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Tracking the Location of Materials on Construction Projects

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Tracking the Location of Materials on Construction Projects

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Dissertation

Presented to the Faculty of the Graduate School of

the University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

The University of Texas at Austin

August 2005

Dedication

To Seonjoo, my wonderful wife.

Acknowledgements

First, I would like to thank my supervisor Carl Haas who had inspired me throughout the research presented in this dissertation. His input and feedback were critical in every major step toward the completion of this dissertation. His financial support through independent funding is also greatly appreciated. Simply, this dissertation would never have been made possible without him. I would also like to thank the dissertation committee members for providing encouraging feedback on the research and recommending improvements to this dissertation. Despite all this intellectual and financial support, I would not have had survived days of my life completing this dissertation, without my wife Seonjoo. I must be one of those who are granted the very blessing of God.

August 12, 2005

Tracking the Location of Materials on Construction Projects

Publication No. _____________________

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The University of Texas at Austin, 2005

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Of the elements that comprise the constructed facility, construction materials account for 50-60% of the total cost of a construction project and most directly represent project progress. Tracking the location of construction materials automatically should both improve project performance and enable effortless derivation of performance indicators. With recent advances in automated data collection (ADC) technologies, tracking the delivery/receipt and the location of materials on site has become more viable. However, the ability to track the delivery/receipt of materials from longer distances with minimal human efforts has yet to be studied. Furthermore, the existing approaches to tracking the location of materials on site imply economically prohibitive deployment of ADC technologies.

The research presented in this dissertation examines the feasibility of applications of Radio Frequency Identification (RFID) technology to automating the tracking of materials and components on construction projects, with an overarching goal of automated project performance monitoring and control. First, based on field tests, it presents on the ability to effectively and simultaneously read RFID tags installed in pipe spools from longer distances, with minimal human efforts, and in moving platforms under realistic shipping conditions. Second, it presents an approach by which a combination of RFID and GPS technologies may offer the opportunity to densely deploy extremely low cost RFID tags with a few mobile RFID readers equipped with GPS to form the backbone of a construction materials’ tracking system. It then reports on field experiments based on the developed framework and algorithms. The solution presented here is intended to extend the use of current RFID technology to tracking the precise movement and location of materials on site, without modifications to current hardware and at a magnitude less cost than pure GPS or other existing approaches.

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Chapter 1: Introduction

1.1. OVERVIEW

Construction of a facility is a process where materials are being installed by crew workers with an aid of equipment according to design and specifications. Of the elements that comprise the constructed facility, construction materials may account for 50-60% of the total cost of a construction project and most directly represent project progress. In industrial construction, thousands of materials go through design, fabrication, interim processing, delivery, storage, installation and inspection. As prefabricated objects such as pipe spools and precast concrete elements are assembled and installed on site, the designed facility literally takes shape.

To effectively control materials management functions, some type of mainframe or large minicomputer system is used in typical size industrial projects with total installed cost in excess of US$100 million. Ideally, such computer-based materials management systems should be based on an automated system that easily and precisely tracks in space and time the status of materials' delivery, movement and installation on site. This automated tracking of materials on construction projects is important for two reasons:

- It provides timely information on material availability to enhance crew-level work planning and improve labor productivity;
- It enables real-time on-site measurement of project performance indicators that can provide the project (or company) management with feedback information for project control.

Thus, automated materials tracking on construction projects should both improve project performance and enable effortless derivation of performance indicators.

1.2. RESEARCH MOTIVATION

Truly, tracking materials on construction projects is not a new problem, as the inability to make materials available at the right time and the right place is one of the most common problems in construction (Thomas et al. 1989). However, all of the research efforts thus far have not structured this problem as one that once resolved, has the potential to serve the dual purpose: improved project performance and effortless derivation of performance indicators.

Since the Business Roundtable (1982) claimed materials management as a distinct management system that can make the significant contribution to the cost effectiveness of construction projects, research efforts in materials management demonstrated the cost effectiveness of materials management systems (Bell and Stukhart 1986, Bell and Stukhart 1987, Thomas et al. 1989). They also identified information needs that are required to implement computer-based systems to control the materials management functions that encompass quantity takeoff, purchasing, expediting, shipping/receiving, warehousing, and material distribution (Elzarka 1994).

In contrast, improvements to field materials management, concerned with tracking, locating, finding, and distributing the right material to the right location at the right time, have remained almost unexamined until recently (Jaselskis and El-Misalami 2003, Caldas et al. 2004). In the mean time, field materials management functions have become even more critical, given that the significantly increased use of prefabrication and preassembly resulted in the greater number of materials going through fabrication, intermediary processing, shipping, receiving, warehousing, and distribution. Considering this state of affairs, it is not surprising that field materials management was identified as one of the areas with the greatest potential for improvement and the greatest positive development impact on engineering construction work processes (Vorster and Lucko 2002).

On the other hand, there have been major developments that present opportunities for real-time on-site measurement of project performance indicators, such as labor productivity and schedule progress:

- The increasing availability of standardized object-oriented product models can provide rich representations of the facility to be constructed (Sacks et al. 2003).
- With advances in automated data collection (ADC) technologies, automatically tracking the location of construction agents, such as laborers and equipment, has become more viable (Navon and Goldschmidt 2003, Sacks et al. 2005).

These developments laid the foundation for the automated project performance control (APPC) initiative at the Technion-Israel Institute of Technology. Research efforts under this initiative thoroughly investigated the feasibility of 1) automatically identifying the basic activity that the agent is engaged in by tracking its location, 2) determining the status of the activity (not yet started, in progress or completed) and 3) deriving project performance indicators, such as labor productivity.

The development of automated measurement of project performance is an impressive achievement because it promotes successful implementation of the project management information and control system. The effectiveness of the information and control system was limited, due to the effort required of field supervisors in reporting project progress data in relation to the lack of benefit from the system to them (Futcher 2001, Kiziltas and Akinci 2005). Ultimately, automated measurement of project performance enables project management to take corrective actions in real-time to control the performance as close as possible to a set of desirable values (Sacks et al. 2003).

However, research efforts, including those under the APPC initiative, have not examined the potential of tracking the location of materials on site, although material consumption was suggested as one of the project performance indicators. This is an important fact because tracking materials' location on the construction site can complement the existing approaches to identifying activities performed by construction agents, which is a prerequisite to the status determination and the derivation of performance indicators. In the framework of the APPC initiative, the automated activity identification is accomplished by geometrically associating a construction agent's location with a work envelop predetermined for each basic activity. A work envelop represents a volume in space in which a worker or piece of equipment must be physically present to perform a basic construction activity on a building element, e.g., placing formwork or concrete on column #1. This approach presents two major challenges:

- Generating and calibrating envelop geometries for each basic activity is non-trivial, given the number of combinations of activity type, element type, and construction technology employed in performing the activity.
- Even with envelop geometries well defined, the agent's location may not be uniquely identified with a single basic activity because overlap between work envelopes is not completely avoidable. Distinct building elements themselves overlap (a column sits in a slab section), and very commonly, more than one basic activity is performed on the same element. Thus, situations of overlap will still remain even with prior knowledge of the project execution status that can narrow the search for the correct work envelope to those of activities that are in progress, or are candidates for execution.

To address this potential ambiguity in associating construction agents' location with a single work envelop, research efforts under the APPC initiative proposed several additional techniques:

- Logical association using decision rules, such as his or her crew affiliation, and proportional division among the activities that the worker performed in a given day – algorithms may also be developed that will choose the right set of the decision rules according to the type of the activity.

- Use of additional characteristics of lifting equipment operation, such as the weight released and the residual weight, for testing against unique sets of characteristic values that may be set a priori for each work envelope.

Another alternative to be examined in the research described here is to automatically identify materials (e.g., a precast concrete element) and auxiliary equipment (e.g., a concrete bucket or steel shutter formwork), and at the same time track their locations with reasonable accuracy. Since almost all materials, components, and auxiliary equipment are moved using lifting or hauling equipment, e.g., a crane or fork-lifter, their presence should be detected in the proximity of the equipment during transportation on site and loading or unloading over the building element. For instance, two different basic activities performed on the same element, e.g., placing formwork and concrete on column #1, are conveniently distinguished if it is known whether a concrete bucket or steel shutter form was present in the proximity of lifting equipment, in addition to the position of the lifting equipment and of affiliated crew workers. Thus, automatically tracking the location of uniquely identified materials and other objects on site will help determine the activity that construction agents are engaged in.

Furthermore, automated tracking of materials' location will also help improve project performance by providing a priori information on materials availability for crew-level work planning. This represents an important distinction from the opportunity presented by automated tracking of construction agents' location in the APPC framework. As the latter is intended to provide a posteriori information on actual construction performance for project management's intervention, the model of control in the APPC framework is a model of project control, rather than production control, according to new management thinking of lean construction (Ballard and Howell 1998). If management devotes its efforts to project control, i.e., monitoring of performance against project budgets, schedules, and other specifications created in the initial planning, and taking corrective actions to conform performance to those specifications, the potential for improvements in project performance is minimal.

Project performance can be further improved with the ability to do quality planning at the crew level in which material and information flows are shaped in a greater detail based on actual receipt of resources and completion of prerequisite work. Adopting the Last Planner methodology, Choo et al. (1999) developed a database program called WorkPlan to help crew foremen reliably assign work tasks for completion and systematically develop weekly work plans. The WorkPlan provides easy mechanism to make quality work assignments before incorporated into the plan, using a set of criteria, including the "soundness" that the requisite materials, information, and prerequisite work is on hand. However, the effectiveness of the WorkPlan depends on the means to ascertain that, for instance, a particular material is factually on hand.

In sum, all of the research efforts discussed above have been useful in varying degree to justify the need to track the location of materials on construction projects, but their main interest was limited to either possible improvement in project performance, or automated measurement of performance indicators. In contrast, the central motivation for the research described here is to bridge the gap between the current paradigms regarding the location tracking of construction objects which individually can only accommodate one of the two purposes.

1.3. RESEARCH CHALLENGES & HYPOTHESIS

The key motivation for this research leads to the formulation of the following research problem:

- How to track the location of materials on construction projects in order to both improve project performance and enable effortless derivation of performance indicators?

In support of these two goals, tracking the location of materials implies different requirements for positional accuracy with identification in common.

The potential for improved project performance is presented by the ability to provide timely and accurate information on materials availability for crew-level work planning, but also the ability to find and distribute requisite materials for crew installation on a construction site. For the former case, tracking the delivery and receipt of materials through the supply chain to a construction site will suffice. In this case, the location of materials implies a location in the supply chain (e.g., a fabrication shop, constructor's laydown yard) or a construction site. As materials are typically shipped and received through a portal gate, this level of positional accuracy may be called the "portal" level.

However, for the latter case, the location of materials needs to be tracked with more accuracy than indicating, for instance, that a certain material is received at and thus within the constructor's laydown yard. Such positional accuracy beyond the portal level is also required to support automated derivation of construction performance indicators. Tracking the location of materials on site should make it possible to determine, for instance, if a certain material is present in the proximity of lifting equipment, in order to identify the basic construction activity being performed using the lifting equipment.

To identify the challenges presented by location tracking beyond the portal level, existing and emerging technologies applicable to location sensing were investigated, including Global Positioning System (GPS), Radio Frequency

Identification (RFID), Real Time Locating System (RTLS), and wireless sensor networks.

State-of-the-art GPS can be used to precisely track the location of craft workers and machines over a great range of geographic and geometric scales, but the technology is still expensive for dense deployment to automate tracking individual material items. Tagging hundreds of materials with simple GPS receivers costing around US$100 per unit would be prohibitively expensive, and still other means for identification would be required. This limits its scope of application.

Current applications of RFID technology in manufacturing, retailing, and transport and logistics industries rely on its capability to identify tagged objects without requiring physical contact, line-of-sight, or clean environments. Its potential applications in the construction industry had also been explored, and several pilot tests demonstrated that the technology could be useful in receiving uniquely identified materials at job site laydown yards. Though RFID technology presents several advantages over barcoding, its primary use is still limited to identification purposes as with barcoding.

This limitation had driven the development of the RTLS for indoor asset tracking applications. Unlike conventional RFID systems, the RFID-based RTLS provides both identification and location of tagged objects by virtue of a pre-configured wired network of fixed RFID readers, using the similar technique as in GPS. However, the RFID-based RTLS requires the significant infrastructural setup of proprietary networks and has difficulty interoperating with the existing 802.11 wireless networks. Most recently, these issues have been resolved by leveraging the IEEE 802.11 standard Wi-Fi networks. Being based on the non-proprietary networks, the Wi-Fi RTLS successfully overcame the substantial cost barrier to scalable location tracking systems, i.e., the infrastructural setup of separate networks. Nonetheless, some Wi-Fi based RTLS still requires extensive calibration to map the Wi-Fi signals to locations throughout the building. Furthermore, the Wi-Fi RTLS relies on existence of 802.11 access points in the building, which is not guaranteed for a facility being built. In summary, due to its evolving and unpredictable nature, a construction site cannot afford location sensing systems relying on the network infrastructure, whether proprietary or not, which should be configured carefully to cover the entire site and calibrated to its RF transmission space.

In the mean time, the research community in electrical engineering and computer science has seen a vision of pervasive computing and come up with the notion of wireless sensor networks of small devices which are deeply embedded in physical environments. This notion envisions our extended ability to monitor and control the physical world through deployment of densely distributed sensors that will provide the sensed data without relying on a fixed communications infrastructure. Thus, location sensing in the wireless sensor network framework would eliminate the need for preconfigured and calibrated communications networks, which renders current applications of RFID technology costly, both economically and environmentally. However, self-configuring, adaptive coordination, and trustworthiness of sensor networks are still research challenges, though established knowledge of related systems may prove partly applicable (National Research Council 2001).

The above analysis reveals that there exists a notable functional gap between ADC technologies and wireless sensor networks in tracking the location of materials with sufficient accuracy. This gap is translated into the following research challenges in tracking the location of materials on construction projects:

- How to meet different requirements for positional accuracy in supporting improved project performance and automated derivation of performance indicators;
- How to deal with the large number and different types of materials to

be tracked through the supply chains and on a construction site;

- How to make a location tracking system compatible with constantly changing environments on the construction site.

These challenges represent accumulated limitations of the existing technologies analyzed earlier. For example, GPS can provide positional accuracy beyond the portal level but is expensive for large scale deployment to track the location of thousands of materials. Conversely, RFID technology is suitable for tagging thousands of materials but its current applications do not provide sufficient location accuracy without relying on a fixed communications network that is environmentally not sustainable on the construction site.

As such, the missing link that may help overcome the challenges faced in tracking material objects' location is the development of economically and environmentally viable applications of ADC technologies while further research and development in wireless sensor networks are underway. Specifically, the research presented here is to investigate the following hypothesis: "Automated tracking of construction objects using RFID technology is technically feasible."

1.4. RESEARCH OBJECTIVES & SCOPE

The objective of the research described here is to examine the feasibility of applications of RFID technology to automating the tracking of materials and components on construction projects, with a dual goal of improved project performance and automated project performance monitoring and control. In support of this main objective, the following specific objectives guided this research:

- Develop an application framework including static (portal) and dynamic (roving) modes;
- Identify algorithms and technology most suited to feasible application of RFID technology for materials tracking;

- Characterize through thorough experimentation the performance trade-offs and limitations of the RFID algorithms and technology for both static and dynamic applications;
- Assess technical feasibility;
- Estimate potential economic feasibility;
- Suggest approaches to integration and implementation.

The research described here is primarily concerned with tracking the location of pieces of materials, components or pallets of significant value or criticality. As part of the research, field trials and experiments were conducted. Field trials were intended to assess the feasibility of tracking the delivery and receipt of prefabricated pipe spools, in simulated field conditions but using real construction components. Field experiments were designed to study the applicability of using RFID in tracking the 2D location of materials on site. For both applications, commercially available active RFID technology was used.

1.5. RESEARCH METHODOLOGY

The research described here began with reviewing the literature. The literature reviewed pertains to (1) related efforts and enabling technologies to automate the tracking of construction resources, (2) RFID fundamentals, (3) location sensing principles, and (4) applicability of current RFID systems to location sensing. Upon literature review, two potential applications of RFID technology in materials tracking have been identified, respectively referred to as portal and roving applications.

To assess the feasibility of a portal application, field tests were conducted in simulated field conditions using real construction components, namely prefabricated pipe spools. In the mean time, a model and algorithms for roving applications were developed based on the occupancy cell framework, and field experiments were conducted. Field test data on pipe spool tracking was analyzed statistically, while analyses of experiments on roving application were performed based on visual recognition. Finally, this dissertation has been written.

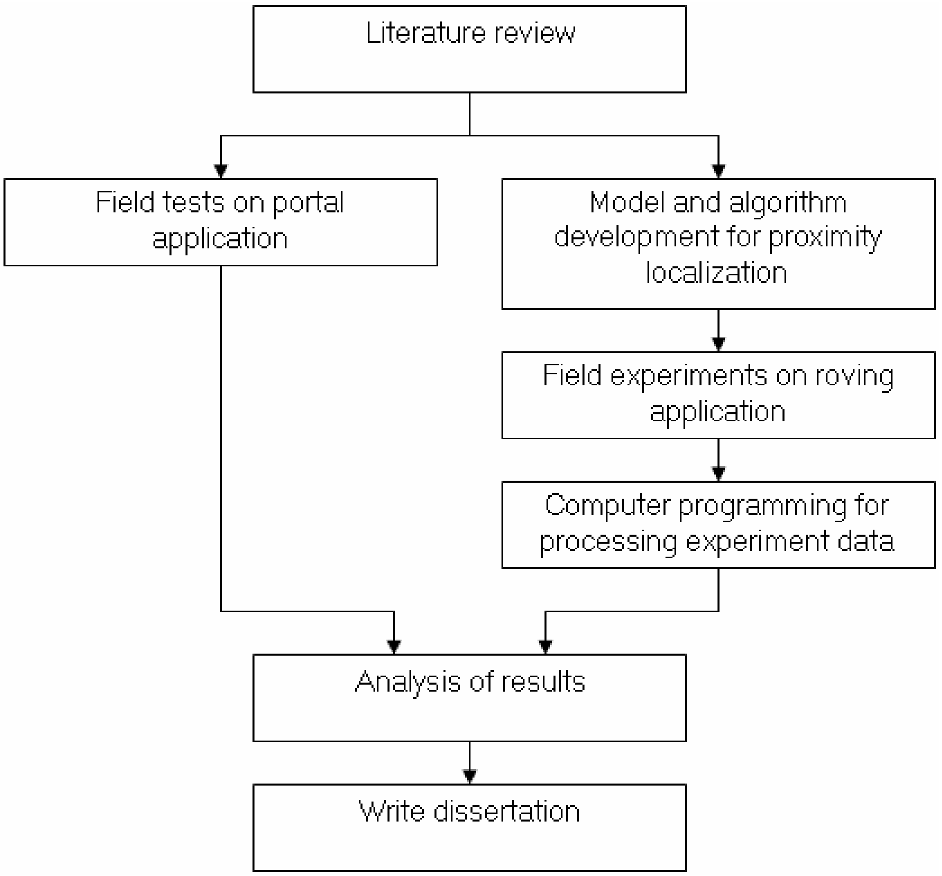


Figure 1.1: Research methodology

1.6. STRUCTURE OF DISSERTATION

This dissertation is organized in six chapters. Chapter 1 provides an overview of tracking materials on construction projects, and describes the motivation, challenges, hypothesis, objectives, scope, and methodology of the research. Chapter 2 presents an overview of past studies on the use of ADC technologies in an effort to automate the tracking of construction resources. It then provides background on location sensing and discusses the issues related to applying current RFID systems to location sensing.

Chapter 3 describes field tests of a portal application that uses RFID technology in tracking the delivery and receipt of fabricated pipe spools, and its potential benefits. Chapter 4 provides the description of the developed framework, a model, and algorithms that are useful in tracking the location of materials on site beyond the portal level. It then describes experiment parameters and procedures in detail. Chapter 5 presents metrics used to assess performance of RFID technology in roving applications, results of analyses performed on experiment data, and discusses possible performance improvements. Finally, this dissertation presents in Chapter 6 the conclusions reached and recommendations for further research.

Chapter 2: Background and Literature Review

2.1. OVERVIEW

The need to track the location of materials on construction projects is two-fold. First, it is necessary to locate/search materials to ensure the availability of materials for installation. Making the right materials available may require 20-40% of field supervisors' time while crew workers are left unsupervised with control of labor productivity and safety being lost (Bell and Stuckhart 1986). Second, to control project performance, it must be monitored in terms of performance indicators, such as cost, schedule, and labor productivity (Sacks et al. 2003). Directly collecting the data based on human observation is time-consuming. Recording and analyzing the data on actual performance may require 30-50% of site supervisors' time (McCullouch 1997). As an alternative to the direct data collection, Navon and Goldschmidt (2003) showed that workers' locations can be automatically collected by GPS and converted into labor hours consumed in particular tasks. By the same token, tracking the location of materials on a construction site can also reflect actual project performance.

Tracking the location of materials on site is generally considered economically prohibitive, though it has become technically more viable with recent advances in automated data collection (ADC) technologies. Laser scanning systems can be used to measure the shape, location and orientation of objects on site, but they lack the ability to perceive anything about the nature of an object without significant human post-processing. Thus, they are useful for producing as-built models and for rapid local area modeling, but they are not feasible in themselves for comprehensive materials tracking. State-of-the-art GPS can precisely track the location of workers and machines over a great range of geographic and geometric scales, using the triangulation principle which requires distance measurements between the object and reference points with known position. However, to determine the location of materials, tagging hundreds of items with simple GPS receivers costing around US$100 per unit would be prohibitively expensive. This limits its scope of application.

On the other hand, recent field trials of RFID technology, described in Chapter 3, indicate that the technology can be used reliably to track prefabricated pipe spools through the supply chain – an RFID tag used in the field trials cost around US$60 and functionally equivalent tags are available for $6. Nonetheless, to determine the location of materials on site, a grid of networked RFID readers would be required so that it could cover the whole site and withstand constantly changing construction environments. Furthermore, the technology usually does not provide distance measurements required for triangulation.

Starting with research efforts in materials management on construction projects, this chapter provides the fundamentals of RFID technology and current applications to tracking materials in the supply chain. With background on location sensing techniques, it then presents recent efforts to track the location of construction resources on site for automated project performance monitoring. Along with the opportunities presented by tracking materials' location on site, the issues related to applying ADC technologies to this end are also discussed. Finally, this chapter introduces the notion of wireless sensor networks and the concepts of ad hoc location sensing, concluding with the applicability of current RFID systems to ad hoc localization.

2.2. CONSTRUCTION MATERIALS AND MATERIALS MANAGEMENT ON CONSTRUCTION PROJECTS

Materials and installed equipment for a construction project comprise three categories that imply variable cost, delivery lead time, and interchangeability; (1) off-the-shelf, (2) long-lead bulks, and (3) engineered items (Halpin et al. 1987).

Generally, engineered items are available at higher costs in smaller quantities and with more unique properties than long-lead bulks and off-the-shelf items, thus implying longer lead time and requiring more front-end planning (Tommelein 1998). Many construction projects executed on a fast-track often involve a significant amount of materials being prefabricated and/or preassembled off-site in factory or shop manufacturing conditions. Good examples of this industry practice include pipe spools, precast concrete components, and structural steel members, all falling into engineered materials. A previous research effort found that the use of prefabrication and preassembly in industrial projects had almost doubled over the preceding fifteen years (Haas et al. 2000).

Such prefabricated materials may receive intermediary processing in another facility, e.g., painting pipe spools, and are delivered to the constructor's laydown yard in advance of scheduled installation while prerequisite work is being completed on site. Under the potential uncertainty in deliveries and in completing prerequisite site work, the constructor's materials managers often choose to build in their laydown yard large buffers of prefabricated materials in an effort to secure flexibility in workable backlogs for installation crews. For instance of one industrial project, they may have "at least 60 percent of all pipe on site when 20 percent of the pipe had been installed" (Howell and Ballard 1996). As such, pipe spools delivered may dwell in the laydown yard as long as 5 to 6 months until they are issued to crews for installation. This "inventory buffer" approach is costly from the standpoint of cash flow, loss and damage potential, increased storage and handling costs, and a general inflexibility for responding to design changes (Bell and Stukhart 1987).

Planning installation of materials and components requires crew foremen to verify the availability of materials and other resource requirements (Choo et al. 1999). By the time crew foremen make requisitions for certain materials, the constructor's laydown yard personnel will locate, identify and issue and/or stage them at the crew’s work area. Once materials and components are installed, an inspection is conducted to determine the compliance of the installation to specifications, and performed work is documented to monitor and control project progress and plan successive work.

Since the Business Roundtable (1982) claimed materials management as a distinct management system that can make the significant contribution to the cost effectiveness of construction projects, research efforts in materials management have:

- identified attributes of properly designed and executed materials management systems (Bell and Stukhart 1986)
- demonstrated the cost effectiveness of materials management systems (Bell and Stukhart 1987, Thomas et al. 1989), and
- developed computer-based data systems that provide the type of information needed to prevent materials shortage, surpluses, cash flow problems, and labor delays (Elzarka 1994).

The Business Roundtable (1982) defined materials management as “the management system for planning and controlling all necessary efforts to make certain that the right quality and quantity of materials are appropriately specified in a timely manner, are obtained at a reasonable cost, and are available when needed.” It also estimated that more than 6% of all construction labor costs could be saved if materials had been available at the job site when needed. In fact, the inability of the contractor to deliver materials at the right time and the right place had been one of the most common problems in construction (Thomas et al. 1989).

Bell and Stukhart (1986) presented a compilation of attributes of desirable materials management systems on large and complex industrial construction projects to control the functions of quantity takeoff, vendor evaluation, purchasing, expediting, receiving, warehousing, and distribution:

- The materials management system should provide information on materials receipt which is particularly important for crew foremen to prepare reliable short-term work plans. When materials are received at the warehouse or laydown yard, such data as identification code, purchase order number, and storage area, may be entered into the computer-based materials management system.

- The system must also identify potential materials shortages or surplus as early as possible, since early purchasing creates cash flow problems and excess purchasing can lead to a wasteful surplus. Information pertaining to projected or actual material shortages is also needed to maximize efficiency of expediting so that timely information regarding anticipated materials deliveries is provided to all concerned project personnel.
- The system should allow the field materials manager to rapidly determine the status of materials that the crafts requested and are not available for distribution, before a backorder is placed. The system must also be capable of flagging instances when the crafts request materials that have already been issued.

The cost of developing and executing such a system was justified qualitatively through the lack of control in its absence. On the case study projects lacking a materials management system, craft foremen reported spending as much as 20% of their time hunting materials and another 10% tracking purchase orders and expediting, while leaving their crews unsupervised for long periods of time had a detrimental effect on labor productivity.

Bell and Stukhart (1987) also quantified the benefits of materials management systems, including those in the areas of 1) improved labor productivity, 2) reduced materials surplus, 3) reduced materials management manpower, and 4) cash flow savings. This research strongly indicated that a very basic materials plan and approach, including such element as providing secure warehouse storage and limiting unnecessary warehouse withdrawals, will produce a minimum 6% savings in craft labor cost. Furthermore, it was suggested that an additional 4 to 6% savings in craft labor costs would probably be produced by comprehensive integrated computer-aided systems that track bulk materials line items. Bell and Stukhart (1987) related this additional savings to improved labor productivity due to the ability of the crafts to schedule their work around material availability. Besides, they assessed that an effective materials management system could reduce bulk materials surplus from a range of 5 to 10% of bulk materials purchased to about 1 to 3% of bulk materials purchased.

The impact of materials management on labor productivity was also studied by Thomas et al. (1989). Their case study on small- and medium-sized commercial projects identified adverse conditions caused by the lack of an effective material management program, and determined the number of work-hours that were wasted because of insufficient material management practices. Adverse materials management conditions observed include: 1) extensive multiple-handing of improperly sorted materials in search of required pieces, 2) running out of materials, and 3) crew slowdowns in anticipation of material shortages. These material management practices affected 10 out of a total 37 crew workdays, and for those 10 days that were affected, an average of 58% of the work-hours were ineffectively used, which is equivalent to 18% loss in labor productivity, three times greater than projected by Bell and Stukhart (1987).

In summary, research efforts in materials management identified cost-effectiveness and information needs that are required to implement computer-based systems to control the materials management functions. However, improvements to field materials management, particularly concerned with locating, finding, and distributing the right material to the right location at the right time, have remained almost unexamined until recently. In fact, a recent construction technology needs assessment identified field materials management as one of the areas with the greatest potential for improvement and the greatest positive development impact on engineering construction work processes (Vorster and Lucko 2002). In addition, tracking the location of materials on construction projects has become technically more viable with recent advances in automated data collection (ADC) technologies.

2.3. RFID FUNDAMENTALS AND CURRENT APPLICATIONS IN CONSTRUCTION

Like barcodes, RFID is an ADC technology for identifying, locating, or tracking objects or assets and people, but presents several advantages over barcoding in that its operation does not require physical contact, line-of-sight, or clean environments devoid of noise, contaminants, glare and dirt. Current RFID systems consist of transponders or tags, interrogators or readers, and a host computer (see Figure 2.1). Attached to host objects or people to be identified or tracked, an RFID tag carries data about the host, such as identification and item specific information or instructions, on its internal memory. A reader is a fixed or mobile device that reads and may write data to the tag through RF wireless communication when tags come within its read range (varying from one inch to 100 feet or more) and passes the data to the host computer for particular application needs.

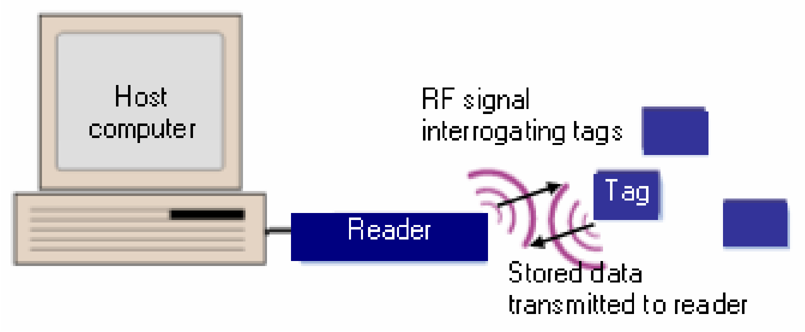


Figure 2.1: RFID system components

RFID tags vary in many specifications, such as power source, carrier frequency, read range and rates, data storage capacity, memory type, size, operational life, and cost. Since their power source dictates other characteristics directly or indirectly, RFID tags are primarily classified as passive, semi-passive, or active, depending on the manner in which they derive operating power to run the digital logic on the chip and transmit the stored data to the reader (Sarma and Engels 2003). With an independent power supply, active RFID tags allow greater communication range, higher carrier frequency, higher data transmissions rates, better noise immunity, and larger data storage capacity than passive tags, and are typically read/write. The trade-off is a finite lifetime (optimally, five or more years), and greater size and higher cost compared with semi-passive and passive tags.

Current RFID systems are used in a variety of applications, such as commodity anti-theft (e.g., electronic article surveillance in retail stores), controlled access to secure or hazardous locations, automated toll collection, animal, postal, or airline baggage identification and tracking, and automated vehicle guidance (AIM 1999). While RFID technology had already seen significant beneficial applications in manufacturing, retailing, and transport and logistics industries, its potential applications in the construction industry have only begun to be explored. Jaselskis et al. (1995) discussed conceptual RFID system designs to track material delivery vehicles, material-handling equipment, and the material itself in general, and for a particular case with tracking concrete delivery vehicles. Peyret and Tasky (2002) applied this concept of tracking delivery vehicles using RFID technology to the case with plant mixed asphalt for quality control purposes. Production data related to a batch of asphalt were automatically collected on an RFID tag mounted on the asphalt hauling truck and transferred to the asphalt paver on site, while the position of a particular batch of asphalt being laid was provided by the GPS receiver mounted on the paver.

Jaselskis and El-Misalami (2003) also reported on several pilot tests conducted to explore the application of passive (opposed to active) RFID technology in the receiving process of palletized pipe hangers and pipe supports at job site laydown yards. The pilot tests demonstrated the usefulness of the technology in receiving the unique engineered materials, but technical difficulties were encountered in that the RFID handheld reader had to be within a few inches of a tag for proper reading. Schell (2001) reported a pilot test at an oil refinery plant that suggested the effectiveness of RFID technology in the pressure relief valve tracking process involving data entry of maintenance records. Most recently the use of RFID technology was considered for tracking construction components through a supply chain. Akinci et al. (2002) and Ergen et al. (2003) proposed the use of RFID technology in tracking precast concrete pieces and storing information associated with them through a supply chain.

Indeed, tracking such unique materials as pipe spools using RFID is one of the potential applications in the construction industry. However, the ability to effectively and simultaneously read active RFID tags installed in pipe spools from longer distances (feet as opposed to inches), with minimal human efforts, and in moving platforms (flatbed trucks) under realistic shipping conditions, had yet to be studied. This ability would eliminate the need to read RFID tags individually from shorter distances using handheld readers and hence minimize associated efforts, such as knee bending (Jaselskis and El-Misalami 2003).

2.4. PRINCIPLES OF LOCATION SENSING TECHNIQUES

Before a survey of related work is further presented, it is necessary to make a distinction between positioning and location tracking systems in determining the location of tagged objects. In positioning systems, individual devices tagged to the object being located compute their own position, while location tracking systems require devices to broadcast, respond with, or emit telemetry to allow the external infrastructure to locate them (Hightower and Borriello 2001a). Thus, positioning systems are less vulnerable to security and privacy issues – no other entity may know where the located object is unless the object specifically takes action to publish that information. However, positioning systems can impose considerable computational and power constraints on small, cheap, low power devices like RFID tags.

In contrast, location tracking systems transfer the computational and power burden to the infrastructure, making possible applications of a large number of smaller, cheaper tagging devices. Nevertheless, the infrastructure cost can still be an impediment to a scalable location tracking system, since its coverage area per unit infrastructure is invariably limited. To encompass positioning and location tracking, the term location sensing is used throughout this paper. Some researchers used the term localization, which originally referred to the problem of determining the position of a mobile robot in some coordinate system (Bulusu et al. 2000). To be clear, the terms localization and location sensing are used interchangeably hereinafter.

Triangulation, scene analysis and proximity are the three principal techniques, employed individually or in combination, for any location sensing system implementation to locate objects, people or both (Hightower and Borriello 2001a).

2.4.1. Triangulation

Triangulation involves computing the position of an object by measuring its distance from multiple reference points with known locations, and is divisible into lateration and angulation, depending on whether ranges or angles relative to reference points are being inferred. The angulation technique is similar to lateration except angles are used in stead of ranges for determining the position of an object. 2D lateration (Figure 2.2a) requires three distance measurements between the object being located and three reference points, while 2D angulation (Figure 2.2b) requires two angle measurements and one length measurement such as the distance between the reference points (Hightower and Borriello 2001a). A good example of the angulation technique is the VHF omnidirectional ranging (VOR) aircraft navigation system.

Lateration can be further classified into the time of flight (TOF) and received signal strength (RSS) methods, where the ranges to reference points are inferred from time of flight and signal strength of the communication signal (e.g., ultrasound, laser, RF), respectively. The TOF approach is employed in the Global Positioning System (GPS), while the RSS technique is used in several indoor location sensing systems, like the Active Bat and the Microsoft's RADAR.

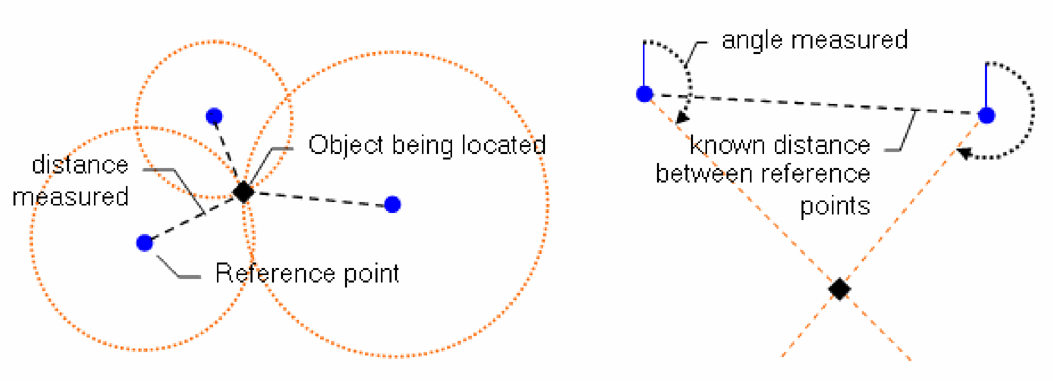


Figure 2.2: (a) 2D lateration, (b) 2D angulation

The TOF based location sensing systems may have to deal with the problem known as time synchronization, and those using light or RF as the communication signal require clocks with much higher resolution than those using ultrasound. However, ultrasound based localization systems may not work very well outdoors because of a high probability of interference from other ultrasound sources (Bulusu et al. 2000). On the other hand, the RSS technique relies on a particular signal propagation model in the coverage area which defines the correlation of signal attenuation of the original strength with the range between the signal transmitter and receiver. In environments with many obstructions such as construction site, signal strength at short ranges (10 m) is subject to unpredictable variation due to fading, multipath, and interference, so does not correlate directly with distance (Bulusu et al. 2000, Hightower and Borriello 2001a). The angulation technique is also not very effective in indoor environments because of signal multipath effects (Bulusu et al. 2000).

2.4.2. Scene analysis

The scene analysis technique infers the location of objects using features of a scene observed which do not correspond to geometric distances or angles, such as visual images. The useful features of a scene also include electromagnetic signal characteristics that occur when a signal transmitter is at a particular location. Such signal characteristics can serve as “RF signature” unique to a given location, but the major drawback of this technique is the extensive effort needed to generate the signal signature database and reconstruct the predefined database with significant changes in the environment (Bulusu et al. 2000, Hightower and Borriello 2001a).

2.4.3. Proximity techniques

The proximity technique determines whether an object is near one or more known locations, by monitoring physical phenomena with limited range, e.g., physical contact to a magnetic scanner and communication connectivity to access points in a wireless cellular network. As opposed to fine-grained triangulation and scene analysis methods, the proximity technique does not attempt to actually measure the object’s distance to reference points, but rather determines its presence within a certain range, for instance, from the scanner or access points with known location.

2.5. LOCATION SENSING OF CONSTRUCTION RESOURCES ON SITE

As described earlier, the ability to provide timely and accurate information on materials availability for crew-level work planning presents the potential for improved labor productivity and project performance. For this purpose, tracking the location of materials implies tracking the delivery and receipt of materials through locations in the supply chain (e.g., a fabrication shop, constructor's laydown yard). Yet, there are two reasons for tracking materials' location with more accuracy than simply indicating that a certain material is received at and hence within the constructor's laydown yard, for instance. First, though materials may be known to be within the premises, they need to be found physically before issued to crew workers who requisite them for installation on site. A field test of using GPS to locate pipe spools in lay down yards showed that time savings in the recalling/flagging step would translate into warehouse personnel labor savings that justify the deployment of the technology for a typical industrial project (Caldas et al. 2004).

The second reason for more accurate location tracking is related to automated derivation of construction performance indicators, such as labor productivity, schedule, and cost, for project control purposes. As Futcher (2001) noted, a major obstacle to the success of a project management information and control system is the need for timely and accurate feedback information describing actual performance and progress on the construction site. This was attributed to the lack of benefit from the system to field supervisors in relation to the effort required of them in reporting project progress data. A case study on a highway construction project also revealed that incomplete and inaccurate site data was due to foremen's unwillingness to spend time collecting production related information, such as quantity, type and description of material, which they perceived as a non-value activity to their primary task (Kiziltas and Akinci 2005). According to McCullouch (1997), field supervisors may have to spend on average

30-50% of their time recording and analyzing site data, while they will be interested only in collecting data items needed for payroll, such as quantity and working hours of labor.

As an alternative to the direct data collection relying on human observers, research efforts under the Automated Project Performance Control (APPC) initiative thoroughly investigated the feasibility of 1) automatically tracking the location of construction agents (laborers and equipment), 2) identifying and determining the status of the basic activity that the agent is engaged in, and 3) deriving project performance indicators. Navon and Goldschmidt (2003) showed that workers' locations can be automatically collected by GPS and converted into labor hours consumed in execution of a particular activity with reasonable accuracy, based on the geometrical association of those locations to the activity. Using the same conceptual framework, Sacks et al. (2005) developed a method for identifying basic activities performed on a building's elements using lifting equipment. Navon and Shpatnitsky (2005) showed that performance indicators can be deduced by monitoring the location and movement of pieces of equipment performing controlled activities in road construction.

At the heart of the APPC framework is the concept of a work envelope which is to be associated with the location of a worker or piece of equipment. Conceptually, a work envelope is a volume in space, typically in the proximity of the element, in which a worker or piece of equipment must be physically present to perform a basic construction activity on that element, e.g., placing and stripping formwork on a column. Thus, specific work envelopes should be instantiated depending on 1) the type of activity, 2) the type and geometry of element, and 3) the construction technology employed in performing the activity. As Sacks et al. (2003) showed, all of the required information may be obtained from a project model in electronic formats that hosts rich representations of the facility to be constructed but also its construction status in terms of completed activities and plans of scheduled activities. However, generating and calibrating envelope geometries for each basic activity performed on a building element is tedious given the number of combinations of activity type, element type, and construction technology.

Furthermore, the location of a construction agent can still be associated with more than one work envelope, thus leading to ambiguous identification of the activity that the agent was engaged in. Knowledge of the current project execution status can narrow the search for the correct work envelope to those of activities that are in progress, or are candidates for execution. Nevertheless, overlap between work envelopes of distinct elements is not completely avoidable because 1) distinct building elements themselves overlap (e.g., a column sits in a slab section), and 2) very commonly, more than one basic activity is performed on the same element. As such, the research efforts under the APPC initiative suggested several other techniques to address situations of ambiguity in the geometrical association. For instance, activity dependent algorithms may be developed that will choose the right set of decision rules according to the division of work sections, or the type of the activity. Another technique may involve characterizing a priori equipment operations for each work envelope, using such parameters as the weight released and the residual weight of the operation.

Yet another alternative to be examined in the research described here is to automatically identify materials (e.g., a precast concrete element) and auxiliary equipment (e.g., a concrete bucket or steel shutter formwork), and at the same time track their locations with sufficient accuracy. For instance, two different basic activities performed on the same element, e.g., placing formwork and concrete on column #1, are conveniently distinguished if it is known whether a concrete bucket or steel shutter form was present in the proximity of lifting equipment. Thus, this alternative presents the potential to complement the existing approaches to automatically identifying the activity performed by construction agents.

In summary, location sensing of construction resources on site is critical to automated measurement of project performance that will promote successful implementation of the project management information and control system. Ultimately, it enables project management to take corrective actions in real-time to control the performance as close as possible to a set of desirable values. However, related research efforts have focused on construction agents (workers and equipment) and not examined the potential of tracking the location of materials. Automatically tracking the location of uniquely identified materials and other objects on site can complement the existing approaches to identifying activities performed by construction agents, which is a prerequisite to the status determination of the activity and the derivation of performance indicators.

2.6. APPLICABILITY OF ADC TECHNOLOGIES TO LOCATION SENSING OF MATERIALS ON SITE

Undoubtedly, GPS can be used to precisely track the location of objects over a great range of geographic and geometric scales. Since the regulatory measure to degrade civilian GPS signals, known as the selective availability, was discontinued, state-of-the-art GPS can now provide positions of centimeter accuracy under non-stationary situations (Navon and Goldschmidt 2002). Though GPS is a viable option for the small number of workers or pieces of equipment, the technology is expensive for dense deployment to automate tracking hundreds of materials. Tagging individual material items with simple GPS receivers costing around US$100 per unit would be prohibitively expensive, and still other means for identification would be required.

A good example of such multisource systems is the Comp-TRAK that Furlani and Pfeffer (2000) developed based on an overall system architecture proposed by Furlani and Stone (1999). The Comp-TRAK accomplished the identification and tracking of the tagged structural steel component, with different technologies, i.e., bar coding or RFID, coupled with 3D fanning laser systems. To determine the object's position and orientation, Comp-TRAK relies upon manual acquisition of fiducial points and a priori calibration which require line-of-sight of multiple laser transmitters and accessibility to the object. Though the laser system of Comp-TRAK is useful for producing as-built models and for rapid local area modeling, it is not feasible in itself for comprehensive materials tracking since it lacks the ability to perceive anything about the nature of the object without significant human post-processing.

In comparison, RFID technology is suited to tracking hundreds of materials with its capability to identify tagged objects in harsh environments. Though its primary use in current applications is limited to identification purposes as with barcoding, the technology may be used for location sensing applications, in the form of portable data capture systems. For instance, a reader, mounted on a vehicle and linked to an on-board computer, can determine the position of the vehicle using RFID tags as reference points, thus being a positioning system under the definitions provided earlier. However, this application requires tags to be embedded in the floor of the operating environment and pre-programmed with known location, thus raising the question: how to pre-determine the location of tags. Perhaps, RFID tags with limited power and computational capability will not be able to determine their own location, which renders this approach impractical.

As opposed to positioning systems illustrated above, location tracking presents an alternative approach to determining the location of tagged objects using current RFID technology. This approach often leverages a network of fixed readers deployed within a given site and connected directly to a host computer, as in the real time location systems (RTLS). Unlike conventional RFID systems, the RFID-based RTLS provide both identification and accurate location of tagged objects by virtue of a pre-configured wired network of fixed RFID readers, using the similar technique as in GPS. For example, Pinpoint’s 3D-iD, a commercial product, deploys a grid of RFID readers in the interior of a building which is subdivided into cell areas. When one object tagged is to be located, a wired network of readers calculates the location of the single tag using the TOF technique, based on range measurements made in one or more tag-to-reader links, thus being a location tracking system. While GPS measures one-way flight time, the 3D-iD measures roundtrip time so as to eliminate the need for time synchronization (Bulusu et al. 2000). Although it provides an accuracy of 10 m for most indoor asset tracking applications, it requires the significant infrastructural setup of proprietary networks and has difficulty interoperating with the 802.11 wireless networks because of radio spectrum collision (Hightower and Borriello 2001b).

Most recently, these problems with the RFID-based RTLS have been resolved by leveraging the IEEE 802.11 standard Wi-Fi networks. Good examples include solutions from Ekahau (www.ekahau.com) and AeroScout (www.aeroscout.com). Being based on the non-proprietary networks, these Wi-Fi RTLS successfully overcame the substantial cost barrier to scalable location tracking systems, i.e., the infrastructural setup of separate networks. Nonetheless, some Wi-Fi RTLS based on the scene analysis principle requires extensive calibration to map the Wi-Fi signals to locations throughout the building. Furthermore, the Wi-Fi RTLS relies on existence of 802.11 access points in the building, which is not guaranteed for a facility being built, and the object it is tracking must support a wireless LAN.

To circumvent calibration efforts in the scene analysis technique, the Wi-Fi RTLS may employ other principles of location sensing. For example, based on the RSS triangulation between IEEE 802.11b wireless Ethernet devices and access points, Stone et al. (2002) conducted research on auto ID and position determination to monitor a randomly distributed field of environmental sensors and track on-site trades/crafts. However, similar to the Microsoft's RADAR, this RSS based location tracking system presents a non-trivial problem in generalizing to multifloored buildings or three dimensions (Hightower and Borriello 2001b), in addition to reliance on existence of 802.11 access points.

In summary, RFID technology suits identification purposes in tracking thousands of materials but its current applications do not provide sufficient location accuracy without relying on a fixed communications network. However, due to its evolving and unpredictable nature, a construction site cannot afford location sensing systems relying on the network infrastructure, whether proprietary or not, which should be configured carefully to cover the entire site and calibrated to its RF transmission space.

2.7. WIRELESS SENSOR NETWORKS AND AD HOC LOCATION SENSING

Traditional wireless networks, such as in RTLS, are based on the cellular concept in which RFID readers or Wi-Fi access points constitute the wired communications infrastructure to support wireless connectivity to mobile nodes, i.e., RFID tags or Wi-Fi devices attached to objects. In contrast, wireless ad hoc networks use no pre-existing fixed infrastructure of distinctive base stations, access points or terminals. In wireless ad hoc networks, network connectivity is based on peer-to-peer communications by which mobile nodes dynamically form a temporary (ad hoc) network to exchange data upon rapid configuration of wireless connections on-the-fly (Sun 2001).

A step further, wireless sensor networks envision that hundreds to thousands of sensor nodes with much less radio range are densely deployed in physical environments, self-configured and adaptively coordinated to frequent topology changes, providing the sensed data (Akyildiz et al. 2002). To process sensor data, the position of each node a wireless sensor network must be determined because, for instance, temperature sensed by a node with unknown location would be practically useless. The most interesting approach to this end is ad hoc location sensing that, unlike the cellular network based approach as in the 3D-iD and Wi-Fi RTLS, does not draw on the infrastructure of a dense grid of networked readers or base stations, thus representing a highly scalable and low-cost approach (Hightower & Borriello 2001). Under the scenario envisioned by wireless senor networks, ad hoc location sensing could be implemented using pair-wise, peer-to-peer range estimates or simply communications connectivity between all sensor nodes.

For the fine granularity of ad hoc localization, nodes being localized ("blindfolded") should be capable of calculating their range (by the TOF or RSS technique) to neighboring peers, and transmitting/receiving pair-wise range estimates to and from other nodes. The combined range information between many pairs of nodes and the known locations of a few "reference" nodes would allow localization of all of the blindfolded nodes. While higher density of blindfolded nodes will increase the accuracy of ad hoc localization, high density of reference nodes, counterpart of RFID readers in the 3D-iD, is not necessary (Patwari et al. 2002). Nor do they need to be any more complicated or expensive than nodes being localized, if fixed at known locations. A good example of this fine-grained ad hoc localization is the prototype system SpotOn that Hightower et al. (2000) built based on a commercial RFID system and that uses the RSS triangulation method with 10-bit signal strength resolution.

Ad hoc location sensing can also be based on the proximity technique using communications connectivity between all sensor nodes. The rationale behind adopting this coarse-grained localization technique is two-fold (Bulusu et al. 2000):

1. Signal strength at short ranges (about 10m, as is often the case with current RFID systems) is subject to unpredictable variation due to

fading, multipath, and interference, and hence does not correlate directly with intertag distance.

2. Commercial off-the-shelf radios do not provide software-accessible signal strength readings.

As such, known peer-to-peer communication in wireless sensor networks is simply modeled as a set of geometric constraints that restrict the feasible set of unknown node positions (Doherty et al. 2001). To illustrate, if a particular RF system can transmit 10 m and two nodes are in communication, their separation must be less than 10 m. The global solution of the feasibility problem under these constraints yields estimates for the unknown positions of the nodes in the network. Provided that the constraints are tight enough, this estimate becomes close to the actual node position.

In summary, location sensing in the wireless sensor network framework would eliminate the need for preconfigured and calibrated communications networks, which renders current applications of RFID technology costly, both economically and environmentally. While research efforts involved either development of customized hardware or idealized radio models to support ad hoc location sensing, wireless sensor networks still present research challenges, such as self-configuring, adaptive coordination, and trustworthiness (National Research Council 2001). As a matter of fact, current RFID tags have no capability even to discover neighboring peer tags though they may be called ‘smart sensor tags’ at the simplest extreme. Only RFID readers can discover and communicate with RFID tags within a certain read range, and tags can only respond to readers by sending back the data stored on internal memory. Furthermore, without hardware modifications, most of current RFID systems will not provide the distance measurements between the tag and the reader, which are critical to accurately determining the location of tagged objects.

Chapter 3: A Portal Application – Tracking the Delivery and Receipt of Fabricated Pipe Spools

3.1. INTRODUCTION

Among engineered materials, pipe spools are of particular interest to industrial projects as piping has been recognized as a critical and costly process (Tommelein 1998). Industrial process facilities often involve hundreds or thousands of fabricated sections of pipe spools, many of which are unique in material (e.g., cast iron), shape, finish, and other properties including final installation location on site. In a typical size industrial project with total installed cost ranging from US$200 to $300 million, there may be as many as 10,000 pieces of pipe spools (Song et al. 2004).

Many industrial projects are executed on fast track, due to the pressing need to bring products to market fast. Given this characteristic, some industrial projects may take the opportunity to fabricate pipe spools off-site while prerequisite work is occurring on site. Several process models based on this scenario have been studied by Tommelein (1998) using the discrete event simulation approach implemented in Stroboscope. In fact, piping has seen significant increase in the use of prefabrication and preassembly over the preceding twenty years (Haas et al. 2000). However, piping in fast-track projects still poses potential uncertainty in deliveries and in completing prerequisite site work, leading to "mis-matches that foul up scheduled work sequences" (Tommelein 1998).

Under this uncertainty, the constructors' materials managers may choose to rely on large buffers of pipe spools in an effort to secure flexibility in workable backlogs for pipe fitting crews so that they have "at least 60 percent of all pipe on site when 20 percent of the pipe had been installed" (Howell and Ballard 1996).

Interviews conducted as part of this study indicated that this situation is still the norm. Such large buffers of pipe spools are accumulated in a constructor's laydown yard from deliveries received five to six months prior to scheduled installation, and received pipe spools dwell in the laydown yard until pipe fitting crews file requisitions. This practice in industrial piping is comparable to the case with precast components which are often stored in the plant's storage areas, possibly as long as six months, until shipping to the erector (Akinci et al. 2002).

When pipe fitting crews make a requisition for certain pipes, the constructor's laydown yard personnel will locate and identify the pipe spools and issue and/or stage them at the crew's work area. In some cases, they may not be able to locate pipe spools in their laydown yard within a reasonable time and have to search for the "misplaced" pipe spools. While such misplaced pipe spools may represent about two percent of all pipes for a single project, the constructor's search for misplaced pipe spools often requires collaboration and coordination with other project entities. If specific pipe spools can not be located within the laydown yard, it is likely that they are in other premises, for instance, in the fabricator's storage areas. Thus, successful recovery of misplaced pipe spools would require extensive search effort across the entire supply chain. If not found, pipe spools are even re-fabricated. In either instance the disruption of overall project progress is substantial and costly.

The above state of practices in industrial piping illustrates the need of field materials management to track materials through the supply chain, accurately and in a timely manner. This capability will help field materials managers to assure availability of materials as they are needed for installation and to make such availability information readily accessible for crew level work planning. In fact, field materials management was identified by a recent construction technology needs assessment as one of the areas with the greatest potential for improvement and the greatest positive development impact on engineering construction work processes (Vorster and Lucko 2002). In addition, tracking such unique materials as pipe spools was suggested as one of the potential applications of RFID technology in the construction industry (Jaselskis and El-Misalami 2003). However, the ability to effectively and simultaneously read active RFID tags installed in pipe spools from longer distances (feet as opposed to inches), with minimal human efforts, and in moving platforms (flatbed trucks) under realistic shipping conditions, had yet to be studied.

This chapter is concerned with the ways in which the use of current RFID technology can be extended to tracking uniquely identified pipe spools during their delivery and receipt. Based on the findings from the field tests conducted, the technical feasibility of RFID technology in automating the task of tracking the delivery and receipt of pipe spools is discussed. Finally, a model of the current tracking process is presented, and potential benefits from the use of the technology in the process are described.

3.2. FIELD TESTS

In response to the compelling opportunity presented in recent construction industry research and advances in RFID technology, the FIATECH (Fully Integrated and Automated Technology) Smart Chips project, in conjunction with Shaw Fabricators and Fluor Corporation, undertook a program of field tests of current RFID technology with the assistance of this author. The primary objective of the tests was to determine the current technical feasibility of using RFID technology to automatically identify fabricated pipe spools and collect other information about them, such as purchase order number, in a laydown yard and through a shipping portal as part of realistic transport environments.

The field tests were conducted in two phases that span from September 2003 to March 2004, to allow a staged assessment of RFID capability in field construction applications. Phase I was intended to document technical issues and learning related to the envisioned applications of RFID technology. Based on the findings of Phase I, Phase II focused on determining the reliability of RFID technology to some statistical significance to automatically identify individual pipe spools as they pass though portal gates in typical transportation conditions.

There have been many technical limitations that prevented RFID technology from working effectively in the construction field environment in the past, though related problems have been solved for automated vehicle identification applications in transportation (Khoury et al. 2003). Technical issues addressed in these field tests that were not directly investigated in the previous research studies included: 1) the RF signal read ranges, which typically need to be longer than the current common commercial RFID applications in the manufacturing and retail industry, 2) metal interference with radio signals, which has been a problem in many common RFID applications, 3) the density of tags in a congested area, 4) the position of RFID tags relative to spool pieces and to the readers, and 5) the amount of information that can be stored on and read from the tags. In order to best assess the capabilities of RFID technology in addressing these issues, recent commercially available active (as opposed to passive) RFID systems were used during the field tests.

3.2.1. Description and Results of Phase I Field Tests

The Phase I trials were conducted using two different types of RFID systems, equipped with handheld and fixed readers. The handheld system was used in determining the ability to read signals at long distances and around metal in manual receiving and inventory application at laydown yards. The handheld reader included an RFID reader in PC card format and an antenna that were inserted in a handheld PC and could be carried around a laydown yard or a flatbed trailer (see Figure 3.1). The handheld RFID reader works with two types of active tags that operate at the same frequency but differ in memory capacity and read/write range (Figure 3.2).

Figure 3.1: Handheld reader unit

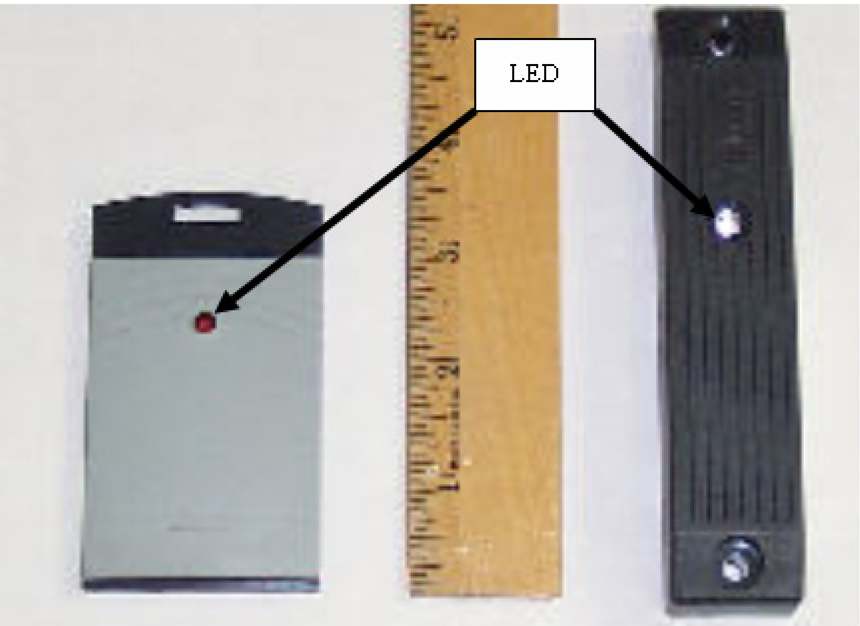


Figure 3.2: Short range tag (left) and long range tag (right)

For the field trials using the handheld system, fabrication shop workers placed fabricated pipes in a laydown yard and on a flatbed trailer, as they would normally do prior to shipping. Next, RFID tags were attached to twelve individual pipe spools in a variety of sizes and shapes using plastic tie wraps or double sided mounting tape. Most of the tags were positioned under large pieces, or on very congested pallets, where the reader would not be in direct line of sight and/or tag RF signals could be more difficult to reach the reader during the tests. Finally, the handheld reader was carried around about two to three feet above the pipe laid down in the yard or loaded on the trailer to collect unique ID's.

The results of field trials using the handheld system indicated that current active RFID technology could function well in a congested, highly metallic environment to improve efficiency in receiving and inventory storage applications, where relatively long read range is desirable. The only difficulties in reading tags in the trials seemed to develop when either: (1) tags were fully surrounded by solid metal (e.g. placed more than an inch or two inside of a spool, or shielded completely by multiple layers of spools creating a "Faraday cage"), especially with the reader's RF power lowered, or (2) tags were placed in full contact with a surface such as flat metal plate, concrete beam, and the ground. Detailed test logs can be found in Akinci et al. (2004) that record each trial with different tag placement under varying levels of RF power.

Confirming that read distances and metal interferences could be addressed, a fixed reader system was installed on a portal structure through which a flatbed trailer could be driven, simulating typical pipe spool transport and receiving operations (see Figure 3.3). Figure 3.4 shows the fixed reader to be mounted on the portal and the tag to be attached to a pipe spool. Description of both RFID systems used in Phase I is summarized in Table 3.1.

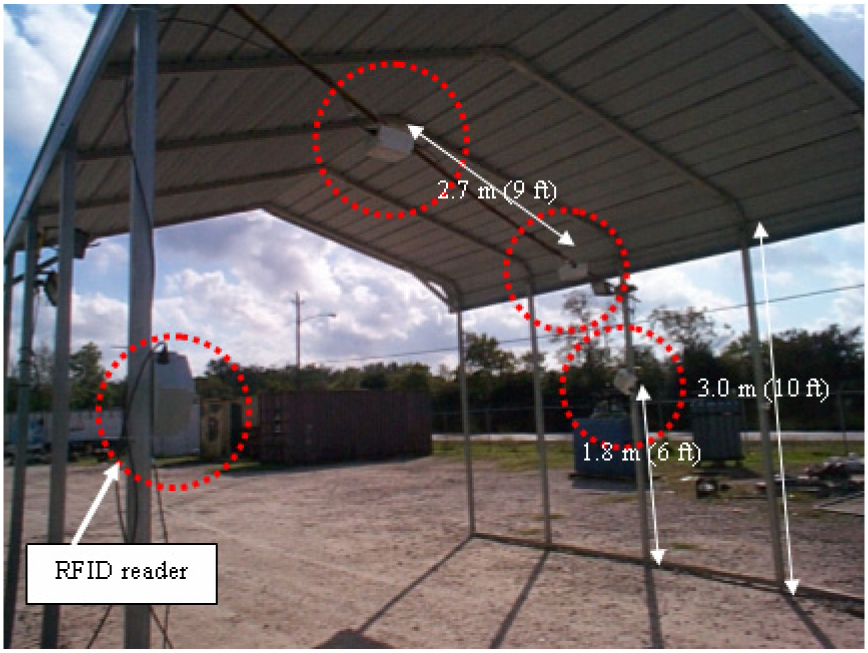


Figure 3.3: Portal structure with four fixed readers installed

Figure 3.4: RFID reader and tag for the fixed system

Table 3.1: RFID Systems Used in Phase I

	Reader (frequency, read range)	Tag (memory cap., total no. attached, stored data)	Tried field conditions
Handheld system	915 MHz, 20-300 ft depending on types of tags	Type D - 64 byte, 12 each; Type Q - 8 KB, 12 each, identification only	In a laydown yard and around a flatbed trailer while loading pipe spools
Fixed reader system	433.92 MHz, 150 ft	500 KB, 20 each, identification and other information	While a pipe loaded trailer passed through the portal

For the field tests with the fixed reader system (or “portal” system), twenty RFID tags were attached to fabricated pipe spools after being inspected for quality control, and were loaded on a flatbed trailer to be driven under the portal equipped with four readers (Figure 3.3). In addition to the unique ID number of each tag, data, such as piece marked number, spool number, sketch number, and purchase order number for each pipe spool, had been written to the tags. The tests were conducted under presumed shipping en route to a construction site, with varying conditions; (1) the density of tags on the trailer, (2) the amount of tag data to be captured - ID only versus ID with additional data stated earlier, (3) the movement of trailer under the portal - pass through or stop-and-go at different speeds, and (4) the number of readers activated - all of the four, those two on top or side, or only one on top center of the portal. The fixed RFID system was tested in twenty-five truck passes under the portal gate, including ten passes involving reading identification and other data associated with individual pipe spools.

The results of field tests indicated that it is technically feasible to use commercially available active RFID technology in automating the tracking of the shipping and receiving of fabricated pipe spools beyond simple identification, in typical transport conditions. In the field trials, ID and other information about pipe spools were captured from more tags when the trailer stopped for a short time under the portal, allowing the readers more time, if on the order of a few seconds, to read data. When reading ID and other data about pipe spools was attempted in a situation where the trailer stopped under the portal, using only one reader on the top center of the portal resulted in more tags to be unread than using multiple readers. However, when reading ID only was attempted, the number of readers did not make any difference, provided that the trailer stopped under the portal and then proceeded slowly through it. For more information on the field tests, refer to Akinci et al. (2004).

3.2.2. Phase II Field Tests

Phase I had targeted the investigation of many technical issues related to applications of current RFID technology in shipping and receiving the deliveries of pipe spools, and indicated that further trials would be promising. Phase II was pursued to determine the reliability of the technology in such an application that would enable automated identification of individual pipe spools as they pass through a portal, or "portal" application, to some statistical significance. Phase II field trials were conducted using a fixed reader system with the same types of tags as in the handheld system of Phase I (Figure 3.2).

RFID system used and the testing procedure

For the fixed reader system to be functional, the reader was connected up to four antennas via a cable on one end, and on the other end to a host computer running software via Ethernet cable (Figure 3.5). According to the vendor Identec Solutions (www.identecsolutions.com), the fixed reader can transmit/receive data at distances of 6 meters (20 feet) from a short range tag or up to 100 meters (300 feet) from a long range tag.

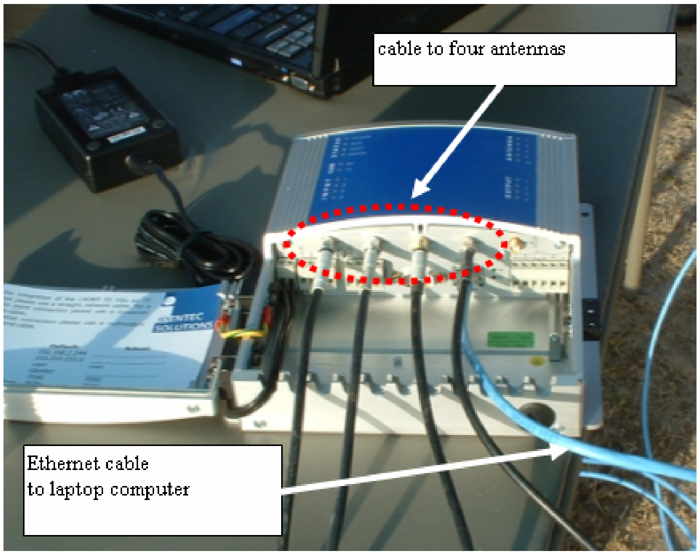


Figure 3.5: Fixed RFID reader used in phase II

The general procedure for the field trials is depicted in Figure 3.6. Steps 1 through 5 comprise the set up process of the overall testing procedure, and Step 6 starts the testing process for technical performance of the technology by determining the values of several parameters that form a particular set of field conditions. The test parameters, which are expected to impact the technical performance, can be divided into two categories, according to how easy it is to change their values during the field trials, as shown in Table 3.2.

Table 3.2: Categories of Test Parameters in Phase II

Category	Governing level	Test parameters
Static	Test bed	- Type and no. of tags - Tag positions relative to antennas
Dynamic	Group of truck passes	- Timing of reader activation/deactivation - Travel speed of trailer - No. of active antennas

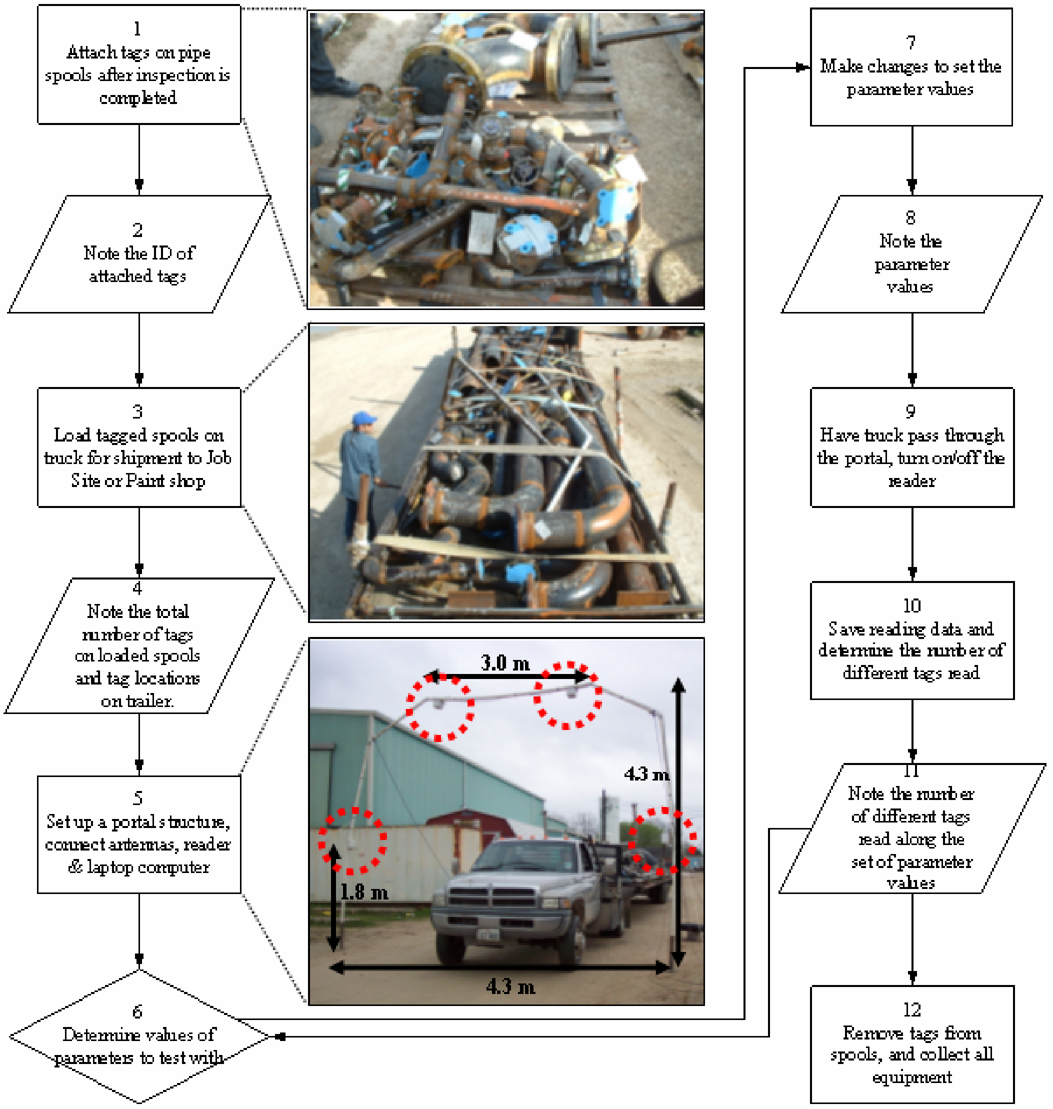


Figure 3.6: General test procedure in Phase II

Parameters fall in the Static category if changing their values meaningfully would require much time and effort to affect the fabricator's tight delivery schedule. As such, each parameter in the Static category was set to a uniform value over one or two days of field tests, or "test bed." Though limited, the relative tag positions has been changed by moving tags around spools or by reversing the traveling direction of the trailer through the portal. On the other hand, parameters under the Dynamic category are those that were given different values within a test bed, but were expected to have some constant value across a group of truck passes (or “trips”) in the same test bed. For instance, one trip in a test bed might include the same type and total number of tags as any other trips in the same test bed, but may be characterized by a different travel speed than some trips in the same test bed. Different categories of test parameters may be thought of as different levels of control that govern the technical performance of the technology.

As the truck, loaded with tagged pipes, approached and left the portal at a predetermined traveling speed (Step 9), the reader was activated and deactivated, and the read data were saved and exported to Excel to determine the number of *different* tags that were read in each pass (Step 10). Finally, the number of different tags read in the pass was noted along with the set of field conditions (Step 11), and the subsequent passes started with Step 6. If some tags were not read in the previous pass, Step 6 involved selectively changing some of the previous parameter values to increase the number of different tags to be read. Following the procedure described above, four days of field tests were completed over a month period and a total of seventy truck passes were made, as shown in Table 3.3.

Table 3.3: Overview of Phase II field tests

Test bed no.	Total no. of tags attached	No. of active antennas	No. of truck passes
1	83^{Q}	4	12
2	50^{D}	4	20
3	56^{Q}	2 or 4	38
Total			70

*^{Q} indicates long range tags; ^{D} short range tags

Technical performance metrics and results of field tests

In determining the technical feasibility of RFID technology for the portal application, the read rate is used as a metric to assess the ability to automatically identify pipe spools as the shipment departs or arrives through the portal. The read rate measures in percentage how many *different* tags of the total loaded are read in each pass. Since in a single pass, tags could be read more than once via any one of the active antennas, the duplicate read ratio is also defined to quantify how many times a particular tag is read in each pass at a cost of energy and redundancy. Table 3.4 shows summary values of the metrics resulting from each test bed which can be thought of as a sample with size being the number of truck passes. The median read rate is the 'middle' read rate, so exactly a half of the passes in the test bed resulted in the read rate greater than the median read rate.

Table 3.4: Summary of Read Rates and Duplicate Read Ratio

Test bed no.	No. of passes	Mean read rate	Mean duplicate read ratio	Median read rate
1	12	98.1%	1.4	98.8%
2	20	96.4%	1.9	98.0%
3	38	96.0%	6.8	100.0%

Test bed 3 yielded a lower mean read rate, but a higher median read rate, than other test beds, as can be seen in Figure 3.7. This is due to several extreme cases (outliers) that Test bed 3 ensued as the read rates observed in Test bed 3 had the most skewed distribution. This skewed distribution may be explained by the fact that Test bed 3 underwent highly dynamic test conditions which arose from parameter values being more actively changed. Test bed 3 also resulted in the largest mean duplicate read ratio, close to seven. This means that if read at all, a single tag was read on average seven times in each pass. This high duplicate read ratio is due to the reader's RF power set to the maximum sensitivity to RF signals transmitted from tags. This increased the reader's burden to handle seven times more but essentially redundant data received from tags. This may have contributed to the low mean read rate by creating a transmission environment in which a relatively weak, shielded signal from a particular spool would be "drowned out" by the other signals.

Nonetheless, in general and as expected, a higher duplicate read ratio due to higher RF power is associated with a larger number of different tags read per pass for all three test beds. This can be seen in Figure 3.8 where duplicate read ratio and read rate is plotted for each pass (the slopes of the fitted line are all positive). Yet, this apparent association may not be generalized to say "the more RF power leads to the larger number of different tags to be read and hence to a higher read rate." Indeed, Test bed 3, with RF power set to maximum, resulted in a lower read rate on average than the other test beds. In a sense, it created a higher "risk" of costly read misses.

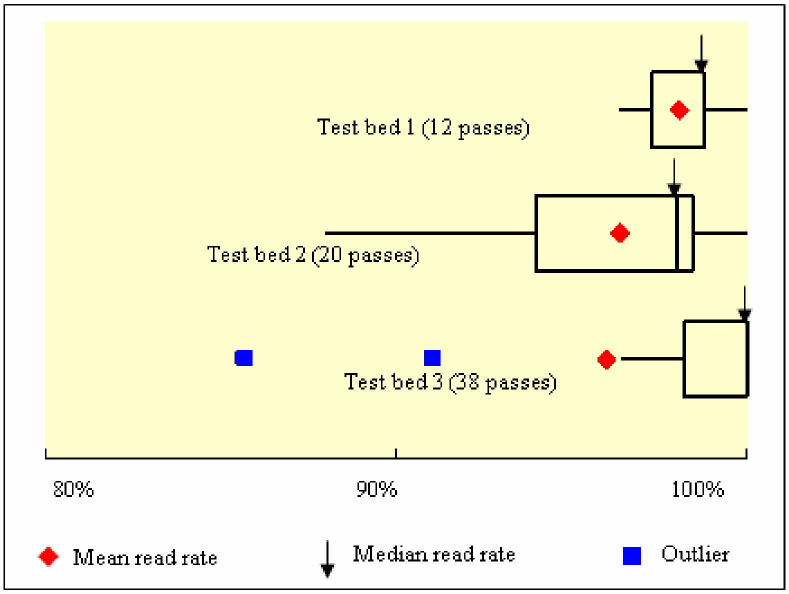


Figure 3.7: Box-whisker plot of read rates

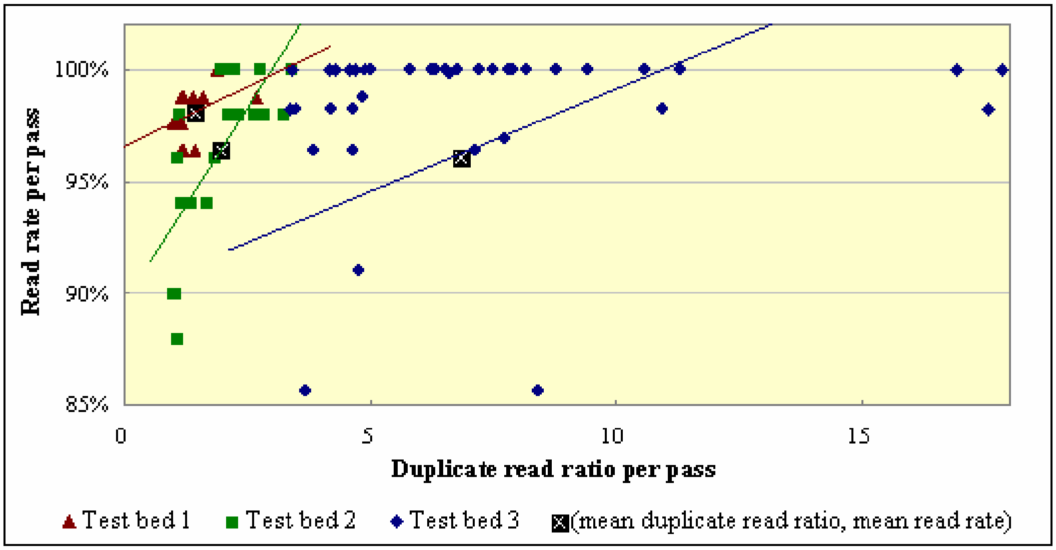


Figure 3.8: Pairwise scatter plot of duplicate read ratio and read rate per pass

Another interesting observation from Figure 3.8 is that the slope of the fitted line for Test bed 2 is steeper than that of Test beds 1 and 3. If slopes for each test bed are thought of as the strength of the relationship between duplicate read ratio and read rate, the steeper slope means the read rates in Test bed 2 were more sensitive to the reader's RF power. In fact, only Test bed 2 included tags with a shorter read range, while the other test beds were dedicated to longer read range tags. Thus, with a small change to the RF power, short range tags would end up with a rather large gain or loss in the read rate. Since the signal strength decays as the square of the distance, this makes sense from the perspective of basic physics (Halliday et al. 1997).

Factors influencing read rate

The variability of the read rates in Test bed 3 has lent itself to further analysis, but the sample that arose from Test bed 3 may not be taken as random since the read rate of one pass is dependent on the outcome of the previous pass to some degree.

This dependency stemmed from the unconscious effort to increase the read rate by selectively changing some of the previous parameter values. To alleviate this dependency structure in the sample, thirty-eight passes from Test bed 3 were re-organized into groups that have similar values for some test parameters, as shown in Table 3.5 (several passes do not fall into any one of the groups). Moving from Group I to V, the mean read rates tend to increase while the variance of read rates is decreasing (Figure 3.9). This observation suggests that under the set of field conditions (table column values) classifying passes into Group IV or V, the technology under consideration is most likely to achieve 100% reading of 56 tags every time the load of pipe spools is shipped/received through the portal.

Table 3.5: Test Bed 3 Decomposed into Groups of Passes

Group no.	No. of passes	Reader on/off timing (before/after trailer front/rear end)	Travel speed	No. of antennas; traveling direction	Mean read rate	Variance of read rates
I	9	5~6 m; 6~7 m	1 mph	2; counter-clockwise	96.4%	0.383%
II	4	5 m; 3~9 m	5 mph	4; counter-clockwise	96.9%	0.157%
III	7	0 m; 2 m	4~5 mph	4; either direction	98.7%	0.018%
IV	9	5~6 m; 6~7 m	1 mph	4; counter-clockwise	99.8%	0.004%
V	6	0 m; 0~1 m	2 mph	4; clockwise	100.0%	0.000%

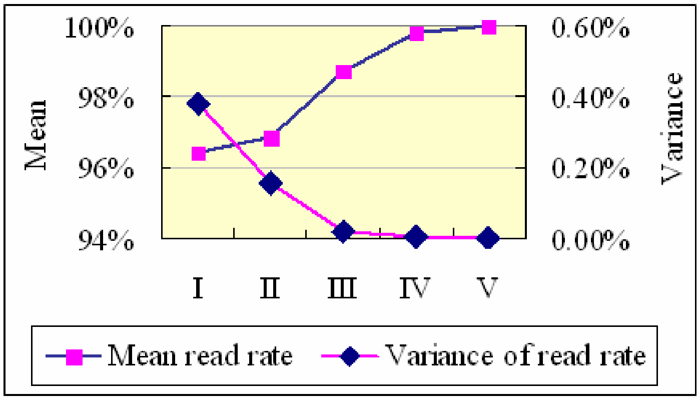


Figure 3.9: Mean and variance of read rates for groups of passes in Test bed 3

Whether the field test data supports the assertion that the differences of the mean read rates between groups of passes are statistically significant is answered by means of statistical hypothesis tests on the differences in mean read rates between groups; 1) Groups I and IV, 2) Groups II and IV, and 3) Groups II and III (Table 3.5). Noting that the number of passes is not a test parameter but rather represents a sample size for each group, these pairs of groups considerably differ in only one test parameter: reader activation timing, travel speed, or the number of active antennas. Thus, comparing each pair of groups allows determining the significance of the effect that a particular test parameter may have on the read rate. Statistical hypothesis testing is usually based on some test statistic (e.g., t or F statistic) to define a rejection region from the sample space where the null hypothesis (H_0) is rejected, and hence the alternative hypothesis (H_1) is accepted. A statistic used in our hypothesis tests is described below.

Let p_i denote the probability that each tag will be read (i.e., the read rate) during the passes of Group i, and each tag is assumed to have the same p_i in every pass under the field conditions characterizing Group i. Then the number of tags of the total 56 that are read in each pass of Group i, Y_i has a binomial distribution with parameters 56 and unknown p_i, or $Y_i \sim \text{Bin}[56, p_i]$. Further, let n_i denote a sample size of Group i (i.e., the number of trials or passes, e.g., $n_1 = n_4 = 9$), and Y_{ij} be the number of tags read in jth pass of Group i. Then observed values of Y_{i1}, Y_{i2}, ... , Y_{ini} would have yielded a random sample of size n_i since 1) they arise from the identical binomial distribution and 2) every Y_{ij} is independent of one another provided that the underlying dependency between successive trials has been addressed by the reconstruction of the overall sample. Without loss of randomness, Y_{ij} can then be added up to represent the total number of tags read in passes of Group i, and approximated to a normal random variable Z_i:

$$\sum Y_{ij} \sim \text{Bin}[56n_i, p_i] \approx Z_i \sim \text{N}[56n_ip_i, 56n_ip_i(1\text{-}p_i)]. \qquad (1)$$

Manipulating Z_i gives us another normal random variable $Z_i/(56n_i) \approx N[p_i, p_i(1-p_i)/(56n_i)]$, which represents the read rate for Group i (note that its mean is p_i). The statistic to be used in the hypothesis tests involves standardizing $Z_i/(56n_i) - Z_j/(56n_j)$, the difference between two normal random variables that represent the read rate of each group.

The resulting standard normal variable denoted by Z_{ij} can be used to test the null hypothesis H_0: $p_i = p_j$ (no difference in mean read rates between Groups i and j) against H_1: $p_i < p_j$. The hypothesis tests result in H_0 being rejected at a significance level α if the observed sample value of the test statistic Z_{ij} is smaller than a critical value Z_α. Given α, the critical value is determined such that $\Pr(Z \leq Z_\alpha) = \Phi(Z_\alpha) = \alpha$, where Φ is the cumulative distribution function of a standard normal variable Z. Table 3.6 shows that there is a statistically significant difference in mean read rates between Groups I and IV (α=0.01). This result suggests that the number of active antennas, which is the single factor notably different between the groups, has a significant impact on the technical performance of the portal application measured by the read rate.

Table 3.6: Hypothesis Test on the Difference of the Mean Read Rates between Groups I and IV

Group no.	No. of passes	Reader on/off timing	Travel speed	No. of antennas; traveling direction	Mean read rate	Z_{14}		$Z_{0.01}$
I	9	5~6 m; 6~7 m	1 mph	2; counter-clockwise	96.4%	-3.968	<	-2.326
IV	9	5~6 m; 6~7 m	1 mph	4; counter-clockwise	99.8%	Reject H_0		

Similarly, the results of hypothesis testing for other groups are presented in Tables 3.7 and 3.8, suggesting that traveling speeds of the truck also have a significant impact on the read rate. However, the duration from reader activation to deactivation does not have such a significant effect on the read rate. Note the present α is 0.05, and if it were set to 0.10, the test would result in rejection of H_0.

Table 3.7: Hypothesis Test Results for Groups II and IV

Group no.	No. of passes	Travel speed	Mean read rate	Z_{24}		$Z_{0.01}$
II	4	5 mph	96.9%	-2.482	<	-2.326
IV	9	1 mph	99.8%	Reject H_0		

Table 3.8: Hypothesis Test Results for Groups II and III

Group no.	No. of passes	Reader on/off	Mean read rate	Z_{23}		$Z_{0.05}$
II	4	5 m; 3~9 m	96.9%	-1.430	>	-1.645
III	7	0 m; 2 m	98.7%	Accept H_0		

Based on the data obtained from field tests, statistically significant factors that can affect the technical performance of RFID technology in the portal application were found. Specifically, using four active antennas and driving the trailer at a speed 1-2 mph will allow automatically identifying all fifty-six tags precisely. Nonetheless, it should be noted that accountability of our statistical inference is challenged by the small sample size n_i. Recall that our construction of the test statistic was based on approximation of the binomial random variable (total number of different tags read during passes of each group) to the normal random variable. The rationale behind this approximation is that exact probabilities concerning a discrete random variable are difficult to compute.

3.3. POTENTIAL BENEFITS

The field tests indicate that current RFID technology can be used to automatically identify unique pipe spools effectively not only as they are stored at laydown yards, but also as they are shipped and received through portal gates. This result suggests that current active RFID can address the technical difficulties with the read range, the need for individual manual tag reading, and metal interference that were encountered during the previous pilot tests on material receiving at laydown yards (Jaselskis and El-Misalami 2003). Thus, the applicability of the technology is not limited to material receiving but can be extended to tracking of uniquely identified materials when portal systems are deployed along the supply chain.

To put this extended use of the technology into perspective, problems and inefficiencies in a model of the current pipe spool tracking process are described, and activities that RFID technology might support and improve are identified. Potential benefits from the use of RFID in tracking pipe spools are also described.

3.3.1. Inefficiencies Associated with the Current Tracking Process.

A sample model of the overall tracking process from fabrication to job site receipt is given in Figure 3.10, with three parties involved: a fabricator, a painter as a typical intermediary processor, and a constructor. This model reflects the process that was observed during the field tests and that was identified during interviews with managers and supervisors. There may be some variations, but a typical pipe spool supply chain uses processes similar to the ones described here.

The sample process exemplifies the iterative cycle in which pipe spools are manually identified, located, shipped/received, and stored at multiple times along the supply chain. In this modeled process, potential problems and inefficiencies have been identified and grouped into three categories:

- *Time-consuming identification and finding the location* of pipe spools, as is prerequisite to shipping and receiving (marked with shaded boxes in Figure 3.10). In steps 5, 13 and 25, there is a potential problem of identifying spools with those that look similar and hardly differ in eighteen alpha-numeric ID numbers on the metal tags. This problem can be compounded if spools are to be located in a crowded or large laydown area. The similar problem affects steps 10 and 20, which involve verifying ('kick and count') the receipt of the spool pieces against the packing list.

- *Error-prone data recording and transcription* (shown as thick outlined boxes). Time-consuming verification of the receipt in steps 10 and 20 is also prone to error. When pipe spools are identified, located and verified, the packing list is produced or updated manually prior to shipping to the downstream party, as in steps 6, 14-16, and 26-28. The manual recording and transcription of shipping and inventory information are prone to error.

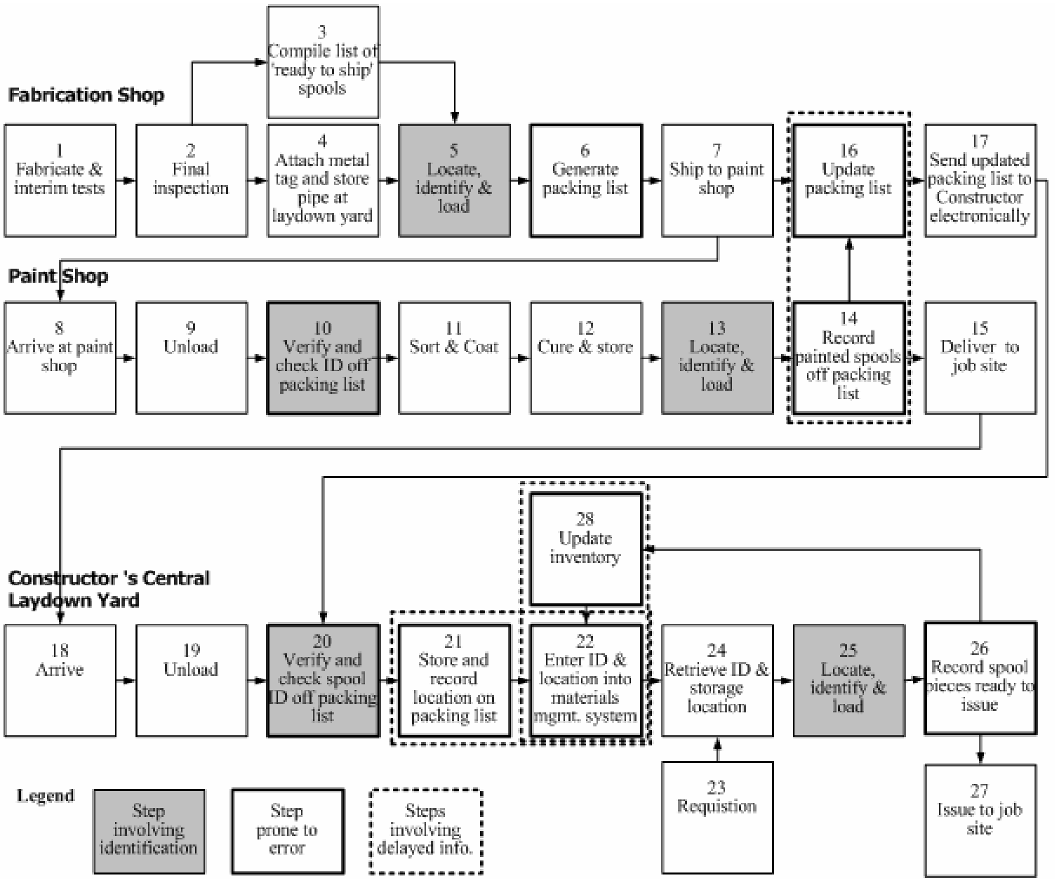


Figure 3.10: Sample process of tracking pipe spools and inefficiencies

- *Delayed information on shipping, receiving, and inventory* (as in boxes with dotted outline). The error-prone recording and transcription of shipping, receiving and inventory information is also subject to delay. In particular, verification of the receipt in step 20 will not immediately inform managers which spools are now in receipt. Materials managers can know about that only after the packing list marked with the storage location of verified spools (step 21) is keyed into the materials control system (step 22). As a consequence of error-prone and delayed information, some of requisite spools may not be able to be located within a reasonable time, and have to be searched over an entire laydown yard and in certain cases in other parties' premises. The misplaced pipes may also have some impact on pipe fitting schedule, depending on the requisition lead time since pipe fitting is a critical path activity on a typical industrial project.

3.3.2. Potential Benefits

The observed process of tracking pipe spools presents the problems and inefficiencies in manually identifying and locating pipe spools and collecting data on shipping, receiving, and inventory. A discussion on how this manual tracking process may be improved with handheld and portal RFID systems deployed at laydown yards and portal gates along the supply chain is included below.

Reduced time in identifying and locating pipe spools

The most direct, but not necessarily the most substantial, benefits are expected in verifying the receipt of pipe spools. In the current manual approach, the average kick and count time per load of one hundred spools ranges from four to six hours, as per the perception of industry practitioners and as reported in (Jaselskis and El-Misalami 2003). Though RFID portal systems can automatically identify pipe spools with near 100% reliability as they arrive through portal gates, the industry practitioners felt that the current kick and count step would not be completely eliminated. Instead of comparing every pipe spool to the packing list, ‘kicking and checking’ will suffice that determines if the number of spools unloaded agrees with that given by RFID systems.

In addition to efficient identification, RFID technology can also help to locate pipe spools along the supply chain. The portal application of RFID technology can tell who received and shipped which pipe spools upon their arrivals and departures through a particular portal gate, thus indicating whether the pipe spools are still within the premises or not. When pipe spools within the premises need to be located for shipping to the immediate supply downstream, the handheld reader can be carried around the premises, and when entering into the read range of the spools to be located, it will indicate the proximity by triggering beeping sound and/or flickering LED on RFID tags. Integration with GPS technology may also be advantageous for this purpose.

More accurate and timely information on material availability and for craft work planning

Other immediate benefits from the use of RFID technology in tracking pipe spools are a function of its capability to automatically collect data on shipping, receiving, and storing inventory, more accurately and in a more timely fashion. The ID number of pipe spools would not need to be transcribed as many times as in the sample manual approach; from a metal tag to packing lists and to a computerized materials control system, to name a few. Since pipe spools are automatically identified as they are shipped and received through portals, packing lists will be rapidly and precisely generated or updated. Thus, for instance, the constructor will be able to flag pipe spools as available as soon as they arrive, without the need to wait until warehouse personnel go through the time-consuming verification and storage processes. As a result, information that certain pipe spools are in receipt can potentially be delivered one or two days earlier, allowing early start of crew level work planning at a construction site.

As the pipe spools are finally issued to the crews, inventory at the constructor's laydown yard will be updated quickly so warehouse personnel will not have to look for the spools that are no longer at their laydown yards. More accurate and timely information about shipping, receiving, and inventory will not only streamline the tracking process and improve efficiency, but also prevent spools from potentially being "misplaced."

Reduced time in searching for misplaced pipes and potential improvements on the pipe fitting schedule

If pipe spools are tracked accurately and expeditiously, it not only helps decrease the probability of spools being misplaced, but also reduces search time and re-fabrication of misplaced spools. According to interviews with materials management personnel, two percent of all pipes for a single project get misplaced with the current tracking process, and the constructor's search for a single misplaced spool can take up to twenty-four hours on average. Since the initial search in the constructor's laydown yard can sometimes be unsuccessful, the pipe fabricator may also need to join the constructor searching for the misplaced spool (in its own yard), spending one third as much as the constructor's search time.

The potential risk of unsuccessful initial searches may be the unwarranted by-product of massive inventory ("buffers") of pipe spools that materials managers have built in an attempt to secure flexibility in workable backlogs for pipe fitting crews. Periodically, the search effort turns out to be unsuccessful so that the lost spools must be reproduced by the fabricator after the initial delay due to search. In addition to requiring an extensive search effort and potential re-fabrication, misplaced spools may cause delays or disruptions in pipe fitting schedules, depending on the requisition lead time since pipe fitting is a critical path activity on a typical industrial project.

3.4. SUMMARY

In response to the compelling need to track uniquely identified materials through the supply chain, field tests of current RFID technology were conducted to determine its technical feasibility for automatically identifying and tracking individual pipe spools in laydown yards and under shipping portals. The field tests indicated that the technology could function effectively in the construction field environment involving large metal objects and requiring relatively long read range. It was also shown to some statistical significance that commercially available active RFID technology can automatically identify pipe spools with 100% accuracy and precision if they are driven at a speed less than 2 mph through portal gates equipped with four antennas.

Potential benefits from the use of RFID technology in automated pipe spool tracking may include (1) reduced time in identifying and locating pipe spools upon receipt and prior to shipping, (2) more accurate and timely information on shipping, receiving, and inventory, (3) reduced misplaced pipes and search time, and (4) increased reliability of pipe fitting schedule. However, most of the potential benefits will be realized when the use of RFID technology is extended through construction and other stages of the project life cycle. This suggests that new applications should be developed so that they can leverage portal and/or handheld systems in other project stages. One example of such applications is locating tagged spools beyond the portal level and tracking their location on a construction site thus providing the backbone of automated piping work progress tracking.

Chapter 4: Roving Applications – Locating Materials On-site Using Proximity Techniques

4.1. INTRODUCTION

Tracking the location of construction materials automatically should both improve project performance and enable effortless derivation of performance indicators. In support of improved project performance, the previous chapter investigated the technical feasibility of using RFID technology in a portal application for automatically tracking the delivery and receipt of pipe spools through the supply chain. However, there are two reasons that the location of materials should be tracked with more positional accuracy than simply indicating that a certain material is received at and hence within the constructor's laydown yard, for instance.

First, though materials may be known to be within the premises through the portal application of RFID technology, they eventually need to be found physically in order to be issued to crew workers who requisite them for installation. The ability to rapidly find and distribute requisite materials for crew installation also presents the opportunity for reduced materials management manpower but also improved labor performance.

Second, positional accuracy beyond the portal level is also required of a materials' location tracking system to support automated derivation of construction performance indicators and real-time project control. For instance, such positional accuracy should allow to determine if a certain material is present in the proximity of a piece of lifting equipment. Thus, automatically tracking the location of uniquely identified materials and other objects on site will complement existing approaches to identifying activities performed by construction agents, which is a required step for determining the status of the activity and deriving performance indicators.

With recent advances in ADC technologies, tracking the location of materials accurately has become more viable. A central issue in using these technologies for this purpose is that the existing approaches imply economically prohibitive deployment. For example, tagging individual material items with simple GPS receivers costing around US$100 per unit would be prohibitively expensive, and still other means for identification would be required. Alternatively, state-of-the-art GPS receiver could be used to acquire the precise coordinates for materials' location without tagging individual material items, as a recent field test demonstrated the effectiveness of the technology in locating pipe spools with immediate payback for large laydown yards (Caldas et al. 2004). However, in addition to positive identification of pipe spools, manual acquisition and potential periodic updates of the GPS coordinates for the spools' storage location would be required.

On the other hand, RFID technology suits identification purposes in tracking thousands of materials but its current applications do not provide sufficient location accuracy without relying on a fixed communications network. However, considering constantly changing construction environments and given the limited capabilities of current hardware, RFID handheld systems, when combined with GPS, may present an alternative solution to accurately tracking the location of hundreds of materials. The solution proposed here is intended to extend the use of current RFID technology to tracking the precise movement and location of materials on a construction site as well as at laydown yards, without modifications to current hardware and at a magnitude less cost than pure GPS or other existing approaches.

This chapter presents an approach by which a combination of RFID and GPS technologies offers the opportunity to densely deploy low cost RFID tags with a few mobile RFID readers equipped with GPS to form the backbone of a construction materials' tracking system. It first describes concepts of the roving applications of RFID technology, and presents a mathematical framework and localization algorithms identified. This chapter then provides a detailed description of experimental set-up and test parameters and the overall data collection procedure ranging from field experiments to software implementation.

4.2. A MODEL AND ALGORITHMS

4.2.1. Concepts and Mathematical Formulation

The basic concepts of the RFID proximity location tracking system are illustrated in Figure 4.1. A field supervisor or piece of materials handling equipment is equipped with an RFID reader and a GPS receiver, and serves as a "rover" as the supervisor, for example, moves around the site on his or her normal business. Note that the position of the reader at any time is known since the rover is equipped with a GPS receiver. The reader is assumed to have a fixed radial range with the maximum radius *r*, and many "virtual" readers can be generated by temporal sampling of a single rover walking around the site. Call this application of an RFID location tracking system the "roving" application. While the situation becomes simplified when a piece of materials handling equipment is moving an item, solely assigning the role of rover to such equipment is not thorough enough to track all materials.

If a tag is within the communication range of the rover, then the RF connectivity exists between a virtual reader *R* and the tag *T*. Such a reader-tag connectivity contributes exactly one proximity constraint to the problem of estimating the tag location, and can be represented as a convex constraint using the Euclidean norm $\|R-T\|_2 \leq r$. As the rover comes into the range *r* from the tag time and again, more virtual readers are generated to form such convex constraints for the tag. Combining these proximity constraints restricts the feasible set of the unknown position of the tag to the region in which the circles centered on the position of the virtual readers intersect with one another, i.e., the shaded region in Figure 4.1. This is equivalent to solving an optimization problem under the convex constraints, with no obvious objective function to optimize – only feasible solutions are found. Then estimating the location of the tag comes down to selecting one from many feasible solutions. Such a point may be selected randomly, or one may bound the feasible set with the smallest rectangle and select the center of this rectangle as the most likely location of the tag (Doherty et al. 2001).

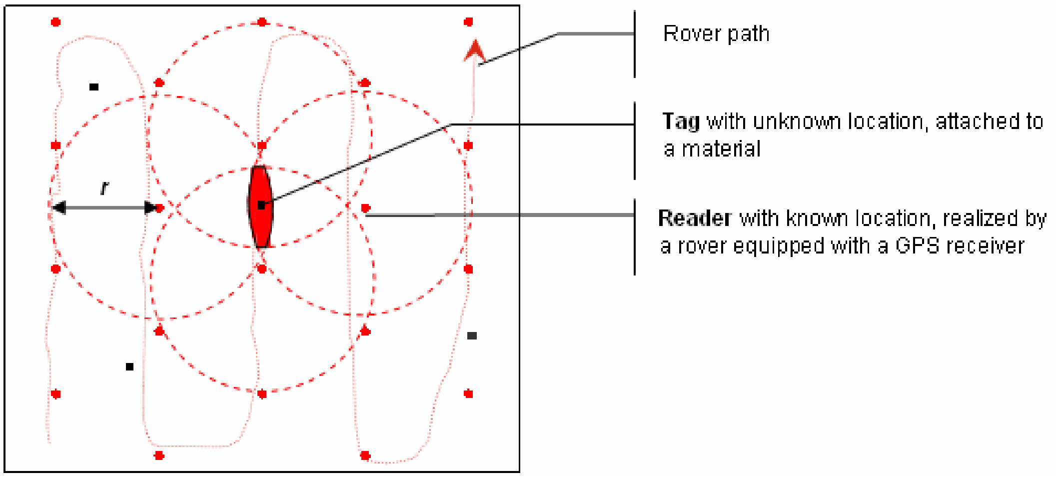


Figure 4.1: Combining proximity constraints from reader-tag connectivity

Formulated as a convex optimization problem, the location estimation can be solved very reliably and efficiently using interior-point methods (Boyd and Vandenberghe 2004). However, unlike the well-known least-squares problems, general convex optimization problems have no analytical formula for the solution. Without analytical solutions, one could only say that the roving application will bring about accurate location estimates if the rover can generate infinitely many virtual readers and proximity constraints for each tag. This asymptotic convergence would be of no practical value because it requires the rover to circle around every material like a hawk. Thus, formulating the proximity localization concepts into convex optimization is completely valid, but it still remains to determine whether the roving application can generate sufficiently large connectivity data to support convex optimization or other mathematical formulations. A useful formulation follows.

4.2.2. Occupancy Cell Framework and Localization Procedure

Now the occupancy cell framework is described as adapted from Simic and Sastry (2002). In this framework (Figure 4.2), a square region Q with sides of length s is partitioned into n^2 congruent squares called cells of area $(s/n)^2$, and one is only interested in finding the cell that contains each RFID tag. It is possible for several tags to lie in the same cell. The RF communication region is modeled as a square centered at a virtual reader and containing $(2\rho + 1)^2$ cells, instead of a disk of radius r. This square region is obtained by taking the read range as ρ cells:

$$\rho = \left[\frac{nr}{s\sqrt{2}} \right] \tag{1}$$

where $[\, nr / s\sqrt{2}\,]$ denotes the integer part of $nr/(s\sqrt{2})$.

Under the same scenario as in the previous section, the GPS-enabled rover collects tag connectivity data while roving in the site Q. The communication region B_k of the rover positioned at the cell R_k is then defined by:

$$B_k = [x_k - \rho, x_k + \rho] \text{ x } [y_k - \rho, y_k + \rho] \tag{2}$$

where (x_k, y_k) denotes the grid coordinates of R_k and $[a, b]$ x $[c, d]$ denotes the union of all cells with grid coordinates (i, j), $a \le i \le b$ and $c \le j \le d$, for integers $1 \le a < b \le n$, $1 \le c < d \le n$.

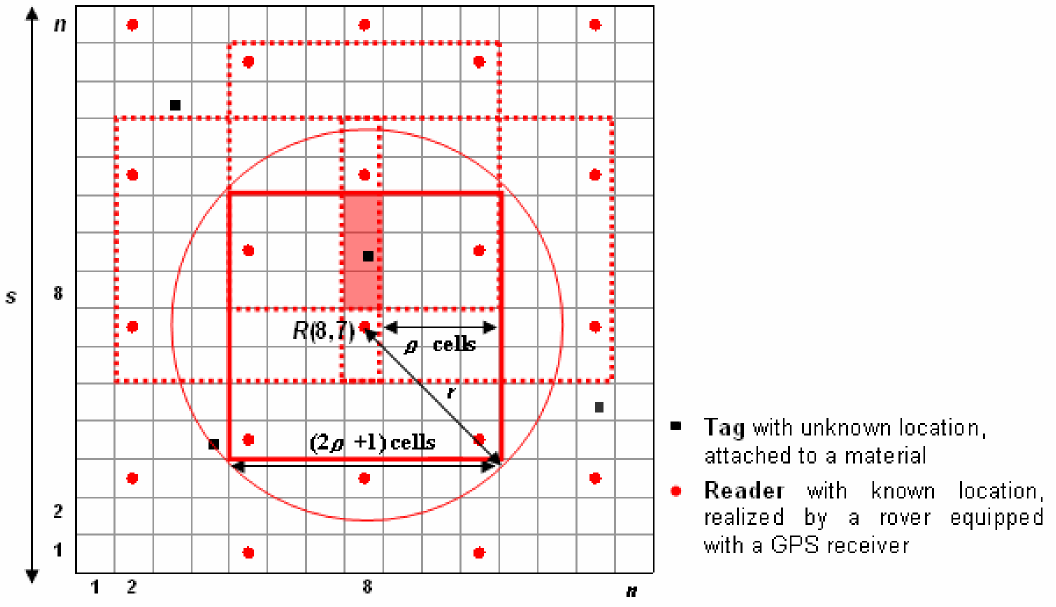


Figure 4.2: Occupancy cell framework

If the rover reads the tag T at discrete time points $1 \le k \le m$, then $T \in B_k$, for all $1 \le k \le m$ and therefore,

$$T \in Q \cap \bigcap_{k=1}^{m} B_k = Q \cap [x_+ - \rho, x_- + \rho] \text{ x } [y_+ - \rho, y_- + \rho] \qquad (3)$$

where $x_+ = \max(x_1, \ldots, x_m)$ and $x\_ = \min(x_1, \ldots, x_m)$, and similarly for y_k's. The estimate of the tag location T is then given by:

$$T \in [\max(x_+ - \rho, 1), \min(x\_ + \rho, n)] \text{ x } [\max(y_+ - \rho, 1), \min(y\_ + \rho, n)] \qquad (4)$$

since $Q = [1, n]$ x $[1, n]$. Let A_t denote the number of cells in the rectangle defined by the right hand side of (4):

$$A_t = \{\min(x\_ + \rho, n) - \max(x_+ - \rho, 1) + 1\}\{\min(y\_ + \rho, n) - \max(y_+ - \rho, 1) + 1\}. \qquad (5)$$

In other words, A_t is the size of the feasible region in which the tag T may lie. If A_t = 1 cell, the location estimate given by (4) would be optimum.

To establish theoretical constraints, limits, and performance functions, virtual readers and tags are collectively called "nodes," and the position of each node is assumed to be random and uniformly distributed in the site Q. Suppose that there are a total of N nodes in the region Q, of which the rover contributes K virtual readers with known locations. Simic and Sastry (2002) proved that if T is a tag randomly picked from an interior region $Q_\rho = [1 + \rho, n - \rho]$ x $[1 + \rho, n - \rho]$, with n, ρ fixed, the expected size of the location estimate for T tends to one, the perfect estimate, as K goes to infinity:

$$\lim_{K\to\infty} E(A_t) = 1 . \tag{6}$$

Thus, the result (6) indicates that the unknown location of some tag $T \in Q_\rho$ can be narrowed down to one cell on average, as the rover generates virtual reader nodes at infinitely many different positions. More importantly, with n, ρ fixed, Simic and Sastry (2002) provided the analytical solution for the minimum number of virtual reader nodes, K, such that the expectation of the estimate A_t, $E(A_t)$, is ε-close to the perfect estimate, i.e., $\left|E(A_t) - 1\right| < \varepsilon$, for some arbitrary $\varepsilon > 0$:

$$K > \frac{-\ln\left[8\rho(2\rho+1)\right] + \ln\varepsilon}{\ln\left(1 - \dfrac{2\rho+1}{n^2}\right)} . \tag{7}$$

4.2.3. Example from Preliminary Experiment

To demonstrate the proximity localization procedure based on the occupancy cell framework, limited field experiments were conducted using an off-the-shelf RFID handheld reader and several tags. First, the communication region was considered to be a disk of radius r, and estimated r to be approximately 9.1 m (30 ft). This estimate was obtained through the following steps:

- Place a tag at the center of a hypothetical circle and record the point at which the tag is first read as the experimenter carries the reader and approach the tag from each of eight different angles.
- Repeat the above for a total of eight different tags and take the medium of a total of eighty-one distance measurements. Distances ranged from 2.3 m (7.5 ft) to 18.3 m (60 ft).
- Place each tag at a distance of the resulting medium range from the center, and try to read all the tags with the reader positioned at the center.

Next the experimenter set up a square region Q with sides of s = 18.3 m (60 ft), which was divided into $n^2 = 15^2$ cells, and placed five tags in the region Q and generated twenty virtual readers, i.e., $K = 20$. Note that given r = 9.1 m, the read range is $\rho = 5$ cells, according to (1).

The estimate of the position of each tag T_i can be calculated via (4). For example, the tag $T4$ was read by thirteen virtual readers, which are marked as solid dots in Figure 4.3. The maximum and minimum x grid coordinates of these thirteen readers, i.e., x_+ and $x\_$ in (4), are 14 and 2, respectively, and the maximum and minimum y grid coordinates 15 and 3, respectively. Given $\rho = 5$ cells, these maximum and minimum grid coordinates do not yield a valid location estimate for $T4$ because some of these thirteen readers are not within the communication region as defined by $\rho = 5$. This indicates that our initial estimate r = 9.1 m was too restrictive.

Relaxing the read range so that $\rho = 6$ cells, which means taking r to be between 10.4 m (34 ft) and 11.9 m (39 ft), gives a valid location estimate as:

$$T4 \in [\max(14-6, 1), \min(2+6, 15)] \text{ x } [\max(15-6, 1), \min(3+6, 15)], \text{ or}$$

$$T4 \in [8, 8] \text{ x } [9, 9],$$

which means that *T*4 occupies one of the cells in the rectangle region [8, 8] x [9, 9], in this case, the single cell with grid coordinates (8, 9). Though the actual location of *T*4 is indeed (8, 9), this should be taken as a special case since a total of about 110 virtual readers on average would be required to locate *T*4 within two cells, according to (7) for $\rho = 6$, $n = 15$, and $\varepsilon = 1$.

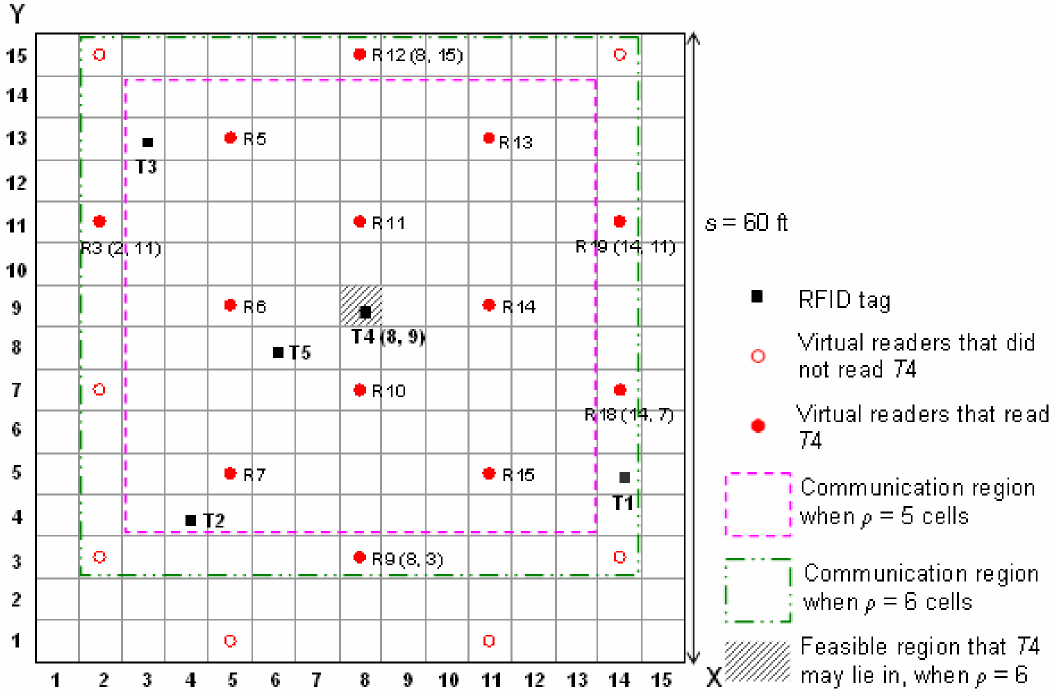


Figure 4.3: Example location estimation of a tag

With ρ *reassigned*, the similar results were obtained for the location estimates of the other tags, except for *T*2. Obtaining a valid location estimate of *T*2 would require expanding the read range to a square region having sides of 21 cells ($\rho = 10$ cells), which surpasses the operating region *Q* with sides of 15 cells ($n = 15$). In addition to adjusting the parameter ρ, robust location estimation may be possible with a larger number *K* of virtual readers by increasing sampling frequency of reads.

4.3. EXPERIMENTS

Further experiments were conducted to delve into the relationships between parameters and accuracy and precision of tag location estimates, as provided by the proximity localization under the occupancy cell framework. While the operating region was still divided into square cells with sides of 4 ft, it was expanded from a square region with sides of 60 ft, to one with sides of s = 120 ft. Thus, a square region partitioned into $n^2 = 30^2$ congruent cells with sides of 4 ft, constitutes the operating region Q where further experiments were conducted. This operating region was set up on the grass in an open field, using stake flags to delineate the boundary and grids of cells (Figure 4.4). Parameters considered for experiments include (1) the level of RF power transmitted from an RFID reader, (2) the number of tags placed, (3) patterns of tag placement, and (4) the number K of virtual readers.

Figure 4.4: Experiment field

4.3.1. Setting Parameters

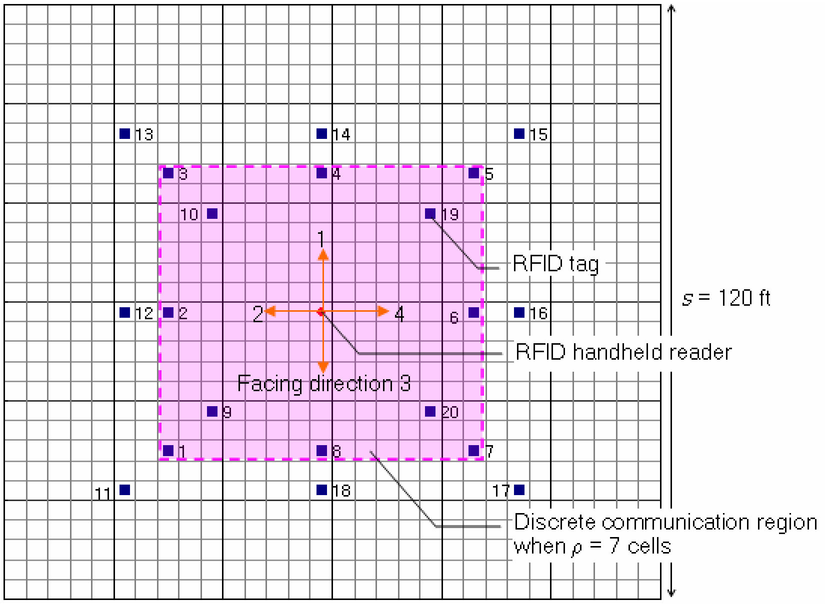
RF Power Level and Estimation of Discrete Read Range

Note that varying levels of RF power changes the read range *r*, thus the discrete communication range *ρ* that is given by the integer part of $nr/(s\sqrt{2})$. A total of 20 RFID tags and a handheld reader were used in estimating the discrete read range, with varying levels of RF power as shown in Table 4.1. Rather than derived from estimated *r*, the discrete read range *ρ* was now estimated directly by observing the frequency that a tag is read when placed within a certain communication region defined by a particular integer value of *ρ*.

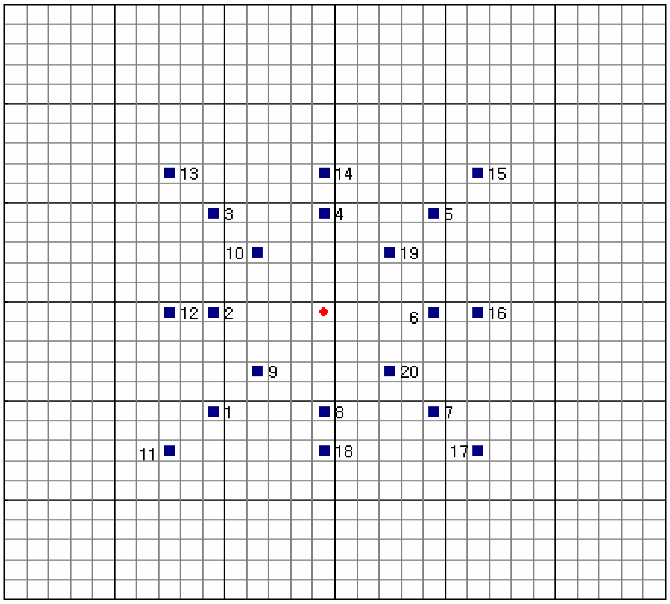
Table 4.1: Different Levels of RF Power in Estimating Discrete Read Range

Power level	Transmission power (dBm)	Receiving power (dBm)
A	0	-80
B	-5	-80
C	-15	-80
D	-20	-80

Figure 4.5 shows where the reader and tags were placed in the square region with sides of 120 ft. Note that tags were placed in a way that they form the boundary of discrete communication regions defined by particular values of *ρ*. For instance, in Figure 4.5 (a), tags numbered 1 to 8 form the boundary of the communication region given by $\rho = 7$ cells. Thus, if these tags are more likely to be read at a certain level of RF power, the discrete read range *ρ* can be said to be at least 7 cells at that level of RF power.



(a) For the RF power levels A and B



(b) For the RF power levels C and D

Figure 4.5: Setup for estimation of discrete read range ρ

Note also from Figure 4.5 that reading tags was attempted with the reader facing in four different directions. For each direction, 50 trials were made to read tags at a certain level of RF power, so the maximum frequency of a tag being read is 50 * 4 = 200 times. Table 4.2 summarizes the average frequency that tags were read at varying levels of RF power when placed within the square region centered at the reader and containing $(2\rho + 1)^2$ cells. Though arbitrary, Levels B and D are called High and Med, and the discrete read range was assigned to be 7 and 5 cells, respectively. Given n = 30 and s = 120 ft, the discrete communication region given by ρ = 5 cells, corresponds to a disk of radius r = 29 ~ 33 ft.

Table 4.2: Average Frequency of Tags being Read for Different Values of ρ

Level	Transmission RF power (dBm)	Number of tags and average frequency of tags being read when within the communication region given by different value ρ					
		ρ = 5 cells		ρ = 7 cells		ρ = 9 cells	
A	0	4	65 (32%)	12	47 (23%)	20	40 (20%)
B	-5	4	68 (34%)	12	53 (26%)	20	45 (23%)
		ρ = 3 cells		ρ = 5 cells		ρ = 7 cells	
C	-15	4	105 (53%)	12	74 (37%)	20	54 (27%)
D	-20	4	99 (50%)	12	60 (30%)	20	37 (19%)

Number of Tags and Patterns of Placement

RFID Tags were placed in the operating region Q with an area of 120 ft x 120 ft, in two different conditions: (1) the total number of tags, and (2) the pattern of tag placement. These two conditions respectively specify the magnitude and the density of tags to be located using the proximity technique under the occupancy cell framework. The total number of tags placed in Q was either 10 or 20, and came in one of seven placement patterns.

Figure 4.6 illustrates one such placement pattern, “Focused,” when there are a total of 10 and 20 tags, respectively. Note that the location of 10 tags is inherited when a total of 20 tags are to be placed in the same pattern. Thus, if there is any difference between different numbers of tags placed in the same pattern, it should be attributed to the additional 10 tags, not to the first 10 tags otherwise placed at different cell locations. Figure 4.7 shows the other six patterns of tag placement when there are a total of 20 tags; in case there are only 10 tags placed, it would look as if tags numbered 11 to 20 are removed.

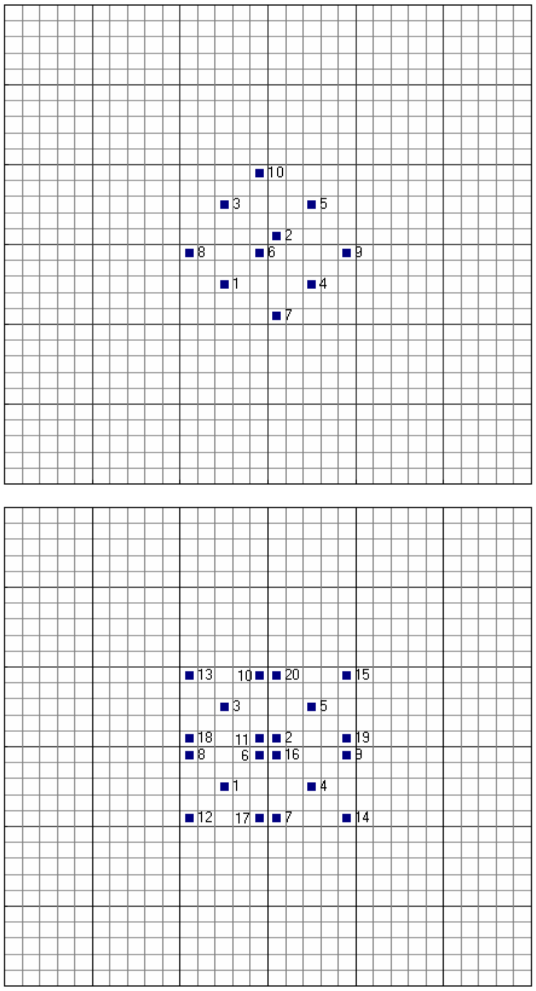


Figure 4.6: Tag placement pattern “Focused”

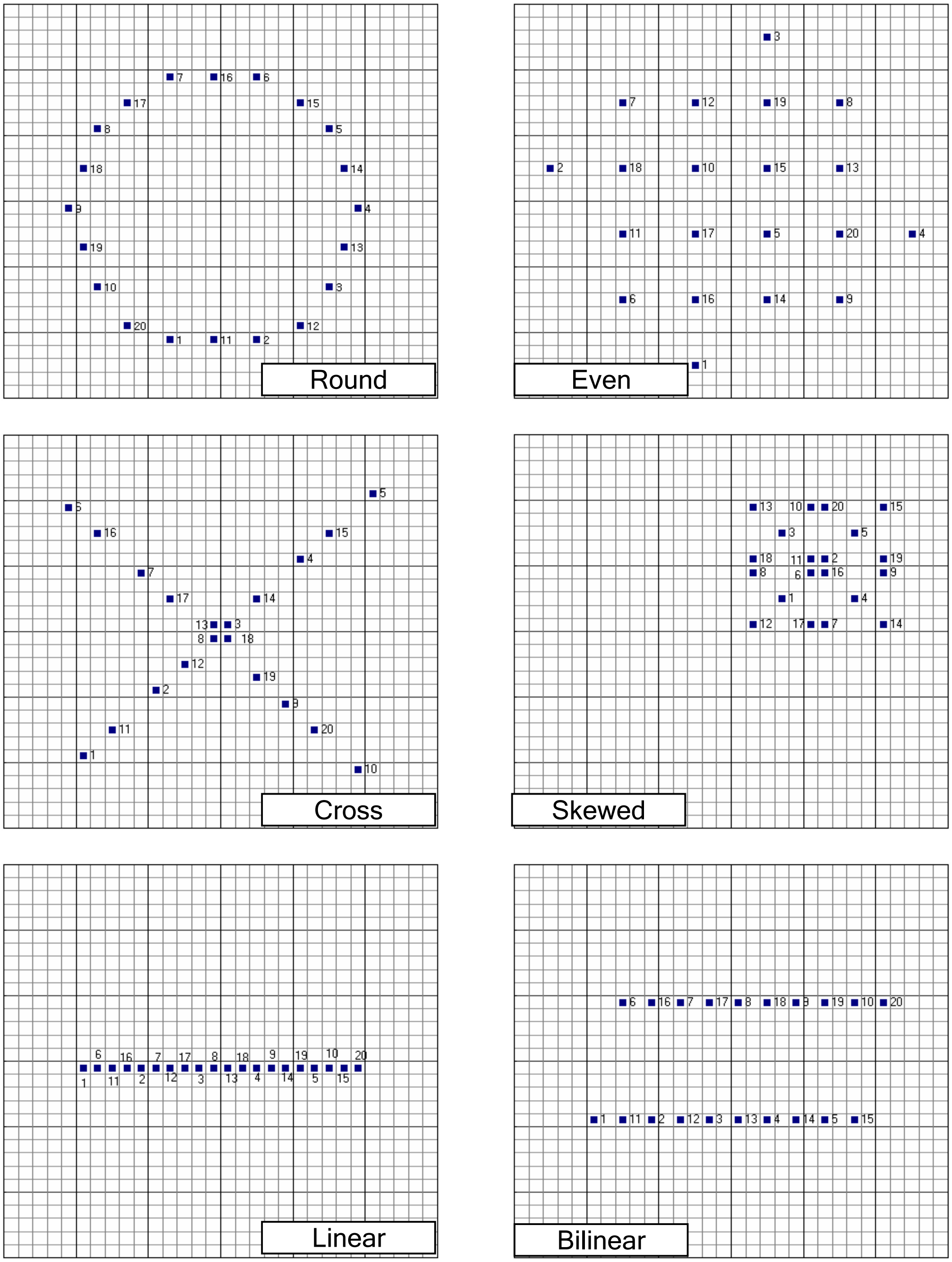


Figure 4.7: Other tag placement patterns for experiments

4.3.2. Obtaining Proximity Information of Tags

Generation of Virtual Readers

Once the level of RF power was set to the handheld reader and a total of 10 or 20 tags were placed in the operating region Q so as to form one of the patterns described earlier, the RFID reader was carried around the region to generate virtual readers and obtain proximity information of tags. Proximity information simply means knowing that a tag with the unique ID number lies in the square communication region which is centered at the "virtual" reader and contains $(2\rho + 1)^2$ cells; in other words, the tag was read by the reader situated at a particular location. In each and every one of a total of 30^2 cells, the experimenter attempted only once to read tags, and if at least one tag was read, the vendor software allowed it to save the 6-digit ID number of each read tag in a CSV (comma separated value) format file.

Although the position of the reader at any time would have been known if the experimenter carrying around the reader was equipped with a GPS receiver, experiments dispensed with a GPS receiver (see Section 5.3.4 for a discussion of the impact). Recall that under the occupancy cell framework, an object, whether a tag or reader, can be located only in terms of cells that are represented by grid coordinates (i, j), i.e., the ith and jth cell along x-axis and y-axis. Having designated an integer number between 1 and 900 to each one of 30^2 cells in the region Q, the experimenter located himself within a single cell by determining its corresponding designated number.

This numbering scheme was also used in naming CSV files that contain the ID number of tags read by the reader situated at a particular cell. For example, the integer number 34 is designated to the cell with grid coordinates (2, 27), and if any tags were read when the reader was positioned at this cell, the ID number of tags read was saved as a file named "34.csv." However, more than one file with the same name can exist since reading tags was attempted at the same cell for different combinations of RF power level and the number and placement pattern of tags. To avoid this confusion, each CSV file was saved under particular folders whose name indicates particular experiment conditions. For example, the “34.csv” file under the folder “Hf20” clarifies that it pertains to some tags read at a high RF power, out of a total of 20 tags placed in the “Focused” pattern.

Overall, field experiments yielded a total of 15,050 CSV files that are saved under 28 different folders corresponding to 28 combinations of experiment parameter values (28 = 2 power levels * 2 numbers of tags * 7 placement patterns; Table 4.3). Each combination of parameter values characterizes the unique ‘test bed.’ As reading tags was tried at every one of 900 cells, a total of 900 virtual readers were generated for each test bed, but not all of them contributed to proximity information of tags partly because there could be some cells where the reader may not read any tags that are far beyond the estimated communication region. This can be seen from that the number of CSV files for a certain set of parameter values is on average 15,050 / 28 ≈ 538.

Table 4.3: Summary of Experiment Parameters

Parameter	Possible setting/values
RF power level	High, Med
Number of tags	10, 20
Tag placement pattern	Focused, Round, Even, Cross, Skewed, Linear, Bilinear

Sampling Proximity Information at Different Intervals

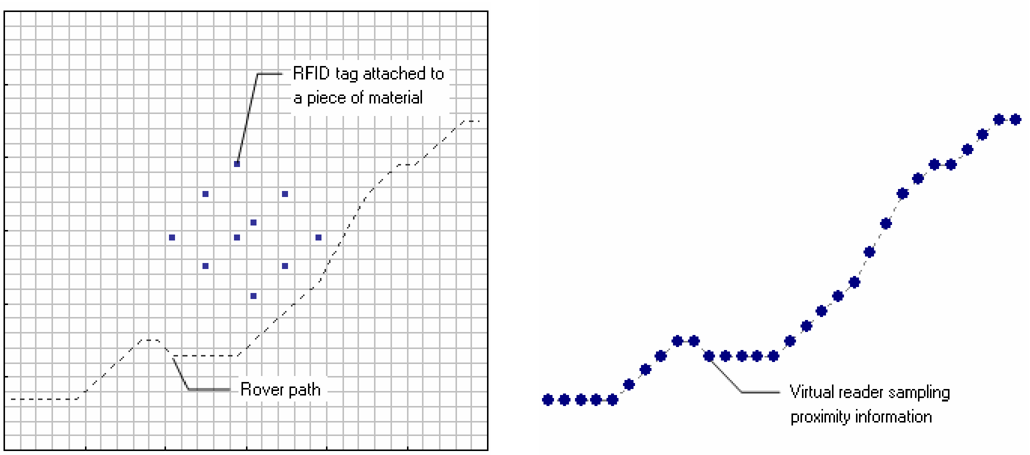
No matter how many of a total of 900 virtual readers that actually yielded proximity information of tags under a particular set of experiment conditions, one would not be able to see the effects of different numbers of readers, if the number of virtual readers is held constant in localizing tags. In other words, varying the number of virtual readers is needed to assess its influence on the proximity localization. On the other hand, different numbers of virtual readers should manifest themselves as part of the same path of the rover in the region Q. This is to simulate the situations in which the rover samples proximity information at different time intervals while taking a single path. Otherwise, the effect of different paths will be convoluted with that of different numbers of virtual readers on the paths.

Figure 4.8 illustrates how it was simulated that proximity information is sampled at different intervals while the rover takes the same typical path. Suppose that the rover is taking one path on its normal business, as shown in Figure 4.8 (a). If every cell location along the path is taken into account (Figure 4.8 b), proximity information given by 30 virtual readers, if any, is used in localizing tags. If one virtual reader is chosen out of every six along the path (Figure 4.8 c), only six virtual readers have the potential to contribute to proximity information that is used for localization. Similarly, proximity information is sampled yet at another interval with three virtual readers (Figure 4.8 d). These intervals might represent paces on site related to strolling, jogging, or driving. Note that regardless of the number of virtual readers put into sampling action, not all of the attempts may be successful in obtaining proximity information.

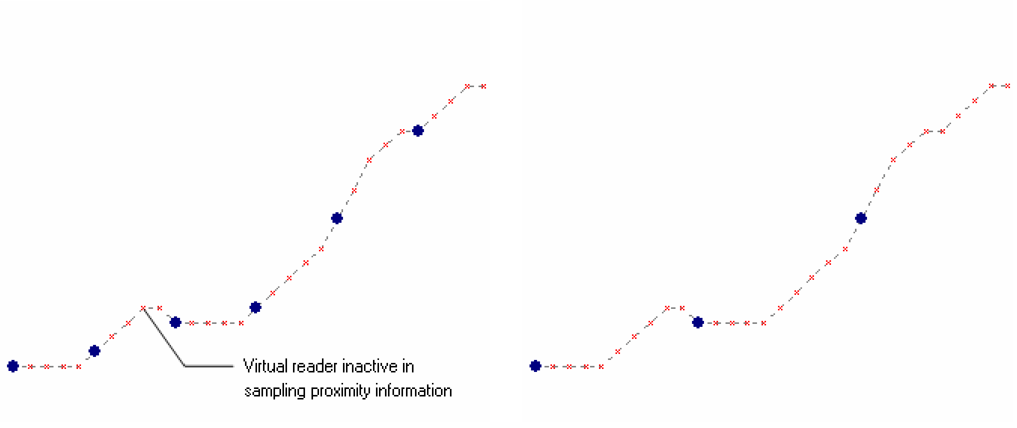
In this research, three different numbers of virtual readers were chosen based on the analytical solution given by Simic and Sastry (2002). Let Q_ρ denote the square region consisting of cells that are at distance $\leq \rho$ cells from the boundary of Q, i.e., $Q_\rho = [1 + \rho, n - \rho]$ x $[1 + \rho, n - \rho]$, where ρ is the discrete read range and n is the number of cells that Q is partitioned into. Simic and Sastry showed that given some arbitrary $\varepsilon > 0$, the expectation of the location estimate A_t, $E(A_t)$, of a randomly picked tag $T \in Q_\rho$ is ε-close to the perfect estimate of size 1 cell, i.e., $E(A_t) - 1 < \varepsilon$, if the number K of virtual readers satisfies:

$$K > \frac{-\ln\left[8\rho(2\rho+1)\right]+\ln\varepsilon}{\ln\left(1-\frac{2\rho+1}{n^2}\right)}, \tag{7}$$

assuming that the position of all K reads are distributed evenly through the region Q. In other words, to localize the tag T within an area having less than $(1 + \varepsilon)$ cells on average, the number K of virtual readers, strictly greater than the right hand side of (7), is necessary.



(a) Generic rover path (b) “strolling”



(c) “jogging” (d) “driving”

Figure 4.8: Example of sampling proximity information at different intervals

As Simic and Sastry (2002) also showed, the minimum value K_ε of all numbers K such that $|E(A_t)-1|<\varepsilon$ satisfies:

$$K_\varepsilon(n,\rho) \le n^2 \frac{\ln[8\rho(2\rho+1)]-\ln\varepsilon}{2\rho+1}. \tag{8}$$

Thus, the right hand side of (8) can be thought of as the minimum number of virtual readers necessary to localize the randomly picked tag T within a $(1+\varepsilon)$ cell area. For the experiments described here, the three different numbers of virtual readers were chosen by applying fractions of K_ε given $\varepsilon = 4$; K = 1.0 K_ε, 0.2 K_ε, 0.1 K_ε. Note that taking the value of K as fractions of K_ε with ε fixed is equivalent to changing the value ε. See Figure 4.9. For the test beds with the Medium RF power ($\rho = 5$), $1.0K_\varepsilon = 385$, and $0.2K_\varepsilon = 77$, given $n = 30$ and $\varepsilon = 4$. $0.2K_\varepsilon = 77$ virtual readers are the minimum requirement for localizing the tag within a 169 cell area. That is, $0.2K_\varepsilon$ given $\varepsilon = 4$ is equal to $1.0K_\varepsilon$ for $\varepsilon = 168$.

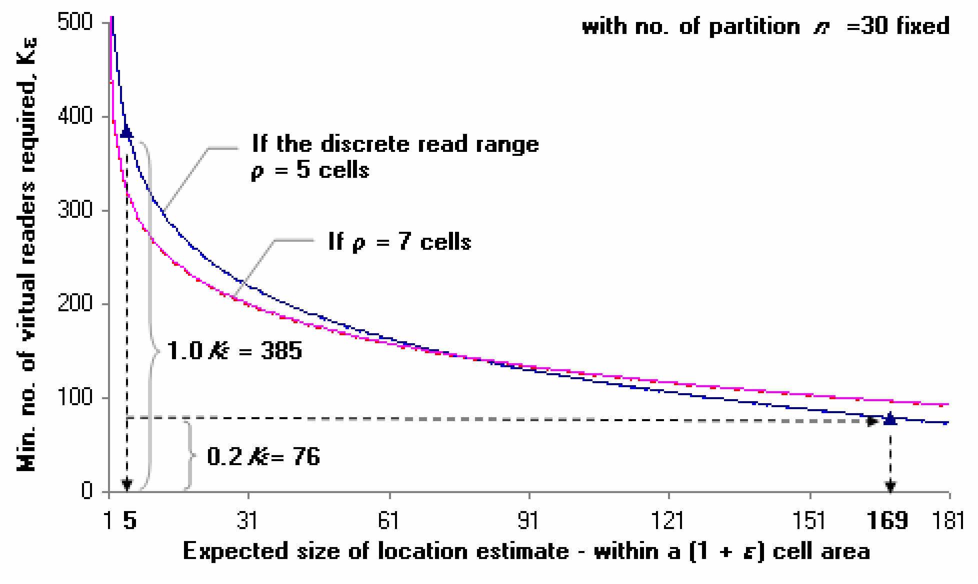


Figure 4.9: Applying fractions of the minimum number of virtual readers

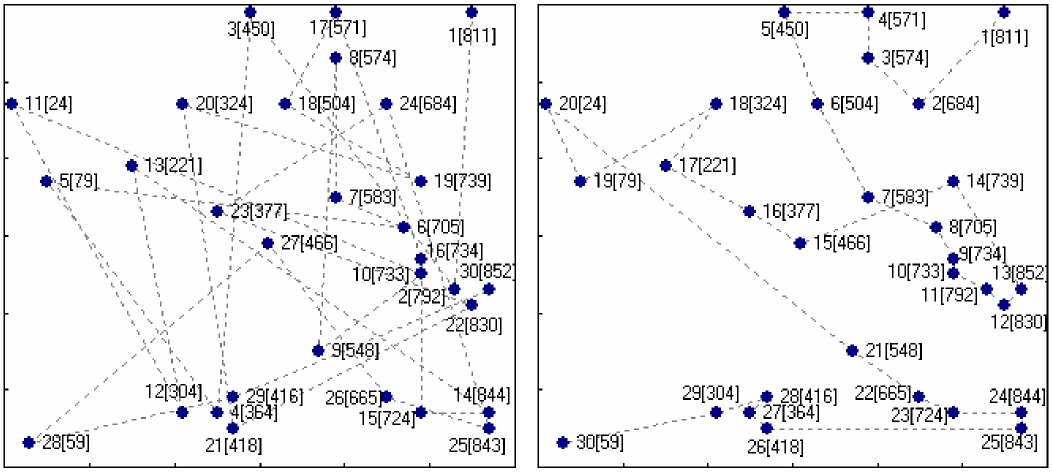
Although $\varepsilon = 4$ is arbitrary, there is a reason that rather than changing the value of ε, fractions of K_ε were applied to sampling proximity information at different frequencies. It is because the latter method allows for a consistent sampling frequency for different values of ρ associated with the RF power level. If proximity information were to be sampled at the same frequency for different values of ρ, different values of ε should have been explicitly applied since K_ε is a function of ρ as well as ε and n. For example, to sample one virtual read every other five along the path, $\varepsilon = 168$ and 288 would have been applied for $\rho = 5$ and 7, respectively, as opposed to simply applying $0.2K_\varepsilon$.

Generation of Random Rover Paths

Using 900 virtual readers generated from each test bed in the experiments, 50 random rover paths were simulated for each test bed. First, the value of K_ε is determined given the values of n, ρ, andε, as described above. Second, for each path, the K_ε number of integer values between 1 and 900 were randomly generated. Recall that these integer values have been assigned to each and every one of a total of 900 cells in the operating region. Thus, the K_ε integer values randomly generated indicate the cell locations in which the K_ε number of virtual readers are positioned. Note also that each of the K_ε integer values indicate the CSV file that contains proximity information, if any tags were read, provided by the virtual reader positioned at the corresponding cell.

Finally, the K_ε integer values randomly generated for each path were ordered following the nearest neighbor heuristic so that the rover starts at the cell corresponding to the first random integer value and goes next to the closest cell not yet visited. Thus, the nearest neighbor of a virtual reader at the cell with grid coordinates (i, j) is another reader at the cell with grid coordinates (i', j') such that

$\max(|i-i'|,|j-j'|) \leq \max(|i-i''|,|j-j''|)$ for any other reader at the grid coordinates (i'',j''). Admittedly, one of any two consecutive integer values ordered in such a way may not be the nearest neighbor of the other in terms of the distance defined in the Euclidean norm. However, following the path consisting of nearest neighbor cell locations helps to keep the rover from moving from one to another cell too radically. This point is illustrated in Figure 4.10, where the first number between 1 and 30 denotes the order that the rover visits each cell corresponding to a randomly generated integer value in brackets between 1 and 900. Note that both rover paths in Figure 4.10 consist of exactly the same cell locations that correspond to 30 random integer values. Figure 4.10 (a) shows the case where the rover visits 30 cell locations in the order that the corresponding integer values (in brackets) were randomly generated. If the same set of random integer values are ordered following the nearest neighbor rule, the rover moves as shown in Figure 4.10 (b).

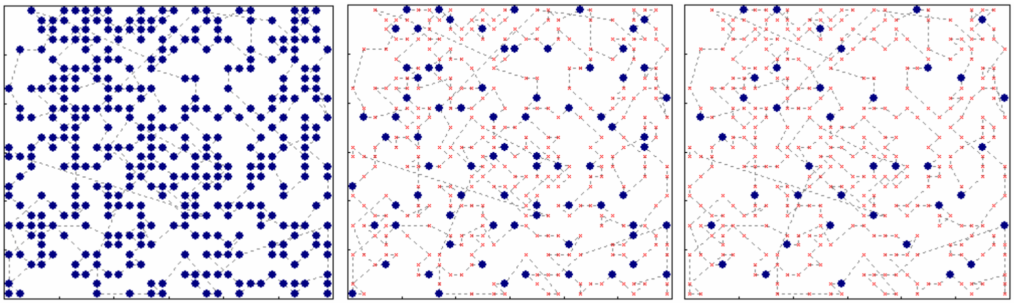


(a) Following the simple random path (b) Taking the nearest neighbor path

Figure 4.10: Example rover paths with the same set of 30 cell locations

Although the rover modeled as taking the nearest neighbor path is more realistic, it does not give proximity information different than if the rover takes the simple random path. Essentially, this is because for each test bed, the field experiments resulted in a single set of proximity information given by a total of 900 virtual readers. Thus, randomly generating a combination of K_ε virtual readers can provide only one subset of proximity information regardless of the order that the rover realizes them while taking on a different path. However, following the procedure stated in Section 4.2.2, proximity constraints can be sampled at different intervals while the rover takes the same path, thereby simulating different subsets of proximity information.

For each test bed, a total of 50 nearest neighbor paths were constructed from 50 random subsets of K_ε virtual readers, using Visual Basic for Application (VBA) codes developed, which can be found in Appendix A. Thus, for each test bed, there are 150 subsets of proximity constraints that are obtained at three different sampling intervals for each of 50 paths. Figure 4.11 shows three subsets of virtual readers that are derived from a single random path, using the VBA codes.



(a) $K = 1.0K_\varepsilon = 385$ (b) $K = 0.2K_\varepsilon = 77$ (c) $K = 0.1K_\varepsilon = 38$

Figure 4.11: Three sets of virtual readers realized in a typical single nearest neighbor path

4.3.3. Overall Data Collected

The overall procedure for collecting data from each test bed is depicted in Figure 4.12. Since for each of 28 test beds, 150 subsets of proximity constraints were simulated using a set of proximity information given by a total of 900 virtual readers generated in the field experiments, overall 4,200 sets of proximity information were obtained.

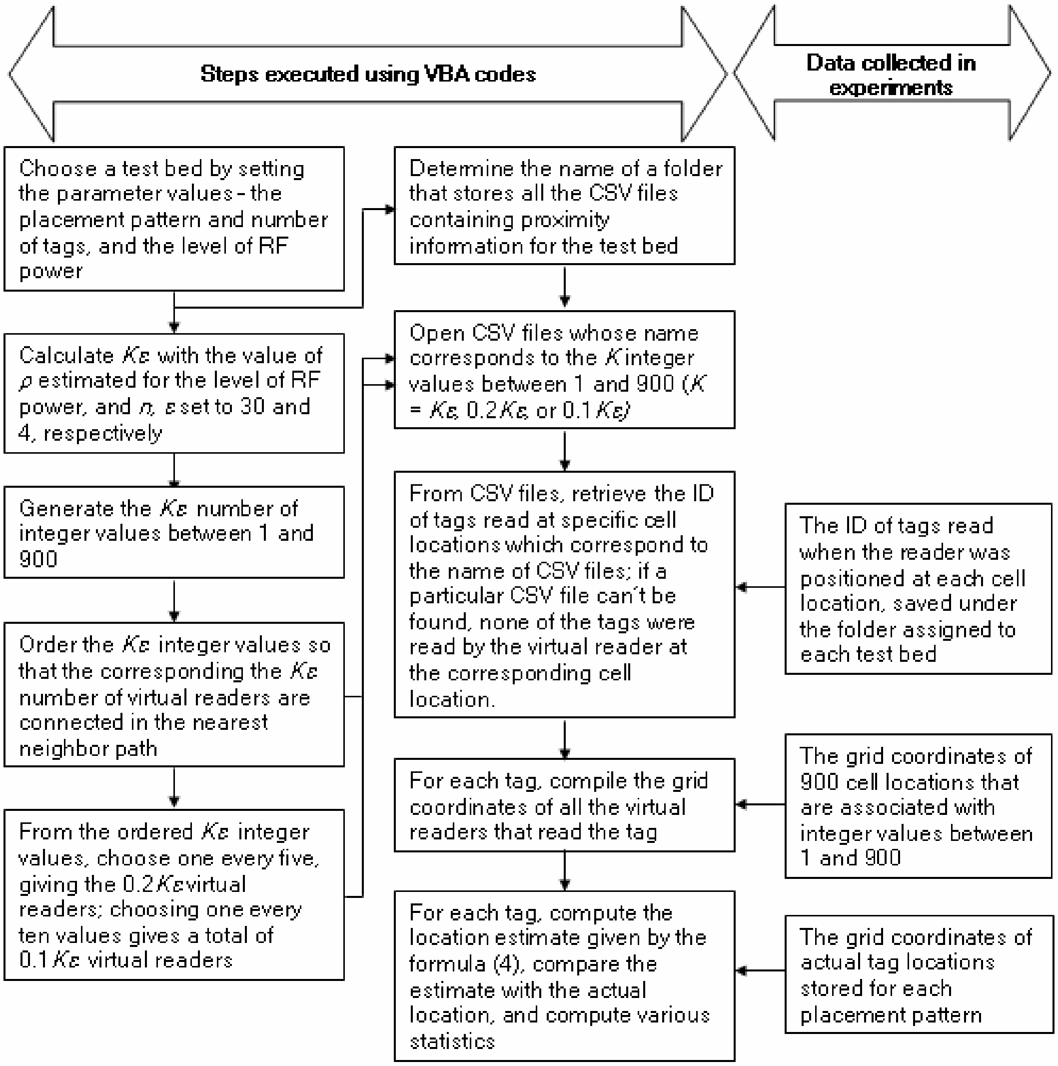


Figure 4.12: Overall data collection procedure

The overall data set can be classified into groups pertinent to a single parameter, as shown in Table 4.4. The data set can be further broken down in a way that groups pertain to more than one parameter. For instance, if of interest is the effect of different levels of RF power on location estimates of tags placed in a particular pattern, then two subgroups, each with 300 sets of proximity information, would be compared for each group with the same pattern. Broken down from the overall data set, any subgroup contains at least 50 sets of proximity information. A smallest subgroup contains proximity information that is obtained from 50 random combinations of K virtual readers, holding constant the pattern and number of tags placed, and the level of RF power.

Table 4.4: Summary of Data Set Classified in Parameters

Parameter	Possible setting/values	Sets of proximity information for each parameter setting/value	Total sets of proximity information
Pattern of tag placement	Focused, Round, Even, Cross, Skewed, Linear, Bilinear	600	4,200
Number of tags	10, 20	2,100	
Level of RF power	High, Med	2,100	
Number K of virtual readers (as a fraction of K_ε)	K_ε, 0.2 K_ε , 0.1 K_ε	1,400	

Chapter 5: Roving Applications - Performance Metrics and Analyses

5.1. TERMINOLOGY

In addition to the location of tags estimated using proximity information provided by one random combination of K virtual readers, various metrics were computed using the VBA codes in Appendix A. These metrics are explained below – metrics are bold-faced when they first appear, and their corresponding variable names in the VBA codes are in brackets {}.

For each tag, the **number of successful reads** {NReadsTag( )}indicates how many of a total of K virtual readers successfully read the tag, and is contributed by two groups of virtual readers. First, a tag with grid coordinates (x, y) can be successfully read by some or all of the virtual readers that are located within the region $[x - \rho, x + \rho]$ x $[y - \rho, y + \rho]$. The number of virtual readers in this group defines the **number of inside reads**. However, it can happen that one or more virtual readers within this region actually did not read the tag. So the **number of missed reads** is defined for each tag as the number of virtual readers that were positioned within this region and thus supposed to read the tag but failed to. Hence, the number of missed reads for each tag reflects the unreliability of the RF connectivity between the reader and the tag. To be clear, for the tag with grid coordinates (x, y), the sum of the numbers of inside reads and missed reads represents all of the virtual readers that were positioned within the region $[x - \rho, x + \rho]$ x $[y - \rho, y + \rho]$.

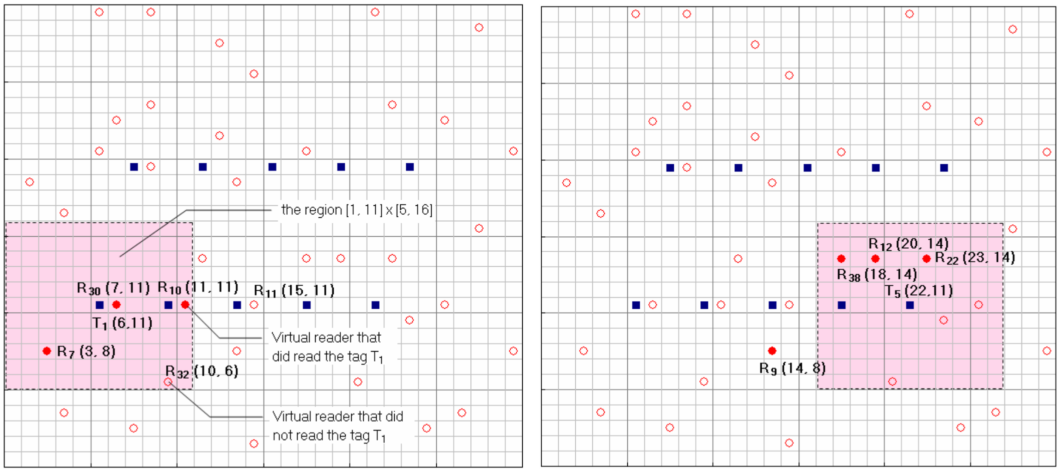
Conversely, it is possible that readers beyond the region actually read the tag. To distinguish this second case, the **number of off-side reads** {NBadReadsTag( )} for a tag at (x, y) is defined as the number of virtual readers that read the tag but were positioned beyond the region $[x - \rho, x + \rho]$ x $[y - \rho, y + \rho]$. Thus, the number of off-side reads indicates the unpredictability of the communication region defined by the value of ρ that was assigned at a certain level of RF power. By definition, the number of successful reads, the number of inside reads, and the number of off-side reads have the following relationship:

(No. of successful reads) = (No. of inside reads) + (No. of off-side reads).

Suppose that a tag T at (x, y) was successfully read by m virtual readers positioned respectively at grid coordinates (x_k, y_k), $k = 1, 2, \ldots, m$. That is, the number of successful reads for the tag T is m, where $1 \le m \le K$. Suppose also that the location estimate of the tag given via formula (4) is $[a, b]$ x $[c, d]$, which is the union of all cells with grid coordinates (i, j), $a \le i \le b$ and $c \le j \le d$. The location estimate is **valid** for the tag T if the integers a, b, c and d satisfy that $1 \le a \le b \le n$, $1 \le c \le d \le n$. The estimate is also **unbiased** for the tag T if its true location with grid coordinates (x, y) satisfies that $a \le x \le b$ and $c \le y \le d$.

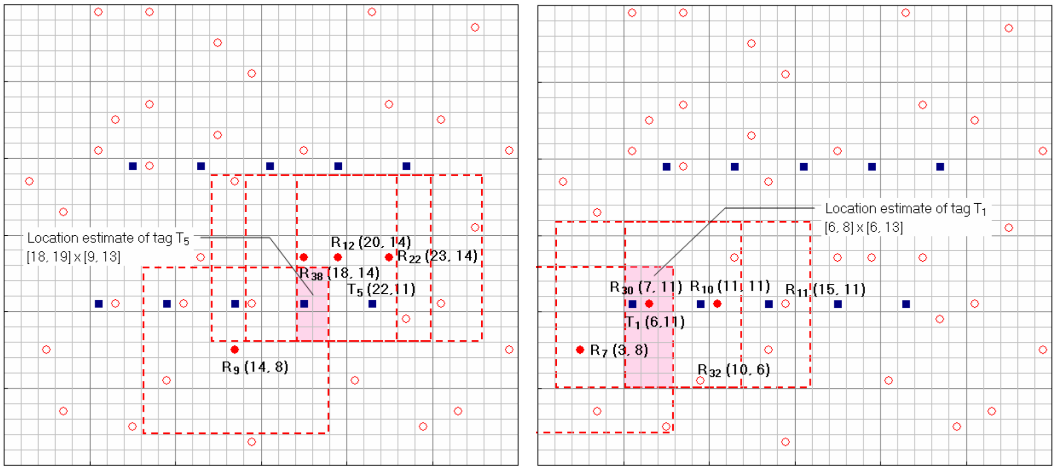
Consider an example with a total of 38 virtual readers (i.e., $K = 38$) and 10 tags. See Figure 5.1(a) and (b). The number of successful reads for the tag T_1 is four, corresponding to four virtual readers, R_7, R_{10}, R_{11}, and R_{30}. Another tag T_5 also has four successful reads. Observe that for each of the tags, there is one off-side read attributable to a virtual reader distant more than $\rho = 5$ cells from the tag, i.e., R_{11} and R_9, respectively. Note that they are not positioned within the shaded square region centered at T_1 and T_5, respectively.

Given the four virtual readers, the location estimate of T_1 is [10, 8] x [6, 13], according to the formula (4). Since this location estimate does not satisfy that $10 \le 8$, it is not valid. On the other hand, as shown in Figure 5.2(a), the location estimate of T_5 is [18, 19] x [9, 13], which is valid but biased because it does not contain the cell (22, 11), the true location of T_5. Figure 5.2(b) shows the location estimate of T_1 if it were not for the off-side read, which is valid and unbiased as well.



(a) For T_1 (b) For T_5

Figure 5.1: Example – number of successful reads and number of off-side reads



(a) Valid but biased estimate of T_5 (b) Unbiased estimate of T_1

Figure 5.2: Example – biased and unbiased location estimates

Thus, there are three possibilities about a location estimate for each tag: 1) invalid, 2) valid but biased, and 3) valid and unbiased. To be clear, if the location estimate of a tag is unbiased, it is always valid since invalid estimates are never considered for the unbiasedness. Consequently, for each random combination of K virtual readers, the number of tags with unbiased location estimates {NEstimateUnbiased} is always less than or equal to the number of tags with valid estimates {NEstimateValid}. However, it is important to know whether a location estimate is valid or not, apart from determining that it is also unbiased. A valid location estimate for a tag can tell at least that the tag is in the vicinity of the estimated region (Figure 5.2a), while an invalid estimate does not tell this at all.

The **size of a valid location estimate** {EstimateSizeVal()}, whether it is also unbiased or not, is the number of cells in the rectangle region given via formula (4). That is, the size of a valid location estimate $[a, b]$ x $[c, d]$ is calculated as $(b - a + 1)*(d - c + 1)$ cells, and is equivalent to the **size of a unbiased location estimate** {EstimateSize()} when the estimate is also unbiased. Recall that if the location estimate of a tag is valid, the integers a, b, c and d satisfy that $1 \leq a \leq b \leq n$, $1 \leq c \leq d \leq n$. Thus, for the experiments in the region partitioned into $n^2 = 30^2$ cells, the size of a valid location estimate is always a positive integer value between 1 and 900. In contrast, for a tag with invalid estimate, i.e., if $a > b$ or $c > d$, the size of the estimate is not defined but assigned an arbitrary non-positive integer value for the sake of identification.

For example, as the tag T_5 in Figure 5.2(a) is estimated to lie within the region [18, 19] x [9, 13], the size of the estimate is (19 – 18 + 1)*(13 – 9 +1) = 10 cells, which is equivalent to an area of $10*4^2$ ft^2 since one cell defined in the experiments is equivalent to a square of area 4^2 ft^2. Similarly, the size of the estimate for the tag T_1 in Figure 5.2(b) is 3*8=24 cells. Although the location estimate of the tag T_5 is more precise since it has a smaller size than that of the tag T_1, it is biased – the estimated region [18, 19] x [9, 13] does not contain the true location (22, 11) of the tag T_5. This suggests that the goodness of location estimates should not be determined solely by their size.

Besides, it should be noted that the valid location estimate [a, b] x [c, d] for a tag may actually lead to the minimum or maximum size. The minimum 1 cell is achieved if and only if $a = b$ and $c = d$; the maximum 900 cells occurs unless at least one virtual reader successfully read the tag. In the latter case, localization by formula (4) defaults to the estimate [1, 30] x [1, 30], which is valid but trivial. As such, a valid estimate with size 900 cells is called a **default estimate**, and is always unbiased because every tag was placed in the region [1, 30] x [1, 30] throughout the experiments. In a sense, default estimates are the worst case in which the number of missed reads manifests itself to the extreme under the unreliable RF connectivity between the reader and the tag.

In addition to distinguishing between biased and unbiased location estimates, it is also necessary to define differences between biased estimates. Of course, the size can be used to compare one with another biased estimate, but the size does not indicate the extent to which a biased estimate [a, b] x [c, d] deviates from the true cell location (x, y) of a tag. Thus, the **bias along the *X*-axis** is defined as the number of cells that the true location is distant along the axis from the boundary of the estimated region and hence calculated as $\min(|x-a|,|x-b|)$, and similarly for the Y-axis, $\min(|y-c|,|y-d|)$.

For example, the bias along X-axis of the estimate [18, 19] x [9, 13] for the tag T_5 (22, 11) in Figure 5.2(a) is $\min(|22-18|,|22-19|) = 3$ cells. However, the bias along the Y-axis is zero since the Y-grid coordinate 11 of the true location falls between the grid coordinates 9 and 13 that form the Y-axis lower and upper bounds of the estimated region. Finally, the **overall bias** of a biased estimate for a tag is defined as the larger of the biases along axes, or $\max(\min(|x-a|,|x-b|)$, $\min(|y-c|,|y-d|))$. For example, the overall bias of the location estimate for the tag T_5 in Figure 5.2(a) is max(3, 0) = 3 cells. To be clear, the overall bias of an unbiased estimate is set to zero.

Using a set of proximity constraints given by a random combination of K virtual readers, the metrics defined above were calculated for each individual tag and then averaged out, resulting in the following summary measures: (1) **average number of successful reads** {ExpNReadsTag}, (2) **average number of off-side reads** {ExpNBadReadsTag}, (3) **average size of valid location estimate** {ExpEstimateSizeVal}, (4) **average size of unbiased location estimate** {ExpEstimateSize}, and (5) **average bias** {ExpBias}. However, note that average size of valid and unbiased location estimates does not take into account those that are a default estimate. This exclusion is necessary to prevent default estimates with size 900 from misleading the average values. To be clear, the derivation of these summary metrics is given below:

$$\text{Average number of successful reads} = \frac{\text{Sum of the numbers of successful reads}}{\text{Total no. of tags placed for a test bed}}$$

$$\text{Average number of off-side reads} = \frac{\text{Sum of the numbers of off-side reads}}{\text{Total no. of tags placed for a test bed}}$$

$$\text{Average size of valid location estimate*} = \frac{\text{Sum of the size of valid estimates}}{\text{No. of tags with valid estimates}}$$

$$\text{Average size of unbiased location estimate*} = \frac{\text{Sum of the size of unbiased estimates}}{\text{No. of tags with unbiased estimates}}$$

$$\text{Average bias} = \frac{\text{Sum of the overall biases}}{\text{No. of tags with biased estimates}}$$

*include only the valid or unbiased estimates that are not a default estimate.

Obviously, there are several cases in which some of the summary metrics can not be calculated as given above: 1) when the location estimates of tags are all invalid, i.e., when the number of tags with valid location estimates is zero, and 2) when the location estimates for some tags are valid but all the valid estimates are biased. For the first case, average size of valid and unbiased estimates is not defined and assigned the value -50, while average bias is given 1,000. For the second case, average size of unbiased estimates is also assigned -50. Table 5.1 summarizes possible values of the summary metrics in these cases along with those in normal cases.

Table 5.1: Possible Values of Several Summary Metrics in Different Cases

Case	No. of tags with valid estimates (Nval)	No. of tags with unbiased estimates	Average size of valid estimates (Sval)	Average size of unbiased estimates	Average bias
All estimates invalid	0	0	-50	-50	1,000
All of the valid estimates biased	Positive integer <= Ntot[a]	0	Positive real	-50	Positive real < 30[b]
Some of the valid estimates biased	Positive integer <= Ntot[a]	Positive integer < Nval	Positive real	Positive real	Positive real < 30[b]
All of the valid estimates unbiased	Positive integer <= Ntot[a]	Positive integer = Nval	Positive real	Positive real = Sval	0

[a] Ntot denotes the total number of tags placed for a test bed.

[b] 30 = min(30, 30) since the experiments were conducted in the region partitioned into 30^2 cells.

5.2. PERFORMANCE ANALYSES

5.2.1. Overall Performance

Using a total of 4,200 sets of proximity information obtained, performance measures were calculated as explained above. Figure 5.3 shows the distribution of each measure in a box plot using 4,200 samples. The median and mean of average number of successful reads were approximately 6.1 and 14.6, respectively; the median and mean of average number of off-side reads were 1.0 and 2.4. Thus, about 16% of successful reads for each tag was "off-side," indicating that the actual RF communication region was larger than the assigned square region. As suggested in Figures 5.1 and 5.2, off-side reads can lead to invalid or biased location estimates. On the other hand, there were instances in which at least one of the tags was not successfully read at all by any virtual readers, resulting in default estimates. These instances of "no-reads" amount to 13% of the total time, and Table 5.2 shows the frequencies broken down for "Focused" and "Even" patterns of tag placement.

Table 5.2: Instances of "no-reads" under Focused and Even Patterns

Frequency of "no-reads" (as % of a total of 300)	Medium RF power	High RF power
Focused pattern	105 (35%)	15 (5%)
Even pattern	38 (13%)	6 (2%)

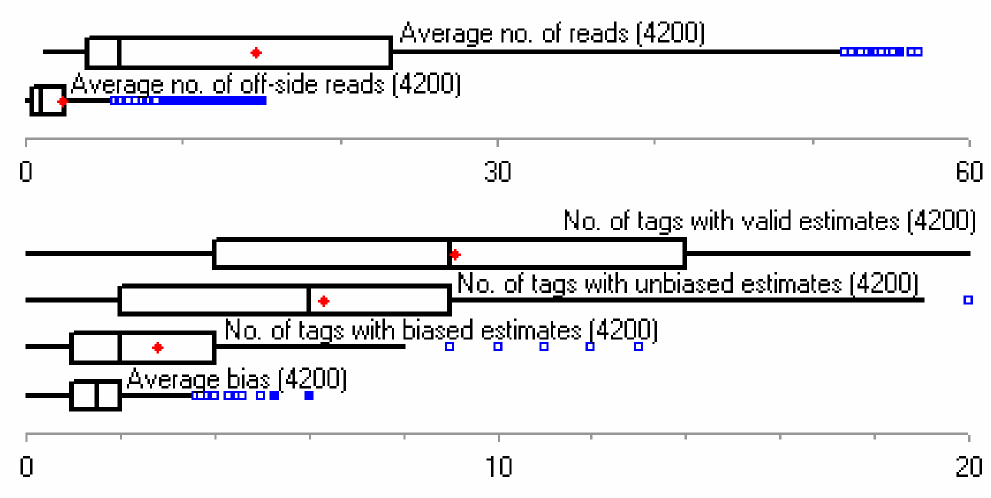


Figure 5.3: Overall distributions of performance measures

In 7% of a total of 4,200 instances, the location estimate of all the tags placed in a test bed was invalid. For 93% of the total instances, nine tags on average were localized with valid estimates. Particularly, in 21% of the total instances, the location of tags was estimated with a region containing less than 10 cells, or with a 3 x 3 cell area. In 69% of the total instances, the tag location was estimated to be within a 7 x 7 cell area – average size of valid location estimates was smaller than 50 cells. More generally, in 92% of the total instances, the tag location was estimated to be within a 9 x 9 cell area. Figure 5.4 shows the frequencies of average size of valid estimates, out of a total of 4,200 instances, categorized in bins of size 10.

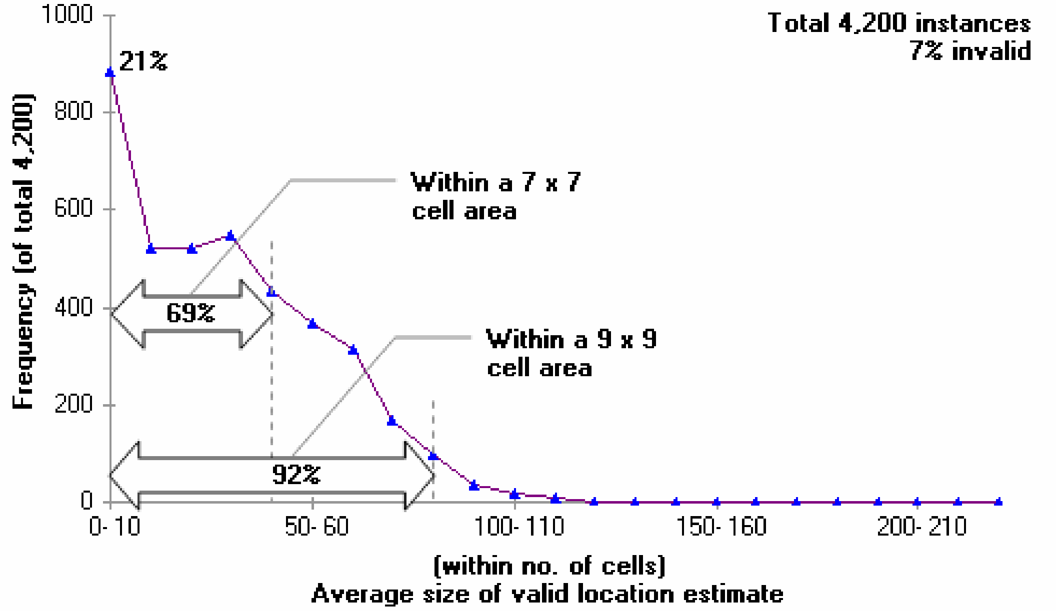
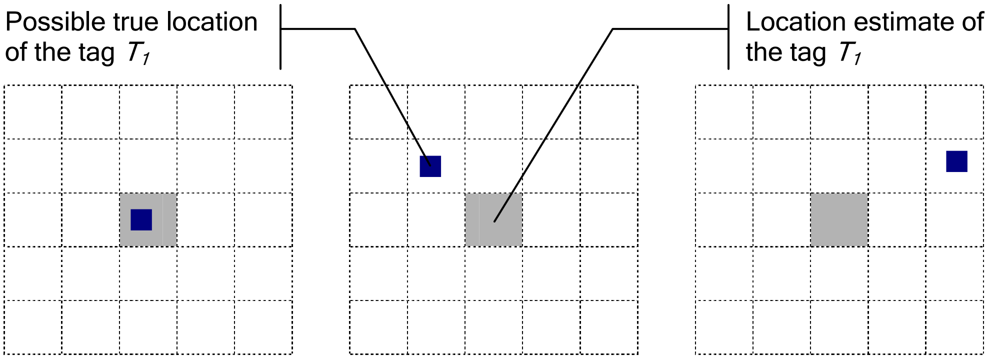


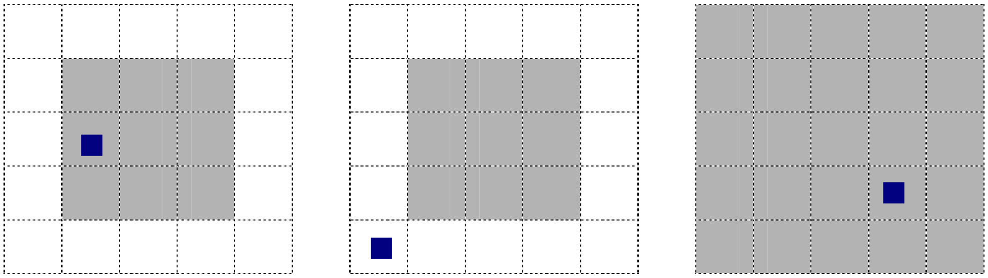
Figure 5.4: Frequency of average size of valid location estimates

However, the valid location estimate of a tag may or may not contain the true location of the tag. In other words, the valid location estimate is not necessarily unbiased – among nine tags with valid estimates, the location estimate of only six tags was unbiased on average (Figure 5.3). Therefore, to come up with an area that is sure to contain the true location of a tag, the overall bias must be taken into account in addition to the size of valid location estimate. For example, suppose that it should be determined how frequently the true location of a tag was within +/−2 cells from the center of the valid location estimate, or within a 5 x 5 cell area. Figure 5.5 shows some of such cases. Other cases are involved with the situation in which the valid location estimate of a tag constituted a rectangle area, instead of a square. However, those cases can be simplified to meet the following condition:

$$\left(\sqrt{\text{valid estimate size}} + 2 * \text{overall bias}\right)^2 \leq 25 \text{ cells} \tag{9}$$



(a) Cases where valid estimate size = 1 cell and bias ≤ 2 cells



(b) Cases where valid estimate size ≤ 25 cells and bias ≤ 1 cell

Figure 5.5: Possible true tag locations within a 5 x 5 cell area

Evaluating a total of 4,200 instances as illustrated above, the lower curve in Figure 5.6 was obtained that represents the frequency of instances in which the true location of a tag is sure to be within a certain number of cells from the center of the valid estimate. For example, in 12% of the total instances, the true location of a tag was within +/−2 cells from the center of an area representing the valid location estimate of the tag. As a comparison, the upper curve in Figure 5.6 shows the frequency of instances in which average size of valid location estimates was smaller than or equal to the corresponding cell area, regardless of whether the estimates were biased or not. Thus, the gap between the lower and upper curves can be attributed to the effects of the biases. Note that the frequencies in percentage add up to 93% and the rest 7% is accounted for by those instances where the location estimate of all tags was invalid.

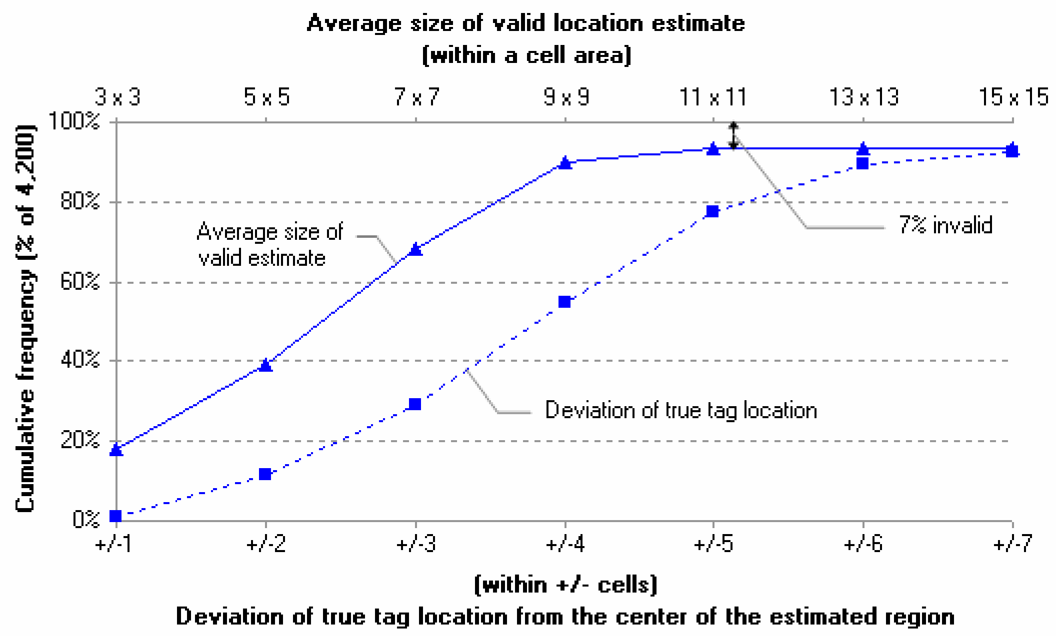


Figure 5.6: Cumulative frequency for deviation of true tag location

5.2.2. Influencing Factors and Performance Trade-offs

Candidate factors that can influence the performance of the RFID proximity localization in roving applications are the experiment parameters shown in Table 4.4: (1) the total number of tags placed, (2) patterns of tag placement, (3) the level of RF power, and (4) the number of virtual readers. Figure 5.7 on the next page shows the distribution of average number of successful reads for each group that has a different parameter value or setting (numbers in parentheses indicate sample size of each group). Groups that are categorized according to the placement pattern or number of tags placed do not appear to make remarkable differences in successful reads. Relatively significant differences exist between groups that have a different number of virtual readers or different levels of RF power. Expectedly, the number of successful reads per tag increased with the number of virtual readers – a tag will be read at more locations as the total number of virtual readers increases. A higher level of RF power can also be associated with more successful reads per tag, since it implies a greater read range that allows virtual readers at a farther location to successfully read the same tag.

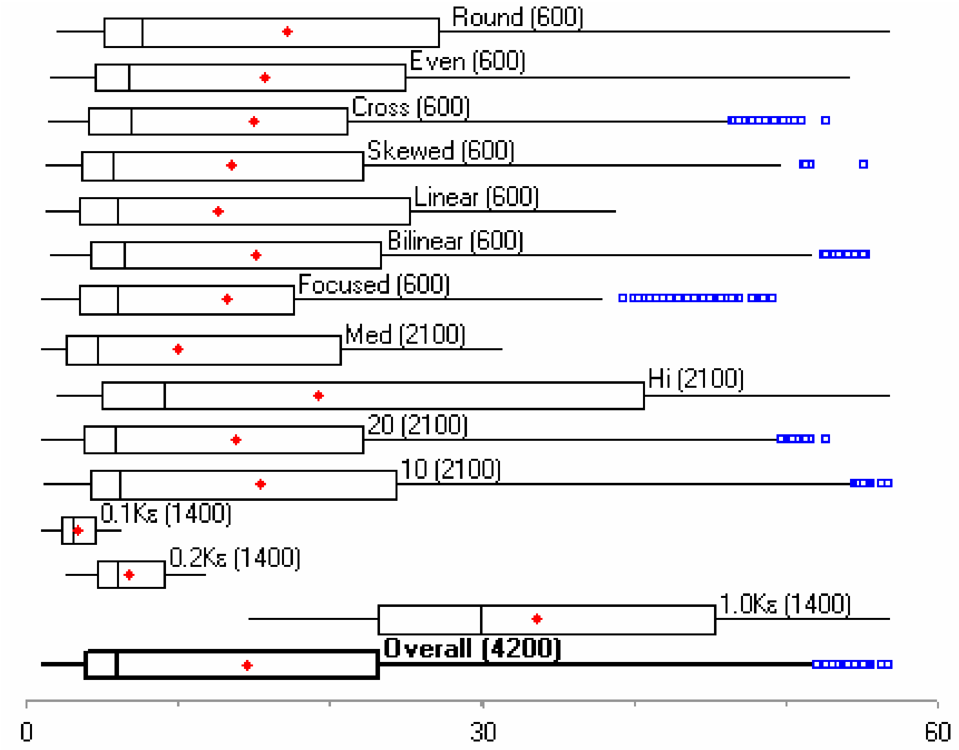


Figure 5.7: Average number of successful reads under different parameter values

Interestingly, the distributions of average number of successful reads are similar to those of average number of off-side reads, as is apparent when comparing Figures 5.7 and 5.8. The differences in off-side reads are also evident between groups with a different RF power level or a different number of virtual readers. The question is how frequently off-side reads occur under a different RF power or with a different number of virtual readers. As shown in Figure 5.9 on the next page, the rate of increase in off-side reads was much greater with higher RF power. In contrast, the increase in the number of virtual readers does not influence the growth rate of off-side reads (see Figure 5.10 on the next page).

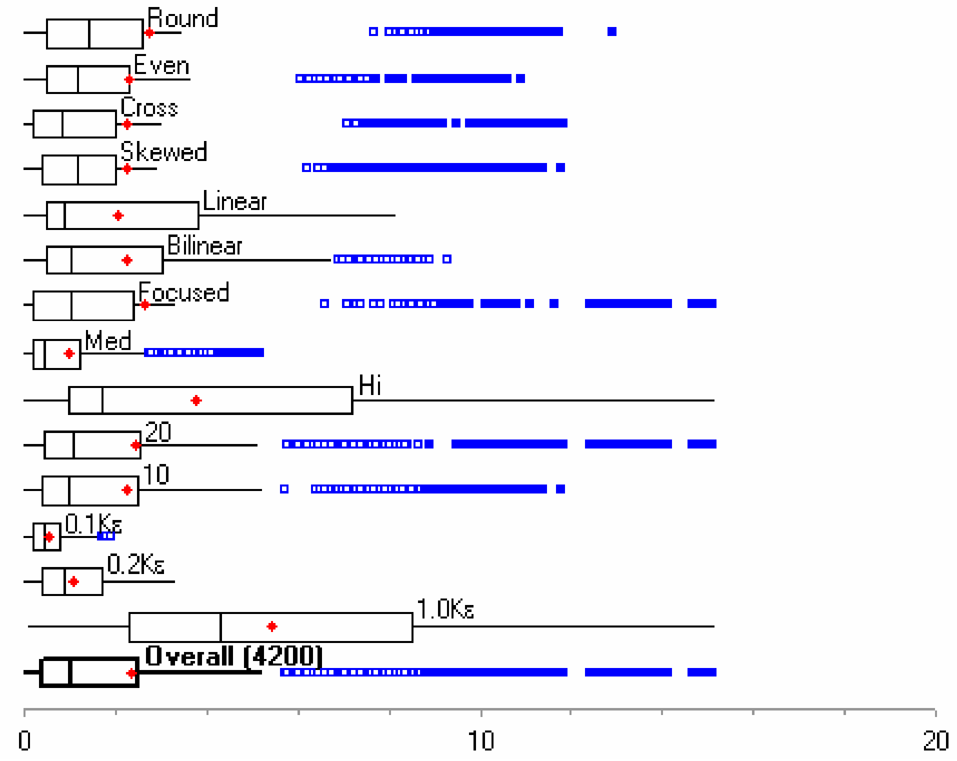


Figure 5.8: Average number of off-side reads under different parameter values

Putting the observations above into perspective, as the rover continues to move around the site and generates virtual readers, higher RF power will allow for more successful reads and thus provide more proximity information for each tag. However, higher RF power will also result in off-side reads growing at a greater rate. Consequently, even with more successful reads for each tag, higher RF power can reduce the probability that each tag is localized with a valid or unbiased estimate. Figure 5.11 on the next page shows that with the High RF power, fewer tags were localized with valid and unbiased estimates, and the average bias of biased estimates was greater than when the Medium power was in use. It is also apparent in Figure 5.11 that the larger number of virtual readers lowered the number of tags localized with valid and unbiased estimates, while increasing the bias on average.

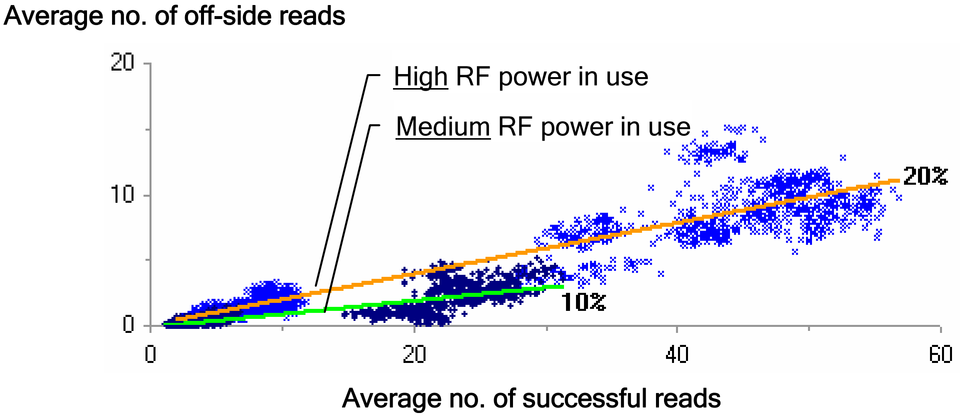


Figure 5.9: Growth rate of off-side reads under different RF power levels

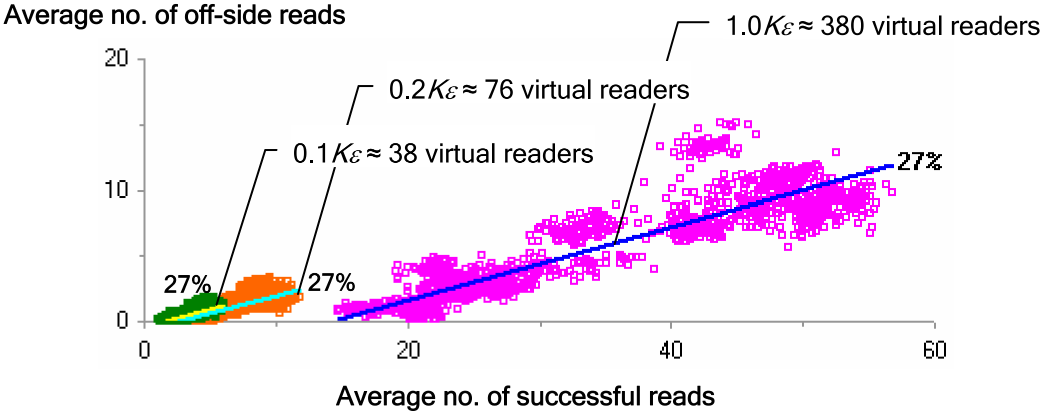


Figure 5.10: Growth rate of off-side reads with varying numbers of virtual readers

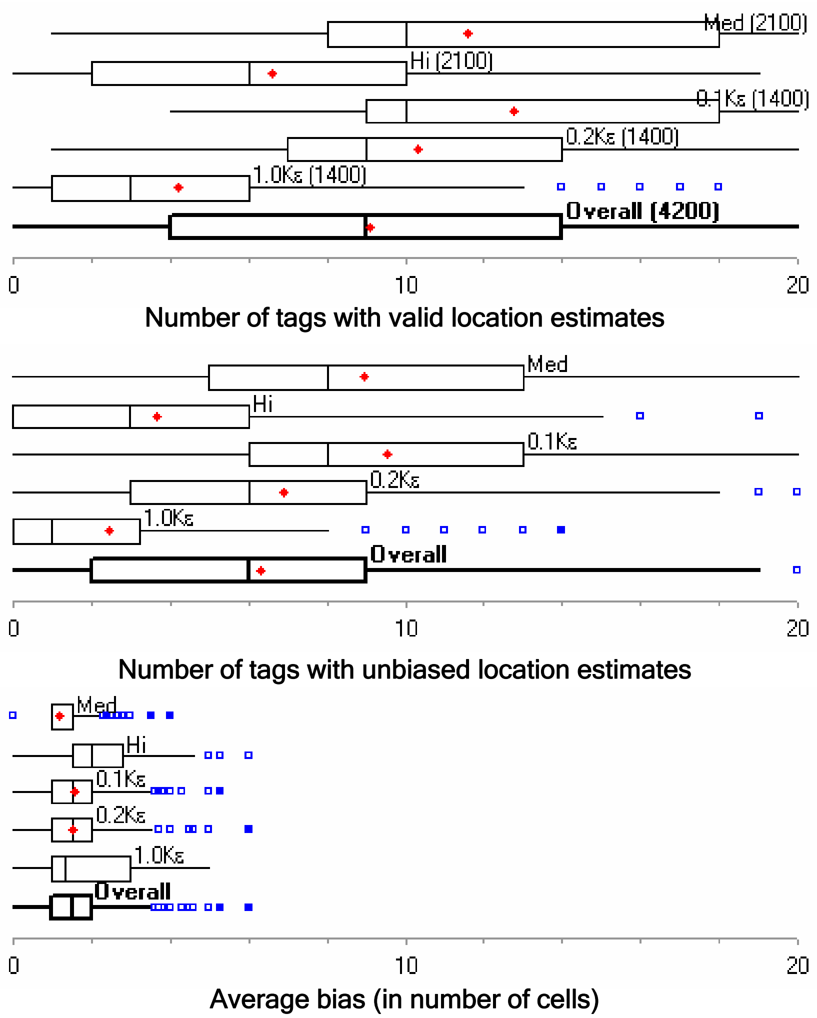


Figure 5.11: Number of tags with valid/unbiased estimates and average bias

In fact, when the High RF power was in use, the larger number of virtual readers often resulted in the location estimate of *all* tags being invalid. Figure 5.12 on the next page shows the bivariate distribution of the number of tags with valid and unbiased estimates, under different power levels and numbers of virtual readers. The instances of all location estimates being invalid, represented in Figure 5.12 by peaks at the origin, are salient when the High RF power and a large number of virtual readers were introduced. Thus, these instances of "failure across the board" must be the result of a large number of virtual readers operating at the High RF power, rather than the sole effect of a good number of virtual readers. Otherwise, this localization failure at large should have been also observed under the Medium RF power.

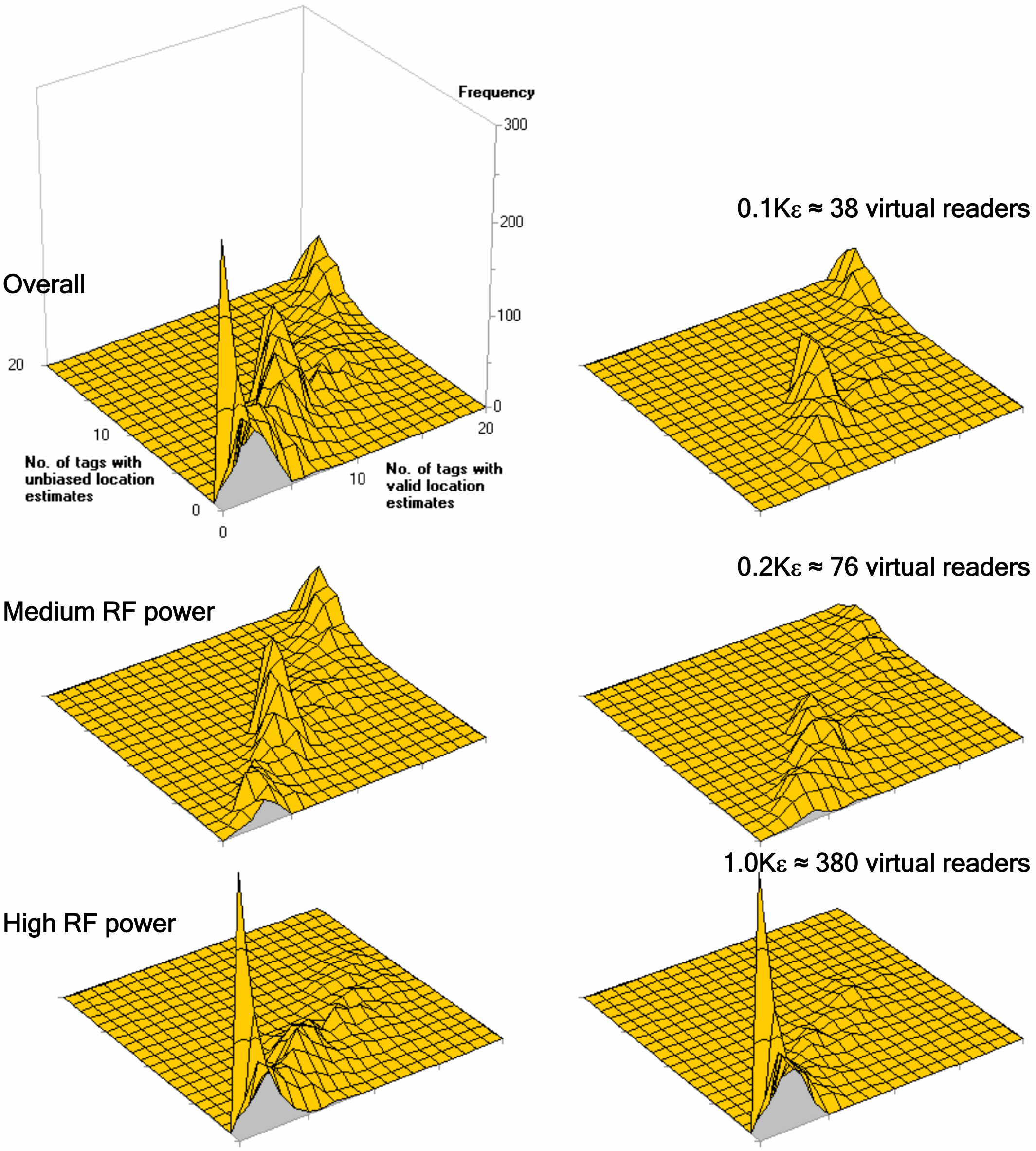


Figure 5.12: Frequency of the number of tags with valid and unbiased estimates

In ideal configurations, peaks in Figure 5.12 should be lined up in the diagonal direction as the valid location estimate for every tag would be also unbiased. In addition, higher peaks should be farther away in the diagonal direction from the origin, as there would be more instances in which the greater number of tags is localized with valid estimates. These ideal situations are more feasible with the lower RF power and relatively sparse virtual readers, as can be seen from Figure 5.12. Then what would be the value of generating a large number of virtual readers?

As stated earlier, both RF power level and number of virtual readers influence how many tags could be localized with a valid estimate. In the worst case, a large number of virtual readers using High RF power can cause none of the tags to be localized with a valid estimate. However, in cases where *some* tags were localized with a valid estimate, more virtual readers allowed for more precise estimates. As shown in Figure 5.13 on the next page, the smaller size of valid estimates is more frequently observed with the larger number of virtual readers. This observation indicates that the number of virtual readers has the impact on the size of valid location estimate. In contrast, the level of RF power did not make such differences in the size of valid estimate, except for the instances where the location estimate of all tags was invalid (see Figure 5.14).

Nonetheless, the RF power level does have the effect on estimation of the true tag locations, yet in a different way than does the number of virtual readers. While the number of virtual readers influences the size of valid location estimate, the power level affects the bias in case that the valid estimate is biased. As illustrated in Figure 5.15 on page 103, with different power levels, a particular size of valid estimates occurred in almost the same number of instances, while a certain degree of deviation of the true location arose in significantly different frequencies as the bias of valid estimates came into play.

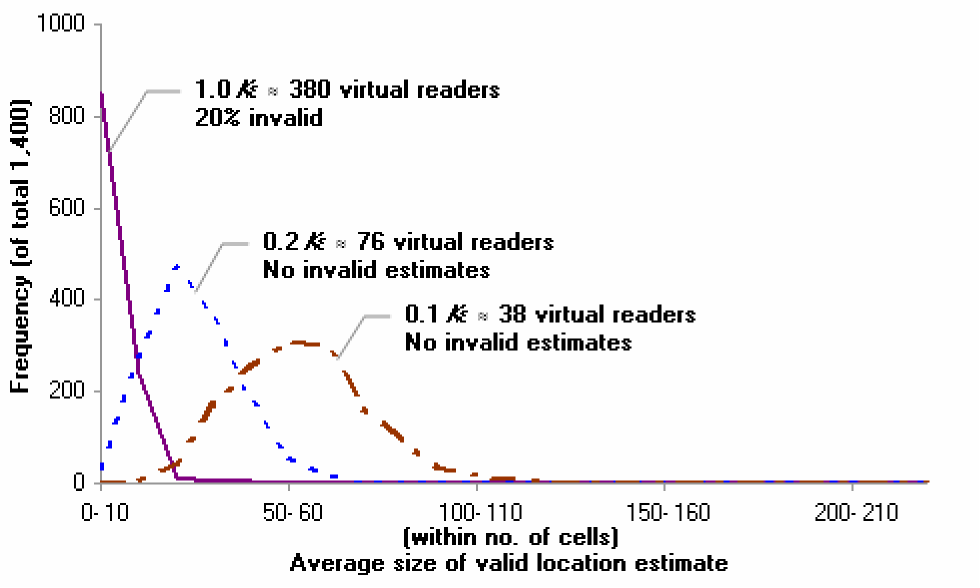


Figure 5.13: Frequency of average size of valid estimates under different numbers of virtual readers

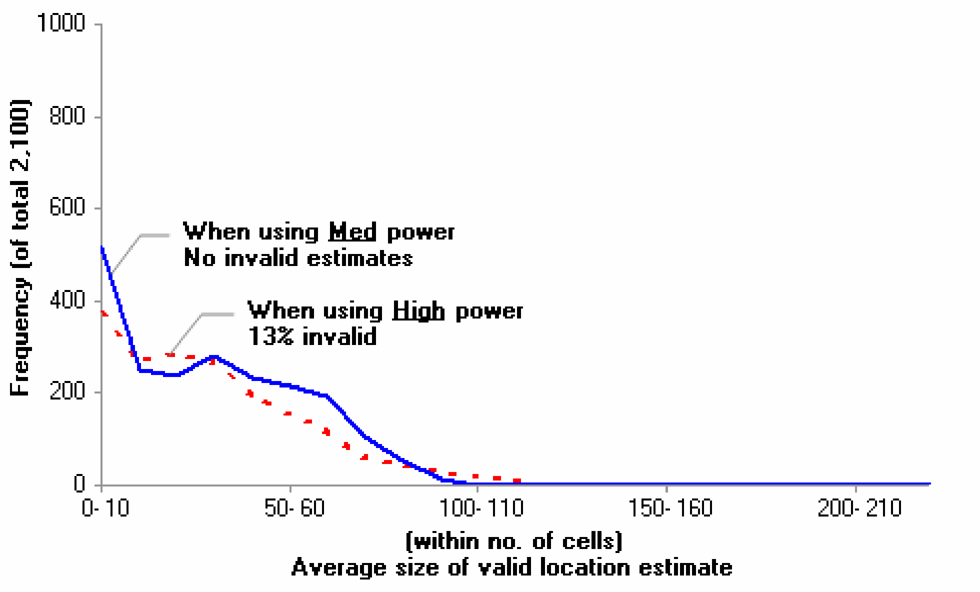


Figure 5.14: Frequency of average size of valid estimates under different RF power levels

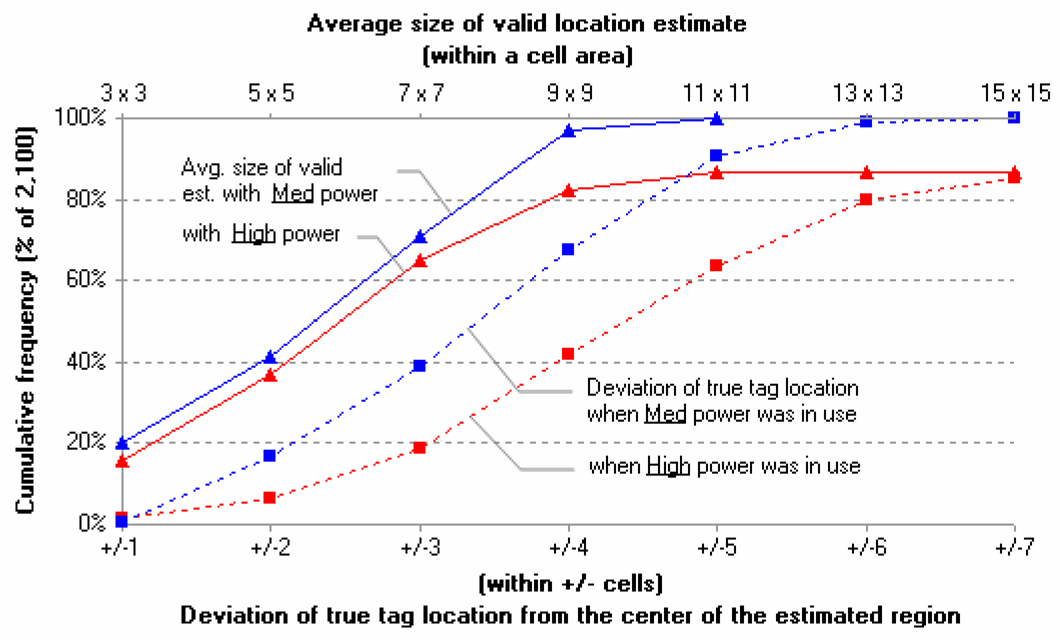


Figure 5.15: Deviation of true tag locations when different power levels in use

To characterize the performance trade-offs of the RFID proximity localization, the observations made on the influencing factors are summarized:

- A higher level of RF power and the larger number of virtual readers, individually and cumulatively, increase the number of off-side reads as well as the number of successful reads per tag.
- The increase in off-side reads is more sensitive to change in the RF power level than to that of the number of virtual readers.
- A high RF power and a large number of virtual readers, individually and cumulatively, have a negative effect on the probability of each tag being localized with a valid estimate, reducing the number of tags with a valid estimate.
- The RF power level and the number of virtual readers both influence the estimate of the true tag locations, yet in different ways. While a

higher RF power level increases the bias of valid location estimates, the larger number of virtual readers reduces the size of the valid estimate.

As shown in Figure 5.16 below, these influencing factors (marked with ovals) can be related to performance metrics (in rectangles or rounded boxes) – the directionality of the relation is denoted by +/– signs. To specify, the RF power level is in inverse relation to the number of tags localized with a valid estimate and in direct relation to the bias of the valid estimate. Thus, a lower RF power level generally leads to more tags with a valid estimate and to the smaller bias of the valid estimate and hence the smaller error in the estimate of true tag location. On the other hand, a smaller number of virtual readers will yield more tags localized with a valid estimate but increase the size of the valid estimate, leading to the greater error in the estimate of true tag location.

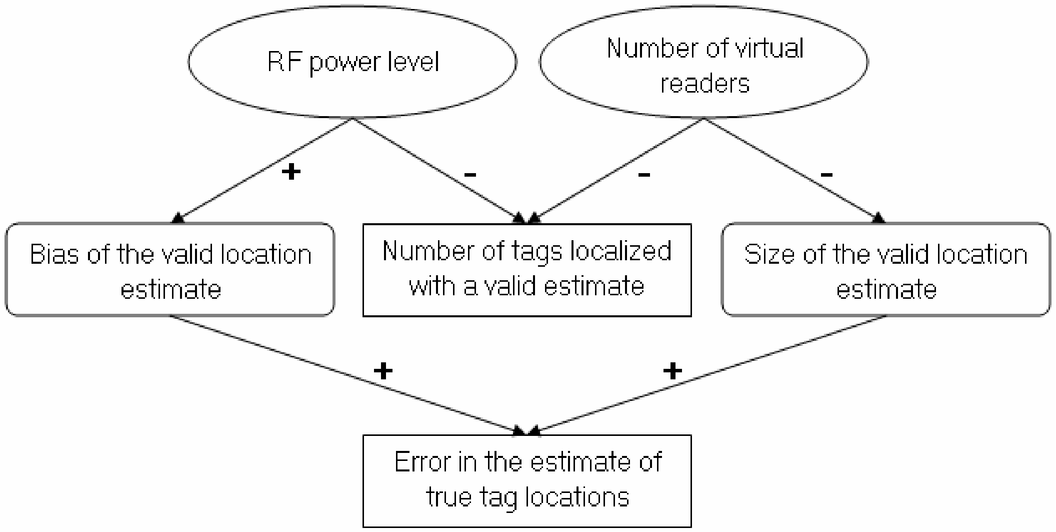


Figure 5.16: Relation of influencing factors to performance

The effects of the number of virtual readers on performance present a trade-off between the number of tags that can be localized and their positional accuracy. Specifically, a sparse sampling of proximity information at a low RF power level will allow the greatest number of tags to be localized only with suboptimal accuracy. As more and more proximity information is acquired, positional accuracy also improves, but some of the location estimates once valid will degenerate into the invalid, reducing the number of tags with a valid location estimate. Thus, to optimize the number of tags with a valid estimate and their positional accuracy at the same time, this degeneration of the valid estimate must be overcome.

5.3. PRACTICAL CONSIDERATIONS

5.3.1. Comparing with Predicted Accuracy

As a final step to assess performance of RFID proximity localization, the results of field experiments are compared with accuracy predicted by the formula (8) under the occupancy cell model. Recall that the formula (8) provides the minimum number of virtual readers required to achieve a certain level of accuracy in estimate of location. In the field experiments, the number of cell partitions was $n = 30$, and the discrete read range $\rho = 5$ when using the Medium RF power. Thus, given $\varepsilon = 4$, the formula (8) gives $K_\varepsilon(n, \rho) = K_\varepsilon(30, 5) \leq 385$, and the number of virtual readers K to simulate sampling at the "strolling" pace (Figure 4.8 on page 78) was set to 385.

For the "jogging" pace, the value of K was taken as $K = 0.2\ K_\varepsilon = 0.2 * 385 = 77$, which is equivalent to the value of $K_\varepsilon(30, 5)$ with $\varepsilon = 168$. Therefore, using 77 virtual readers at the Medium RF power, the location of a tag is expected to be within a (1 + 168) cell area, or 13 x 13 cell area. This means that the occupancy cell model predicts the true location of a tag with accuracy of +/−6 cells. Similarly, 64 virtual readers generated at the "jogging" pace using the High RF power should allow the location of a tag to be estimated within a 17 x 17 cell area, i.e., with accuracy of +/−8 cells.

Figure 5.17 below depicts accuracy curves resulting from the test beds with the “Even” or “Focused” pattern using Medium or High RF power, for the number of virtual readers sampled at the jogging pace. Note that these accuracy curves are based on the deviation of true tag location that has taken into account possible bias of valid estimates. As shown in Figure 5.17, location estimates resulting from field experiments converge to points of predicted accuracy under the occupancy cell model. It is also observed that the test bed with the “Even” pattern has reached predicted accuracy more quickly than that of “Focused” pattern using the same power level.

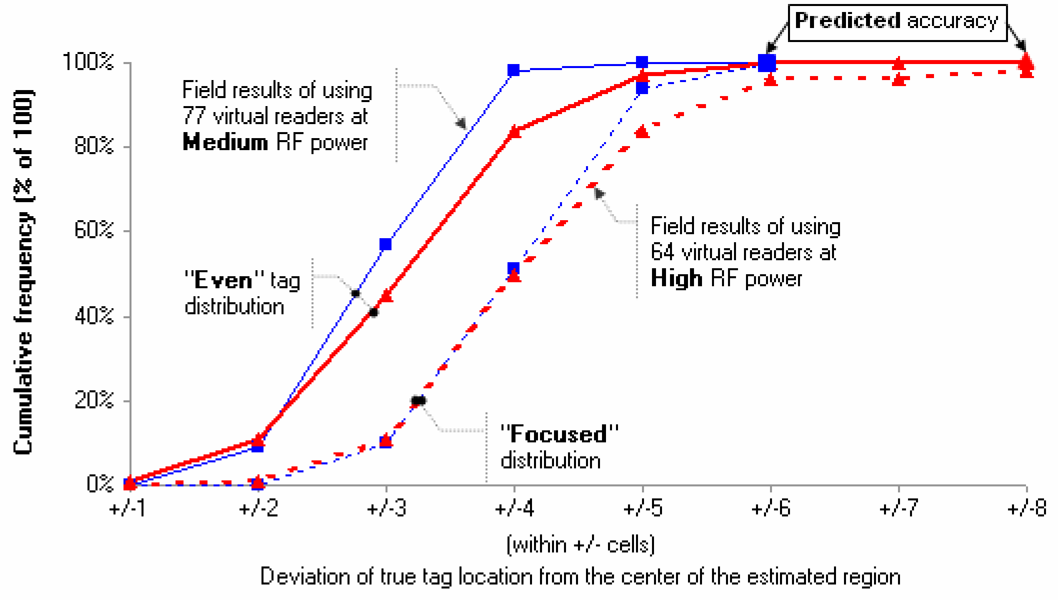


Figure 5.17: Model vs. field results of error in estimate of tag location

5.3.2. Expanding the Discrete Read Range at the Same RF Power Level

If a certain level of confidence about the true tag location is to be accomplished, the RF power level is the more convenient and effective means than the number of virtual readers. For example, Figure 5.6 shows that 12% of the time, the true location of each tag was within +/−2 cells from the center of its valid estimate. To accomplish this confidence level, a valid estimate with bias 2 cells would be required to have the size 1 cell, while an unbiased estimate could have the size as large as 25 cells – for illustration, see Figure 5.5. That is, the impact of the bias outweighs the goodness of the valid estimate.

As discussed earlier, the bias is a function of off-side reads, and to mitigate the impact of the bias on the estimate of tag locations, much more virtual readers would be required so that valid estimates can have a very small size. Furthermore, a large number of virtual readers generated at high RF power can raise off-side reads that result in invalid or biased estimates. However, without increasing the number of virtual readers or changing the power level, the estimate of tag locations may be improved by expanding the prescribed read range.

Recall that for the test beds using the High power level, the discrete read range ρ was *assigned* to be 7 cells, and that this value of ρ as well as proximity information was plugged into the formula (4) to compute the location estimate for each tag. However, this assignment of discrete read range did not completely eliminate ambiguity of the RF communication region at the power level. As such, it happened that some virtual readers read a tag that lied outside the communication region containing $(2\rho + 1)^2$ cells, thereby resulting in off-side reads.

Figure 5.18 on the next page shows the effects of expanding the read range by one cell, while remaining at the same High power level, for the test beds with the “Focused” tag placement. When the increased value of the discrete read range ρ was applied in the localization algorithm, the number of instances was dramatically decreased in which the location estimate of all tags was invalid. The improvements also can be seen from Figure 5.19 on the next page that shows the error in the estimate of true tag locations when different values were assigned to the read range under the same level of High power. Despite the improvements, the High RF power is still outperformed by the Medium RF power.

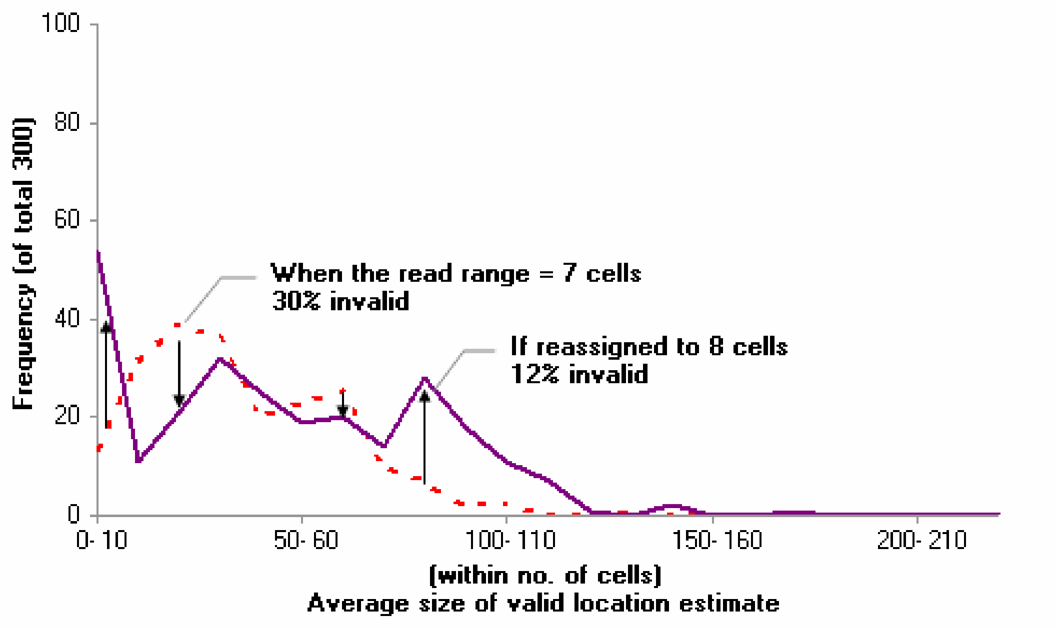


Figure 5.18: Effects of expanding discrete read range using the same RF power – tags placed in the "Focused" pattern

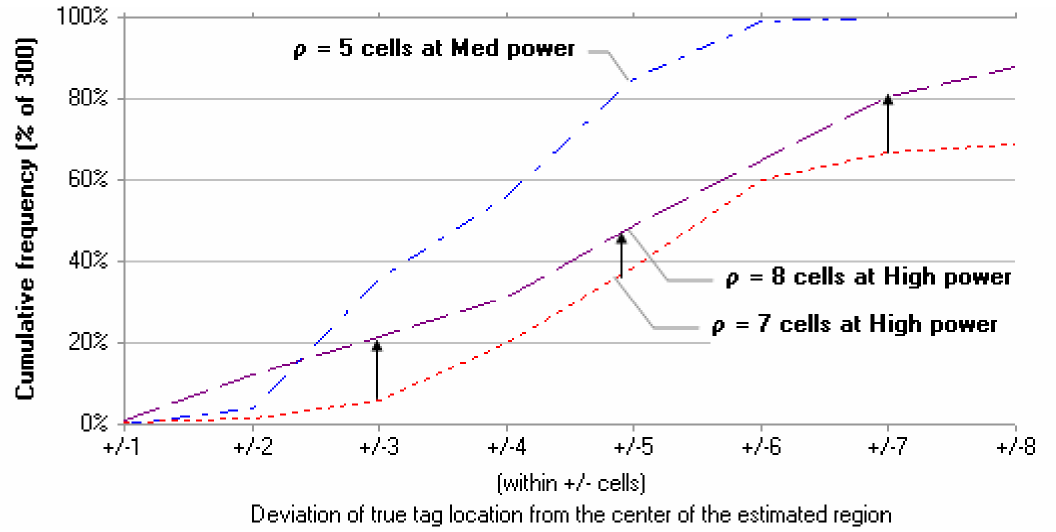


Figure 5.19: Error in the estimate of tag locations with different assigned values of discrete read range ρ – tags placed in the "Focused" pattern

Nonetheless, in some instances the valid estimates obtained with the read range 7 cells are still better than those of 8 cells, as can be seen in Figure 5.18 on the previous page. This suggests that the improvements by expanding the read range arise from reduced off-side reads and bias, rather than the reduced size of valid estimates. This observation is confirmed with Figure 5.20 below which shows that with the increased value of ρ, both average number of off-side reads and average bias were decreased, while average size of valid estimates was increased.

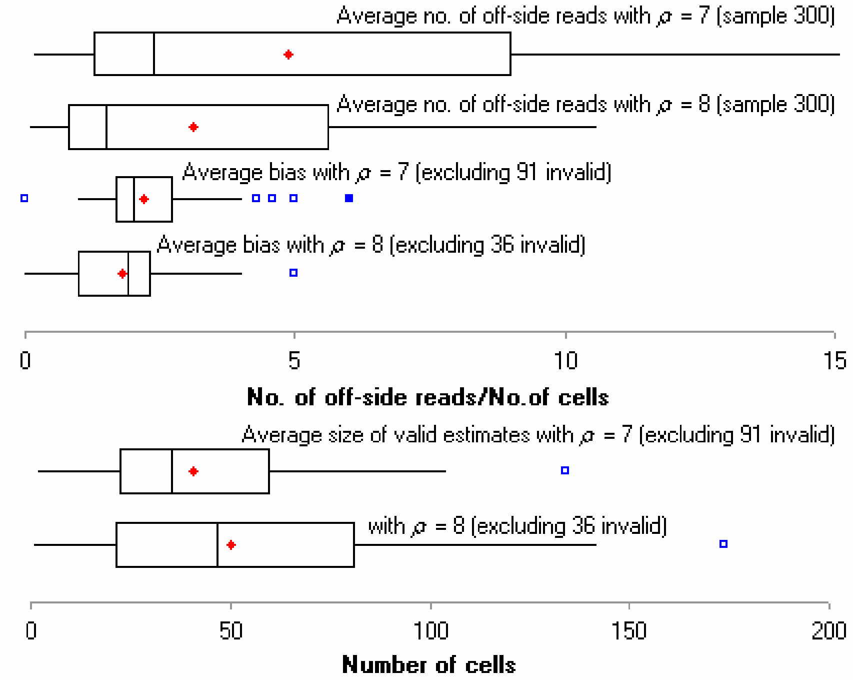


Figure 5.20: Average number of off-side reads, average bias, and average size of valid location estimates, with different discrete read ranges

5.3.3. Considering the Effects of Tag Density

Among the experiment parameters, the RF power level and the number of virtual readers have been investigated in the preceding section to assess their effects on performance and trade-offs. The point of departure to this investigation was the observation that groups of test beds with a different RF power level or number of virtual readers showed significant differences in average number of successful reads and of off-side reads (see Figures 5.7 and 5.8). It was also observed that once categorized according to the placement pattern or a total number of tags placed, groups of test beds showed relatively insignificant differences in the performance metrics. However, these parameters may prove to have an impact on performance, when they are specifically factored into the bottom line performance metrics, i.e., the number of tags localized with a valid estimate and the error in the estimate of true tag locations.

Of the seven placement patterns, the Focused and the Even represent the extremes in terms of the density of tags. Table 5.3 below shows the frequency of "no-reads" in the test beds with 20 tags placed in these patterns, for different RF power levels and numbers of virtual readers. Recall that the instances of "no-reads" occur when at least one of the tags was not successfully read by any virtual readers. Table 5.3 indicates that for both placement patterns, an incidence of "no-reads" typically decreased with a higher RF power level and the larger number of virtual readers. As such, if the number of virtual readers grows sufficiently large, this incidence would not differ from pattern to pattern. Nonetheless, tags in the Focused pattern more frequently experienced "no-reads," particularly when the Medium RF power was in use.

Table 5.3: Frequency of "No-reads" out of 50 Instances in Test Beds with 20 Tags Placed in an Extreme Pattern

	Medium RF power with ρ = 5 cells			High RF power with ρ = 7 cells			High RF power with ρ = 8 cells		
	$0.1K_\varepsilon$[a]	$0.2K_\varepsilon$[b]	$1.0K_\varepsilon$	$0.1K_\varepsilon$	$0.2K_\varepsilon$	$1.0K_\varepsilon$	$0.1K_\varepsilon$	$0.2K_\varepsilon$	$1.0K_\varepsilon$
Focused	47	15	0	13	1	0	13	0	0
Even	23	2	0	6	0	0	12	0	0

[a, b] Represent the number of virtual readers as a fraction of $K_\varepsilon(n=30, \rho=5)$ with $\varepsilon = 4$; the resulting values are 38 and 77, respectively.

The Focused pattern also underwent "all-invalid," more frequently than the Even pattern, which entails the location estimate of all the 20 tags being invalid (see Table 5.4 below). In fact, all the instances of "all-invalid" arose among tags in the Focused pattern when a very large number (300 or so) of virtual readers were operating at the High RF power. Note that this is consistent with the case where the placement pattern had not been factored in. However, no incidence of "all-invalid" occurred among tags in the Even pattern, even under the dominant RF power level and number of virtual readers. Thus, observations from Tables 5.3 and 5.4 suggest that the impact of the dominant factors on performance can become more or less prevalent depending on the density of tags.

Table 5.4: Frequency of "All-invalid" out of 50 Instances in Test Beds with 20 Tags Placed in an Extreme Pattern

	Medium RF power with ρ = 5 cells			High RF power with ρ = 7 cells			High RF power with ρ = 8 cells		
	$0.1K_\varepsilon$[a]	$0.2K_\varepsilon$[b]	$1.0K_\varepsilon$	$0.1K_\varepsilon$	$0.2K_\varepsilon$	$1.0K_\varepsilon$	$0.1K_\varepsilon$	$0.2K_\varepsilon$	$1.0K_\varepsilon$
Focused	0	0	0	0	0	48	0	0	25
Even	0	0	0	0	0	0	0	0	0

[a, b] Represent the number of virtual readers as a fraction of $K_\varepsilon(n=30, \rho=5)$ with $\varepsilon = 4$; the resulting values are 38 and 77, respectively.

Table 5.5 on the next page shows the median number of tags that were localized with a valid estimate, when placed in an extreme pattern. As is the case where the placement pattern had not been factored in, a smaller number of virtual readers at a lower RF power level generally allowed the greater number of tags to be localized, for both patterns. However, when placed in the Even pattern, typically more tags were localized with a valid estimate. Also observe that for both patterns, dilating the discrete read range at the same High RF power level helped to increase the number of tags with a valid location estimate. Nonetheless, as the number of virtual readers grew, tags in the Focused pattern led to a relatively insignificant improvement from dilating the discrete read range, while subjected to increasingly more significant performance degradation given the increased RF power level (see Figure 5.21).

Table 5.4: Median Number of Tags Localized with a Valid Estimate in Test Beds with 20 Tags Placed in an Extreme Pattern

	Medium RF power with $\rho = 5$ cells			High RF power with $\rho = 7$ cells			High RF power with $\rho = 8$ cells		
	$0.1K_\varepsilon$	$0.2K_\varepsilon$	$1.0K_\varepsilon$	$0.1K_\varepsilon$	$0.2K_\varepsilon$	$1.0K_\varepsilon$	$0.1K_\varepsilon$	$0.2K_\varepsilon$	$1.0K_\varepsilon$
Focused	17	19	15	12	6	0	16	11	0.5
Even	19	18	11	15.5	11	3	18	15	7

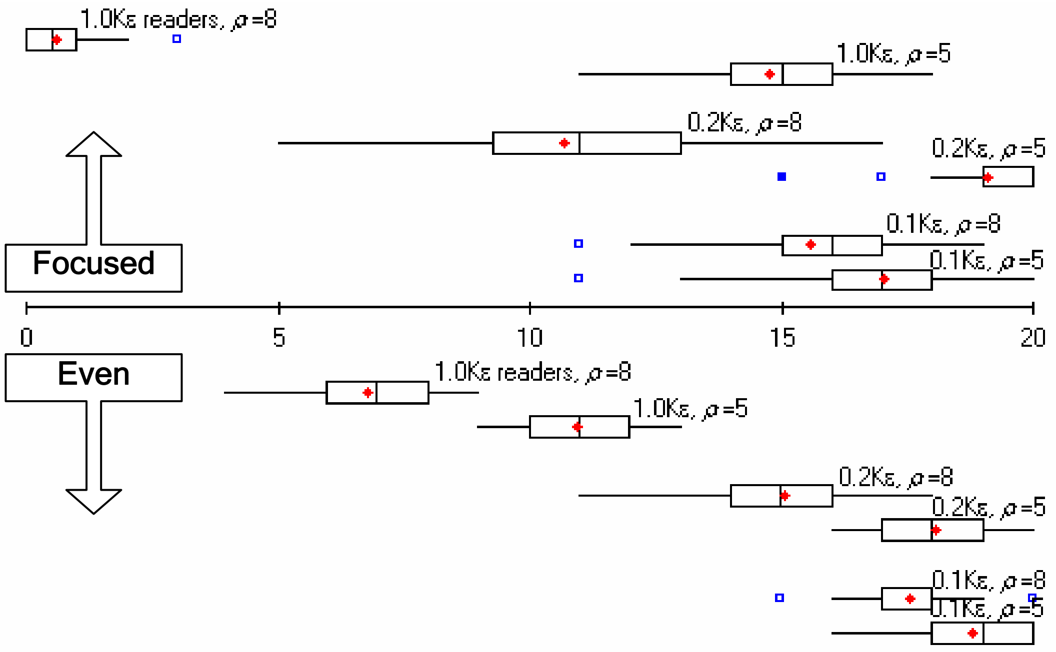


Figure 5.21: Number of tags with a valid estimate given the increased RF power level, when 20 tags placed in the Focused and Even pattern

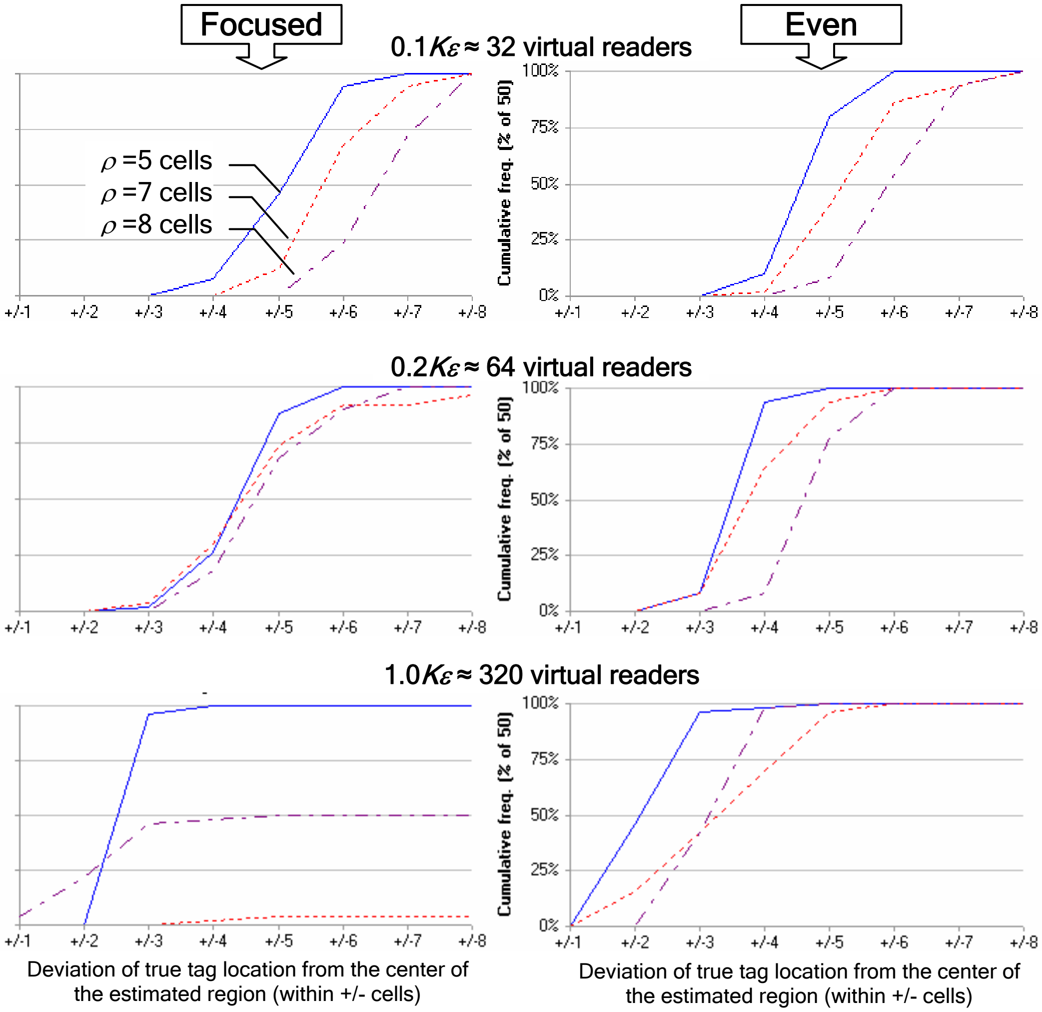


Figure 5.22: Cumulative frequency of the error in the estimate of true location, for 20 tags placed in Focused and Even patterns

Besides, having the tag density factored in reveals that the bottom line performance, in terms of the error in the estimate of true tag location, varied according to the placement pattern as well as the RF power level and number of virtual readers. As shown in Figure 5.22 above, the true location of tags in the Even pattern (charts in the right column) is likely to be estimated with a smaller error, given the discrete read range assigned at an RF power level and the number of virtual readers. As the number of virtual readers grew, the location estimate for tags in the Even pattern was improved regardless of the discrete read range – each line in one chart is always above its counterpart in another chart below. However, this was not always the case with tags in the Focused pattern, as a large number of virtual readers did not yield the better location estimate given the increased RF power level.

In summary, observations thus far lead to the conclusion that a low density of tags is conducive to achieving better performance given the RF power level and number of virtual readers. Conversely, optimizing the performance of the proximity localization may be constrained by the density of tagged materials on a construction site or at laydown yards, which is often impractical to control. Nevertheless, the principal relationships between the dominant factors and the performance remain intact. As such, irrespective of the tag density, proximity information acquired at a moderate rate with a low RF power level will allow more tags to be localized with better positional accuracy. Positional accuracy could be further improved by increasing the sampling frequency, without suffering from the degeneration of the valid estimate, if proximity information is filtered out by dropping those contributed by off-side reads.

5.3.4. Combining Errors in Location Estimate Using GPS/RFID Proximity

Analyses based on the field experiments took it for granted that the position of the rover at any time was known precisely. This was possible under the occupancy cell framework by mapping the exact position of the rover to a cell location in reference to physical grids. If this is not the case in reality, the error in estimate of the rover position using GPS should be added in when the true location of tags is estimated.

For example, suppose that the rover is carrying around a GPS receiver subject to errors in estimate of 2D location with one standard deviation 1 m. In addition, assume that the error in estimate of the tag's location using RFID is distributed approximately to the normal distribution. Then the estimate of the tag's location by proximity localization using the Medium RF power will have the error +/−4 m in approximately 68 % of the time, as shown in Figure 5.15, which is commensurate with one standard deviation 4 m under the normal distribution. Therefore, using RFID combined with GPS, the estimate of the tag's location has the overall error with one standard deviation 4.1 m = $\sqrt{1^2 + 4^2}$.

Chapter 6: Conclusions

6.1. INTRODUCTION

Of the elements that comprise the constructed facility, construction materials may account for 50-60% of the total cost of a construction project and most directly represent project progress. The inability to make materials available at the right time and the right place is one of the most common problems in construction. To effectively control materials management functions, the status of materials' delivery, movement and installation on site should be easily and precisely tracked in space and time. Particularly, field materials management functions have become more critical, given the significantly increased use of prefabrication and preassembly.

While improvements to field materials management have remained almost unexamined until recently, research efforts in automated measurement of performance indicators have focused on tracking the location of construction laborers and equipment on site. Automated project performance monitoring provides a posteriori information on actual construction performance and enables project management to take corrective actions to control the performance. However, tracking materials' location on a construction site can complement the existing approaches to identifying activities that construction agents are engaged in, which is a prerequisite to derivation of performance indicators. Besides, tracking materials' location in the supply chain provides a priori information on materials availability for crew-level work planning. Thus, automated materials tracking on construction projects should both improve project performance and enable effortless derivation of performance indicators.

The central motivation for the research described here was to bridge the gap between the current paradigms regarding the location tracking of construction resources. Automated materials tracking on construction projects represents a challenging research problem for the following reasons: 1) different requirements for positional accuracy with identification in common; 2) the large number of materials to be tracked in the supply chains and on a construction site; and 3) constantly changing environments on a construction site. These challenges characterize the limitations of existing ADC technologies and suggest the need to develop economically and environmentally viable applications of RFID technology.

To examine the feasibility of applications of RFID technology to automating the tracking of materials on construction projects, an application framework including portal and roving modes was developed, and algorithms and technology most suited were identified. The performance trade-offs and limitations of the algorithms and technology were also characterized through thorough experimentation using commercially available active RFID technology.

6.2. CONCLUSIONS

The application framework developed applies to multiple stages in the construction project life cycle. A portal application of RFID technology is intended to automatically track the delivery and receipt of prefabricated materials through the supply chain to a construction site. A roving application of the technology is to track the location of materials on a construction site as well as at laydown yards, with positional accuracy beyond the portal level.

The main conclusions of the research described in this dissertation are:

- A portal application of RFID technology can simultaneously read tags installed in materials in moving platforms under realistic shipping conditions. Field trials demonstrated that the technology can automatically identify pipe spools with 100% accuracy and precision if they are driven at a speed less than 2 mph through portal gates equipped with four antennas.

- A roving application of RFID technology can inexpensively determine the approximate 2D location of materials using the proximity localization technique. Field experiments showed that in 68% of the time when the Medium RF power in use, the true location of a tag was within approximately +/−4 m from the center of the estimated region. In addition, location estimates resulting from experiments achieved the accuracy predicted by the occupancy cell model.
- In a roving application, proximity information acquired at a modest sampling frequency with a low RF power level allows more tags to be localized with better positional accuracy, irrespective of the tag density. Positional accuracy could be further improved by increasing the sampling frequency, if proximity information is filtered out by dropping those contributed by off-side reads.

The developed application framework of RFID technology presents the following advantages:

- A portal application leverages automatic passive reading with opportunity for near off-the-shelf implementation. It eliminates the need to read RFID tags individually under stationary situations.
- A roving application provides the capability to automatically identify hundreds of materials and track their location at the same time, at a magnitude less cost than pure GPS or other existing approaches.
- A roving application leverages automatic passive reading with opportunity for active confirmation, and does not require line of sight for positive identification or manual updates of materials' location. Thus, this approach is potentially much faster than existing approaches for surveying laydown yards and a construction site.
- A roving application does not rely on a fixed communications network to

determine the identification and location of tagged materials, and is compatible with constantly changing construction environments.

- A roving application leverages the basic functionality of commercially available RFID systems, and does not require modifications to current RFID hardware.
- A roving application works with multiple rovers and potentially with cheap passive RFID tags, providing multi-tiered capability for tracking items of varying criticality.
- The scope of a roving application can be broadened beyond construction materials and components to form the backbone of a location tracking system for other construction resources. Mobile RFID readers equipped with GPS can be mounted on materials handling and lifting equipment as well as key site personnel, to track craft workers, tools and auxiliary equipment (e.g., a concrete bucket, non-conventional formwork) besides materials and components.

6.3. CONTRIBUTIONS

The first contribution of the research presented here is the development of an application framework to automating the tracking of materials on construction projects. The application framework provides a unified platform to automatically identify materials and track their location in multiple stages of the project life cycle. This unified platform makes RFID technology economically more attractive and drives implementation of the technology in realizing potential benefits, including:

- Provides timely and accurate information on materials availability for crew-level work planning.
- Prevents crew workers from being idle or slowing down in anticipation of material shortages.

- Reduces time in identifying materials upon receipt and in locating them prior to shipping.
- Reduces misplaced material items and search time for misplaced pieces, minimizing disruptions to short interval planning.
- Helps to identify basic activities being performed on a construction site.

Summarizing, the application framework improves field materials management and presents the potential for improved workflow reliability and labor performance and for effortless derivation of performance indicators for project management's control.

The second contribution is the adaptation to current ADC technologies of the occupancy cell model that was envisioned with wireless sensor networks. This theoretical model, previously only studied through computer simulation, was validated in this research through experimentation using commercially available active RFID technology. This methodology can be used in developing localization algorithms for small devices that mount additional sensing modalities such as heat, vibration, etc.

6.4. RECOMMENDATIONS FOR FUTURE RESEARCH

The research presented in this dissertation focused on the technical feasibility of applications of RFID technology to automating the tracking of materials and components on construction projects. Although economic considerations of ADC technologies factored into the development of the application framework, potential economic feasibility of portal and roving applications should be estimated to justify the up-front cost of implementation.

To implement the application framework developed in real world projects, further research and development is also needed:

- To elicit heuristics on off-side reads and develop algorithms for filtering out noisy proximity data to improve positional accuracy;

- To determine optimal configurations given actual rover paths and density of tags, through field trials in real project settings;
- To expand the occupancy cell model to 3D localization;
- To develop methods to determine the position of the rover when GPS may not function;
- To develop protocols and architectures to integrate identification, approximate location and GPS data collected by multiple rovers, with project information management systems;
- To formalize methods to complement existing approaches to identifying basic activities that construction resources are performing;
- To demonstrate the multi-tiered capability for tracking objects of varying criticality, through experiments with passive RFID technology alone or in combination with active RFID.

In the future, embedded with the capability to record and communicate their properties, transformations, movements, and progress, material objects would embody the state of the constructed facility through its entire life cycle, forming an ambient intelligence that could communicate facility state or “health” with project processes and with facility constructors, owners and operators.

Appendix: Visual Basic for Applications Codes

Module 1

```
Option Explicit
Option Base 1
Public s As Integer, _
    ConfigToAdd() As String, NConfigs As Integer, PathToAdd() As String, NPathItems As Integer,
_
    PathRect As Boolean, PathButterfly As Boolean, PathSerpentine As Boolean, PathRand As
Boolean, _
    NIteration As Integer, _
    ConfigsToAnalyze() As String, PathsToGenerate() As String, _
    NeUnique As Integer, e() As Integer, eCount() As Integer, _
    ProjectFileName As String, ModelNo As Integer, _
    ConfigType As String, NTags As Integer, n As Integer, r As Integer, rho As Integer, _
    err As Integer, OneKe As Integer, K As Integer, StepSize As Integer, CoeffKe As Single, _
    RandReaderNo() As Integer, RandPath() As Integer, _
    ReaderNo() As Integer, ReaderPos() As Integer, TagNo() As Integer, TagPos() As Integer, _
    TagID() As Integer, TagReads() As Boolean, _
    NReadsTag() As Integer, NBadReadsTag() As Integer, LocationEstimate() As Integer, _
    EstimateValid() As Boolean, EstimateUnbiased() As Boolean, EstimateSize() As Integer, _
    TagIsInterior() As Boolean, NTagsInt As Integer, _
    ExpNReadsTag As Single, ExpNBadReadsTag As Single, _
    ExpNReadsTagInt As Single, ExpNBadReadsTagInt As Single, _
    NEstimateValid As Integer, NEstimateUnbiased As Integer, _
    NEstimateValidInt As Integer, NEstimateUnbiasedInt As Integer, _
    ExpEstimateSize As Single, ExpEstimateSizeInt As Single

Sub Main()
    Application.ScreenUpdating = False
    Call GetInputs
    Call CreateProjectFile
    Dim ConfigNo As Integer, PathNo As Integer, PathItemNo As Integer
    ModelNo = 0
    For ConfigNo = 1 To NConfigs
        'Capture ConfigsToAnalyze array items into public variables for a specified ConfigNo.
        ConfigType = ConfigsToAnalyze(ConfigNo, 2)
        NTags = ConfigsToAnalyze(ConfigNo, 3)
        n = ConfigsToAnalyze(ConfigNo, 4)
        r = ConfigsToAnalyze(ConfigNo, 5)
        rho = ConfigsToAnalyze(ConfigNo, 6)
        For PathNo = 1 To NeUnique 'PathNo represents a unique value of e.
            err = e(PathNo)
            OneKe = Int(Ke(n, rho, err)) + 1
            'Generate a path for each combination of n, rho, and err.
            'While n and rho are determined by ConfigNo and remain the same for the ConfigNo,
            'err is determined by the PathNo.
```

```
            Call GenRandReaderNo 'Returns RandReaderNo(OneKe) array.
            'Construct a rover path using the array RandReaderNo() based on the nearest
neighbor heuristic.
            Call GetNearestNeighborPath 'Returns RandPath(OneKe) for a particular set of n,
rho, and err.
            'Capture a coefficient of each PathItem in the current PathNo. These coefficients
            ' represent a fraction of OneKe and hence imply a sampling frequency of reads.
            For PathItemNo = 1 To eCount(PathNo)
                ModelNo = ModelNo + 1
                StepSize = PathsToGenerate(PathItemNo, 3)
                Call GetReaderNo 'Returns ReaderNo(K) array.
                Call AnalyzeModel
                Call GetAnalysisResults(ConfigNo, PathNo, PathItemNo)
            Next
        Next
    Next
    Application.ScreenUpdating = True
End Sub

Sub GetInputs()
    InputParametersForm.Show
    'Capture ConfigsList items into array variable ConfigsToAnalyze.
    Dim i As Integer, j As Integer
    ReDim ConfigsToAnalyze(NConfigs, 6)
    For i = 1 To NConfigs
        For j = 1 To 6
            ConfigsToAnalyze(i, j) = ConfigToAdd(j, i) 'Transpose columns and rows.
        Next
    Next
    'Sort PathsList through the range "PathsListSource" according to "e" and then "K".
    With Range("PathsListSource")
        .CurrentRegion.Sort key1:="e", key2:="StepSize", header:=xlYes
    End With
    'Capture the sorted PathsList into arrary PathsToGenerate.
    Dim l As Integer, m As Integer
    ReDim PathsToGenerate(NPathItems, 3)
    For l = 1 To NPathItems
        For m = 1 To 3
            PathsToGenerate(l, m) = Range("PathsListSource").Cells(l, m)
        Next
    Next
    'Loop through all paths and find how many path items (eCount) there are for each unique e.
    Dim p As Integer, q As Integer, Newe As Boolean
    NeUnique = 0 'Initialize the number of unique e to 0.
    For p = 1 To NPathItems
        Newe = True
        If NeUnique > 0 Then
```

```
                For q = 1 To NeUnique
                    If PathsToGenerate(p, 2) = e(q) Then
                        Newe = False
                        eCount(q) = eCount(q) + 1
                        Exit For
                    End If
                Next
            End If
            If Newe Then
                NeUnique = NeUnique + 1
                ReDim Preserve e(NeUnique)
                ReDim Preserve eCount(NeUnique)
                e(NeUnique) = PathsToGenerate(p, 2)
                eCount(NeUnique) = 1
            End If
    Next
End Sub

Sub CreateProjectFile()
    Dim ProjectFilePath As String, FileSpec As String, FileCount As Integer, FileName As String
    Workbooks.Add (ThisWorkbook.Path & "\ProjectFileTemplate.xls")
    ProjectFilePath = ThisWorkbook.Path & "\DataGenerated"
    FileSpec = ProjectFilePath & "\Project*.xls"
    FileCount = 0
    FileName = Dir(FileSpec)
    If FileName = "" Then
        ProjectFileName = "Project1"
        ActiveWorkbook.SaveAs FileName:=ProjectFilePath & "\" & ProjectFileName
    Else
        'Loop until no more project files are found.
        Do While FileName <> ""
            FileCount = FileCount + 1
            FileName = Dir()
        Loop
        ProjectFileName = "Project" & FileCount + 1
        ActiveWorkbook.SaveAs FileName:=ProjectFilePath & "\" & ProjectFileName
    End If
    ThisWorkbook.Worksheets("Inputs").Range("ConfigsListSource").Copy Destination:= _

Workbooks(ProjectFileName).Worksheets("Inputs").Range("A2")
    ThisWorkbook.Worksheets("Inputs").Range("PathsListSource").Copy Destination:= _

Workbooks(ProjectFileName).Worksheets("inputs").Range("H2")
    ThisWorkbook.Activate
End Sub

Sub GenRandReaderNo()
```

```
    'Redimension RandReaderNo array once the value of Ke is determined in the calling sub.
    ReDim RandReaderNo(OneKe)
    'Randomly generate a total Ke number of virtual readers.
    Dim i As Integer, j As Integer, FoundMatch As Boolean
    FoundMatch = False
    Randomize
    For i = 1 To OneKe
        Do
            RandReaderNo(i) = Int(Rnd * 900) + 1 'Generate a random integer value b/w 1 and
900.
            For j = 1 To i - 1
                If RandReaderNo(i) = RandReaderNo(j) Then
                    FoundMatch = True
                    Exit For 'Exit For j loop and try another random no. for the ith reader no.
                Else
                    FoundMatch = False 'Without this line, Do loop can be infinite.
                End If
            Next
        Loop While FoundMatch 'Keep generating ith random no. as long as there is a duplicate.
    Next
End Sub
Sub GetNearestNeighborPath()
'NRandReaders - number of virtual readers in the problem, equal to OneKe in the calling sub
'This sub consists of two parts, one to obtain distances between a pair of readers, and
' the other to obtain a path according to the nearest neighbor rule.
'First part to get the distance between a pair of two readers using a function sub CellDist.
    Dim NRandReaders As Integer, l As Integer, m As Integer, DistMatrix() As Integer
    NRandReaders = OneKe
    ReDim DistMatrix(NRandReaders, NRandReaders)
    For l = 1 To NRandReaders - 1
        For m = 2 To NRandReaders
            DistMatrix(l, m) = ReaderDist(l, m, n)
        Next
    Next
    For l = 2 To NRandReaders
        For m = 1 To l - 1
            DistMatrix(l, m) = DistMatrix(m, l)
        Next
    Next
'Second part is to get the nearest neighbor path, results in array PathIndex().If PathIndex(i)=j,
' this means i-th visit is j-th randomly generated reader, whose unique no is RandReaderNo(j).
' Definitions of variables:
'    i - index of i-th randomly generated reader, as in the array RandReaderNo(i)
'    Visited - a Boolean array: True if the rover has visited the i-th random reader
'    Step - a counter for the number of readers visited so far
'    PathIndex - an array where element i is the index of random reader visited at the i-th step
'        e.g., If Path(2) =38, then second visited reader's index is 38 and the unique reader no
```

```
'                is determined by the array RandReaderNo(38).
'    NowAt - index of the random reader current at, ranging from 1 to OneKe or NRandReaders
'    NextAt - index of the random reader to visit next
'    TotDist - total distance roved
'    MinDist - the minimum distance to the nearest neighbor reader (not yet visited)
    Dim i As Integer, Visited() As Boolean, Step As Integer, PathIndex() As Integer, _
        NowAt As Integer, NextAt As Integer, MinDist As Integer, TotDist As Integer
    ReDim Visited(NRandReaders)
    ReDim PathIndex(NRandReaders)
    PathIndex(1) = 1
    Visited(1) = True
    For i = 2 To NRandReaders
        Visited(i) = False
    Next
    NowAt = 1
    TotDist = 0
    For Step = 2 To NRandReaders
        MinDist = 1000 '1000 is an arbitray big number to initialize.
        For i = 2 To NRandReaders
            If i <> NowAt And Visited(i) = False Then
                If DistMatrix(NowAt, i) < MinDist Then
                    NextAt = i
                    MinDist = DistMatrix(NowAt, NextAt)
                End If
            End If
        Next i
        PathIndex(Step) = NextAt
        Visited(NextAt) = True
        TotDist = TotDist + MinDist
        NowAt = NextAt
    Next Step
    'Capture the nearest neighbor path in the RandPath array whose i-th element is now
    ' the reader no. that the rover visited at the i-th step.
    ReDim RandPath(NRandReaders)
    For i = 1 To NRandReaders
        RandPath(i) = RandReaderNo(PathIndex(i))
    Next
End Sub
Sub GetReaderNo()
    Dim i As Integer
    K = 0
    Do While StepSize * (K + 1) <= OneKe
        K = K + 1
    Loop
    ReDim ReaderNo(K)
    'Picks reader no's from RandPath() at a sampling frequency determined by the coefficient.
    For i = 1 To K
```

```
        ReaderNo(i) = RandPath(1 + StepSize * (i - 1))
    Next
    CoeffKe = K / OneKe
End Sub

Sub AnalyzeModel()
    Call GetReaderPos
    Call GetTagPos
    Call GetTagReads
    Call EstimateTagLocations
End Sub
Sub GetReaderPos()
    Dim i As Integer, j As Integer, ReaderCoord As Integer
    ReDim ReaderPos(K, 2)
    With ThisWorkbook.Worksheets("roverpos").Range("A1")
        For i = 1 To K 'i stands for an index as in ReaderNo(i).
            For j = 1 To 2 'If j=1, ReaderPos(i,j) returns x-grid coordinate of ReaderNo(i).
                ReaderCoord = .Offset(ReaderNo(i), j)
                ReaderPos(i, j) = AdjustedPos(ReaderCoord, n)
            Next
        Next
    End With
End Sub
Sub GetTagPos()
    Dim TagPosFileName As String, ConfigShtName As String, _
        i As Integer, j As Integer, TagCoord As Integer
    'The tag position file is in the same folder as this workbook.
    TagPosFileName = "TagConfig"
    ConfigShtName = ConfigType & Format(NTags, "00")
    ReDim TagNo(NTags)
    ReDim TagPos(NTags, 2)
    With Workbooks(TagPosFileName).Worksheets(ConfigShtName).Range("A1")
        For i = 1 To NTags
            TagNo(i) = .Offset(i, 0) 'Note the reader numbers for a particular model is stored
            'in ReaderNo(), not in RandReaderNo(). RandReaderNo() stores random reader
numbers
            'each of which does not manifest itself in a rover path.
            For j = 1 To 2
                TagCoord = .Offset(i, j)
                'Adjust tag positions depending the value of n (no. of partitions)
                TagPos(i, j) = AdjustedPos(TagCoord, n) 'using a custom function AdjustedPos.
            Next
        Next
    End With
    ReDim TagID(NTags) 'TagID stores last 2 of total 6 digits since the first 4 is always 3696.
    With ThisWorkbook.Worksheets("TagNo-ID").Range("A1")
        For i = 1 To NTags
```

```
            TagID(i) = Right(.Offset(TagNo(i), 1), 2)
        Next
    End With
End Sub
Sub GetTagReads()
    Dim PowerSetting As String, _
        ReadsFolderName As String, ReadsFilePath As String, ReadsFileName As String, _
        HasReadsFile As String, DataFileSpec As String, DataFileName As String, _
        DataFileCount As Integer, i As Integer, j As Integer, NDataFiles As Integer, _
        DataFileNo As Integer, CurReaderNo As Integer, Cell As Range
    Application.DisplayAlerts = False
    If r >= 40 Then
        PowerSetting = "H" 'for the High setting
    ElseIf r >= 29 Then
        PowerSetting = "M" 'for the Med Setting
    End If
    ReadsFolderName = PowerSetting & ConfigType & Format(NTags, "00")
    ReadsFilePath = ThisWorkbook.Path & "\ReadsTestbed\" & ReadsFolderName
    ReadsFileName = ReadsFolderName & "comb"
    'One data file with extension .csv represents one reading of RFID tags.
    HasReadsFile = Dir(ReadsFilePath & "\*comb.xls")
    DataFileSpec = ReadsFilePath & "\*.csv"
    DataFileName = Dir(DataFileSpec)
    DataFileCount = 0
    If HasReadsFile = "" Then 'If no readsfile exists, create one.
        Workbooks.Add
        ActiveWorkbook.SaveAs FileName:=ReadsFilePath & "\" & ReadsFileName
        With Workbooks(ReadsFileName).Worksheets(1).Range("A1")
            Do While DataFileName <> ""
                DataFileCount = DataFileCount + 1
                Workbooks.Open FileName:=ReadsFilePath & "\" & DataFileName
                Workbooks(DataFileName).Worksheets(1).Range("A1").CurrentRegion.Copy
                .Offset(DataFileCount - 1, 1).PasteSpecial Transpose:=True
                .Offset(DataFileCount - 1, 0) = Left(DataFileName, Len(DataFileName) - 4)
                Workbooks(DataFileName).Close
                DataFileName = Dir() 'Get the next data file in the ReadsFilePath
            Loop
            .CurrentRegion.Sort key1:=Range("A1")
            .CurrentRegion.Columns(1).Name = "DataFileName"
        End With
        Workbooks(ReadsFileName).Save
    Else 'Otherwise, just open the existing one.
        Workbooks.Open FileName:=ReadsFilePath & "\" & ReadsFileName
    End If
    ReDim TagReads(NTags, K)
    With Workbooks(ReadsFileName).Worksheets(1).Range("A1")
        NDataFiles = .CurrentRegion.Rows.Count
```

```
        For j = 1 To K 'j stands for an index of ReaderNo array
            CurReaderNo = ReaderNo(j)
            For DataFileNo = 1 To NDataFiles
                If .Offset(DataFileNo - 1, 0) = CurReaderNo Then
                    For i = 1 To NTags
                        For Each Cell In Range(.Offset(DataFileNo - 1, 1), .Offset(DataFileNo -
                                                      1, 1). End(xlToRight))
                            If Right(Cell.Value, 2) <> TagID(i) Then
                                TagReads(i, j) = 0
                            Else
                                TagReads(i, j) = 1
                                Exit For 'Each cell loop
                            End If
                        Next
                    Next i
                ElseIf .Offset(DataFileNo - 1, 0) > CurReaderNo Then
                    Exit For 'Exit DataFileNo loop and go to next ReaderNo(j).
                End If
            Next DataFileNo
        Next j
    End With
    Workbooks(ReadsFileName).Close
End Sub
Sub EstimateTagLocations()
    Dim i As Integer, j As Integer, Axis As Integer, Counter1 As Integer, Counter2 As Integer, _
        MaxReaderPosTag() As Integer, MinReaderPosTag() As Integer
    ReDim NReadsTag(NTags), NBadReadsTag(NTags), _
        MaxReaderPosTag(NTags, 2), MinReaderPosTag(NTags, 2), LocationEstimate(NTags, 4)
    For i = 1 To NTags
        Counter1 = 0
        Counter2 = 0
        For Axis = 1 To 2
            MaxReaderPosTag(i, Axis) = -1000
            MinReaderPosTag(i, Axis) = 1000
        Next
        For j = 1 To K
            If TagReads(i, j) = True Then
                Counter1 = Counter1 + 1
                For Axis = 1 To 2
                    If ReaderPos(j, Axis) < MyMax(TagPos(i, Axis) - rho, 1) Or _
                       ReaderPos(j, Axis) > MyMin(TagPos(i, Axis) + rho, n) Then
                        Counter2 = Counter2 + 1
                        Exit For
                    End If
                Next
                For Axis = 1 To 2
                    If ReaderPos(j, Axis) > MaxReaderPosTag(i, Axis) Then
```

```
                    MaxReaderPosTag(i, Axis) = ReaderPos(j, Axis)
                End If
                If ReaderPos(j, Axis) < MinReaderPosTag(i, Axis) Then
                    MinReaderPosTag(i, Axis) = ReaderPos(j, Axis)
                End If
            Next
        End If
    Next
    NReadsTag(i) = Counter1
    NBadReadsTag(i) = Counter2
    LocationEstimate(i, 1) = MyMax(MaxReaderPosTag(i, 1) - rho, 1) 'lower bound for x coord.
    LocationEstimate(i, 2) = MyMin(MinReaderPosTag(i, 1) + rho, n) 'upper bound for x coord.
    LocationEstimate(i, 3) = MyMax(MaxReaderPosTag(i, 2) - rho, 1) 'lower bound for y coord.
    LocationEstimate(i, 4) = MyMin(MinReaderPosTag(i, 2) + rho, n) 'upper bound for y coord.
Next
ReDim EstimateValid(NTags), EstimateUnbiased(NTags), EstimateSize(NTags)
For i = 1 To NTags
    If LocationEstimate(i, 1) <= LocationEstimate(i, 2) And _
       LocationEstimate(i, 3) <= LocationEstimate(i, 4) Then
        EstimateValid(i) = 1
        If TagPos(i, 1) >= LocationEstimate(i, 1) And _
           TagPos(i, 1) <= LocationEstimate(i, 2) And _
           TagPos(i, 2) >= LocationEstimate(i, 3) And _
           TagPos(i, 2) <= LocationEstimate(i, 4) Then
            EstimateUnbiased(i) = 1
            EstimateSize(i) = (LocationEstimate(i, 2) - LocationEstimate(i, 1) + 1) * _
                              (LocationEstimate(i, 4) - LocationEstimate(i, 3) + 1)
        Else
            EstimateUnbiased(i) = 0
            EstimateSize(i) = 0
        End If
    Else
        EstimateValid(i) = 0
        EstimateUnbiased(i) = 0
        EstimateSize(i) = 0
    End If
Next

ReDim TagIsInterior(NTags)
NTagsInt = 0
For i = 1 To NTags
    If TagPos(i, 1) >= rho + 1 And TagPos(i, 1) <= n - rho And _
       TagPos(i, 2) >= rho + 1 And TagPos(i, 2) <= n - rho Then
        TagIsInterior(i) = 1
        NTagsInt = NTagsInt + 1
    Else
        TagIsInterior(i) = 0
```

```
        End If
    Next

    NEstimateValid = 0
    NEstimateUnbiased = 0
    NEstimateValidInt = 0
    NEstimateUnbiasedInt = 0
    For i = 1 To NTags
        If EstimateValid(i) = True Then
            NEstimateValid = NEstimateValid + 1
            If TagIsInterior(i) = True Then
                NEstimateValidInt = NEstimateValidInt + 1
            End If
            If EstimateUnbiased(i) = True Then
                NEstimateUnbiased = NEstimateUnbiased + 1
                If TagIsInterior(i) = True Then
                    NEstimateUnbiasedInt = NEstimateUnbiasedInt + 1
                End If
            End If
        End If
    Next

    Dim SumNReadsTag As Integer, SumNBadReadsTag As Integer, SumNReadsTagInt As
Integer, _
        SumNBadReadsTagInt As Integer
    SumNReadsTag = 0
    SumNBadReadsTag = 0
    SumNReadsTagInt = 0
    SumNBadReadsTagInt = 0
    For i = 1 To NTags
        SumNReadsTag = SumNReadsTag + NReadsTag(i)
        SumNBadReadsTag = SumNBadReadsTag + NBadReadsTag(i)
        If TagIsInterior(i) = True Then
            SumNReadsTagInt = SumNReadsTagInt + NReadsTag(i)
            SumNBadReadsTagInt = SumNBadReadsTagInt + NBadReadsTag(i)
        End If
    Next
    ExpNReadsTag = SumNReadsTag / NTags
    ExpNBadReadsTag = SumNBadReadsTag / NTags
    ExpNReadsTagInt = SumNReadsTagInt / NTagsInt
    ExpNBadReadsTagInt = SumNBadReadsTagInt / NTagsInt

    Dim SumEstimateSize As Integer, SumEstimateSizeInt As Integer
    SumEstimateSize = 0
    SumEstimateSizeInt = 0
    For i = 1 To NTags
        If EstimateUnbiased(i) = True Then
```

```
                SumEstimateSize = SumEstimateSize + EstimateSize(i)
                If TagIsInterior(i) = True Then
                    SumEstimateSizeInt = SumEstimateSizeInt + EstimateSize(i)
                End If
            End If
        Next
        If NEstimateUnbiased <> 0 Then
            ExpEstimateSize = SumEstimateSize / NEstimateUnbiased
        Else
            ExpEstimateSize = -1
        End If
        If NEstimateUnbiasedInt <> 0 Then
            ExpEstimateSizeInt = SumEstimateSizeInt / NEstimateUnbiasedInt
        Else
            ExpEstimateSizeInt = -1
        End If
    End Sub

    Sub GetAnalysisResults(ConfigNo As Integer, PathNo As Integer, PathItemNo As Integer)
        With Workbooks(ProjectFileName).Worksheets("Models").Range("A1")
            .Offset(ModelNo, 0) = ModelNo
            .Offset(ModelNo, 1) = ConfigNo
            .Offset(ModelNo, 2) = PathNo
            .Offset(ModelNo, 3) = PathItemNo
            .Offset(ModelNo, 4) = ConfigType
            .Offset(ModelNo, 5) = NTags
            .Offset(ModelNo, 6) = s
            .Offset(ModelNo, 7) = n
            .Offset(ModelNo, 8) = r
            .Offset(ModelNo, 9) = rho
            .Offset(ModelNo, 10) = err
            .Offset(ModelNo, 11) = OneKe
            .Offset(ModelNo, 12) = StepSize
            .Offset(ModelNo, 13) = CoeffKe
            .Offset(ModelNo, 14) = K
            .Offset(ModelNo, 15) = ExpNReadsTag
            .Offset(ModelNo, 16) = ExpNBadReadsTag
            .Offset(ModelNo, 17) = NEstimateValid
            .Offset(ModelNo, 18) = NEstimateUnbiased
            .Offset(ModelNo, 19) = ExpEstimateSize
            .Offset(ModelNo, 20) = NTagsInt
            .Offset(ModelNo, 21) = ExpNReadsTagInt
            .Offset(ModelNo, 22) = ExpNBadReadsTagInt
            .Offset(ModelNo, 23) = NEstimateValidInt
            .Offset(ModelNo, 24) = NEstimateUnbiasedInt
            .Offset(ModelNo, 25) = ExpEstimateSizeInt
        End With
```

```
    Workbooks(ProjectFileName).Activate
    Worksheets("ModelSht").Copy before:=Worksheets("ModelSht")
    ActiveSheet.Name = "Model" & ModelNo
    Dim i As Integer, j As Integer, l As Integer
    With Workbooks(ProjectFileName).Worksheets("Model" & ModelNo).Range("A1")
        For i = 1 To NTags
            .Offset(i, 0) = i
            .Offset(i, 1) = TagNo(i)
            .Offset(i, 2) = TagPos(i, 1)
            .Offset(i, 3) = TagPos(i, 2)
            .Offset(i, 4) = NReadsTag(i)
            .Offset(i, 5) = NBadReadsTag(i)
            .Offset(i, 6) = EstimateValid(i)
            .Offset(i, 7) = EstimateUnbiased(i)
            .Offset(i, 8) = EstimateSize(i)
            .Offset(i, 9) = TagIsInterior(i)
            .Offset(i, 10) = LocationEstimate(i, 1)
            .Offset(i, 11) = LocationEstimate(i, 2)
            .Offset(i, 12) = LocationEstimate(i, 3)
            .Offset(i, 13) = LocationEstimate(i, 4)
        Next
        For j = 1 To K
            .Offset(j, 14) = j
            .Offset(j, 15) = ReaderNo(j)
            .Offset(j, 16) = ReaderPos(j, 1)
            .Offset(j, 17) = ReaderPos(j, 2)
            For l = 1 To NTags
                .Offset(j, 17 + l) = TagReads(l, j)
            Next
        Next
    End With
    Worksheets("Models").Activate
    Workbooks(ProjectFileName).Save
End Sub
```

Module 2

```
        Option Explicit
        Option Base 1

        Function Ke(n As Integer, rho As Integer, e As Integer) As Single
            Ke = n ^ 2 * (Log(8 * rho * (2 * rho + 1)) - Log(e)) / (2 * rho + 1) 'The Log is Natural log.
        End Function

        Function ReaderDist(u As Integer, v As Integer, n As Integer) As Integer
            'u and v represent an index of two different readers in the RandReaderNo() array,
between which
            'the distance is calculated by ReaderDist function.
            'n represents the number of cell partitions.
            Dim R1xCoord As Integer, R1yCoord As Integer, R2xCoord As Integer, R2yCoord As
Integer, _
                R1xPos As Integer, R1yPos As Integer, R2xPos As Integer, R2yPos As Integer
            With ThisWorkbook.Worksheets("roverpos").Range("a1")
                R1xCoord = .Offset(RandReaderNo(u), 1)
                R1yCoord = .Offset(RandReaderNo(u), 2)
                R2xCoord = .Offset(RandReaderNo(v), 1)
                R2yCoord = .Offset(RandReaderNo(v), 2)
            End With
            R1xPos = AdjustedPos(R1xCoord, n)
            R1yPos = AdjustedPos(R1yCoord, n)
            R2xPos = AdjustedPos(R2xCoord, n)
            R2yPos = AdjustedPos(R2yCoord, n)
            ReaderDist = Application.WorksheetFunction.Max(Abs(R1xPos - R2xPos),
Abs(R1yPos - R2yPos))
        End Function

        Function AdjustedPos(NodeCoord As Integer, NPartitions As Integer) As Integer
            Select Case NPartitions
                Case 30: AdjustedPos = NodeCoord
                Case 15: AdjustedPos = Int((NodeCoord + 1) / 2)
                Case 10: AdjustedPos = Int((NodeCoord + 2) / 3)
            End Select
        End Function
        Function MyMax(i As Integer, j As Integer) As Integer
            If i > j Then
                MyMax = i
            Else
                MyMax = j
            End If
        End Function
        Function MyMin(i As Integer, j As Integer) As Integer
```

```
    If i < j Then
        MyMin = i
    Else
        MyMin = j
    End If
End Function

Sub CalEstimateIfValid()
'After running the Main sub in Module 1, it was advised that the estimate size should also be calculated
' even if the estimate is biased, that is, the estimate does not contain the actual location of a tag.
'This sub calculates the estimate size for those tags whose estimate is biased but valid.
'The estimate is valid if x- <= x+ and y- <= y+, where x- and x+ represents the estimated lower and upper
' bounds of x grid coordinates of the tag, respectively.
    Dim ProjectFilePath As String, ProjectFileSpec As String, ProjectFileName As String, _
        NModels As Integer, ModelNo As Integer, ModelShtName As String, NTags As Integer, i As Integer, _
        NEstimateValid As Integer, SumEstimateSizeVal As Integer, ExpEstimateSizeVal As Single, _
        NEstimateValidInt As Integer, SumEstimateSizeValInt As Integer, ExpEstimateSizeValInt As Single, _
        NEstimateValButBiased As Integer, SumBiasX As Integer, SumBiasY As Integer, SumBias As Integer, _
        NEstimateValButBiasedInt As Integer, SumBiasXInt As Integer, SumBiasYInt As Integer, _
        SumBiasInt As Integer, _
        ExpBiasX As Single, ExpBiasY As Single, ExpBias As Single, _
        ExpBiasXInt As Single, ExpBiasYInt As Single, ExpBiasInt As Single
    ProjectFilePath = ThisWorkbook.Path & "\DataGenerated"
    ProjectFileSpec = ProjectFilePath & "\Project*.xls"
    ProjectFileName = Dir(ProjectFileSpec)
    Do While ProjectFileName <> ""
        Workbooks.Open FileName:=ProjectFilePath & "\" & ProjectFileName
        With Workbooks(ProjectFileName).Worksheets("Models").Range("A1")
            .CurrentRegion.Sort key1:="ModelNo", header:=xlYes
            NModels = Range(.Offset(1, 0), .Offset(1, 0).End(xlDown)).Rows.Count
            'Insert a column left to the column T with heading "ExpEstimateSize", and give to this new
            ' column a heading "ExpEstimateSizeVal" and change the "ExpEstimateSize" to
            ' "ExpEstimateSizeUnb".
            .Offset(0, 19).EntireColumn.Insert
            .Offset(0, 19) = "ExpEstimateSizeVal"
            .Offset(0, 20) = "ExpEstimateSizeUnb"
```

```
                    .Offset(0, 21).EntireColumn.Insert 'Insert three new columns left to the
column "NTagsInt"
                    .Offset(0, 21) = "ExpBias"
                    .Offset(0, 21).EntireColumn.Insert
                    .Offset(0, 21) = "ExpBiasY"
                    .Offset(0, 21).EntireColumn.Insert
                    .Offset(0, 21) = "ExpBiasX"
                    .Offset(0, 29).EntireColumn.Insert
                    .Offset(0, 29) = "ExpEstimateSizeValInt"
                    .Offset(0, 30) = "ExpEstimateSizeUnbInt"
                    .Offset(0, 31) = "ExpBiasXInt"
                    .Offset(0, 32) = "ExpBiasYInt"
                    .Offset(0, 33) = "ExpBiasInt"
                End With
                For ModelNo = 1 To NModels
                    NEstimateValid = 0 'Reset the number of valid estimates to be 0 for each
ModelNo.
                    SumEstimateSizeVal = 0 'Reset the sum of valid estimate size for each tag
to be 0.
                    NEstimateValButBiased = 0
                    SumBiasX = 0
                    SumBiasY = 0
                    SumBias = 0
                    NEstimateValidInt = 0
                    SumEstimateSizeValInt = 0
                    NEstimateValButBiasedInt = 0
                    SumBiasXInt = 0
                    SumBiasYInt = 0
                    SumBiasInt = 0
                    ModelShtName = Worksheets("Model" & ModelNo).Name
                    With Worksheets(ModelShtName).Range("A1")
                        NTags = Range(.Offset(1, 0), .Offset(1, 0).End(xlDown)).Rows.Count
                        .Offset(0, 8).EntireColumn.Insert
                        .Offset(0, 8) = "EstimateSizeVal"
                        .Offset(0, 9) = "EstimateSizeUnb" 'Change from "EstimateSize".
                        .Offset(0, 10).EntireColumn.Insert
                        .Offset(0, 10) = "Bias"
                        .Offset(0, 10).EntireColumn.Insert
                        .Offset(0, 10) = "BiasY"
                        .Offset(0, 10).EntireColumn.Insert
                        .Offset(0, 10) = "BiasX"
                        For i = 1 To NTags
                            If .Offset(i, 6) = "True" Then 'If the EstimateValid value for a tag is
true
                                NEstimateValid = NEstimateValid + 1
                                .Offset(i, 8) = (.Offset(i, 15) - .Offset(i, 14) + 1) * _
                                                (.Offset(i, 17) - .Offset(i, 16) + 1)
```

```
                SumEstimateSizeVal = SumEstimateSizeVal + .Offset(i, 8)
                'If the tag is in interior, calculate the previous statistics similarly.
                If .Offset(i, 13) = "True" Then
                    NEstimateValidInt = NEstimateValidInt + 1
                    SumEstimateSizeValInt      =      SumEstimateSizeValInt
+ .Offset(i, 8)

                End If
                'If the estimate is valid but not unbiased, calculate biases.
                If .Offset(i, 7) = "False" Then
                    NEstimateValButBiased = NEstimateValButBiased + 1
                    '.offset(i,10) contains the bias in X grid coordinate, and is
calculated as

                    ' the minimum distance b/w the tag's actual X grid
coordinate and estimated
                    ' lower/upper X coordinate.
                    ' The tags actual X grid coord. is in .offset(i,2), and the
estimated

                    ' lower and upper X grid coordinates are in .offset(i,14)
and .offset(i,15).
                    If .Offset(i, 2) >= .Offset(i, 14) And .Offset(i, 2) <= .Offset(i,
15) Then

                        .Offset(i, 10) = 0 'The estimated x coord's contain
actual x coord.
                    Else
                        .Offset(i, 10) = MyMin(Abs(.Offset(i, 2) - .Offset(i, 14)),
_

                                                  Abs(.Offset(i, 2) - .Offset(i,
15)))
                    End If
                    SumBiasX = SumBiasX + .Offset(i, 10)
                    'Similarly for Y grid coordinate,
                    If .Offset(i, 3) >= .Offset(i, 16) And .Offset(i, 3) <= .Offset(i,
17) Then

                        .Offset(i, 11) = 0
                    Else
                        .Offset(i, 11) = MyMin(Abs(.Offset(i, 3) - .Offset(i, 16)),
_

                                                  Abs(.Offset(i, 3) - .Offset(i,
17)))
                    End If
                    SumBiasY = SumBiasY + .Offset(i, 11)
                    'Then the bias is defined as the maximum of BiasX and
BiasY.

                    .Offset(i, 12) = MyMax(.Offset(i, 10), .Offset(i, 11))
                    SumBias = SumBias + .Offset(i, 12)
                    'If the tag is in interior, compute the corresponding biases.
                    If .Offset(i, 13) = "True" Then
```

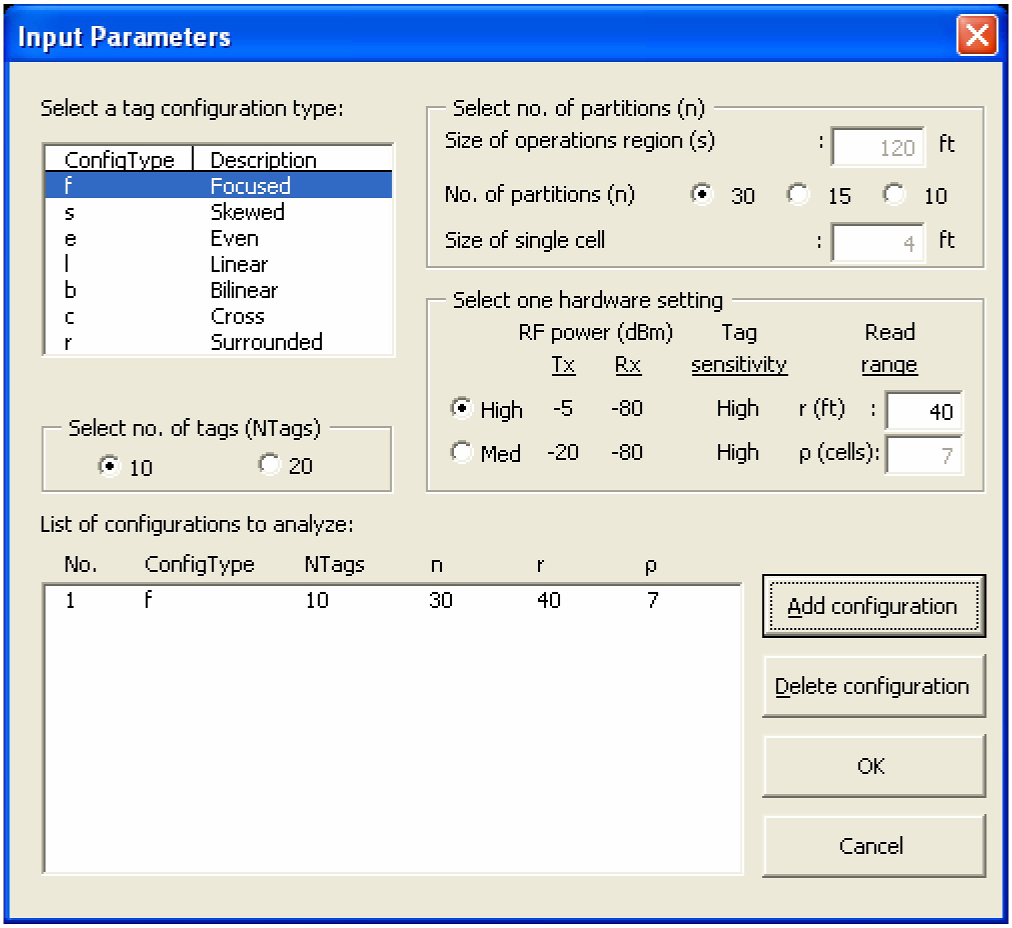
```
                                        NEstimateValButBiasedInt =
NEstimateValButBiasedInt + 1
                                        SumBiasXInt = SumBiasXInt + .Offset(i, 10)
                                        SumBiasYInt = SumBiasYInt + .Offset(i, 11)
                                        SumBiasInt = SumBiasInt + .Offset(i, 12)
                                    End If
                                Else 'if the estimate is valid and unbiased, then the bias is 0 by
definition.
                                    .Offset(i, 10) = 0
                                    .Offset(i, 11) = 0
                                    .Offset(i, 12) = 0
                                End If
                            Else
                                .Offset(i, 8) = 0 'If the estimate is invalid, the estimate size is
coded as 0,
                                .Offset(i, 10) = 1000 'and biases are coded to be 1000.
                                .Offset(i, 11) = 1000
                                .Offset(i, 12) = 1000
                            End If
                        Next 'TagNo loop
                    End With
                    If NEstimateValid = 0 Then 'If there is no single valid estimate, then code as
follows.
                        ExpEstimateSizeVal = -1
                        ExpBiasX = 1000
                        ExpBiasY = 1000
                        ExpBias = 1000
                    'If all valid estimates are also unbiased,i.e., there are no valid estimates that
are biased
                    ElseIf NEstimateValButBiased = 0 Then
                        ExpEstimateSizeVal = SumEstimateSizeVal / NEstimateValid
                        ExpBiasX = 0 'By definition of bias, there is no bias, thus the value being
0.
                        ExpBiasY = 0
                        ExpBias = 0
                    Else 'If there is at least one valid estimate which may be biased
                        ExpEstimateSizeVal = SumEstimateSizeVal / NEstimateValid
                        ExpBiasX = SumBiasX / NEstimateValButBiased
                        ExpBiasY = SumBiasY / NEstimateValButBiased
                        ExpBias = SumBias / NEstimateValButBiased
                    End If
                    'Similarly for the tags that lie in interior
                    If NEstimateValidInt = 0 Then
                        ExpEstimateSizeValInt = -1
                        ExpBiasXInt = 1000
                        ExpBiasYInt = 1000
                        ExpBiasInt = 1000
```

```
                    ElseIf NEstimateValButBiasedInt = 0 Then
                        ExpEstimateSizeValInt = SumEstimateSizeValInt / NEstimateValidInt
                        ExpBiasXInt = 0
                        ExpBiasYInt = 0
                        ExpBiasInt = 0
                    Else
                        ExpEstimateSizeValInt = SumEstimateSizeValInt / NEstimateValidInt
                        ExpBiasXInt = SumBiasXInt / NEstimateValButBiasedInt
                        ExpBiasYInt = SumBiasYInt / NEstimateValButBiasedInt
                        ExpBiasInt = SumBiasInt / NEstimateValButBiasedInt
                    End If
                    Worksheets("Models").Range("T1").Offset(ModelNo, 0) =
Format(ExpEstimateSizeVal, "0.0")
                    Worksheets("Models").Range("V1").Offset(ModelNo, 0) = Format(ExpBiasX,
"0.0")
                    Worksheets("Models").Range("W1").Offset(ModelNo, 0) = Format(ExpBiasY,
"0.0")
                    Worksheets("Models").Range("X1").Offset(ModelNo, 0) = Format(ExpBias,
"0.0")
                    Worksheets("models").Range("AD1").Offset(ModelNo, 0) =
Format(ExpEstimateSizeValInt, "0.0")
                    Worksheets("Models").Range("AF1").Offset(ModelNo, 0) =
Format(ExpBiasXInt, "0.0")
                    Worksheets("Models").Range("AG1").Offset(ModelNo, 0) =
Format(ExpBiasYInt, "0.0")
                    Worksheets("Models").Range("AH1").Offset(ModelNo, 0) =
Format(ExpBiasInt, "0.0")
                Next 'ModelNo loop
                Workbooks(ProjectFileName).Save
                Workbooks(ProjectFileName).Close
                ProjectFileName = Dir() 'Go to the next project file that satisfies the
ProjectFileSpec.
            Loop
        End Sub
        Sub ChangeModelShtName()
            Dim WkSht As Worksheet, ShtNameIndOld As Variant, ShtNameIndNew As Variant
            For Each WkSht In Workbooks("e20rho3").Worksheets
                If WkSht.Name <> "Inputs" And WkSht.Name <> "Models" And WkSht.Name <>
"ModelSht" Then
                    ShtNameIndOld = Right(WkSht.Name, 3)
                    ShtNameIndNew = ShtNameIndOld - 150
                    WkSht.Name = "Model" & ShtNameIndNew
                End If
            Next
        End Sub
        Sub CopyAllProjModels()
```

```
      Dim ProjectFilePath As String, ProjectFileSpec As String, ProjectFileName As String,
_
        NModelsBefore As Integer, NModelsAfter As Integer, RowOffset As Integer, _
        ProjectNo As String
      ProjectFilePath = ThisWorkbook.Path & "\DataGenerated"
      ProjectFileSpec = ProjectFilePath & "\Project*.xls"
      ProjectFileName = Dir(ProjectFileSpec)
      Workbooks.Add
      ActiveWorkbook.SaveAs FileName:=ProjectFilePath & "\AllProjModels.xls"
      Worksheets(1).Name = "All"
      Worksheets("All").Range("A1") = "ProjNo"
      Do While ProjectFileName <> ""
        Workbooks.Open FileName:=ProjectFilePath & "\" & ProjectFileName
        NModelsBefore =
Workbooks("AllProjModels").Worksheets("All").UsedRange.Rows.Count - 1
        With Workbooks(ProjectFileName).Worksheets("Models").Range("A1")
          Range(.Offset(1, 0), .Offset(1, 0).End(xlDown).End(xlToRight)).Copy
Destination:= _
            Workbooks("AllProjModels").Worksheets("All").Range("B1").Offset(1 +
NModelsBefore, 0)
          NModelsAfter = NModelsBefore + Range(.Offset(1, 0), .Offset(1,
0).End(xlDown)).Rows.Count
        End With
        ProjectNo = Mid(ProjectFileName, 8, Len(ProjectFileName) - 11)
        With Workbooks("AllProjModels").Worksheets("All").Range("A1")
          For RowOffset = (NModelsBefore + 1) To NModelsAfter
            .Offset(RowOffset, 0) = ProjectNo
          Next
        End With
        Workbooks("AllProjModels").Save
        Workbooks(ProjectFileName).Close
        ProjectFileName = Dir() 'Go to the next project file that satisfies the
ProjectFileSpec.
      Loop
    End Sub
```

User Form "InputParametersForm"

Graphic User Interface



Input Parameters

Select a tag configuration type:

ConfigType	Description
f	Focused
s	Skewed
e	Even
l	Linear
b	Bilinear
c	Cross
r	Surrounded

Select no. of tags (NTags)

● 10 ○ 20

Select no. of partitions (n)

Size of operations region (s) : 120 ft

No. of partitions (n) ● 30 ○ 15 ○ 10

Size of single cell : 4 ft

Select one hardware setting

	RF power (dBm) Tx	Rx	Tag sensitivity	Read range	
● High	-5	-80	High	r (ft) :	40
○ Med	-20	-80	High	p (cells):	7

List of configurations to analyze:

No.	ConfigType	NTags	n	r	p
1	f	10	30	40	7

VBA Codes

```
Option Base 1
Dim ConfigType As String, NTags As Integer, n As Integer, r As Integer, _
      RowCounter As Integer, NDeletedRows As Integer

Private Sub CancelButton_Click()
      Unload Me
      End
End Sub
```

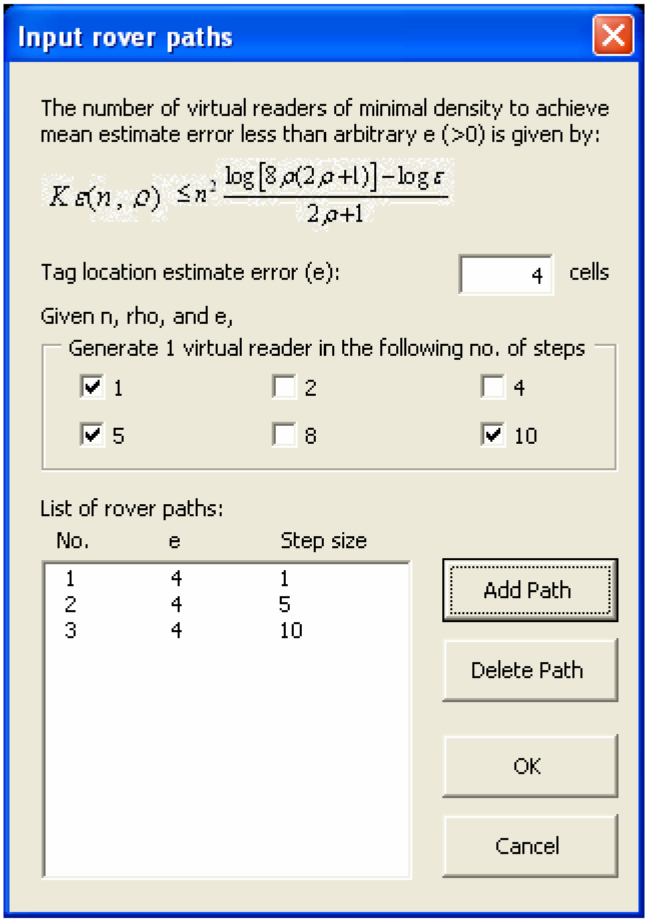
```
Private Sub UserForm_initialize()
    Range("ConfigsListsource").Clear
    ConfigTypeList.Selected(0) = True
    ConfigType = "f"
    NTags10Option = True
    RegionSizeBox = "120" 'ft
    s = RegionSizeBox 's is a pulic variable.
    HighSettingOption = True
    n30Option = True
    RowCounter = 0
End Sub

Private Sub ConfigTypeList_change()
    ConfigType = ConfigTypeList.Value
End Sub

Private Sub n30option_click()
    n = 30
    CellSizeBox = s / n
    RhoBox = Int((n * CommRangeBox) / (Sqr(2) * s))
End Sub
Private Sub n15option_click()
    n = 15
    CellSizeBox = s / n
    RhoBox = Int((n * CommRangeBox) / (Sqr(2) * s))
End Sub
Private Sub n10option_click()
    n = 10
    CellSizeBox = s / n
    RhoBox = Int((n * CommRangeBox) / (Sqr(2) * s))
End Sub
Private Sub HighSettingOption_click()
    CommRangeBox = 40 'may be up to 51 ft.
End Sub
Private Sub MedSettingOption_click()
    CommRangeBox = 29 'ft
End Sub

Private Sub commrangebox_change()
    On Error GoTo EmptyBox
    RhoBox = Int((n * CommRangeBox) / (Sqr(2) * s))
'Error handler in case the CommRangeBox is empty.
EmptyBox:
    CommRangeBox.SetFocus
End Sub
```

```
Private Sub AddConfigButton_click()
    'Check if a read range is proper.
    If HighSettingOption = True And CommRangeBox < 40 Then
        MsgBox "Read range for the High setting must be greater than or equal to 40 ft.",
vbExclamation
        CommRangeBox.SetFocus
        Exit Sub
    ElseIf MedSettingOption = True And (CommRangeBox < 29 Or CommRangeBox > 39) Then
        MsgBox "Read range for the Med setting must be between 29 and 39 ft.", vbExclamation
        CommRangeBox.SetFocus
        Exit Sub
    Else
        r = CommRangeBox
    End If
    'Capture the number of tags.
    If NTags10Option = True Then
        NTags = 10
    Else
        NTags = 20
    End If
    Dim i As Integer, j As Integer
    RowCounter = RowCounter + 1 'Rowcounter indicates the number of rows in ConfigsList.
    ReDim Preserve ConfigToAdd(6, RowCounter) 'Resize the array depending on the number of
rows.
    'Set each element of the last row in ConfigsList to the value of appropriate controls.
    ConfigToAdd(1, RowCounter) = RowCounter
    ConfigToAdd(2, RowCounter) = ConfigType
    ConfigToAdd(3, RowCounter) = NTags
    ConfigToAdd(4, RowCounter) = n
    ConfigToAdd(5, RowCounter) = r
    ConfigToAdd(6, RowCounter) = RhoBox
    'Populate the ConfigsList using the ConfigToAdd arrary.
    ConfigsList.Column() = ConfigToAdd
End Sub

Private Sub DelConfigButton_click()
    Dim i As Integer, j As Integer, K As Integer
    RowCounter = 0 'Reset RowCounter to 0.
    NDeletedRows = 0 'Initialize the number of rows to be deleted to 0.
    If ConfigsList.ListCount = 0 Then
        MsgBox "There is no analysis to delete.", vbInformation
        Exit Sub
    Else
        For i = 0 To ConfigsList.ListCount - 1
            If ConfigsList.Selected(i) Then
                NDeletedRows = NDeletedRows + 1
            Else
```

```
                RowCounter = RowCounter + 1
                ReDim Preserve ConfigToAdd(6, RowCounter)
                For j = 1 To 6
                    ConfigToAdd(j, RowCounter) = ConfigsList.Column(j - 1, i)
                Next j
                ConfigToAdd(1, RowCounter) = ConfigsList.Column(0, i) - NDeletedRows
            End If
        Next i
    End If
    If NDeletedRows = 0 Then
        MsgBox "Select at least one item from the list."
    ElseIf NDeletedRows = ConfigsList.ListCount Then
        ConfigsList.Clear
    Else
        ConfigsList.Column() = ConfigToAdd
    End If
End Sub

Private Sub OkButton_Click()
    NConfigs = ConfigsList.ListCount 'Capture the number of analyses in a public variable.
    If NConfigs > 0 Then
        With Worksheets("Inputs").Range("A2")
            For i = 0 To ConfigsList.ListCount - 1
                For j = 0 To 5
                    .Offset(i, j) = ConfigsList.List(i, j)
                Next j
            Next i
            Range(.Offset(0, 0), .Offset(NConfigs - 1, 5)).Name = "ConfigsListSource"
        End With
    Else
        MsgBox "There is no item to analyze. Add at least one."
        Exit Sub
    End If
    InputPathForm.Show
End Sub
```

User Form “InputPathForm”

Graphic User Interface



The number of virtual readers of minimal density to achieve mean estimate error less than arbitrary e (>0) is given by:

$$K_{\varepsilon}(n, \rho) \leq n^{2} \frac{\log[8\rho(2\rho+1)] - \log \varepsilon}{2\rho+1}$$

Tag location estimate error (e): 4 cells

Given n, rho, and e,

Generate 1 virtual reader in the following no. of steps

☑ 1 ☐ 2 ☐ 4

☑ 5 ☐ 8 ☑ 10

List of rover paths:

No.	e	Step size
1	4	1
2	4	5
3	4	10

VBA Codes

```
        Option Explicit
        Option Base 1
        Dim e As Integer, ctl As Control, StepCount As Integer, StepSize() As String, RowCount
As Integer, _
            NDeletedRows As Integer

        Private Sub CancelButton_Click()
            Unload Me
        End Sub
```

```
Private Sub UserForm_initialize()
      Range("PathsListsource").Clear
      eBox = 1
      EveryTwoStepsCheck = True
      StepCount = 0
      RowCount = 0
End Sub

Private Sub AddPathButton_Click()
      'Capture estimate size error e.
      e = eBox
      StepCount = 0 'Reset StepCount to 0 every time the button is clicked.
      For Each ctl In Me.Controls
            If TypeName(ctl) = "CheckBox" Then
                  If ctl.Value = True Then
                        StepCount = StepCount + 1
                        ReDim Preserve StepSize(StepCount)
                        StepSize(StepCount) = ctl.Caption
                  End If
            End If
      Next
      If StepCount = 0 Then
            MsgBox "Make at least one choice for a step size."
            EveryTwoStepsCheck.SetFocus
            Exit Sub
      Else
            RowCount = RowCount + StepCount
            ReDim Preserve PathToAdd(3, RowCount)
            Dim i As Integer
            For i = 1 To StepCount
                  PathToAdd(1, RowCount - StepCount + i) = RowCount - StepCount + i
                  PathToAdd(2, RowCount - StepCount + i) = e
                  PathToAdd(3, RowCount - StepCount + i) = StepSize(i)
            Next
            PathsList.Column() = PathToAdd
      End If
End Sub

Private Sub DeletePathButton_Click()
      Dim i As Integer, j As Integer
      RowCount = 0 'Reset RowCount to 0.
      NDeletedRows = 0 'Initialize the number of rows to be deleted to 0.
      If PathsList.ListCount = 0 Then
            MsgBox "There is no path to delete.", vbInformation
            Exit Sub
      Else
```

```
            For i = 0 To PathsList.ListCount - 1
                If PathsList.Selected(i) Then
                    NDeletedRows = NDeletedRows + 1
                Else
                    RowCount = RowCount + 1
                    ReDim Preserve PathToAdd(3, RowCount)
                    For j = 1 To 3
                        PathToAdd(j, RowCount) = PathsList.Column(j - 1, i)
                    Next j
                    PathToAdd(1, RowCount) = PathsList.Column(0, i) - NDeletedRows
                End If
            Next i
        End If
        If NDeletedRows = 0 Then
            MsgBox "Select at least one item from the list."
        ElseIf NDeletedRows = PathsList.ListCount Then
            PathsList.Clear
        Else
            PathsList.Column() = PathToAdd
        End If
    End Sub

    Private Sub OkButton_Click()
        NPathItems = PathsList.ListCount 'Capture the number of paths in a public variable.
        Dim i As Integer, j As Integer
        If NPathItems > 0 Then
            With Worksheets("Inputs").Range("H2")
                For i = 0 To PathsList.ListCount - 1
                    For j = 0 To 2
                        .Offset(i, j) = PathsList.List(i, j)
                    Next j
                Next i
                Range(.Offset(0, 0), .Offset(NPathItems - 1, 2)).Name = "PathsListSource"
            End With
        Else
            MsgBox "There is no item to analyze. Add at least one."
            Exit Sub
        End If
        'SelectPathForm.Show
        Unload Me
        Unload InputParametersForm
    End Sub
```

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Vita

Jongchul Song was born in Yosu, South Korea on July 7, 1971, the son of Haengjoon Song and Misook Kim. After completing his work at Yosu High School, Yosu, in 1990, he entered Yonsei University in Seoul, South Korea. After the first two years studies in Architectural Engineering, he served as a Korean Augmentation Troops to the United States Army for 26 months. He received the degree of Bachelor of Science from Yonsei University in February, 1997. During the following years he was employed by Lotte Engineering and Construction Co., Ltd. and worked as an assistant engineering manager on a building construction site in Malaysia and a project engineer in the head office. In September, 2000, he entered the Graduate School at The University of Texas at Austin.

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