Systems [47] and WinRFID [81] consider item tracking applications as opposed to guidance applications. RF^2ID [16] exploits the data flow for item tracking applications as opposed to guiding techniques. The concept of *path* is used in many different contexts including fault tolerance [37], profiling distributed systems [24, 53], and resource allocation [108, 85]. Scout OS [73] defines path abstraction to navigate through the layers of the network stack and Ninja project [52] utilizes path abstraction as a way to compose multiple services distributed on the Internet into a single logical unit. Our work is inspired by the use of paths in these various contexts.

6.5 Summary

We have presented a low-cost and effective middleware solution (GuardianAngel) based on passive RFID technology that can be used as a building block for indoor guidance and unobtrusive monitoring applications, such as in an assisted living environment. We proposed the basic system abstractions that would be necessary for such environments and showed an efficient implementation of these abstractions using passive RFID technology. By virtualizing the position information into zones, obfuscating precise timing information, and by giving user control on when and what to report for monitoring purposes, we make the system more user friendly for such environments. We showed through experimentation using real RFID devices in the small, and emulated readers in the large that GuardianAngel delivers close to 100% accuracy for zone information allowing the construction of very robust guidance and monitoring applications.

CHAPTER VII

DISCUSSION ON ITEM TRACKING AND ITEM GUIDANCE-MONITORING

In this section we share our experiences with working in two different application domains using RFID technology. The unreliable properties of RFID is common for many sensor technologies and hence our results have broader applicability. Item tracking and item guidance-monitoring applications are common and use a wide variety of sensors. We have mainly focused on instances of these applications using state of the art RFID readers and tags as a low cost solution that has a wide applicability.

7.1 Common Requirements

There are many requirements from the application perspective that are common for item tracking and item guidance-monitoring systems. It is observed that the applications require a scalable solution that is able to perform well with increasing load in the system, while at the same time increasing the performance with high availability of resources. The concept of path is useful for item tracking where tagged items follow a path; at the same time it is evident that a path is created along the line of movement of a mobile object through the tagged environment for item guidance-monitoring applications. The concept of geographic distinction is useful for both application scenarios as it opens up new possibilities for the application layer that is not achievable otherwise. The general scalable system concept is presented in Figure 68. We discuss this concept in detail in the following subsections.

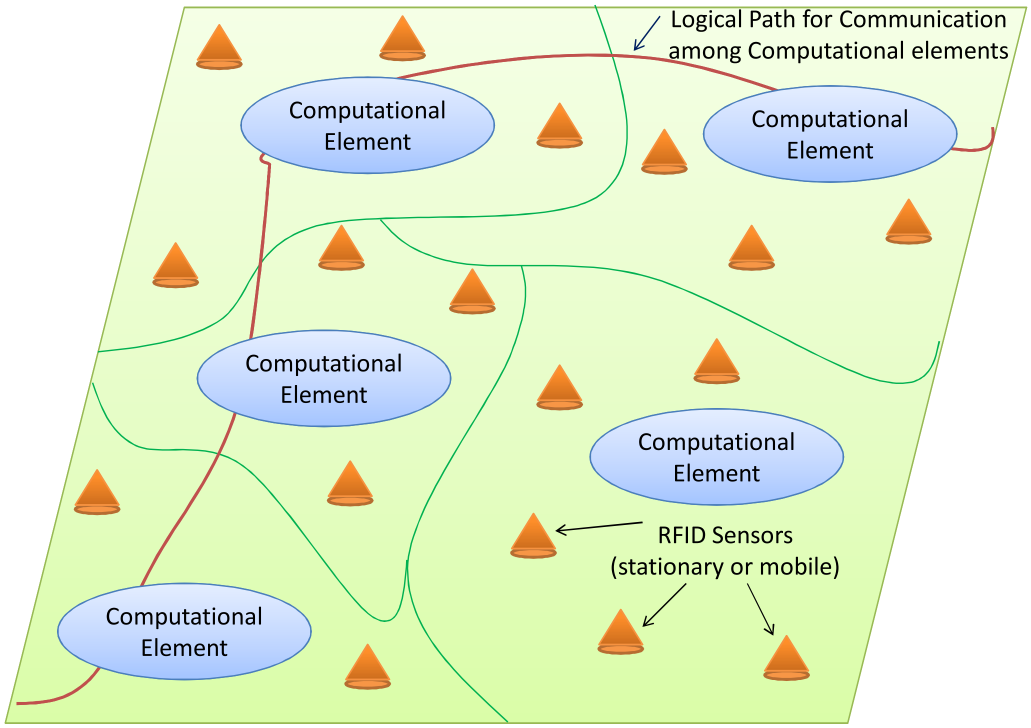


Figure 68: The Path based Communication across Computational Elements (Virtual Reader or Virtual Stations)

7.1.1 Scalable Solution

The large scale data in the item tracking applications and high mobility data for item guidance-monitoring systems require a scalable solution approach as opposed to a centralized control system. We have considered a distributed architecture that is transparent to the application layer and the lower hardware layer. The item tracking and item guidance-monitoring applications have a common requirements of a scalable infrastructure for large scale deployment. The computational elements must be logically or physically distributed to serve the RFID readers in the environment. The scalability requirement is reflected in the basic architecture of RF^2ID and GuardianAngel.

In RF^2ID we have virtual readers (VR) in charge of different geographic regions.

The individual VRs are able to serve geographically distributed stationary RFID readers for item tracking applications. In very large scale deployments like supply chain scenarios, the system needs a coordinator among the VRs - the name server serves this purpose to make important decisions and expedite the VR to VR coordinations. The distribution of VRs that is based on the geographic topology is able to relate the actual physical environment with the application requirements in real time. The VRs are able to create a path among themselves that takes into account the actual flow of the data items. The distributed VRs are also able to coordinate with each other in real time to make dynamic resource management decisions based on application requirements. We use the load shedding based resource management techniques that use the spatial information for space based load shedding and the temporal property of data to perform time based load shedding in the presence of unexpected heavy load in the system.

For guidance-monitoring applications, we have virtual stations (VS) that are in charge of various geographic regions of the environment. The VSs are able to serve the mobile objects (MO) in various geographic locations as the MOs traverse the environment. The logical separation of physical space to computational elements provides a scalable way to distribute the computational load in the system. The VS are in charge of providing the MOs with information regarding the environment while at the same time keeping status information in the form of sequence of states. The rule engine is in charge of matching the state information to make sure the MOs do not require closer surveillance or immediate attention (e.g., special care needed for an elderly person in an assisted living center). The VSs share the status information among themselves as the MOs traverse through the environment.

7.1.2 Path Based Information

The data flow oriented concept at system level is the underlying theme of the dissertation research. We have explored the concept of path in item tracking applications as well as item guidance-monitoring applications.

The item tracking applications require the computational elements to interact based on the actual flow of tagged items. The virtual readers create a logical path that resembles the actual data flow. The VRs use the logical path to dynamically compare, contrast, refine the data and make valuable decisions in real time. The path eases the query process that can be regular aggregation queries as well as flow centric queries such as information regarding a missing item or a misplaced item. Such queries are very difficult in a large scale deployment. The resource management also takes place along the logical path to make dynamic adjustments for incoming heavy load during the course of operation.

The concept of path holds true for the item guidance-monitoring applications. The virtual stations create a logical path that follows the mobile user's (MO) intended route. The path here is used to share the status information of the MO across the VSs. The path is used also within the MO to provide guidance information to the user with fine granularity. The concept of path at system level eases the guidance and monitoring information to flow naturally as the MO traverses through the environment.

Our discussion on the similar requirements open up new possibilities to explore unique solution approach that may be applicable for item tracking and item guidance-monitoring systems.

7.2 Differences in Requirements

There are certain requirements in item tracking applications and item location applications that are very different and ask for a different set of solution approaches to deal with them. These set of requirements are the reason behind the distinct system architectures for item tracking applications and item guidance-monitoring applications. The actors in the environment are the main reason behind the differences in the application requirements. The inclusion of the human actors in the environment for item guidance-monitoring raises many important concerns unlike the item tracking applications. The level of transparency of information and the type of information being shared are the key differences in the application requirements.

7.2.1 Information Transparency

The application requirements for item tracking applications ask for the ability to figure out the previous, current and future possible location of a tagged item There are also query requirements for missing and misplaced items which are very tedious in a large system setup where numerous items are processed. The question of privacy does not arise as the item tracking application scenarios consider tagging of non-living objects mainly.

The item guidance-monitoring applications require a level of abstraction to preserve the privacy as in these scenarios, we are considering human actors. The information about the actors are aggregated over the dimensions of time and space and presented as virtual position of an actor. The nature of the application scenarios ask for a two layer architecture that separates the detailed information and virtual information (over space and time).

7.3 Information Exchange

The level of information exchange through the path is different in the two applications. The virtual readers transfer information regarding the tagged items along the path where the tagged items traverse through the route. The VRs first locally refine the data gathered from the physical RFID readers attached to them. The VRs must generate a set of timestamped data that includes the observed items (intersection of items received and items expected from previous VR) and spurious items (items not expected but received at the current VR) and missing items (items expected from previous VRs but not received in current VR). Then a VR shares the timestamped list of items with its neighbor along the path. The main goal of the information exchange is to improve the global reliability in terms of items observation, detection and tracking in the system.

In the case of item guidance-monitoring, the virtual stations create a logical path that follows the flow of the movement of the mobile objects (MO). The VSs are in charge of the status information of the MOs in that particular region. As the MO provides the VS with its intended source to destination traversal plan, the VSs are able to share the MO status information among participating VSs as the MO progresses through the environment. In the case when the MO is not able to provide the source to destination route, the VS dynamically determines the MO's current location and updates the corresponding VS accordingly. The VSs do not share dynamic information of the environment along the path which is done for the item tracking applications. The status information is shared among the VSs instead.

It is interesting to note the differences in the requirements for item tracking applications and item location applications and how the internal operations vary although the high level architecture looks similar.

7.4 Summary

Our experience on working with RFID technology has given us the opportunity to deal with the limitations of the current technology and has guided us to come up with simple but powerful solution approach to use it in various environmental setup. There are common goals to achieve in item tracking applications and item guidance-and-monitoring applications which ask for a scalable solution having knowledge of data flow through the system. The flow of data is different for two different application requirements as the item tracking aims to share the tagged object through a path while the guidance-monitoring application asks for status information to be shared across a designated path. The way the information is shared is very unique in the two application scenarios. For example, the goal of the item tracking application is transparency of information, being able to determine the object's placement in a particular window of time. On the other hand, the item guidance-monitoring applications bring in challenges as information transparency conflicts with the privacy requirements of the indoor residents. We present two distinct solution approaches that are very specific for the individual problems in RF^2ID and GuardianAngel.

CHAPTER VIII

CONCLUSIONS

We conclude this dissertation with some possible future research directions that may be useful for interested future researchers in this area.

8.1 Conclusions

The widespread adoption of RFID technology brings in many opportunities and challenges. The inherent unreliable property of the RFID technology needs special care at system level to guarantee accuracy at the application level. The research work focuses on large scale RFID deployment which requires efficient data handling in real time. We focus on two key applications: item tracking and item guidance-monitoring. In item tracking applications, the readers are placed at various static locations to observe the mobile items that are tagged. Airport baggage handling and supply chain management systems are two major application examples that are considered for item tracking. The item guidance-monitoring applications consider an environment that is equipped with RFID tags and the mobile users use their mobile RFID sensor to find out important information regarding the environment as well as serve the monitoring purpose for safety of the mobile users. We have considered an assisted living center for elderly residents as a motivating application scenario. The involvement of the human characters incorporate interesting challenges on top of traditional system design challenges.

We observe that there is a notion of path in the item tracking and item guidance-monitoring applications. The mobile objects in the item tracking applications create a path along the way the items travel. Similarly, the mobile users create a path in the item guidance-monitoring applications. We have considered the system level incorporation of the concept of path to increase the performance of the system. The path uses the data flow nature of the applications at system level. The main theme of the middleware solution is a data flow centric computation at system level which is incorporated for item tracking applications as well as item guidance-monitoring applications.

The item tracking and item guidance-monitoring applications have many similarities in requirements. The applications require a scalable solution for large scale deployment. The system must be able to handle large amount of data efficiently in real time for both of the application scenarios. On the other hand, the sharing of data is done at two different levels for two kinds of applications. The item tracking applications require transparency in handling of the data as the system is interested in finding out where the items are and how the items are at real time. However, the item guidance-monitoring applications face challenges in data sharing as the human characters are involved in the system. The data must be available to the system in some abstract form so that the human users are not worried about compromising their privacy. The differences lead to two different solution approaches that has the same underlying theme of data flow centric computing.

RF^2ID is the middleware system that stands for ***R****eliable* ***F****ramework for* ***R****adio* ***F****requency* ***ID****entification*. It is the middleware level solution for item tracking applications. It uses two major system abstractions named virtual reader (VR) and virtual path (Vpath). The VRs are the distributed computing elements that are placed at various geographic locations. Each VR is in charge of collecting and managing data acquired from Physical RFID readers placed in that particular geographic location. The VRs coordinate to transfer data using a logical Vpath that resembles the actual flow of data in the environment. The VRs are able to coordinate and intelligently dynamically manage load in the presence of unexpected system load. We propose two resource management mechanism that uses load shedding among the VRs to dynamically manage the system load. One mechanism is called *space based load shedding* and the other one is *time based load shedding* that manages system load on the basis of space and time, respectively. We have designed and implemented the RF^2ID system and evaluated the entire system using real RFID devices as well as emulated RFID devices for scalability purposes. Our evaluation has shown improved system reliability in terms of number of tracked items in the system which provides a scalable infrastructure.

The middleware solution for item guidance-monitoring application is called *GuardianAngel*. The application considers a tagged indoor scenario with residents having their own RFID readers to provide them with adequate information about the environment. The guidance and monitoring requirement can be conflicting with each other. The guidance information requires very fine grain information about the environment to make proper decisions. On the other hand, the monitoring system must not have a fine grain knowledge which can introduce privacy concerns. We consider this aspect during the design and implementation. The system is a two layered infrastructure that has the upper layer which is the monitoring layer. This layer is in charge of monitoring of the actors in the environment. The monitoring layer is physically a set of distributed virtual stations that have knowledge about the environment. The environment itself is equipped with RFID tags. The residents of the environment carry a mobile object that has a sensing element and a computing element (e.g., handhold device with a portable RFID reader) - the guidance server runs on this mobile object. The guidance server is in charge of making local decisions to the users. It is resource limited and asks for new information from the virtual stations as needed. The guidance server also provides the monitoring server with the information regarding the status of the mobile object. But the status information is not fine grain information - the guidance server wraps up the information over a period of time and over a larger region to hide the detailed information of the users. We have implemented a real testbed using grid structured RFID devices along with scalability study using emulated RFID readers. The current implementation of GuardianAngel shows promising performances

8.2 Future Work

We discuss different avenues for future research.

8.2.1 Generalized Architecture for Heterogeneous Sensors

There are numerous real world application that require handling with variety of sensor data in real time. Example application can be a surveillance system that uses several forms of sensor input for decision making. The data flow based architecture can be very useful for data prioritization and data fusion for multimodal sensor system. Our path based architecture that is geared towards RFID based data can be generalized to use the data flow centric information for a scalable, reliable and resource aware framework. A general framework introduces many interesting research challenges and can be an active area to explore for today's emerging technology.

8.2.2 Applications

There are avenues for interdisciplinary work that involves application of sensor data in a real world setup. One example application is a healthcare facility which introduces a new set of challenges for real time data fusion, data processing, data dissemination and delivery of the data for improved system performance. A hospital using low cost sensor devices like RFID technology to reduce medication error is a specific application scenario geared towards this direction.

Outdoor sensing applications are also very important. These sensing techniques are useful for rural areas to improve the quality of life (e.g., reduce the impact of an upcoming natural disaster). The real time processing of sensor data and interpreting the data involves challenges that we have already mentioned. Moreover, the outdoor sensors have the added challenges of being severely influenced by the dynamic nature of the environment.

8.2.3 Combining Sensing with High Performance Resources

The current research can be extended along the line of today's high performance resources to mitigate the computational challenges introduced by dynamic incoming sensor data. There are multicore machines which allow tremendous amount of parallel processing. There are also new trends like cloud computing that would help deal with the computation load of sensor generated data.

8.3 Open Problems

RFID based applications are growing and middleware systems are emerging in recent years to meet various application requirements. However, there are remaining challenges to be addressed in near future that are of great importance. We consider security, energy awareness and generality to be of greater interest.

8.3.1 Security

Security is a major concern in RFID systems as it is for any other system. The middleware system must be cautious to deal with large amount of data as some of it may be malicious. The large amount of information available in RFID middleware systems makes it very attractive for malicious users to access sensitive information. The current middleware systems discussed from research perspective do not incorporate security as a feature in the system. The commercial solutions do not mention security as a major service to offer. Security can be incorporated on top of a middleware solution. However, the middleware layer is very suitable for incorporating security such that malicious devices, data or queries can be eliminated at the lowest level.

8.3.2 Energy Conservation

Energy conservation is becoming a major concern in large scale systems of recent years. Large scale RFID based systems are being designed and deployed - these systems must consider a way to minimize the energy footprint. A middleware solution is best suited for such measures as it couples closely with hardware devices. It is believed that there will be new design considerations for energy aware RFID middleware or existing middleware systems enhanced for energy conservation features in the near future.

8.3.3 Generality

A system that may serve a diverse set of applications is hard to generalize. There are many existing solutions offered for RFID based systems. However, there is still a requirement for a generic middleware system that offers solutions for a wide range of applications such as tracking, monitoring, guidance etc. In the future we expect to see more generic solutions that can be tuned to specific needs. The open problems indicate the growth of interest in improvement in the area of middleware for RFID technology.

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